This is to certify that the

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THE CHILLED AERATION AND STORAGE OF CEREAL GRAINS

presented by

DIRK E. MAIER

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F.W. Bakker-Arkema
Major professor

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THE CHILLED AERATION AND STORAGE OF CEREAL GRAINS

Volume I

By

Dirk E. Maier

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ABSTRACT

THE CHILLED AERATION AND STORAGE OF CEREAL GRAINS

By

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Grain chilling is a non-chemical preservation technology that utilizes a refrigeration system to control the temperature and moisture content in stored grain independent of the ambient conditions. Over 10 million metric tonnes of grain are chilled annually throughout the world, but very little in the U.S.A. A comprehensive analysis of chilled aeration and storage of cereal grains is made considering physical, operational and biological factors.

A model was developed of the performance of a commercial grain chiller. It predicts the flowrate, temperature and relative humidity of the air under transient conditions. The chiller model was incorporated into a grain-aeration model, which predicts the temperature and moisture content in a grain mass. A third model describes the influence of the ambient conditions on the chilled grain during non-ventilated storage periods. Experimental data for a three-year period was used to validate the MSU Systems Model for Chilled Aeration and Storage of Cereal Grains.

The main results of the tests with corn and wheat revealed that (1) the ambient conditions significantly affect the airflow rate through the chiller, (2) the reheating of the chilled air significantly affects the cool-down time and moisture loss of the grain, (3) a small change in the cold-air set-point hardly changes the refrigeration capacity of the chiller, (4) the geographic location and surface-to-volume ratio of the grain bin have the greatest influence on the temperature distribution in the chilled grain during non-ventilated storage, and (5) in order to preserve grain quality, chilled aeration is preferred over ambient aeration and over no-aeration.

A new procedure was developed to chill grain immediately as the bin is filled and to intermittently rechill the outer grain layers only. This management technique minimizes the dry-matter loss and the risk of insect-infestation. The process of chilled aeration followed by low-temperature storage was found to be technically feasible and biologically desirable for cereal grains in the Midwestern U.S.A. Economic and environmental considerations must be taken into account in the final evaluation of the process of grain chilling in the United States.

F.W. Bakker-Arkema
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DEDICATION

To Heidi & Sophie,

and Maude & Rudy.

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I am forever indebted to my wife Heidi. Her patience while pursuing my education to this final goal has been extraordinary. Her love, her support and her understanding make life meaningful and beautiful.

Above all, praise to the Lord Jesus Christ, who came into this world to die for us on the cross, so that our sins may be forgiven, and that we may have eternal life!

East Lansing, Michigan
February 1992

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A	surface area, m^2
A_f	face area of heat transfer coils, m^2
A_{fl}	perforated floor area, m^2
A_g	level grain surface area, m^2
A_{gr}	plenum floor area, m^2
A_{pr}	plenum perimeter surface area, m^2
AST	allowable grain storage time, hr
B_b	dimensionless factor in heat conduction equation
B_p	dimensionless factor in heat conduction equation
D	mechanical damage, %
DM	dry matter loss, %
E	dimensionless factor in heat conduction equation
F	chiller refrigeration cycle loss factor, decimal
F_{BG}	radiative ground-to-bin shape factor, dimensionless
F_{BS}	radiative sky-to-bin shape factor, dimensionless
$\underline{H}$	absolue humidity, kg/kg
$\underline{H}_D$	average day diffuse solar radiation, W/m^2
H_T	average day total solar radiation, W/m^2
I_B	hourly beam solar radiation, W/m^2
I_D	hourly diffuse solar radiation, W/m^2
$\underline{I}_T$	hourly total solar radiation, W/m^2
K_T	average day clearness index, dimensionless
L	bed depth of grain pile, m
M	moisture content, decimal dry basis
M_w	moisture content, percent wet basis
N'	electrical frequency multiplier, decimal
P	vapor pressure, Pa
Pr	Prandtl number, dimensionless
Q_G	airflow rate through grain, m^3/h
Q_F	airflow delivered by chiller fan, m^3/h
R_B	solar collector tilt factor, dimensionless
Re	Reynolds number, dimensionless
RH	relative humidity, decimal (or percent)
T	temperature, °C
T_a	ambient temperature, °C
T_b	bin head space temperature, °C
T_c	condensing refrigerant temperature, °C
T_e	evaporating refrigerant temperature, °C
T_g	grain surface temperature, °C
T_{gr}	deep ground temperature, °C
T_{fl}	perforated floor temperature, °C
T_o	condenser outlet air temperature, °C
T_p	bin plenum temperature, °C
T_{pr}	plenum perimeter wall temperature, °C
T_R	reference time for dry matter loss, hr
T_s	sky temperature, °C

U overall heat transfer coefficient, $W/m^2/°C$, or dimensionless factor in heat conduction equation

U_{Ew} overall wet heat transfer coefficient, $W/m^2/(kJ/kg)$

U_g overall heat transfer coefficient from grain surface to head-space, $W/m^2/°C$

U_{gr} overall heat transfer coefficient from concrete floor to plenum, $W/m^2/°C$

U_{fl} overall heat transfer coefficient from perforated floor to plenum, $W/m^2/°C$

U_{pr} overall heat transfer coefficient through plenum perimeter, $W/m^2/°C$

U_r radiative top loss coefficient from bin roof, $W/m^2/°C$

V velocity, m/s

V_a air velocity through grain, $m^3/s/m^2$

V_b bin head space volume, m^3

V_f face velocity onto heat transfer coils, m/s

V_p plenum volume, m^3

V_{wind} wind speed, m/s

W_F chiller fan power, kW

W_p compressor capacity, kW

X_b bin head space air exchange, volumes/hour

X_p bin plenum air exchange, volumes/hour

a_i compressor function parameters, i = 1,2,3

b_i compressor function parameters, i = 1,2,3

c specific heat, kJ/kg/°C

c_i compressor function parameters, i = 1,2,3

c_b volumetric air heat capacity, $J/m^3/°C$

d bin diameter, m

g_i chiller characteristic compressor function, i = 1,2

f_i chiller characteristic compressor function, i = 1,2,3

h enthalpy, kJ/kg

h_o condenser outlet air enthalpy, kJ/kg

$h_{s,R}$ fictitious enthalpy of saturated air at the evaporating temperature, kJ/kg

h_{fg} latent heat of vaporization, kJ/kg

h'_b convective heat transfer coefficient top grain surface to bin head space, $W/m^2/°C$

h'_i convective heat transfer coefficient bin roof to bin head space, $W/m^2/°C$

h'_o convective heat transfer coefficient sloped bin roof to ambient air, $W/m^2/°C$

h'_p convective heat transfer coefficient bottom grain surface to bin plenum, $W/m^2/°C$

h'_r linearized radiative heat transfer coefficient for bin roof, $W/m^2/°C$

h'_w convective heat transfer coefficient wall grain surface to ambient air, $W/m^2/°C$

k thermal conductivity, W/m/°C

m_D dry matter loss damage multiplier, decimal

m_M dry matter loss moisture multiplier, decimal

m_T dry matter loss temperature multiplier, decimal

$\dot{m}_a$ dry air mass flow rate through the chiller, kg/s
q energy, W
q_b beam solar radiation, W/m^2
q_d diffuse solar radiation, W/m^2
q_{fl} heat flow perforated floor to plenum, W
q_g heat flow top grain surface to bin head space, W
q_{gr} heat flow concrete floor to plenum, W
q_{pr} heat flow through plenum perimeter wall, W
q_r total thermal radiation, W/m^2
q_{re} radiative heat exchange ground and bin, W/m^2
q_{ro} radiative heat exchange bin and surroundings, W/m^2
q_{rs} radiative heat exchange sky and bin, W/m^2
q_{rf} heat flow bin-roof to head-space, W
q_{vth} heat flow due to air exchange in bin head space, W
q_{vtp} heat flow due to air exchange in bin plenum, W
q'_E characteristic compressor evaporating capacity, W
q'_C characteristic compressor condensing capacity, W
r radial position in two-dimensional grid, m
r_t ratio of hourly total to daily total radiation, decimal
t bin roof thickness, m
v specific air volume, m^3/kg
x vertical position in one-dimensional grid, m
z vertical position in two-dimensional grid, m

ΔP static pressure drop through grain, Pa
$\Delta P'$ static pressure drop per unit depth of grain, Pa/m
ΔT log-mean temperature difference, °C
Δh log-mean enthalpy difference, kJ/kg
Δx vertical space step in one-dimensional grid, m
Δz vertical space step in two-dimensional grid, m
$\Delta \tau$ time step, s

α thermal diffusivity, m^2/s
α_L long-wave absorptivity, decimal
α_s short-wave absorptivity, decimal
β slope of receiving surface, degrees
γ surface azimuth angle, degrees
δ declination, degrees
ε porosity, decimal
ε_L emissivity, decimal
θ angle of incidence, decimal, or
grain temperature, °C
θ_z zenith angle of the sun, degrees
ν kinematic viscosity, m^2/s
ϱ density, kg/m^3
ϱ_r ground reflectance, decimal
τ time, s
ϕ geographic latitude or bin circumference angle, degrees
ω_s sunset hour angle, degrees
ω current hour angle, degrees

Superscript

n time step

Subscripts

A before the chiller fan
C condenser
E evaporator
F fan
H reheater

a air
e equilibrium
i vertical coordinate
j radial coordinate
o initial
p product
v vapor
w water

el electrical
rf bin roof

sat saturated
atm atmospheric

1 before the evaporator
2 before the reheater
3 before the connecting duct
4 at the bin inlet

INTRODUCTION

In a major 1989 study on "Enhancing the Quality of U.S. Grain for International Trade" (U.S. Congress 1989a) the following main conclusions were drawn:

· more competitors exist in the international grain market now than ever before, and grain quality has become an extremely important competitive factor

· no other country can offer such a wide range of intrinsic differences in grains to customers than the United States

· the premiums established for grain in the U.S.A. are via the interaction of supply and demand for measurable quality characteristics

· the process of drying (and cooling) has a greater influence on grain quality than all other grain-handling operations combined

· a switch by farmers from non-bin drying to combination drying (i.e. high-temperature non-bin drying followed by slow low-temperature/chilled-air in-bin drying) will significantly improve the quality of U.S. corn

· maintaining low temperature- and moisture-levels in the grain is the main way to preserve grain quality, and to prevent damage from molds and insects.

In the 1970's countries representing one-third of the world population supplied grain to the other two-thirds of the world. Growth in grain-trade was dynamic. Today, countries representing two-thirds of the world population supply grain to the other third of the world. The growth in trade has become stagnant. In such a competitive environment, foreign buyers of U.S. grain have become increasingly sensitive about the quality of the grain they receive.

Concern was expressed during the 1985 and 1990 debates of the Food Security Act before the United States Congress over the quality of U.S. grain exports. Accusations were leveled that U.S. elevator managers and grain traders adulterated grain shipped to foreign buyers. A sharp increase occurred in foreign complaints concerning quality. U.S. traders and handlers argued that they had been shipping grain according to the U.S. grain standards, and that most buyers complained only in order to obtain a higher grade of grain at a lower price. The main focus of the debates centered on the adequacy of the grain standards, some of which were developed over 70 years ago. Critics argued that the grain standards had not kept up with a changing world market, and that they were frequently misunderstood by foreign buyers.

Improving U.S. grain quality - or even the perception of quality - will require much more than changing the standards. Grain is vulnerable to quality deterioration at every stage of the production and marketing process. Many aspects of the interactions of producing, harvesting, storing, handling, and testing grain need to be better understood before positive changes in the system can be expected.

One technology that has been successfully utilized to preserve grain quality during storage is grain chilling. It permits the short- to long-term storage management of grain independent of the ambient conditions. The chilled aeration of grain has been applied commercially in over 50 countries during the past 30 years (Brunner 1990), but not the United States. In 1992, over 10 million metric tonnes (MMT) of grain are cooled with grain chilling systems. Commonly, grain is cooled in-situ using conventional aeration systems, which are able to lower the temperature of the stored grain to within several degrees of the minimum ambient temperature. In contrast, grain chilling is defined as the cooling of grain <u>independent</u> of the minimum ambient temperature using a mechanical refrigeration system.

In a mobile grain chilling system, ambient air is ducted over a bank of refrigeration coils in order to decrease the air dry and wet bulb temperatures (see Figure 1.1). The chilled air dry and wet bulb temperatures are set by the operator. Since grain absorbs moisture at high humidity levels, the chilled air is reheated to the desired 60 - 75 percent relative humidity range. When the trailing edge of the cooling front exits the top of the pile, the cooling cycle is completed. The ability to control the bin-inlet air temperature and humidity to the desired values, regardless of the ambient conditions, is a distinctive feature of a well-designed grain chilling unit. After the initial cool-down, a rechilling cycle is run periodically in order to maintain the grain at the desired temperature. Figure 1.2 shows a typical commercial grain chiller, and Table 1.1 summarizes its design specifications.

A cooperative research project on grain chilling, that is in part the basis of this dissertation, has been a three-year effort (beginning in 1988) between Michigan State University, East Lansing, Michigan, the University of Hohenheim, Stuttgart, Germany, and the Sulzer-Escher Wyss Company, Lindau, Germany. One of the goals of the project has been to evaluate the potential application of commercial grain chilling in the United States' grain industry. Understanding the structure of the industry and the quality parameters important to the industry aid a company, such as Sulzer-Escher Wyss, to evaluate the commercial potential of

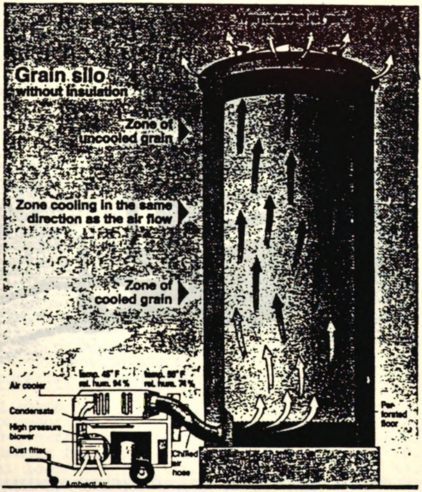


Figure 1.1 Schematic of the grain chilling process using a mobile grain chiller connected to an upright grain storage silo (Sulzer USA 1991).

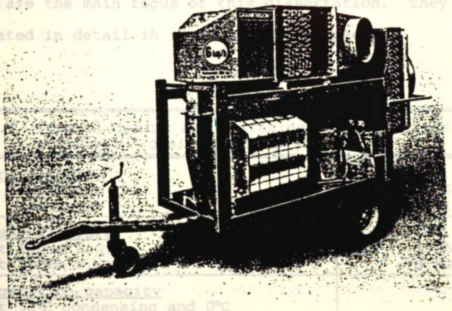


Figure 1.2 Typical commercial mobile grain chilling unit (Sulzer USA 1991).

grain chilling in the United States. Consequently, the characteristics of the U.S. grain production, processing, and marketing system is discussed first, including the quality standards currently in use in the U.S. grain industry. The technical aspects of applying chilled aeration and storage of cereal grains in the U.S. grain industry are the main focus of this dissertation. They will be evaluated in detail in the remaining chapters.

Table 1.1 Typical design and operating specifications of a commercial[1] grain chilling unit.

Cooling capacity	
maximum	160 t/day
average	95 - 110 t/day
Cold air flowrate	
at 100mm W.G.	5,050 m^3/h
at 300mm W.G.	3,500 m^3/h
Refrigeration capacity	
at 30°C condensing and 0°C evaporating temperature	32,700 W
Connected loads	
compressor	7.9 kW
cold-air fan	5.5 kW
condenser fan	0.55 kW
total load	13.0 kW

[1]KK140 manufactured by Sulzer-Escher Wyss, Lindau, Germany

1.1 U.S. Climate

In order to fully understand the production of grain and subsequent processing problems in the United States, a knowledge of the prevalent climatic conditions is necessary. Furthermore, the variation of the climate prevalent in the United States is important to the proper sizing of the refrigeration capacity of a grain chiller in U.S. storage and processing facilities.

The climate of the United States is a continental climate. However, this term fails to describe the climatic extremes that occur throughout the year. Both hot and cold temperatures at any location are determined by the ease with which abnormally cold and hot air flow across the continent. The rate of the movement of the air from a so-called major source region to a particular location affects the extreme temperatures (Ecodyne 1980). Figures 1.3 and 1.4 show major source regions for the temperature extremes throughout the United States. Extreme cold temperatures are caused by rapid movement to a particular location of cold air within a one- or two-day period from the Polar source region. Mountainous terrain does not present a physical barrier to the spread of cold air since it runs from North to South, i.e. the Continental Divide in the Western United States and the mountain range in the Eastern part of the United States.

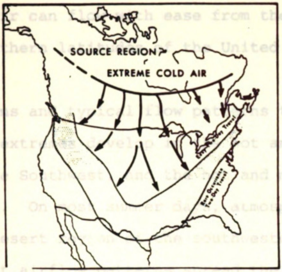


Figure 1.3 Source region and typical flow pattern that produces the low temperature extreme throughout the United States (Ecodyne 1980).

Figure 1.4 Source regions and typical flow patterns which produce the high temperature extremes throughout the United States (Ecodyne 1980).

Thus, cold air can flow with ease from the Polar region deep into the Southern latitudes of the United States.

Source regions and typical flow patterns that produce high temperature extremes develop in the hot and dry desert region of the Southwest, and the hot and moist Gulf region of the South. On most summer days, atmospheric air flows toward the desert region of the southwestern United States. The prevalent airflow patterns spread the hot and dry air away from the source region to the northeast across the continent. The major source region for high dry-bulb temperatures with a high moisture content lies inland from the Gulf of Mexico and the Atlantic Ocean. When moist air, which has originated over a warm ocean, is permitted to stagnate 100 to 200 miles inland, it increases to higher temperatures and humidities. The northward flow of this air produces the highest temperatures and humidities, mainly in the eastern third of the United States. There is a zone in the Middle West which can alternate from year to year depending on whether hot, dry air moves up from the desert southwest, or hot, moist air flows from the Gulf south.

The mean wet-bulb temperatures and wet-bulb depressions in the U.S.A. for the month of July are shown in Figure 1.5 (ASAE 1991). The maps are based upon weather records from 127 U.S. sites averaged over 21 years. The wet-bulb

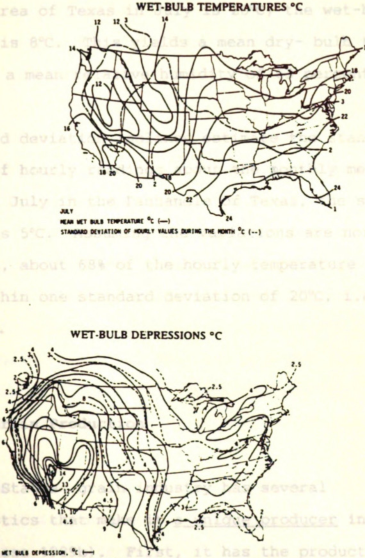


Figure 1.5 Wet-bulb temperatures and wet-bulb depressions in the United States in the month of July (ASAE 1991).

temperature and depression lines allow the estimation of the mean dry-bulb and relative humidity values across the United States. For example, the mean wet-bulb temperature in the Panhandle area of Texas in July is 20°C; the wet-bulb depression is 8°C. This yields a mean dry- bulb temperature of 28°C and a mean relative humidity of 63 percent.

The standard deviation isolines estimate the standard deviation of hourly readings about the monthly mean. For example, in July in the Panhandle of Texas, the standard deviation is 5°C. Assuming the variations are normally distributed, about 68% of the hourly temperature readings will be within one standard deviation of 20°C, i.e. between 15 and 25°C.

1.2 U.S. Grain Production

The United States' grain industry has several characteristics that make it a unique producer in the world (U.S. Congress 1989b). First, it has the productive and distributional capability to meet practically any demand for grain. Second, the United States produces every type of grain. Third, a buyer can purchase nearly any type of grain at any time of the year. Fourth, grain can be moved from farm to terminal to buyer very efficiently because of the extensive interstate highway system, rail system, and waterways, and because of the high-volume, high-speed elevator facilities.

Grains are categorized in the United States according to primary utilization. The feed grains (corn, sorghum, barley, and oats) lead all crops in terms of value and acres; their 1988 value totaled $15.3 billion, or 22 percent of the total U.S. crop value (USDA 1990d). Thirty-three percent of the cultivated crop acreage consists of feed grains. Domestic use accounts for 73 percent of the total disappearance, mainly for livestock and poultry. Food, seed, and industrial use claim the remaining share. Products such as ethanol, high-fructose corn syrup, barley malt, oats bran, and other food and beverage items are for industrial usage. The export of feed grains claims 27 percent and consists primarily of corn, sorghum, and barley.

The principal food grains are wheat and rice (USDA 1990a, 1990c). Wheat is the fourth leading field crop produced in the United States in terms of value of production. Only corn, hay, and soybeans are more valuable. In 1987/88, the value of wheat was $5.4 billion, or 8% of the total U.S. field crop value. Wheat is mainly used for food consumption, both in the United States and throughout the world. Rice ranks ninth among major U.S. field crops in terms of value, i.e. about 2% of the value of U.S. field crops, or about $1.2 billion. The United States supplies about 19% of the world's rice exports.

The soybean industry is one of the world's fastest growing agricultural sectors (USDA 1990b). With an estimated farm value of $11.4 billion in 1988/89, soybeans are second only to corn in production value in the United States. The primary demand for soybeans is for meal and oil. Soybean and soybean-product exports averaged $6.2 billion over the past few years.

Production trends in the United States for the three primary grains - wheat, corn, and soybeans - from 1971 to 1986 are shown in Table 1.2. Annual wheat production has increased by 29 percent since 1971, peaking at 2,785 million bushels (80 million tonnes) in 1981. The 1991 U.S. crop forecast published by the U.S. Department of Agriculture (USDA) predicts a wheat harvest of 526 million bushels (15 million tonnes) (The Wall Street Journal 1991). The annual corn production peaked at 8,235 million bushels (206 million tonnes) in 1982. The 1991 U.S. crop is forecast to be 7,490 million bushels (187 million tonnes) of corn (The Wall Street Journal 1991). Except for 1983, when the production was reduced drastically through government programs, and for 1988, when a severe drought reduced the harvest, U.S. corn production has been fairly constant in the 1980's. Soybean production has increased by 71 percent since 1971, peaking at 2,268 million bushels (65 million tonnes) in 1979. The harvest of soybeans is estimated at 1,960 million bushels (56 million tonnes) in the 1991 crop forecast (The Wall Street Journal 1991), which would be the fifth largest on record.

There are five market classes of wheat in the United States: hard red winter (about 48% of the total wheat production), soft red winter (17%), hard red spring (20%), white (10%), and durum (4%). Figure 1.6 shows the general areas where the various types of wheat are grown. Forty-two states produce wheat; however, almost 42 percent of the U.S. wheat is grown in five States - Kansas, Oklahoma, Texas, Nebraska,

Year	Wheat	Soybeans	Corn
1971	1,618.6	1.176.1	5.641.0
1972	1.546.2	1.270.6	5.573.0
1973	1,170.8	1.547.5	5.647.0
1974	1,781.9	1,216.3	4.701.4
1975	2.126.9	1,547.4	5.829.0
1976	2,148.8	1.287.6	6.266.4
1977	2,045.0	1.767.0	6,425.5
1978	1,775.5	1,869.0	7,081.8
1979	2,134.1	2,268.0	7.938.8
1980	2.380.9	1,798.0	6,644.8
1981	2.785.4	1.989.0	8.201.6
1982	2.765.0	2.190.0	8.235.1
1983	2,419.8	1.636.0	4,174.7
1984	2,594.8	1,861.0	7,674.0
1985	2.425.1	2,099.0	8.876.7
1986	2,086.8	1,940.0	8.252.8
1987	2.105.0	1.905.0	7.064.0
1988*	1.821.0	1.472.0	4.462.0

Table 1.2 U.S. wheat, corn, and soybean production between 1971 and 1988 (in millions of bushels) (U.S. Congress 1989a).

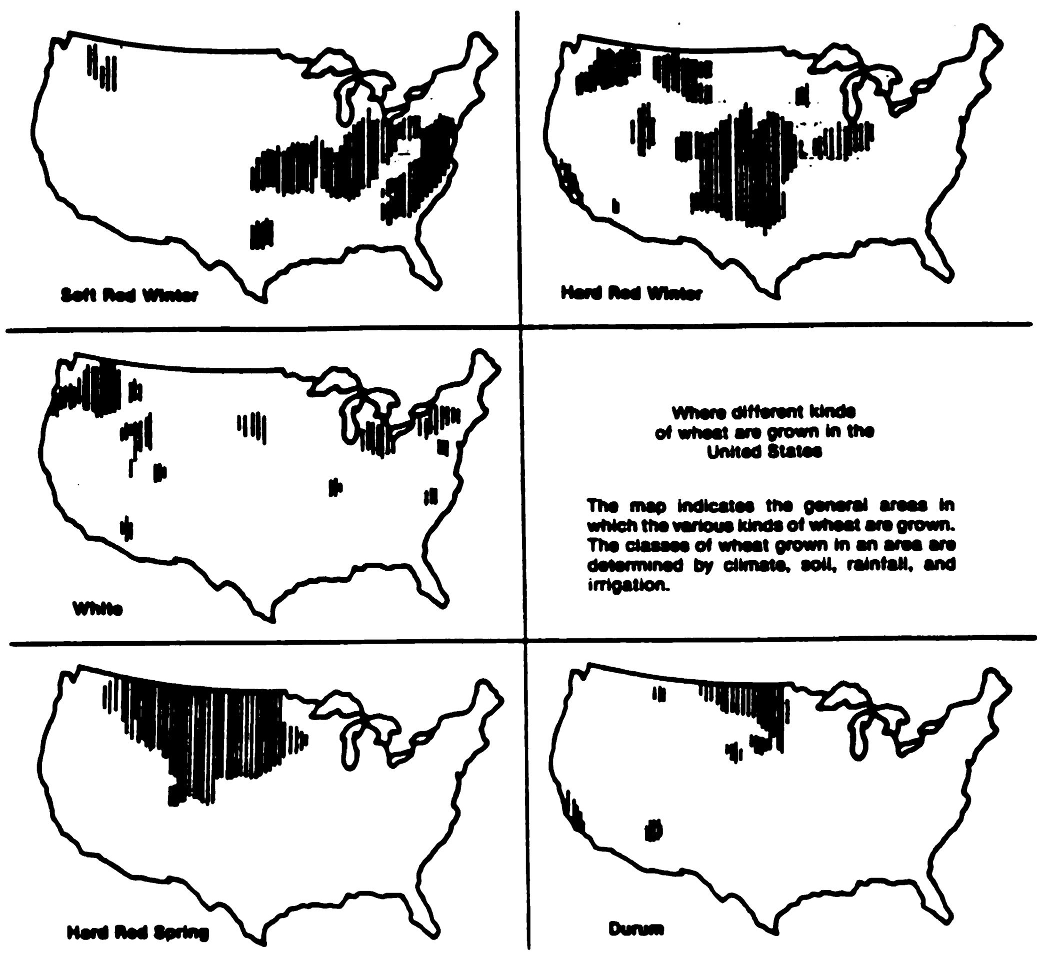


Figure 1.6 Wheat-producing areas in the United States (U.S. Congress 1989a).

and Colorado, which produce Hard Red Winter wheat, the major type grown in the United States. About 25 percent of the wheat produced in the U.S. is grown in North and South Dakota, Minnesota, and Montana, which primarily produce Hard Red Spring wheat. Durum wheat is grown mainly in North Dakota, Montana and California; and white wheat is grown mainly in the Pacific Northwest, i.e. Washington, Oregon and Idaho. Soft Red Winter wheat is grown from Missouri to Ohio and in the Atlantic States. The harvest time for winter wheat in the principal areas of the United States is shown in Figure 1.7, and ranges from late spring to after July 15.

Figure 1.8 shows the principal corn growing areas in the United States and their approximate harvesting period. Harvesting takes place between late summer and the middle of fall. Corn is produced in 47 States. The six Corn Belt States - Iowa, Illinois, Indiana, Nebraska, Minnesota, and Ohio - produced about 70 percent of the 1985 corn crop. Corn production in recent years has increased in other parts of the country as a result of the availability of new, short-season hybrid seed corn and government-support programs.

Soybeans are produced in 29 States. Six account for almost two- thirds of the output: Illinois, Indiana, Missouri, Ohio, and Minnesota. Illinois and Iowa are the dominant

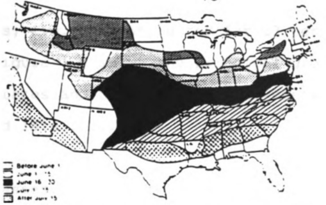


Figure 1.7 Harvest dates of winter wheat in the United States (MADA 1989).

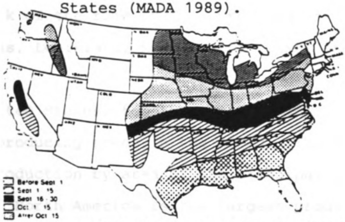


Figure 1.8 Harvest dates of corn in the United States (MADA 1989).

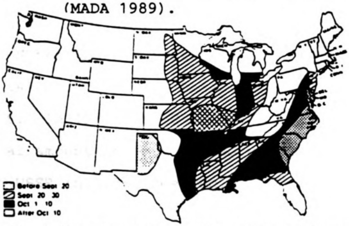


Figure 1.9 Harvest dates of soybeans in the United States (MADA 1989).

producers, i.e. they accounted for 33 percent of the 1985 crop. Figure 1.9 shows the principal growing areas in the United States and the respective harvesting times between early and late fall.

Three classes of rice are produced in the United States - long, medium, and short grain - with long grain predominant. The bulk of the rice crop is produced in five States: Arkansas, Louisiana, Mississippi, Texas and California.

The United States, together with Canada, is one of the major grain producing areas in the world. Table 1.3 lists the 1986 production by area of the principal grain crops in the world. North America is the largest producer of corn and sorghum, ranks second in the production of rice and third in the production of wheat. Only Asia produces more total grain. North America is the largest exporter of wheat (see Table 1.4), with most of the crop going to the USSR and the Far-East. In 1985, the U.S.A. exported almost 50 percent of the total amount of corn traded world-wide, mainly to Japan and the USSR in 1985 (see Table 1.5).

The world supply of wheat and feed grain (i.e. corn and sorghum), and their utilization and stocks in 1986 and 1988, are summarized in Table 1.6. At the beginning of the harvest, about 20-30 percent of the world-wide available wheat is stored in the U.S.A., and about 60-65 percent of the corn. In other words, the United States is <u>the principal storer of grains in the world</u>.

The information contained in this section furnishes proof of the importance of the production and the subsequent storage of cereal grains in North America. The technique of grain-chilling can provide an essential link between the production and post-harvest processing phase for cereal grains.

Table 1.3 World production of cereal crops by region in million metric tonnes (MMT) in 1986 (FAO 1987).

Area	Wheat	Rice	Corn	Sorgum	Millet	Barley	Other	Total
Africa	11.6	9.8	30.8	14.3	11.8	6.3	0.3	84.9
N.America	93.5	98.3	231.3	30.4	0.0	28.7	10.8	403.0
S.America	16.8	15.3	38.2	6.2	0.1	0.8	1.0	78.4
Asia	189.6	434.1	99.7	17.4	15.3	18.7	2.5	777.3
Australia	16.7	0.7	0.2	1.4	0.04	3.5	1.7	24.2
Europe	115.8	2.2	68.0	0.4	0.03	70.3	27.1	283.8
USSR	92.3	2.6	12.5	0.1	2.4	53.9	37.2	201.0
World	536.5	473.1	480.9	70.2	29.7	182.7	80.5	1853.6

Note: Other is oats and rye

Table 1.4 The structure of the world wheat trade in 1985 in million metric tonnes (MMT), and as a percentage of export and import trade (Uhlmann 1988).

Total Trade (MMT)	84.4
Export (%)	100.0
EC	16.9
USA	29.6
Canada	19.9
Australia	19.1
Argentina	7.3
Import (%)	100.0
W. Europe	4.3
E. Europe	3.4
USSR	19.4
Far East[1]	17.3
Africa	14.8
S. America	11.3
China	8.1
Middle East	10.3

[1] India, Pakistan, Bangladesh, Taiwan, Indonesia, Japan

Table 1.5 The structure of the world feed grain[1] trade in 1985 in million metric tonnes (MMT), and as a percentage of export and import trade (Uhlmann 1988).

Total Trade (MMT)	88.4
Export (%)	100.0
EC	10.0
USA	45.3
Canada	4.9
Australia	6.6
Argentina	11.1
Thailand	4.7
S. Africa	1.3
Import (%)	100.0
W. Europe	9.7
E. Europe	6.4
USSR	15.0
Japan	26.0
Saudi-Arabia	8.7

[1] corn, sorghum, oats, rye, feed-barley

Table 1.6 World wheat and feed grain supply, utilization and stocks in million metric tonnes (MMT) in 1986 and 1988 (NGFA 1988).

	Wheat		Feed grain	
	1986	1988	1986	1988
Beginning Stocks				
United States	51.8	34.5	126.9	138.1
Non-U.S.	116.3	111.3	80.7	75.9
World Total	168.2	145.7	207.6	214.0
Production				
United States	56.9	49.3	252.8	136.7
Non-U.S.	472.8	455.4	581.2	573.9
World Total	529.7	504.6	834.0	710.7
Total Supply[1]				
United States	108.7	83.8	370.7	274.8
Non-U.S.	589.1	566.7	661.9	649.8
World Total	697.9	650.3	1041.6	924.7
Utilization				
United States	32.5	30.1	181.6	169.5
Non-U.S.	490.0	502.9	627.7	630.3
World Total	522.5	533.0	809.3	799.8
Ending Stocks				
United States	49.6	14.6	152.6	58.6
Non-U.S.	125.8	102.7	79.8	65.7
World Total	175.3	117.3	232.2	124.4

[1]Before Imports

1.3 U.S. Grain Storage

1.3.1 Facilities and Capacities

The annual surplus of U.S. grains means that storage is required for certain periods of time. Grain is a perishable commodity with a finite safe-storage period. Storage can maintain grain quality, but cannot improve it.

The total U.S. grain storage capacity in 1987 was approximately 23,000 million bushels (575 MMT), of which about 14,000 million bushels (350 MMT) was on-farm storage and about 9,000 million (225 MMT) was considered off-farm (i.e. commercial) storage (Anon 1990b). The 1991 USDA crop report forecasts the stockpile of corn to exceed 1,280 million bushels (32 MMT), a decrease of about four percent compared to the previous year (The Wall Street Journal 1991). The U.S. wheat stockpile is predicted to reach 514 million bushels (15 MMT), the tightest since 1975; and soybean stockpiles are predicted to reach 315 million bushels (9 MMT) (The Wall Street Journal 1991). These figures imply that only about 20 percent of the available U.S. storage capacity will be used by the current stocks; in 1986 over 40 percent of the storage capacity was used.

The 1990 North American Grain Yearbook lists the major grain companies and cooperatives in the United States and their corporate grain storage capacities (Anon 1990b). To be among the top 100, a company must have more than one facility and more than 6.5 million bushels (162,500 MT) of storage capacity. The storage capacity of the top 100 grain companies in the United States in 1990 totaled over 3,467 million bushels (87 MMT), an increase of 3.6 million bushels (90,000 MT) compared to 1989. [Canadian companies and cooperatives account for 405 million bushels (10 MMT) of the capacity.]

In 1989, the major North American grain companies operated 3,540 grain storage facilities, a decrease of 394 compared to 1988. A breakdown for the U.S.A. shows 58 port-, 196 river-, 267 terminal-, 243 subterminal- and 1,179 country elevator facilities; [and for Canada 29 port-, 6 terminal-, 1,554 country elevator- and 8 storage facilities at processing plants.]

Table 1.7 lists the top and bottom ten largest commercial grain handling and storage companies in North America with their total number of facilities and capacities in 1989 (Anon 1990b). The average size of the Top-10 facilities range from 250,000 to 9.7 million bushels (6,250 to 242,500 MT), while the average size of the Bottom-10 range from 180,000 to 2.5 million bushels (4,500 to 62,500 MT).

Table 1.7 The top and bottom 10 commercial grain handling and storage companies in North America with the total number of facilities owned and total storage capacity (in million bushels) in 1989 (Anon 1990b).

Rank	Company	Facilities	Storage
1	Cargill	234	340
2	Peavey	103	190
3	Continental Grain	79	188
4	Union Equity	17	165
5	Bunge	55	164
6	Sasketchawan Wheat	486	120
7	Scoular Grain	44	95
8	Riceland Foods	35	94
9	Cargill Canada	132	65
10	Harvest States	108	64
94	B&W Co-op	5	8.5
95	Garden City Co-op	8	7.8
96	Goderich Elevators	3	7.6
97	Dixie-Portland Elevator	6	7.0
98	Columbia Grain	4	6.9
99	Gold Kist	38	6.8
100	Whitman County	21	6.8
101	Stegner Grain	5	6.7
102	Cereal Food Processors	9	6.6
103	Alberta Terminals	3	6.5

Table 1.8 lists the off-farm storage capacity by principal states. The off-farm commercial grain storage capacity increased in 1988 by 4.2 million bushels (105,000 MT) from

1987. During the 1980's - a period in the U.S.A. considered to be the "commercial storage decade" due to favorable tax laws - 2,629 million bushels (66 MMT) of storage capacity was added. According to the USDA, the off-farm storage capacity in 1988 totaled 9,615 million bushels (240.4 MMT) compared to 9,611 million bushels (240.3 MMT) the previous year. The off-farm grain storage capacity between 1943 and 1988 is illustrated in Figure 1.10. Between 1987 and 1988 the storage capacity decreased in 25 states and increased in 17 states.

Commercial storage in the U.S.A. is dominated by five states - Illinois, Iowa, Kansas, Texas, and Nebraska - which hold about 52.1% of the nation's total storage capacity. Illinois ranks first with over 1,202 million bushels (30 MMT), or 12.5% of the total off-farm storage capacity. The second largest commercial storage state is Iowa with 1,127 million bushels (28 MMT), or 11.7% of the total capacity. Kansas ranks third with 944 million bushels (24 MMT), or 9.8 percent, followed by Texas with 942 million bushels 24 MMT), or 9.8 percent, and Nebraska with 879 million bushels (22 MMT), or 9.1 percent.

The largest change in commercial storage between 1987 and 1988 occurred in Texas, which increased its storage capacity by 5%, i.e. by 44 million bushels (1.1 MMT). Iowa and

	Dec. 1, 1988	Dec. 1, 1987	Change
Alabama	40.200	42.180	-1.980
Arizona	29.790	31.500	-1.710
Arkansas	225.460	231.580	-6.120
California	119.340	110.400	+8.940
Colorado	145.220	142.860	+2.360
Delaware	19.150	19.750	-600
Florida	9.800	8.120	+1.680
Georgia	63.840	65.720	-1.880
Idaho	113.850	115.380	-1.530
Illinois	1.202.400	1.225.600	-23.200
Indiana	384.510	390.820	-6.310
Iowa	1.127.770	1.153.670	-25.900
Kansas	943.820	936.760	+7.060
Kentucky	70.210	71.420	-1.210
Louisiana	92.610	93.670	-1.060
Maryland	42.450	51.540	-9.060
Michigan	170.000	172.000	-2.000
Minnesota	633.800	628.140	+5.660
Mississippi	77.500	78.470	-970
Missouri	292.460	292.000	+460
Montana	56.250	54.360	+1.890
Nebraska	878.880	879.730	-850
New England	7.620	7.600	+20
New Jersey	1.450	1.510	-60
New Mexico	17.500	19.260	-1.760
New York	58.190	60.450	-2.260
North Carolina	98.260	92.070	+6.190
North Dakota	249.140	232.100	+17.040
Ohio	362.260	346.420	+15.840
Oklahoma	261.430	267.450	-6.020
Oregon	82.050	81.750	+300
Pennsylvania	38.620	38.920	-300
South Carolina	38.240	38.690	-450
South Dakota	127.530	136.220	-8.690
Tennessee	77.520	72.440	+5.080
Texas	941.730	897.920	+43.810
Utah	32.200	33.580	-1.380
Virginia	37.320	36.860	+460
Washington	236.800	238.170	-1.370
Wisconsin	196.000	202.000	-6.000
Wyoming	10.480	10.370	+110
U.S.	9.614.800	9.610.590	+4.210

Table 1.8 Off-farm storage capacity by principal state (in thousand bushels) (Anon 1990b).

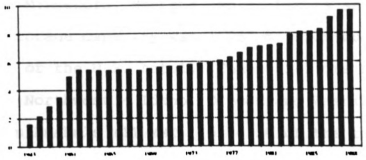


Figure 1.10 Rated off-farm grain storage capacity from 1943 through 1988 (in million bushels) (Anon 1990b).

Illinois both decreased by 26 and 23 million bushels (650,000 and 575,000 MT), respectively. The fourth and fifth largest changes occurred in North Dakota and Ohio, which increased by 17 and 16 million bushels (425,000 and 400,000 MT), respectively. On a percentage basis, the largest changes in off-farm storage capacity from 1987 to 1988 occurred in Florida, up 21%, Maryland, down 18%, New Mexico, down 9%, California, up 8%, and North Dakota, Tennessee and North Carolina, up 7% each.

In the five hard winter wheat states of the Southwest - Colorado, Kansas, Nebraska, Oklahoma and Texas - commercial storage capacity totaled 3,125 million bushels (78 MMT), or 33% of the U.S. total. The total commercial storage capacity in the Central states - Illinois, Indiana, Michigan, Missouri and Ohio was 2,412 million bushels (60 MMT), or 25.1% of the U.S. total. In the four major spring wheat states - Minnesota, Montana, North Dakota and South Dakota - the storage capacity was 1,067 million bushels (27 MMT), or 11.1% of the U.S. total. Commercial grain storage in the Pacific Northwest - Idaho, Oregon and Washington - was 433 million bushels (11 MMT), or 4.5% of the total U.S. off-farm storage capacity.

The number of off-farm storage facilities as of December 1, 1989 was 13,799, a decrease by 90 from the year before.

States with the largest numbers of off-farm storage facilities were Illinois, 1,295,; Kansas, 941; Iowa, 907; Texas, 875; and Minnesota, 803. Thus, the potential number of grain chilling units that could be employed in commercial facilities throughout the United States is enormous.

1.3.2 Technology and Management

Grain handling and storage systems provide an economical means of moving grain into storage, preserving its quality, and unloading it from storage. The on-farm and off-farm storage and handling systems use the same basic type of equipment.

Storage structures in the United States are categorized as upright metal bins and concrete silos, flat warehouse buildings, and on-ground piles. Upright bins and concrete silos are the most easily managed type and are found on-farm as well as at commercial facilities. They range from 3,000 bushel farm-bins to commercial facilities with bins larger than 500,000 bushels. The storages are loaded from the top and unloaded from the bottom. The bottom of a grain bin can be flat or be constructed with a hopper bottom. In most U.S. facilities, the stores are equipped with aeration fans to maintain cool and uniform grain temperatures. Some bins can be sealed for fumigation. Stores can be unloaded with an under-floor auger.

The recent demand for additional storage space has increased the use of flat-storage warehouses, and of on-ground tarp-covered piles. These storages are more difficult to load, unload, fumigate, and aerate than upright bins. Horizontal stores have flat floors and are filled with portable conveyers. In the summer of 1987 on-ground piling of 600 million bushels (15 MMT) occurred in the U.S., mostly for feed corn.

Grain breakage occurs during harvesting and handling. It is more significant in corn than in wheat and soybeans. High grain moisture contents and temperatures minimize breakage, but are not safe for storage. Uniform low grain moisture content and temperature within a storage facility are critical for maintaining grain quality. Knowledge of the moisture content range is a key element in determining storability. Table 1.9 shows the relationship for corn between the grain temperature, moisture content and the allowable storage time (U.S. Congress 1989a). At the end of the AST, corn is on the verge of dropping one grade as defined by the U.S. standard for corn, and will have lost about 0.5 percent of its original dry matter weight.

Grain temperature (°F)	Corn moisture (percent) 18	20	22	24	26	28	30
	days in storage						
30	648	321	190	127	94	74	61
35	432	214	126	85	62	49	40
40	288	142	84	56	41	32	27
45	192	95	56	37	27	21	18
50	128	63	37	25	18	14	12
55	85	42	25	16	12	9	8
60	56	28	17	11	8	7	5
65	42	21	13	8	6	5	4
70	31	16	9	6	5	4	3
75	23	12	7	5	4	3	2
80	17	9	5	4	3	2	2

Table 1.9 Allowable storage time for corn (U.S. Congress 1989a).

Moisture and temperature do not stay uniform during the storage time. Moisture will migrate in response to temperature differentials (see Figure 1.11 and 1.12). When the average ambient air is colder than the grain, the area of condensation occurs on the grain surface; when the average ambient air is warmer than the grain, the area of condensation is found several feet beneath the grain surface. Cold-weather moisture migration primarily affects grain in land-based storage, causing deterioration as temperatures rise in the spring. Warm-weather moisture migration occurs particularly in grain in transit within the United States, and during transport to foreign buyers.

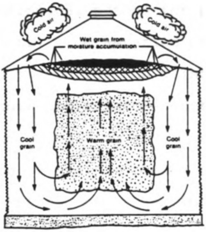


Figure 1.11 Moisture migration pattern at low ambient temperatures (MWPS-13 1988).

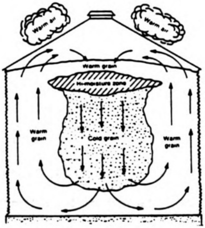


Figure 1.12 Moisture migration pattern at high ambient temperatures (MWPS-13 1988).

Maintaining low temperatures and moisture levels in stored grain is the principal method for preventing damage from molds and insects. The aeration of cereal grains has long been practiced to control and maintain the physical, e.g. grain temperature and moisture content, and qualitative, e.g. prevention of molding and insect infestation, characteristics of grain while held in storage until subsequent marketing and processing. The two primary objectives of aeration are (1) to maintain uniform temperature in the grain bulk, and (2) to keep the temperature as low as practical (Foster and Tuite 1982). According to the Midwest Plan Service "more stored dry grain goes out of condition because temperatures are not controlled than for any other reason" (MWPS-13 1988).

Aeration involves moving low volumes of ambient air through the grain over extended periods of time. The airflow rates range from as low as 0.05 m^3/min/t (0.05 cfm/bu) to over 1.0 m^3/min/t (1.0 cfm/bu) (MWPS-13 1988). Commonly, an airflow rate of 0.1 m^3/min/t (0.1 cfm/bu) is used to aerate shelled corn and soybeans in farm bins and flat storages, and 0.05 m^3/min/t (0.05 cfm/bu) for wheat and other smaller kernel crops (Foster and Tuite 1982). In deeper bins or silos, commonly found at commercial elevators and processing plants, lower airflow rates are used as a compromise between recommended airflow rates and fan power requirements, i.e.

0.05 m^3/min/t (0.05 cfm/bu) for corn and soybeans and 0.025 m^3/min/t (0.025 cfm/bu) for wheat and other small kernel crops. In warmer climates, higher airflow rates areutilized in the aeration of dry grain to take advantage of short periods of cooler weather.

In the United States, it is recommended to cool the grain uniformly to below 4.4°C (40°F) in the fall to prevent moisture migration, and to rewarm the grain to 10 to 15.6°C (50 to 60°F) to store through the spring and summer (MWPS-13 1988). The maximum recommended storage moisture contents in the United States for safe grain storage are summarized in Table 1.10. The values are for good quality, clean grain and properly aerated storage bins.

Table 1.10 Maximum moisture contents for the safe storage of shelled corn and wheat in the United States (MWPS-13 1988).

Grain Type and Storage Time	Maximum Moisture [%, w.b.]
Shelled Corn:	
Sold as #2 corn by spring	15.5
Stored 6 - 12 months	14.0
Stored more than 1 year	13.0
Wheat:	
Stored up to 6 months	14.0
Stored more than 6 months	13.0

Aeration can change the moisture content of the grain, depending on the initial grain temperature, the humidity, the airflow rate, and the length of aeration. A relative humidity above 70 percent tends to add moisture to the grain. Most storage bins in the United States are equipped with aeration fans but are frequently not used effectively. A majority of on-farm aeration systems is manually controlled and either not operated sufficiently or operated when the relative humidity of the air is too low or too high. A common problem is not operating the fans long enough to bring the entire grain mass to a uniform temperature. If a cooling front is moved through only part of the grain, moisture condensation is likely at the point where the warm and cool grain meet.

Aeration fans are mounted at the base of the storage structure and either push or pull air through the grain mass. Some installations use fans mounted in the roof or bin top to assist the removal of the outlet air from the storage structure. Condensation in aeration ducts can be a problem when fans are not running during warm weather and the grain mass is cold. Likewise, moisture from warm grain can condense on cold aeration ducts exposed to outside air. The accumulated moisture allows molding of the grain, sometimes caking the grain around the perforated ducts. Tight-fitting covers should therefore be used to prevent air infiltration when the fans are not running.

In general, the U.S. grain industry with the exception of the South has been quite successful in achieving low grain temperatures using the existing aeration systems in the storage facilities. The aeration of grain during the cooler nights and during the cold winter months allows the lowering of the grain temperatures to less than 15.6°C, even as far south as Texas. Well-managed facilities in the Northern U.S.A. are able to maintain the low temperatures in the larger storage structures even throughout the warm summer months, provided the moisture content of the stored grain is sufficiently low. After the harvest, the grain can be aerated until colder climatic temperatures become available. The economic costs in terms of power consumption and grain quality loss have todate not been assessed in the U.S. grain industry.

The equipment and methods used to fill a storage bin affect the performance of an aeration system. Filling the bin without a grain spreader causes a cone to develop - with the lighter, less dense material concentrated in the center (i.e. forming a spoutline), while the heavier, denser material flows to the sides. This impedes uniform airflow and may result in mold growth. Spoutlines are often removed from upright storage bins by drawing some of the grain out of the bin, a practice called coring. It should be noted that in the United States the grain is frequently not cleaned before filling the storage structure. The general argument is that during the short harvest period the amount of grain taken in by an elevator facility is too large to allow proper cleaning. Furthermore, the handling of the cleanings is considered to be a nuisance. Thus, both the drying and storing operations frequently occur with uncleaned grain in the United States.

Storage structures should be equipped with temperature sensing cables, which allow the monitoring of the grain temperatures during the storage period. The cables are hung from the roof or bin top and extend down through the grain mass. Each cable has a steel support cable and a number of thermocouples in a protective plastic shield. Heating of the grain more than one meter from the thermocouple may not be detected. Commercial facilities have used temperature monitoring systems for years; farmers now frequently also monitor grain temperatures. The monitoring at commercial facilities is usually done on a fixed schedule, either manually or by automatic recording equipment. Some facilities have installed programmable micro-processors that can be used in conjunction with aeration fan controllers.

Turning is the process of physically moving grain from one storage bin to another. It is expensive and is seldom used in the U.S.A. anymore. The turning process mixes the grain and helps to equalize the grain moistures and temperatures. When hot spots are detected, the affected bin is unloaded and transferred to another bin to break up the hot spots. This process is more costly than aeration since it requires more electrical energy and contributes to the physical damage of the grain kernels.

1.3.3 Fungi and Pest Control

Fungi (molds) grow on any kernel or group of kernels stored under certain relative humidity/temperature conditions. Molds are plants without roots, leaves or chlorophyll; therefore they are forced to live off other organisms. Over 100 fungi species have been isolated from cereal grains. Each has an optimum and minimum temperature and relative humidity value for growth.

The development of fungi in cereal grains can be controlled by chemical or by physical means. Propionic and acetic acids are used as chemical mold preventives in high moisture grain. Although grain properly treated does not mold, its viability reduces to zero, its germs turn brown, and a strong acid odor is given off. Thus, such chemicallytreated grain is only suitable as feed grain.

Insects create numerous economic and quality problems in stored grain. Preventing insect infestations should begin on the farm with efforts to clean the stores and to remove foreign material. In the United States it is recommended to use a protective treatment for long-term on-farm storage. Protective treatments are used most frequently in the southern grain-producing States, where the climate is most favorable for insect activity. As grain is marketed and moves through the various facilities, the identity of a lot is usually lost and additional treatments may occur. Thus, additional doses of insecticides are added to the grain. This can result in excessive chemical residues in the final product; a point that will be discussed in more detail under the topic of grain quality.

The major insects identified in the United States are the (1) granary weevil, (2) saw-toothed grain beetle, (3) red flour beetle, (4) foreign grain beetle, (5) rice weevil, (6) Indian- meal moth, (7) flat grain beetle, and (8) Angoumis grain moth (see Figure 1.13) (Storey et al. 1983). The pests have in common that they reproduce rapidly, feed on dry grain, migrate into the grain mass, and cause extensive physical damage. The damage to the grain includes bored holes and the disappearance of a large percentage of the inside of the kernels, the injury to the germ, the heating and subsequent condensation and molding of the grain mass, the contamination with excrements, and webbing.

Often infestation is controlled only on a case-by-case basis as it occurs rather than using preventive treatments. A 100-percent kill is usually not achieved by a treatment. The population may be reduced to an undetectable level and several generations may pass before infestation is detected again; however, numerous immature and even pre-emerging adult insects may remain inside the grain kernels. Often insect fragments are not removed in the pre-conditioning process of a mill, and thus can frequently be found in finished products. In the United States, pesticides are considered the only present technology available, although not considered entirely satisfactory to rid grain of live insects. The use of other control measures is severely limited by the inability to penetrate large grain depths, the short available time for application and kill, the quantity to be treated, the pesticide cost, and the labor.

Pest control in grain is economically driven. Anything that costs money will in all likelihood not be undertaken unless omission decreases income or prohibits grain sales. The pesticides used to control insects are divided into two broad categories: insecticides and fumigants. Insecticides

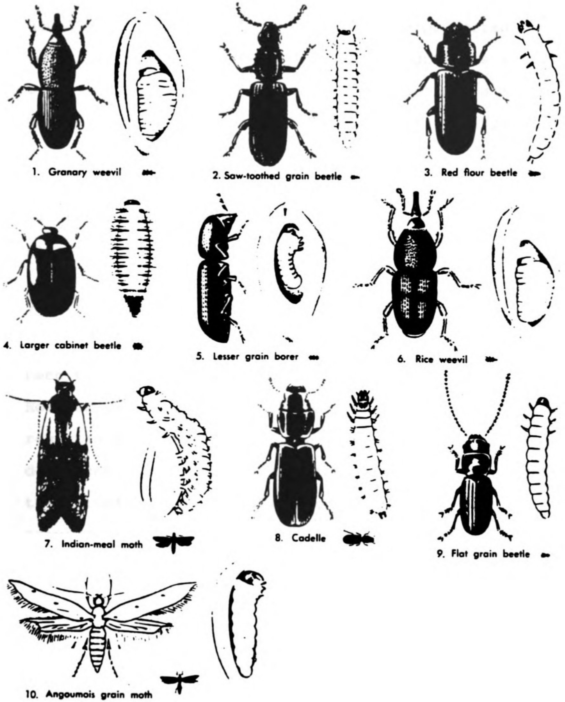


Figure 1.13 Principal stored grain insects in the U.S.A. (Brooker et al. 1974).

are applied to facilities and/or directly to the grain, usually during loading. The term "grain protectant" refers to the application of an insecticide to grain as it is conveyed into storage. When properly applied, grain protectants can prevent and minimize insect damage caused.

The primary grain protectants used in the United States are: (1) synergized pyrethrins, (2) malathion, (3) pirimiphos-methyl (commercial name: Actellic; for legal use in sorghum and corn), and (4) chlorpyrifos-methyl (commercial name: Reldan 4E; for legal use in wheat, oats, barley, rice, sorghum, and on empty bins). Malathion has been the insecticide of choice for more than 20 years. However, during the last 15 years high levels of insect resistance to this chemical have been reported. Recent developments seem to indicate the end of malathion-use in the United States. Manufacturers have decided not to provide the Environmental Protection Agency (EPA) with updated information on pest persistence, environmental impact, and mammalian toxicity (Weinzierl 1991). This data has been requested by the EPA before production licenses will be reissued. Other protectants such as *Bacillus thuringiensis* (a bacterium) and inert dusts (such as silica aerosols, aluminum oxide, diatomaceous earth, and clays) have been found to have varying degrees of effectiveness. They are not used extensively in the United States.

The term "fumigation" is often used incorrectly. A fumigant is a chemical which, at a required temperature and pressure, can exist in the gaseous state in sufficient concentration to be lethal to a given pest organism. Thus, fumigants are gases that penetrate into the treated material, and are subsequently removed by aeration. Some wrongly believe that any application of an insecticide as an aerosol, fog, mist or smoke is a fumigation treatment. Fumigation is highly specialized and involves very toxic pesticides; their application requires professionally licensed personnel. A structure must be gas-tight for fumigation to be successful. The fumigant gas concentration must be maintained long enough to kill the least susceptible life stage of an insect. The primary fumigants used in the United States are: (1) methyl bromide, and (2) hydrogen phosphate. The latter is at present the fumigant of choice.

The effectiveness of an insecticide or a fumigant is limited by the amount of time available, the moisture and temperature of the grain to be treated, and the legal restrictions on the use of the pesticide by local, State, and Federal authorities. The insect must come in contact with the residual before it is killed, and must be exposed to the correct level of fumigant for the required time.

Other technologies slowly emerging for controlling mold development and insect infestation are modified atmosphere storage, hermetic storage, irradiation, and microwave heating. Recently developed growth-regulators show some promise to control insects without toxicity to humans or chemical residues (Büchi 1991). Predator ("beneficial") insects have also been proposed. Adding them to the grain constitutes an illegal adulteration according to the present regulations of the U.S. Food and Drug Administration (FDA) (Weinzierl 1990). Research has shown that adding beneficial insects in large numbers greatly curtails the rate of increase of pest populations, but not necessarily below levels required by the standards of the Federal Grain Inspection Service (FGIS).

During the storage period the quality of cereal grains and oilseeds cannot be improved. The preservation of the quality during the handling operations is critical to the subsequent processing operations. Grain chilling has been shown to be an effective technology in achieving grain quality preservation in countries throughout the world. The U.S. grain industry is expected to also benefit from the utilization of grain chilling technology in the future.

1.4 U.S. Grain Processing

To appreciate the quality requirements of each industry segment involved in the processing of grain, a basic understanding of the processing operations is necessary. Each grain has multiple end-uses. Wheat is used for domestic food consumption, export, animal feed and seed (see Table 1.11). The proportion used for domestic purposes in the U.S.A. has fluctuated between 32 and 53 percent over a 15 year period (U.S. Congress 1989a). Wheat is very dependent on export. By the early 1980's as much as 68 percent of U.S. wheat was exported. During the past several years, the export share has leveled off to about 50 percent. Almost all wheat other than that fed to livestock and used for seed is milled into flour for a variety of bakery products for human consumption.

The major use of corn in the U.S.A. is as animal feed; it accounts for well over half the corn consumed (see Table 1.12). Feed use has fluctuated due to price changes and a changing livestock inventory. Other domestic uses are for food, industrial utilization, and as seed. The industrial use has steadily increased since 1971. Domestic utilization has accounted for 70 to 85 percent of the corn crop over the past 15 years. Although not as dependent on world markets as wheat, about 30 percent of the U.S. corn is exported

Year	Food	Seed	Animal feed	Total domestic	Domestic share (percent)	Exports	Export share (percent)
1971-72	523.7	63.2	262.4	849.3	58.2	609.8	41.8
1972-73	531.8	67.4	199.8	799.0	41.3	1,135.0	58.7
1973-74	544.3	84.1	125.1	753.5	56.1	1,217.0	43.9
1974-75	545.0	92.0	34.9	671.9	39.7	1,018.5	60.3
1975-76	588.6	99.0	38.3	725.9	38.2	1,172.9	61.8
1976-77	588.0	92.0	74.4	754.4	44.2	949.5	55.8
1977-78	586.5	80.0	192.5	859.0	43.3	1,123.9	56.7
1978-79	592.4	87.0	157.6	837.0	41.2	1,194.1	58.8
1979-80	596.1	101.0	86.0	783.1	36.2	1,375.2	63.8
1980-81	610.5	113.0	59.0	782.5	34.1	1,513.8	65.9
1981-82	602.4	110.0	134.8	847.2	32.4	1,770.7	67.6
1982-83	616.4	97.0	194.8	908.2	37.6	1,508.7	62.4
1983-84	642.6	100.0	369.1	1,111.7	43.8	1,428.6	56.2
1984-85	651.0	98.0	404.5	1,153.5	44.7	1,424.1	55.3
1985-86	678.1	93.0	273.5	1,044.6	53.3	915.4	46.7
1986-87	696.0	84.0	413.3	1,193.3	54.3	1,003.5	45.7
1987-88[b]	719.0	85.0	280.1	1,084.2	40.5	1,592.1	59.5

[a]Differences between utilization and production are attributable to imports
[b]Preliminary

Table 1.11 U.S. utilization of wheat by type of use, 1971-88 (in million bushels and percentage) (U.S. Congress 1989a).

Year	Food, alcohol, and industrial	Seed	Animal feed	Total domestic	Domestic share (percent)	Exports	Export share (percent)
1971-72	394.0	15.0	3,978.0	4,387	84.8	786.0	15.2
1972-73	407.0	16.0	4,310.0	4,733	79.2	1,243.0	20.8
1973-74	417.0	18.0	4,265.0	4,700	79.8	1,188.0	20.2
1974-75	432.6	18.8	3,225.6	3,677	76.2	1,148.5	23.8
1975-76	469.9	20.2	3,591.6	4,081.7	70.5	1,711.4	29.5
1976-77	493.3	19.8	3,586.6	4,099.7	70.9	1,684.2	29.1
1977-78	532.9	18.0	3,709.5	4,260.4	68.6	1,947.8	31.4
1978-79	557.0	18.0	4,198.1	4,773.1	69.1	2,133.1	30.9
1979-80	655.1	20.0	4,518.6	5,193.7	68.1	2,432.6	31.9
1980-81	715.1	20.2	4,139.0	4,874.3	67.4	2,355.2	32.6
1981-82	792.1	19.4	4,276.0	5,087.5	72.1	1,966.9	27.9
1982-83	880.3	14.5	4,520.7	5,415.5	74.7	1,833.8	25.3
1983-84	956.0	19.1	3,817.6	4,792.7	71.6	1,901.5	28.4
1984-85	1,070.0	21.2	4,079.0	5,170.2	73.5	1,865.4	26.5
1985-86	1,140.0	19.5	4,095.3	5,254.8	80.9	1,241.2	19.1
1986-87	1,175.0	16.7	4,713.7	5,905.4	79.7	1,504.4	20.3
1987-88	1,207.0	17.0	4,649.7	5,873.7	77.3	1,725.0	22.7

[a]Differences between utilization and production are attributable to imports

Table 1.12 U.S. utilization of corn by type of use, 1971-88 (in million bushels and percentage) (U.S. Congress 1989a).

annually. Most food corn is used for dry and wet milling. Several by-products of the corn dry and wet milling industries are used for animal feed, including gluten feed and meal, Brewer's dried grain, and distiller's dried grain.

Soybeans are processed for domestic food and feed consumption, seed use, and export. Domestic processing is the most important use of soybeans, and has increased steadily over the past 15 years (see Table 1.13). Domestic soybean utilization accounts for about 60 percent of the total, while 40 percent of the soybeans are exported. Soybeans are used for oil extraction and as a high-protein feed source. Other products made from soybeans include lecithin, soy flour, and soy grits. Soybean meal usage has increased 49 percent relative to the livestock inventory since 1971.

The domestic use of rice is small compared with other grains (USDA 1990a). Food, processed food, and beer comprise the domestic outlets for rice. The domestic use of rice has increased from less than 18 million hundredweights (0.8 MMT) in 1950 to over 55 million hundredweights (2.5 MMT) in 1987/88. Direct food use averages 60-64 percent of the total domestic usage of rice. Beer manufacturing requires 20-25 percent, and processed foods the remainder of the balance. Processed foods include soups, cereals, pet foods,

Year	Domestic processing	Seed, feed, and residual	Total domestic	Domestic share (percent)	Exports	Export share (percent)
1971	720	65	785	65.3	417	34.7
1972	722	82	804	62.7	479	37.3
1973	821	75	896	62.4	539	37.6
1974	701	79	780	64.9	421	35.1
1975	865	71	936	62.8	555	37.2
1976	790	76	866	60.6	564	39.4
1977	927	82	1,009	59.0	700	41.0
1978	1,018	99	1,117	60.2	739	39.8
1979	1,123	85	1,208	58.0	875	42.0
1980	1,020	99	1,119	60.7	724	39.3
1981	1,030	89	1,119	54.6	929	45.4
1982	1,108	86	1,194	56.9	905	43.1
1983	983	79	1,062	58.8	743	41.2
1984	1,030	93	1,123	65.3	598	34.7
1985	1,053	86	1,139	60.6	740	39.4
1986	1,179	104	1,283	62.9	757	37.1
1987	1,170	96	1,266	61.7	785	38.3
1988[b]	1,075	95	1,170	65.2	625	34.8

[a] Differences between utilization and production are attributable to imports
[b] Preliminary

Table 1.13 U.S. utilization of soybeans by type of use, 1971-88 (in million bushels and percentage) (U.S. Congress 1989a).

rice cakes, and baby foods. Most of the direct food use consists of long-grain rice. Processors and brewers usually purchase short and medium grain rice, and brokens. Only rice millfeed - a mill by-product consisting of bran and hulls - is fed to animals.

The objective of milling is to make cereals more palatable and thus more desirable as food (Hoseney 1986). Milling involves the removal of bran. The germ is usually removed during milling: it is relatively high in oil content, and may cause rancidity. There are two types of milling processes - dry and wet. Dry milling separates the anatomical parts of the grain cleanly. Wet milling attempts to separate the bran or germ from the endosperm, and separates the endosperm into its chemical components of starch and protein.

1.4.1 Wheat Milling

Wheat is dry-milled to remove the bran and germ; the process reduces the wheat kernel to flour for various baked and non-baked goods. In general, 100 pounds of wheat produces 72 pounds of flour (Hoseney 1986). The remaining 28 pounds is classified as millfeed; this product is mostly used for livestock in formulated rations. The Association of American Feed Control Officials differentiates between eight types of millfeed. In recent years, wheat bran has become an important fiber ingredient in foods for human consumption, especially in breakfast cereals. Soft-wheat and yeast-leavened products, pasta, and noodles are made from wheat flour. The flour is produced from the dry-milling of wheat.

The number of wheat flour mills in the United States in 1989 was 208 with a total capacity of 1.2 million hundredweights [cwt] (54,000 MT) per day (see Figure 1.14) (Anon 1990c). The average capacity was 5,700 cwt (259 MT) per U.S. mill per day. The basic flour types (and the daily production capacities) are hard wheat flour (over 840,000 cwt; 38,000 MT), soft wheat flour (over 240,000 cwt; 11,000 MT), whole wheat flour (about 40,000 cwt; 1,800 MT), and Durum flour (about 95,000 cwt; 4,300 MT).

Table 1.14 lists the number of wheat flour mills and the capacity per state (Anon 1990c). The largest numbers are located in Kansas (19), Pennsylvania (19), New York (12), Minnesota (11), North Carolina (11), Ohio (11), and California (10). These seven states had a total capacity in 1989 of over 517,000 cwt (23,500 MT), or 48.2% of the total U.S. capacity. The largest capacity mills are located in Minnesota with an average of 10,650 cwt (484 MT) per mill, followed by New York with 9,625 cwt (438 MT) per mill.

State	Number of Mills	Active Capacity in Hundredweights	State	Number of Mills	Active Capacity in Hundredweights
Alabama	1	9,000	Nebraska	6	29,170
Arizona	2	9,500	New Jersey	1	12,000
California	10	76,200	New Mexico	1	1,000
Colorado	3	19,000	New York	12	115,500
Delaware	2	472	North Carolina	11	33,110
Florida	3	27,500	North Dakota	1	7,000
Georgia	3	13,100	Ohio	11	69,575
Hawaii	1	2,200	Oklahoma	4	29,500
Illinois	7	66,760	Oregon	3	17,500
Indiana	5	30,400	Pennsylvania	19	42,050
Iowa	2	14,900	South Carolina	2	1,600
Kansas	19	118,440	South Dakota	1	3,000
Kentucky	6	4,025	Tennessee	9	44,600
Louisiana	2	11,500	Texas	7	44,060
Maryland	2	4,000	Utah	9	35,470
Michigan	7	27,600	Virginia	8	17,508
Minnesota	11	117,110	Washington	4	28,800
Missouri	8	75,848	Wisconsin	1	13,500
Montana	4	14,820	Total	208	1,187,318*

* Total includes approximately 39,000 cwts of durum capacity at various locations.

Table 1.14 Wheat flour milling capacity by state in the U.S.A. (Anon 1990c).

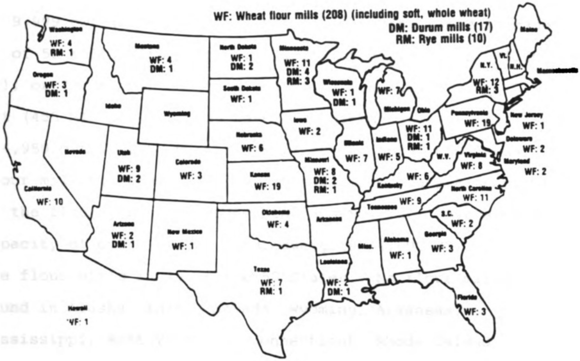


Figure 1.14 Number of mills by state in the U.S.A. (Anon 1990c).

The majority of the wheat flour mills in the United States have a daily capacity ranging from 1,000 to 4,999 cwt (45 to 230 MT) (Anon 1990c). The 60 mills have a combined capacity of 163,620 cwt (7,400 MT), or 13.8% of the total. The 5,000 to 9,999 cwt (230 to 455 MT) per day capacity range is made up of 53 mills with a total capacity of 352,300 cwt (16,000 MT), or 29.7%. In addition, 44 mills are larger than 10,000 cwt (455 MT) per day, and have a combined capacity of 654,950 cwt (30,000 MT), or 55.2% of the total U.S. wheat flour milling capacity; 24% of the mills produce 84 percent of the flour. Kansas, Minnesota, and New York have a daily capacity of over 100,000 hundredweights (4,600 MT). There are flour mills in 38 of the 50 States. No flour mills are found in Alaska, Idaho, Nevada, Wyoming, Arkansas, Mississippi, West Virginia, Connecticut, Rhode Island, Vermont, New Hampshire and Maine.

Table 1.15 lists the top 15 flour milling companies in the United States in 1990 (Anon 1990c). The top four companies - ConAgra, ADM Milling, Cargill and Pillsbury - have a combined wheat-durum-rye milling capacity of 711,800 cwt (32,000 MT) per day, or about 60% of the total U.S. daily milling capacity. Furthermore, these four companies have a combined grain storage capacity of 124.9 million bushels (3.1 MMT), or 1.3% of the total U.S. storage capacity. Most of the larger companies are multiple mill companies, i.e. besides the wheat-flour milling operation they also mill durum, rye, bulgur, dry corn, soy, buckwheat, oat, and rice, operate specialty flour mills, flour-packaging facilities, mix-manufacturing plants, and corn refineries.

Company	Wheat flour mills	Durum and rye mills	Wheat Flour Capacity Soft wheat (cwts)	Whole wheat (cwts)	Total (cwts)	Durum capacity (cwts)	Rye capacity (cwts)	Wheat-Durum-Rye Total (cwts)
ConAgra, Inc.	29	2	35,000	5,400	266,000*	0	0	266,000
ADM Milling Co.	20	1	29,500	3,700	169,700	5,000	0	174,700
Cargill, Inc.	14	1	5,000	2,000	148,700	1,400	1,300	151,400
Pillsbury Inc.	8	0	29,300	3,700	119,700	0	0	119,700
Cereal Food Processors	9	0	15,300	2,500	68,300	0	0	68,300
General Mills, Inc.	7	0	4,800	0	66,700	0	0	66,700
Bay State Milling Co.	7	2	4,500	4,250	53,250	2,500	2,600	58,350
Dixie-Portland Flour Mills	6	0	21,000	500	55,000	0	0	55,000
Nabisco Brands, Inc.	1	0	28,000	0	28,000	0	0	28,000
Mennel Milling Co.	4	0	22,700	1,500	22,700	0	0	22,700
N. Dakota Mill & Elevator	1	0	0	0	7,000	11,000	0	18,000
Fisher Mills Inc.	1	0	5,000	1,000	15,000	0	0	15,000
Bartlett Milling Co.	2	0	1,400	0	13,000	0	0	13,000
Shawnee Milling Co.	2	0	0	0	9,500	0	0	9,500
Star of the West Milling	3	0	9,500	400	9,500	0	0	9,500

*Includes unspecified durum capacity.

Table 1.15 The major U.S. wheat-durum-rye milling companies (Anon 1990c).

Although a significant amount of wheat is wet-milled into starch in the United States, the major source of starch is corn. Wheat starch is produced mainly because of the co-production of wheat gluten fraction.

1.4.2 Corn Milling

Dry milling of corn is a process by which the corn kernel is separated into the hull, germ, and endosperm (Hoseney 1986). The two processes used - tempering-degerming and alkaline dry milling - produce flaking grits for breakfast cereals, baking, and snack-food. The corn kernel presents a number of problems for the miller. It is large, hard, flat and contains a larger germ than other cereals (i.e. 12% of the kernel). The germ is high in fat (about 34%) and must be removed if the product is to be stored without becoming rancid. In corn milling, the desired products are low-fat grits rather than corn flour. Thus, the miller has to remove the hull and germ without affecting the endosperm. The hulls are sold as animal feed, and the germs are processed in order to recover corn oil.

The dry milling industry processed 161 million bushels (4 MMT) of corn in 1986 (U.S. Congress 1989a). Total corn milling has ranged from a low of 154 million bushels (3.9 MMT) in 1975 to a high of 170 million bushels (4.3 MMT) in 1982 (see Table 1.16). The dry-milling share of the U.S. corn utilization is 1.8 - 3.9 percent.

Year[a]	Dry-milled and alkaline cooked products (million bushels)	Total U.S. corn production (million bushels)	Dry-mill share (in percent)
1975 ...	154	5,841	2.6
1976 ...	155	6,289	2.5
1977 ...	158	6,505	2.4
1978 ...	155	7,268	2.1
1979 ...	158	7,928	2.0
1980 ...	160	6,639	2.4
1981 ...	162	8,119	2.0
1982 ...	170	8,235	2.1
1983 ...	164	4,175	3.9
1984 ...	160	7,674	2.1
1985 ...	161	8,865	1.8
1986 ...	161	8,253	2.0

[a]Year begins Sept. 1.

Table 1.16 Amount of corn used annually for dry milled products in the United States (U.S. Congress 1989a).

The low-fat flaking grits are the highest valued products, and are used primarily in breakfast foods. General food use accounted for 1,125 million pounds (0.5 MMT) of dry milling product in 1977 (see Table 1.17), with breakfast cereals using the most, i.e. 800 million pounds (0.36 MMT) or 71%, followed by snack foods and mixes, i.e. 100 million pounds (0.05 MMT) or 9% each (U.S. Congress 1989a). The single largest product sold by dry millers is hominy feed which consists of all the by-products such as hull fractions, non-separable mixtures of hull, endosperm, germ, germ meal, and corn cleanings; hominy is used as an ingredient in the feed industry.

Use		Quantity (million lbs)
Brewing		1,850
Food, general		1,125
Breakfast cereals	800	
Mixes (pancake, cookie, muffins, etc.)	100	
Baking	50	
Snack foods	100	
Breadings, batters, baby foods, etc.	75	
Fortified Public Law 480 foods		485
Nonfood		530
Gypsum board	100	
Particle, fiber board, plywood	40	
Pharmaceuticals, fermentation	200	
Foundry binders	90	
Charcoal binders	75	
Other (paper, corrugating, oil well drilling fluids	25	
Animal feed		2,200
Total		6,190

Table 1.17 Estimated dry milling product quantities classified according to end use in 1977 (U.S. Congress 1989a).

The number of dry corn mills in the United States had decreased to 68 in 1986 (Anon 1990c). Of these, 55 had a daily capacity of under 12,000 bushels (300 MT), 8 handled between 12,000 and 36,000 bushels (300 and 900 MT), and 5 processed more than 36,000 bushels (900 MT). The majority of corn dry mills are located in the Midwest (i.e. 10 in Illinois, Indiana, and Iowa) and the Southeast of the United States (i.e. 24 in Kentucky, Tennessee and North Carolina). The 13 largest mills have a combined estimated daily capacity of 445,000 bushels (11,000 MT), or about 69%, of the total corn usage for dry milling.

Wet milling strives for the same separations as dry milling but also separates some primary components into their chemical constituents (Hoseney 1986). The main products of the wet milling process are starch, protein, oil, and fiber. More than half of the corn starch manufactured from wet milling is converted into syrups and sugar. Corn starches and sugars are used for human food, beverages, industrial products, and livestock feed. The protein is separated, dried and sold as corn gluten meal for animal feeds. Crude corn oil, which is extracted from the germ during starch recovery, is used for human food, industrial products, and animal feed. The water used to soak the corn is called steep water and is used in pharmaceuticals and animal feeds.

The fiber screenings are used in animal feed. Corn that has been dried at excessive temperatures gives low amounts of soluble protein. Thus the corn also produces greatly reduced yields of starch and therefore is not desired for wet milling. The amount of oil contained in cereals is relatively low. Its recovery is as a by-product of other manufacturing processes. The major cereal oil produced is corn oil. It has good nutritional properties because of its high degree of unsaturated fats. The amount of corn processed by the wet-milling industry had increased to 645 million bushels (16 MMT) in 1985, and accounts for about 12 percent of the domestic corn use.

1.4.3 Soybean Processing

Soybean processing separates the oil by solvent-extraction from the non-oil portion of the bean. The moisture content of the soybeans must be between 9.5 and 10 percent. The soybeans are cleaned, cracked, hulls removed, heated, and rolled into flakes. The crude oil is extracted from the flakes with hexane. After the oil is extracted, the flakes are toasted, and are ground into soybean-meal. The two primary products in soybean processing are oil and high-protein meal. Food uses of oil include shortening, margarine, and cooking and salad oils; non-food uses include paint, varnish, resins, and plastics. Soybean meal is used by the feed industry as a protein supplement for manufactured feeds.

1.4.4 Rice Processing

Four different products can be produced from rough rice, or paddy: parboiled, brown, milled, and broken rice. In parboiling, the rough rice is soaked and pressure-cooked which causes the bran constituents to blend with the inner kernel. Millers gain by purchasing low quality rice at a discounted price, parboil it, and sell it at a higher price than regular milled rice. In general, only long-grain rice is parboiled.

After removing the hull, which is about 20% of the paddy, brown rice is left. By also removing the bran, white milled rice is produced. Many of the rice kernels are broken in the milling process. They are classified and priced according to their length: second heads (the longest), screenings, and brewers (the shortest). Brokens are used in processed foods, primarily cereals, candy, pet food, and beer brewing, where the length of grain and appearance are less important.

Long-grain rice usually sells at a premium compared to medium- grain rice since it is usually processed for specific domestic and export markets. Prices for milled rice are roughly two or three times the farm price. On average, the whole kernel yield from milling is about 58-63 percent, and is known as head yield. At least 145 pounds of rough rice must be processed to obtain about 100 pounds of milled, edible rice.

1.4.5 Breakfast Cereal Manufacturing

Morning is traditionally the time when many cereal products are consumed. Those products, in addition to bread and sweet rolls, either require cooking or they are ready-to-eat. Some cereals that require cooking are farina, which is made form wheat middlings, and hominy grits, which is made from small pieces of endosperm of white corn. The most-widely cooked breakfast cereal is rolled oats (i.e. oatmeal). Among the ready-to-eat cereals are corn and wheat flakes, cereal granules, and puffed cereals. The starting material for corn flake manufacturing, for example, is the large pieces of endosperm (i.e. grits) produced during the dry-milling process. Each grit produces one flake.

1.4.6 Snack Food Manufacturing

Snack foods are defined as foods to be eaten directly out of the package, with the notable exceptions of cookies, crackers, bread, and breakfast cereals. In the United States, the two major raw materials for snack foods are potatoes and corn.

The U.S. snack food industry had sales of $11.93 billion in 1989 (up 9.4 percent from 1988) at a volume of 4,560 million pounds (2.1 MMT), up 3.8 percent from 1988 (Anon 1990a). Snacks outperformed the average volume growth for all grocery products. Some of the major categories showing double-digit volume growth included ready-to-eat popcorn, pretzels, and tortilla chips. The corn chip consumption increased 8.5 percent and microwavable popcorn 6.5 percent in 1989.

Figure 1.15 shows that potato chips constitute the largest volume snack-food sold in the United States (32.2 percent) (Anon 1990a). It is followed by corn and tortilla chips (25.4 percent), and popcorn (14 percent). Thus, corn-based snack foods make up over 39 percent of the market share. Total sales of tortilla chips were $2.1 billion (up 14.1 percent from 1988) and 912 million pounds (0.4 MMT), $635.7 million in corn chips (up 22 percent) and 245.1 million pounds (0.1 MMT), and $1.375 billion in popcorn (up 8.4 percent) and 641.5 million pounds (0.3 MMT). The largest expense in the costs and operations of snack food companies consist of the commodities and ingredients (33 percent) (see Figure 1.16) (Anon 1990a). Thus, the quality of the raw material and its preservation is key to the sellers and buyers of potatoes and food corn in the snack-food industry.

Popcorn is considered the original snack food. The quality of popped corn is determined by such factors as popped volume, shape of the popped kernels, tenderness, and flavor. The popped volume is of particular importance because popped corn is generally bought by weight and sold by volume. During popping, the volume of the corn increases as much as

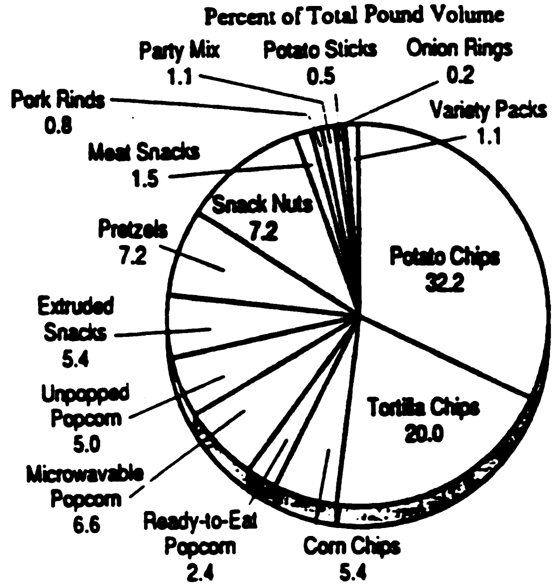


Figure 1.15 Market shares of various snack foods in 1989 (Anon 1990a).

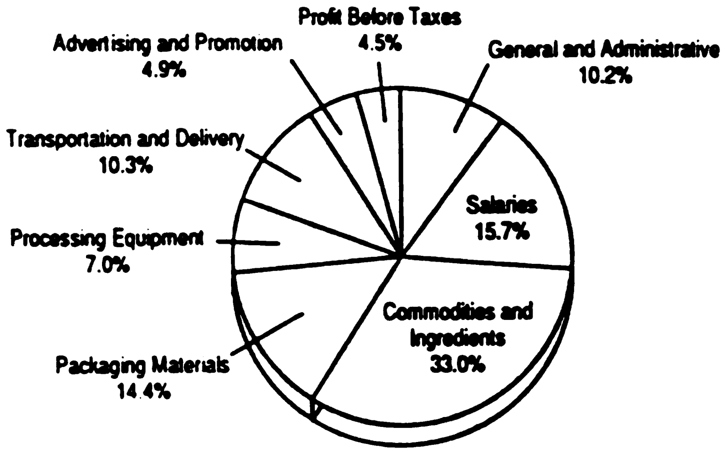


Figure 1.16 Expenses of snack food companies in 1989 (Anon 1990a).

30 times. Among the cereal grains, only popcorn and certain lines of sorghum and pearl millet can pop. Cornnuts constitute another popular corn snack. It is made from a special variety of corn which has very large, opaque, white kernels. The kernels are tempered, fried in fat, and flavored. Corn curls are another corn-based snack; they are extruded from corn flour. The production of tortillas, taco shells, and corn chips requires masa; this is made from corn. Other popular snack foods manufactured in the United States from cereal grains include synthetic nuts, pretzels, crackers and other extruded products.

1.4.7 Feed Processing

Feed processing refers to any treatment that a feedstuff or part of a feedstuff undergoes prior to the consumption by animals. The processing may consist of one step or a series of steps, including cooking, extraction, dehydration, grinding, and pelleting.

In the United States approximately 60% of the non-forage feeds are processed in feed mills (Perry 1984). The commercial feed industry ranks among the top 25 industries in the country. In 1984, 119.6 MMT of feed were produced in the United States (Lin and Ash 1988). Livestock and poultry consumed about 85 percent of the domestic corn production during the 1980's. Wheat use in feed is significantly lower, i.e. wheat and rye use accounted for 16.9 percent of the total feed grain consumption in 1985.

The central process in the feed mill is the pelleting operation. After the feed pellets leave the pellet press, immediate cooling is required to maintain the pellet quality. Cooling of larger- sized pellets (i.e. alfalfa pellets) with ambient air in a so-called pellet cooler is often insufficient to remove the residual heat and moisture from the core of the pellets.

By 1984, the number of feed mills in the United States was 6,720, a decrease of 1,200 mills since 1970 (Lin and Ash 1988). On the average, a U.S. feed mill produced 17,750 MT per year in 1984, compared to 18,200 MT in 1975. The largest mills are located in the Pacific region. They have an average production of 47,700 MT per annum. The size of mills has expanded rapidly in the Southeast from 26,800 MT per mill per year in 1975 to 34,000 MT in 1984 - a 27% increase - primarily due to the increase of the broiler industry in that region. In the Corn Belt, Northern Plains, Appalachians, and Lake States, the average yearly production of a feed mill is from 11,000 to 14,700 MT.

Recent concern about Salmonella and Aflatoxins found in feed has raised the level of awareness of quality preservation of the feed ingredients. The technology of grain chilling has the potential to become a significant asset in preserving feed ingredients, and in chilling feed pellets that have been insufficiently cooled in the pellet cooling operation.

All cereal-grain processing operations require short- to medium- term grain storage, and thus are suitable for the application of the grain chilling technology. An understanding of the end-use of the cereal grains as pasta, noodles, breakfast cereals, and snack foods, as yeast-leavened products (such as bread), and as soft-wheat products (such as cookies, crackers, cakes and biscuits) is fundamental to the appreciation of the preservation of quality of the cereals and oilseeds at the farm and elevator level.

1.5 U.S. Grain Marketing

1.5.1 Grain Flow from Producer to Processor

The major tasks of the U.S. grain industry are to cost-effectively assemble grain from farmers, combine it in their facilities according to quality differentiations, store it until its sale, and transport it to the final market destination.

Generally, farmers transport the grain from the farm in tractor wagons or trucks to country elevators. From there the grain moves to subterminals or terminal elevators, and then to export elevators or domestic processors (see Figure 1.17). Domestic processors and export elevators receive some grain directly from the farmers. In essence, the movement of grain from the farm to the buyer is accomplished by the system of country, subterminal, and terminal elevators.

In most cases, grain is delivered by the farmer to the country elevator, where it is dried, cooled and stored, and later moved to the subterminal elevator. There the grain is again stored. At subterminal elevators it can be shipped to domestic processors, terminal or export elevators. Once grain is received at an export elevator it is briefly, i.e. a few hours, stored and loaded onto vessels for shipment. At export elevators the emphasis is on throughput capacity with minimal storage, while at inland elevators the main emphasis is on storage. Grain moves by truck, railroad (so-called unit trains), barge, or ship as it makes its way from the farm to its final destination. About 70 to 80

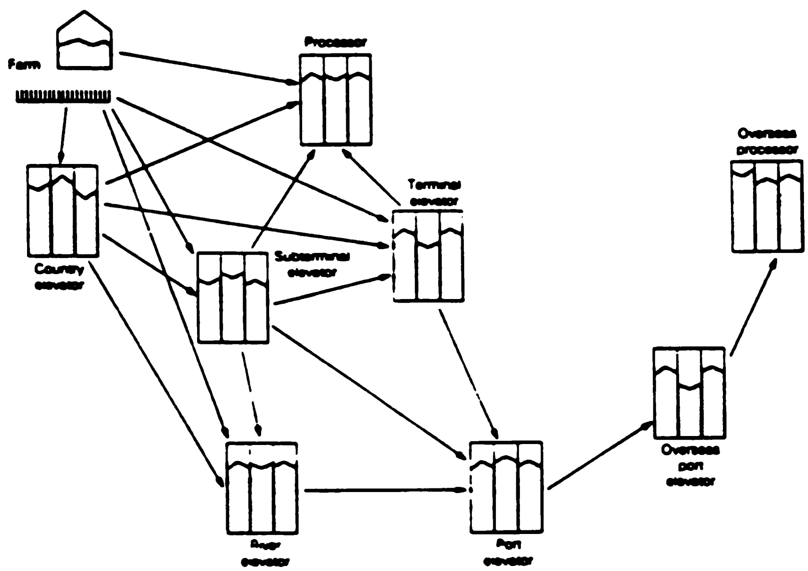


Figure 1.17 Grain flow from farm to final destination (U.S. Congress 1989a).

percent of the large quantities of grain hauled over long distances are moved by rail, while 20 to 30 percent are moved by barges. Almost all grain moved by barges is destined for export ports in the New Orleans area. Ocean vessels carry the exported grain to their overseas destinations.

Figures 1.18 and 1.19 show the basic flow of the grain through a typical country elevator and a typical export terminal, respectively. Country elevators can have less equipment than shown, and export elevators may have cleaners on the outbound side.

A fundamental principle of the U.S. grain marketing system is that of self-selection. Producers, handlers, and users all act in their own best interest. Producers select grain varieties with the objective to maximize their profits. Handlers assemble, condition, and deliver grain subject to negotiated contract terms with the objective to maximize their profits. Users select among different quality factors available to optimize end-use and maximize profit.

The market for quality characteristics is central to these decisions. Price differentials develop and provide incentives and disincentives for participants throughout the system. An important aspect of the process is the

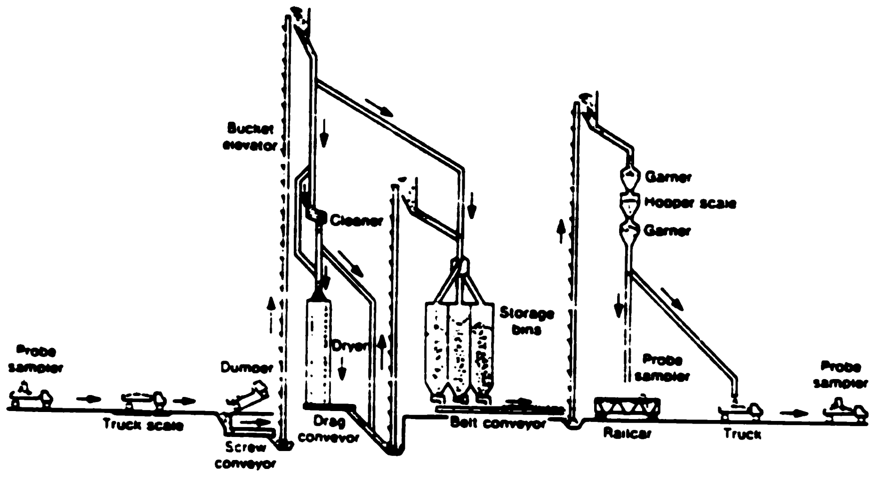


Figure 1.18 Flow of grain through a typical country elevator (U.S. Congress 1989a).

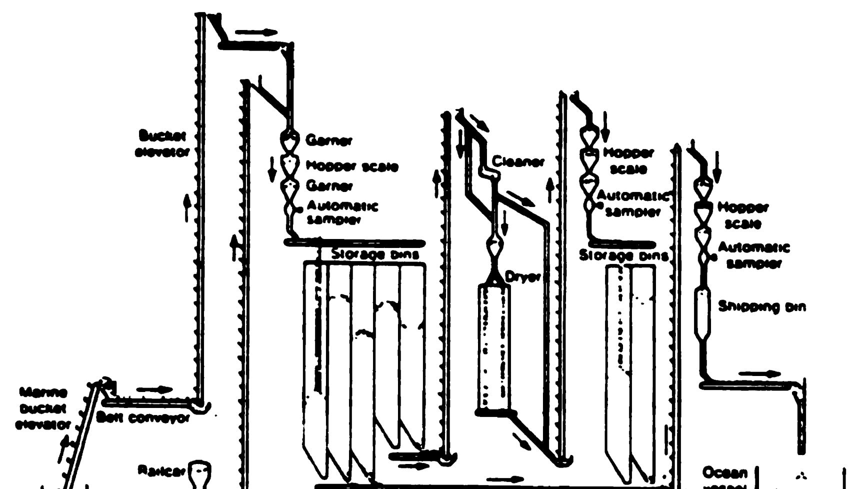


Figure 1.19 Flow of grain through a typical export elevator (U.S. Congress 1989a).

development of premiums and discounts for quality characteristics. Bargaining and contracting for quality specifications occur throughout the system between buyers and sellers. The premiums and discounts reflect the value to the participants. Table 1.18 represents a discount schedule of a commercial elevator in Michigan to assess corn drying and storage charges during the 1989-90 season.

Generally, farmers sell and deliver grain to local country elevators for cash. Since the middle of the 1960's farmers have increasingly searched for bids at competing elevators located as far as 40 or more miles from their farm. They deliver the grain to the elevator offering the highest net bid, i.e. the grain price minus delivery costs. After buying from farmers, the country elevator manager decides when and where to sell the grain. Typically, elevators switch shipments from one destination to another for a fraction of a cent per bushel. Thus, in this highly competitive setting, participants are almost certain to adopt quickly innovations in technology, services, and transportation. Gains that accrue to an innovator through cost-reducing procedures soon become apparent to competing firms. This forces competitors to adopt the innovation or accept a declining volume of business.

1989 CORN DISCOUNT SCHEDULE

MOISTURE	DRYING CHARGE (PRICED)	DRYING CHARGE (STORED)	DAMAGE	DISCOUNT
14.0 - LESS	.00	.00	5.0 - LESS	.00
14.1 - 14.5	.00	.01	5.1 - 6.0	.02
14.6 - 15.0	.00	.02	6.1 - 7.0	.04
15.1 - 15.5	.01	.03	7.1 - 8.0	.06
15.6 - 16.0	.02	.04	8.1 - 9.0	.08
16.1 - 16.5	.03	.05	9.1 -10.0	.10
16.6 - 17.0	.04	.06	10.1-11.0	.12
17.1 - 18.0	.06	.08		
18.1 - 19.0	.08	.10		
19.1 - 20.0	.10	.12		
20.1 - 21.0	.12	.14		
21.1 - 22.0	.14	.16		
22.1 - 23.0	.16	.18		
23.1 - 24.0	.18	.20		
24.1 - 25.0	.20	.22		
25.1 - 26.0	.22	.24		
26.1 - 27.0	.24	.26		
27.1 - 28.0	.26	.28		
28.1 - 29.0	.28	.30		
29.1 - 30.0	.30	.32		

FOREIGN MATERIAL	DISCOUNT	TEST WEIGHT	DISCOUNT
3.0 - LESS	.00	54.0 - OVER	.00
3.1 - 4.0	.02	53.0 - 53.9	.02
4.1 - 5.0	.03	52.0 - 52.9	.04
5.1 - 6.0	.06	51.0 - 51.9	.06
6.1 - 7.0	.08	50.0 - 50.9	.08
7.1 - 8.0	.10		
8.1 - 9.0	.12		

***** DISCOUNTS ARE SUBJECT TO CHANGE WITHOUT NOTICE *****
***** DISCOUNTS ARE TAKEN ON NET BUSHELS *****
***** MOISTURE SHRINK 1.4% EACH 1% OVER 14 (STORAGE) *****
***** MOISTURE SHRINK 1.4% EACH 1% OVER 15 (PRICED) *****

***** STORAGE RATE IS .025 @ BUSHEL PER MONTH *****

Table 1.18 Discount schedule for corn drying and storing during the 1989-90 season at a commercial elevator (Turner 1990).

Country elevators usually hedge their grain purchases by selling a futures contract for a similar quantity on the Chicago Board of Trade (see Table 1.19). When country elevators sell their grain directly or through a broker to a grain processor, exporter, or cash merchandiser, the country elevator "lifts" the hedge by buying back a future contract for a similar quantity from the Chicago Board of Trade. The hedge protects the elevator from the price risks associated with changes in the international grain supply and demand. In exchange, the elevator receives the smaller price risk from the "basis" - that is the difference between the appropriate Board of Trade futures contract and the local price of the grain. Almost all participants in the grain trade - except speculators at the Chicago Board - hedge their purchases and sales.

The sales contract between the country elevator and the processors, exporters, and cash merchandisers typically specifies the terms of the sale. Unless otherwise specified in the contract, title and risk of loss or damage on domestic sales pass to the buyer. Thus, the buyer is responsible for loss or damage during transit on f.o.b. sales and on delivered contracts when the shipment is turned.

In the U.S., sales for export are generally made directly

COMMODITIES FUTURES PRICES

Thursday, September 12, 1991.

Open Interest Reflects Previous Trading Day.

—GRAINS AND OILSEEDS—

	Open	High	Low	Settle	Change	Lifetime High	Lifetime Low	Open Interest
CORN (CBT) 5,000 bu.; cents per bu.								
Sept	249	253½	249	251¾	+ 3¾	287½	218½	4,898
Dec	253¾	256¾	253¾	255¼	+ 3	275	220	137,817
Mr92	260½	263¾	260½	262¾	+ 3¼	277¼	228½	39,815
May	265¼	268	265¼	266¾	+ 2½	279½	234¾	13,857
July	267	269¼	267	268½	+ 2¾	282	239½	10,646
Sept	253¾	255¼	253¾	254½	+ 1¾	265	236½	1,226
Dec	249¾	251¾	249½	250¾	+ 1½	262½	236½	3,915
Est vol 42,000; vol Wed 26,728; open int 212,174, −59.								
OATS (CBT) 5,000 bu.; cents per bu.								
Sept	121½	122¼	121½	121½	+ 1¼	153	109½	88
Dec	134	134	131½	131¾	+ ½	151½	118½	9,023
Mr92	140½	141	139¾	139¾	+ 1	157	126½	977
Est vol 1,500; vol Wed 564; open int 10,235, −87.								
SOYBEANS (CBT) 5,000 bu.; cents per bu.								
Sept	586	590½	585½	589¼	+ 6½	670	513½	618
Nov	594½	599½	593	596¾	+ 5¾	674	517	55,769
Ja92	603½	609½	603½	607¼	+ 6¼	659	527½	11,865
Mar	615	620	614	616¾	+ 5¾	666	538	10,476
May	620	625½	620	624	+ 6¾	668	547	4,283
July	624½	629¾	624	627½	+ 6	668	554	3,685
Aug	619	625½	619	622	+ 6¾	660	565	237
Sept	599	600½	598	598	+ 3½	628	557	361
Nov	590	593½	590	592¾	+ 4½	620¾	552	2,471
Est vol 34,000; vol Wed 25,110; open int 89,765, +477.								
SOYBEAN MEAL (CBT) 100 tons; $ per ton.								
Sept	191.70	194.00	191.70	193.80	+ 2.30	195.20	160.00	6,748
Oct	189.50	191.70	189.30	191.40	+ 2.40	195.00	159.90	14,761
Dec	188.00	189.50	187.60	189.20	+ 2.10	196.50	160.00	26,794
Ja92	186.50	188.00	186.50	187.30	+ 1.70	197.00	161.30	6,868
Mar	185.00	186.30	184.80	185.50	+ 1.40	197.00	163.50	7,550
May	182.50	183.20	182.00	183.00	+ 1.40	194.00	164.50	2,281
July	181.50	182.50	181.10	182.00	+ 1.30	196.00	166.00	1,407
Aug	181.40	181.50	181.40	181.00	+ 1.50	184.50	172.00	354
Sept	181.00	181.40	181.00	181.00	+ 1.50	183.50	172.00	100
Est vol 19,000; vol Wed 19,482; open int 66,863, +2,159.								
SOYBEAN OIL (CBT) 60,000 lbs.; cents per lb.								
Sept	20.45	21.00	20.37	20.68	+ .27	25.10	18.37	2,728
Oct	20.50	21.15	20.43	20.72	+ .29	24.90	18.50	14,074
Dec	20.88	21.50	20.78	21.02	+ .24	24.75	18.81	27,775
Ja92	21.02	21.60	21.02	21.22	+ .25	24.15	19.00	10,680
Mar	21.40	22.05	21.35	21.51	+ .22	24.10	19.31	7,497
May	21.70	22.15	21.65	21.75	+ .23	24.00	19.60	2,535
July	22.20	22.45	22.10	22.12	+ .40	24.30	19.88	1,147
Aug	....	....	....	22.20	+ .48	22.10	20.05	409
Est vol 21,000; vol Wed 17,050; open int 66,910, +930.								
WHEAT (CBT) 5,000 bu.; cents per bu.								
Sept	321½	323½	321	322½	+ 3¾	326	258½	674
Dec	327	330¾	326	329½	+ 3½	326	272½	34,453
Mr92	330	333¼	329	332¼	+ 2½	332½	279	9,984
May	322	326½	322	326½	+ 5½	331	280½	2,803
July	309½	312¼	309½	311	+ 2	313	279	4,677
Sept	316	318	316	316½	+ 4	319	292	215
Est vol 11,000; vol Wed 7,916; open int 52,806, −579.								

Table 1.19 Commodity future prices at the Chicago Board of Trades (The Wall Street Journal 1991).

between the export firm and the buyer of an importing country. Over 50 percent of the U.S. export sales are made under terms specified under a North American Export Grain Association (NAEGA) f.o.b. contract. This contract specifies:

(1) The quality and condition of the commodity is final at the port of loading in accordance with the official inspection certificate.

(2) The seller shall retain title to the commodity until the seller has been paid in full; thus, the risk of loss passes to the buyer at the discharge of the loading spout.

Therefore, the seller retains title of the grain until paid, but the buyer assumes all risk once the grain leaves the discharge spout at the export elevator.

1.5.2 Grain Policy of the U.S. Government

The main purpose of the U.S. government farm policy appears to be the maintenance of farm income. Among the many programs available, two programs are particularly important to the grain industry: (a) the loan rate, and (b) the deficiency payment/ target price.

The Commodity Credit Corporation (CCC) makes non-recourse loans to farmers at established loan rates for corn, wheat and soybeans. The loan plus the interest and storage costs can be repaid within 9 to 12 months, or when the commodity is sold on the cash market. If it is not profitable for the farmer to repay the loan, CCC accepts the commodity as payment for the loan. Commodity loans are frequently referred to as a price support, since national season-average prices generally do not fall below the loan levels. The major objective of the programs is to bring price stability to the commodity market by releasing CCC stocks when prices are high and withdrawing them when prices are low. A second objective is to encourage the orderly marketing of crops throughout the year, and to prevent gluts at harvest.

Deficiency payments are made to farmers for the difference between the target price, which is determined as a politically acceptable income, and the average market price or the loan rate, whichever is higher. Deficiency payments are made on the planted farm acres and the farm program yield, which is based on the farm's yield history. Deficiency payments are intended to raise and stabilize farm incomes while allowing crop prices to be competitive in the export market.

Consumers and taxpayers are concerned over the cost of the U.S. Government support programs. Recent payments, for example, have reached levels up to 30 percent of the total crop value. Substantial support programs existed during the 1980's. It made the storage of grain a lucrative business. However, the subsidies have been cut over the past two years.

1.5.3 Grain Inspection in the U.S.

The United States Grain Standards Act (USGSA) is administered by the Federal Grain Inspection Service (FGIS), an arm of the USDA. FGIS has the statutory authority to develop the grain standards, which facilitate the moving of grain in interstate and foreign commerce in an orderly manner.

Standards for wheat, corn, barley, oats, rye, sorghum, flaxseed, soybeans, triticale, sunflower seed, and mixed grain have been set by the FGIS. Each standard consists of numerical grades, i.e. 1, 2, 3, and Sample Grade. Factors are included in each standard along with maximum limits for each factor have. The grade for any lot of grain is based on the results of an inspection.

Grain is usually inspected each time it is handled, i.e. into and out of a grain elevator, or terminal. This can result in many inspections as grain moves through the marketing chain. No single national policy exists on inspection requirements for domestic grain. Inspection can be performed by FGIS, an FGIS- licensed inspector, by a private individual licensed by USDA's Agricultural Stabilization and Conservation Service (ASCS), or by a private company. Inspection of export grain is mandatory, and must be conducted by the FGIS, or a FGIS-licensed inspector.

1.6 U.S. Grain Quality

Grain quality is dependent on a number of factors which include: (1) the species and variety characteristics, (2) the environmental conditions during the storage period, (3) the time and procedure of harvesting, (4) the drying method, and (5) the storage practices. It is noted that once the grain is harvested, its quality cannot be improved. Thus, the preservation of the grain quality is the basic challenge.

Quality could be defined in terms of sanitary, physical and intrinsic characteristics (U.S. Congress 1989a):

Sanitary quality characteristics refer to the cleanliness of the grain. They include the presence of material other than grain, such as dust, broken and mold-damaged kernels, rodent excreta, insects, residues, and other non-millable materials. They are essentially characteristics that detract from the appearance of the grain.

Physical quality characteristics are associated with the outward visible appearance of the kernel, such as kernel size, shape, color, moisture, damage, and density.

Intrinsic quality characteristics are critical to the specific use of the grain, and can only be determined by analytical tests. In wheat, for example, such characteristics refer to protein, ash, and gluten content. For corn, they include starch, protein, and oil content; for soybeans, protein and oil content.

1.6.1 Quality Standards

The importance of the quality characteristics depends on the grain and its final use.

U.S. Wheat Standard

The U.S. wheat standard establishes the class (i.e. Hard Red Spring, Hard Red Winter, Soft Red Winter, White, Durum, Unclassed, Mixed), as well as information on:

- test weight
- moisture content
- heat-damaged kernels
- damaged kernels total
- foreign material
- shrunken and broken kernels
- total defects
- contrasting classes, and
- wheat of other classes.

Also measured are the number of live insects; the amount of dockage (i.e. the material other than wheat that can be removed by scalping, aspiration, and screens); special conditions such as the presence of garlic and ergot; and the amount of stones, metal, glass, and toxic weed seeds. In a recent survey (U.S. Congress 1989a), domestic millers ranked live insects as the most important factor; containing wheat of other classes was ranked least important. All other factors were ranked equally important across the four major wheat flour types (i.e. hard, whole, soft, and semolina). It was noted that domestic millers use the wheat standard and include limits on one or more of the above factors in their contracts.

U.S. Corn Standard

The U.S. corn standard differentiates classes based on color (i.e. Yellow, White, Mixed), and provides information on:

- test weight
- moisture content
- heat-damaged kernels
- damaged kernels total, and
- broken corn and foreign material (i.e. BCFM).

The number of live insect, stones, and toxic weeds are also included. The corn standards are used differently by different industries (i.e. dry millers, wet millers, and feed manufacturers) because each industry requires different corn quality characteristics. The most important factors to wet millers are the percentage of damaged kernels, BCFM, and live insects; least important is the color class (U.S. Congress 1989a). Moisture, test weight and heat damage are of equal importance. Dry millers regard live insects, moisture, and heat and total damaged kernels as most important. Equally ranked are color class, test weight, total damaged kernels and BCFM. The most important factors to feed manufacturers are live insects, heat and total damaged kernels; of equal importance are BCFM, test weight and moisture, and color class is of least importance. Limits in contracts are always set by feed manufacturers on moisture content, by dry millers on heat damaged kernels, and by wet millers on total damaged kernels. Some limits are set on the other factors by most of the industries, except for color class.

U.S. Soybean Standard

The U.S. soybean standard distinguishes two color classes (i.e. Yellow, Mixed), and provides additional information on the following:

- test weight
- moisture content
- heat-damaged kernels
- damaged kernels total
- foreign material, and
- splits.

The number of live insects, garlic, stones, and toxic weeds are also specified. The most important factor ranked in the survey is the percentage of heat-damaged kernels. Total damaged kernels, moisture, foreign material, and live insects are considered of equal importance. The least important factors are splits, test weight, and color class. Limits in contracts are most often specified for heat damaged kernels and moisture content. Limits on total damaged kernels and foreign materials are also often set.

1.6.2 Quality Attributes

Besides the characteristics specified in the standards for corn, wheat, and soybeans, other attributes that affect the wholesomeness, or the yield and quality of the finished product, may be important. These factors include pesticide residue, molds, mycotoxins, insect fragments, as well as kernel size, shape, and hardness.

Wheat Attributes

The ultimate test for wheat quality is whether the flour can bake an acceptable product. Protein quantity and quality, the amount of alpha amylase, and the dough handling capabilities (i.e. water absorption, mixing time, and extensibility) are used as indicators of baking quality. Due to the different attributes of the major wheat classes, millers blend wheat in order to produce the flour that can best meet the demands of the various finished products. Among 28 attributes not currently included in the wheat standards, pesticide residue, mycotoxins, and hidden/dead insects are ranked highest. Other important attributes are protein, alpha amylase, falling number, flour protein and bake test. The falling number test, pesticide residue and hidden/dead insects are the attributes most often recommended to be included in the wheat standards.

Corn Attributes

The corn standards are not adequate to differentiate between the quality needs of the three major corn industries.

The dry milling of corn is affected by the following factors:

- corn hardness
- drying temperature
- breakage susceptibility
- BCFM
- kernel size and shape, and
- wholesomeness (i.e. freedom from molds, aflatoxins, insects, etc.).

Dry millers need hard corn to produce large flaking grits. Excessively high drying temperatures lead to stress cracks of the corn kernels and reduces the yield and size of the flaking grits. Among the most important attributes currently not part of the corn standards are mold, hidden/dead insects, and mycotoxins. Pesticide residue, breakage susceptibility, drying temperature, stress cracks, age, and color are other important factors not included.

In the wet milling of corn the important factors include:

- BCFM
- drying temperature

- breakage susceptibility
- heat-damaged kernels, and
- wholesomeness.

High levels of mold-damaged kernels affect germ recovery and crude oil quality. High drying temperatures cause stress-cracking and breakage susceptibility, which affects starch recovery. Among the attributes mycotoxins, starch, mold, pesticide residue, oil, and hidden/dead insects are ranked as most important.

In <u>feed manufacturing</u> the most important attributes that are currently not included in the corn standards include mycotoxins, mold, pesticide residue, hidden/dead insects, and protein content. Limits on one or more of the attributes are included in contracts of many of these three industries. Hidden/dead insects, mold, mycotoxins, pesticide residue, and stress cracks are most often part of the contracts.

<u>Soybean Attributes</u>

The quantity and quality of soybean protein and oil are the most important attributes since the main products are high-protein meals and oil. In addition, oil stability and neutral oil loss were ranked most important among the 16 attributes not currently included in the soybean standards.

However, no limits seem to be included in the contracts.

1.7 Summary of U.S. Grain Industry Traits

Grain quality has recently gained attention at the highest levels of the U.S. government. Economic consequences are at stake for the United States, which is the single most important producer, processor, storer, and exporter of grain in the world. Not only inconsistent grain quality, but also the U.S. climate is such that a need for an alternative grain storage technology exists. In the primary regions of U.S. wheat, corn, soybean, and rice production, which are located in the Midwest, the Great Plains, the South, the Southwest, and California, problems with molds, insects, and other quality losses are such that grain chilling should find successful application and commercial acceptance. Since on-farm and off-farm storage structures in the U.S. are commonly equipped with aeration systems, grain chillers could easily be connected to existing aeration ducting.

The primary competing technology to chilled aeration is the traditionally employed ambient (natural) aeration technology. However, in the control of storage pests and molds grain chilling has been shown superior to ambient aeration (see Chapters 3 and 6). Furthermore, grain chilling could help to reduce the dependency of the United States' grain industry on chemicals, which have become an ever-increasing public concern.

The U.S. grain processing industry consists of different sectors, each with specific quality requirements. Grain chilling could give processors the ability to ensure better and more consistent product quality. The role of grain quality in the U.S. is influenced not only by the official grain standards, but also by quality attributes specified in sales contracts. The application of the grain chilling technology in the U.S. grain industry will potentially give the producers and processors, the sellers and the buyers, the means to significantly improve the quality consistency of grain. Since the U.S. grain marketing system is very competitive, the need for profit maximization makes the U.S. system receptive to technological innovations, such as grain chilling. Currently, there exists an economic incentive to improve the overall quality of U.S.-produced grain.

2. OBJECTIVES

The primary objective of this research is to undertake a comprehensive analysis of the aeration of grain with chilled air and the subsequent storage of the chilled grain in upright circular, steel bins. Simulation techniques are utilized that incorporate physical, biological, and operational factors. The theoretical work is supported by experimental data collected over a three-year period at a commercial elevator, by published data, and by data provided by a commercial grain chiller manufacturer.

The specific objectives are:

(1) To develop a model to simulate the performance of a commercial grain chiller under transient ambient conditions.

(2) To integrate the chiller model into a time-dependent grain aeration and storage model for upright, steel grain bins.

(3) To determine the sensitivity of the various design and operating parameters of a chilled grain aeration and storage system.

(4) To evaluate the operational chilling and rechilling strategies for different physical and biological criteria of a chilled grain aeration and storage system.

(5) To investigate the feasibility of chilled aeration and storage versus the conventional aeration and storage of cereal grains.

3. REVIEW OF LITERATURE ON GRAIN CHILLING

3.1 Historical Development of Grain Chilling

As early as 3,000 B.C. grain was stored above ground in the humid regions of the world (Bauder 1967b). In the grain stores of the monasteries of the Middle Ages grain was redried and kept cool by turning. In the arid regions of the world much of the grain was stored underground. Air-tight sealing kept grain cool and dry, and prevented spoilage in Israel and Syria as early as 8,000 B.C (Nash 1978). Generally, today's storage technologies are developments of principles which have been worked out by trial and error over many centuries.

The interaction between moisture content, temperature and storage time on the preservation of grains grew in importance after World War II with the advent of the self-propelled, front-cut combined harvester-thresher. The change-over from traditional harvesting methods to high-volume combining of grain crops caused problems with the post-harvest treatment (Dencker et al. 1952). The lack of suitable shelled-corn drying equipment, for example, delayed the acceptance of the first corn picker-shellers until the late 1950's (Kepner et al. 1978). To avoid losses during subsequent handling and storage, wet grain has to be preserved as quickly as possible (Hall 1980). The use of heated air for rapid drying expanded readily in commercial elevators and large-scale farm operations. However, in many installations the limited capacity of grain dryers soon created bottlenecks (Saul and Lind 1958).

In order to handle the large quantities of incoming wet grain alternative preservation methods were needed. In Europe the search led to the application of refrigerated aeration, i.e the artificial cooling of grain with cold, saturated air (Burrell 1974). It was determined that lowering the temperature of wet grain to less than 10°C within 24 hours of harvest using a grain chiller allowed for the 2 - 3 week risk-free storage of small grains up to 20% moisture and of corn up to 35% moisture (Heidt 1963). Aeration with ambient air was not sufficient to preserve wet grain during the warm harvesting months (Bolling 1964).

According to Reimann (1927) the idea of cooling grain artificially was first proposed by Dienst in 1917, a German engineer. The concept did not materialize as it seemed impractical and expensive for the storage of grain at the time. Linge (1960) discussed two continuous-flow chilling technologies considered as early as 1940. The first involved the counterflow chilling of grain in a rotating drum. The second method consisted of the chilling of grain flowing through an array of 50 mm diameter columns. The ducts were held at -15°C, and achieved conduction heat transfer coefficients of 47 - 58 $W/m^2/°C$. Neither design resulted in commercial application.

According to Burrell (1974), the use of a refrigeration system to store grain at 18 to 20% moisture and dry it to 16 to 18% was proposed in France by Leroy in 1950. A 1953 French patent utilized an evaporator coil above the bulk to lower the temperature of the warm air rising through the grain by convection (Burrell 1974). The chilled air was recirculated through the grain, drying a 40-tonne batch from 17.5 to 14.5% moisture over a two month period, and lowering the temperature to 7°C at the top of the pile. A 1958 French patent improved on the idea and provided forced-air convection via a heat-pump to either chill grain at low temperatures or dry it at high temperatures (Burrell 1974).

A fore-runner of a commercial grain chiller was manufactured as early as 1958 and sold as a cold-air drying system to German farmers (Escher-Wyss 1960a). These closed-cycle batch systems consisted of a heat pump to dehumidify and cool the exhaust air from the top of the grain pile. The cold, dry air was forced back into the bottom of the bulk. It was claimed that the drying capacity and grain quality were superior to ambient air drying at equal or lower operating costs (Escher-Wyss 1960b).

In 1961 the Escher-Wyss company of Lindau, Germany began with the production of commercial grain chillers (Heidt 1963). The units consisted of the cold-air fan, evaporator coil, compressor, condenser and cooling fan (see Figure 3.1). The chillers had cooling capacities of 50 tonnes of grain per day. The cost for a 14 kW unit was DM15,000 (about $3,750). The operating costs were about DM0.60 ($0.15) per ton of grain at DM0.10 ($0.025) per kWh (Bauder 1965).

The so-called "Granifrigor"-technology was only slowly accepted by the grain industry (Ihne 1967). The break-through year was 1963 when about 150 units were sold in Germany and in at least five other countries. Ihne (1967) stated that "on the basis of fundamental research, long-term field testing and practical experience, a risk-free technology and a reliable piece of equipment were developed for the ready use by the grain industry" [Note: Quote was translated from German]. By 1968 the largest silo equipped with a Granifrigor grain chiller had a 1000-tonne capacity and was 33 m high (Boser 1968).

Burrell (1965) warned early on of moisture content increases of the grain around the ducts due to the incoming saturated

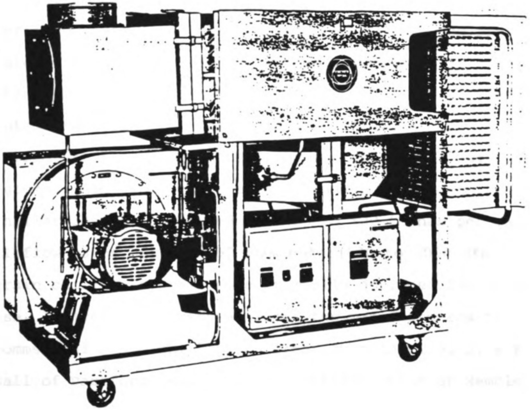


Figure 3.1 First generation grain chiller with a cooling capacity of 50 tonnes per day (Heidt 1963).

cold air. He recommended to reheat the chilled air by 1.5 - 2.5°C in order to lower the relative humidity after the evaporator with waste heat from the condenser, or by placing the cold air fan behind the evaporator. Munday (1965) described commercial grain chilling units manufactured in England. They incorporated reheating of the saturated cold air after the evaporator by 1 - 1.5°C, a cold air fan with variable speed or automatic damper to control the airflow rate, the automatic cut-out of the compressor via thermostat whenever the ambient air dropped below a set point, an automatic defrosting device, and a two-compressor refrigeration cycle that allowed for one to cut-out automatically when the cooling load was low enough. The chiller capacities ranged from 25 to 100 tonnes per day with airflow rates of 14 to 57 m^3/minute (500 to 2000 cfm). The grain chilling systems were primarily designed for on-farm use. In 1965 there were at least two manufacturers of commercial grain chillers in Great Britain, i.e. J. & E. Hall of Dartford, and Lightfoot Refrigeration of Wembley (Burrell 1965). The total number of British installations was estimated between 30 to 40 at the time (Munday 1965).

Bauder (1967b) investigated the possibility of continuous-flow chilling of grain. The efficiency was as low as 30 percent, and recycling of the air was considered too expensive. In discussing future applications of grain chilling, he expected the use of chillers for the temporary storage of wet grain to peak by the end of the 1960's because drying capacities were catching up. A trend towards preserving the quality of dry grain in storage with grain chillers was expected.

By 1970 Granifrigor grain chillers incorporated automatic cold air regulation (Hygromat) and a device to reheat the saturated air after the evaporator to control the relative humidity of the chilling air automatically (Hygrotherm) (Sulzer-Escher Wyss 1970). Previously, the cold air had to be adjusted manually, and not controlling the relative humidity had caused problems with certain applications (Ihne 1971). By 1988 all manufacturers of commercial grain chillers were standard equipped with reheaters (Mühlbauer 1988).

Table 3.1 illustrates the range of models available from one manufacturer at the close of the first decade of commercial grain chilling.

Table 3.1 Range of Granifrigor models available in 1970 (Sulzer-Escher Wyss 1970).

Model	Chilling [t/day]	Connected Load [kW]
30	30 - 35	4.8
60	60 - 70	14.0
110	110 - 120	26.5
300	290 - 310	58.0

Note: t = tonne

Retail prices of 30 to 200 tonne capacity units ranged from DM13,990 to DM47,930 ($5,600 - $19,200) (Sulzer-Escher Wyss 1970). Chilling costs in Germany were quoted as DM0.40 - DM0.70 ($0.16 - $0.28) per tonne with an energy consumption of 4 - 8 kWh per tonne of grain (Boser 1971).

The increase in the application of commercial grain chilling between 1961 and 1989 is illustrated in Table 3.2 using public sales figures of Granifrigor units manufactured by Sulzer-Escher Wyss, Lindau, Germany.

Table 3.2 Commercial growth of Granifrigor grain chillers between 1961 and 1989 in terms of number of units in the field, total annual tonnes chilled, and number of countries units operate in (Ihne 1967, Bauder 1967b, Sulzer-Escher Wyss 1968, 1969b, 1970, 1972, 1973, Brunner 1989).

Year	Units	Tonnes Chilled	Countries
1961	first units	-	1
1963	150	<100,000	5
1968	>300	>200,000	13
1969	>300	1,500,000	>13
1970	500	2,300,000	15
1972	700	>2,300,000	21
1974	800	>3,000,000	23
1989	>800	>25,000,000	55

Today there are at least four manufacturers of commercial grain chilling equipment supplying the grain industry world-wide: (1) "Goldsaat" Fritz Döring GmbH, Remscheid, Germany; (2) "Grain Cooler" PM-Luft, Kvänum, Sweden; (3) "Granifrigor" Sulzer-Escher Wyss GmbH, Lindau, Germany; (4) "Uniblock" Zanotti SAS, Suzzara, Italy. Table 3.3 summarizes the main design parameters of the largest chilling unit of each manufacturer.

Table 3.3 Summary of the main design parameters of the largest commercial grain chiller of each og four manufacturers (Fritz Döring 1991, Sulzer USA 1991, PM-Luft 1990, Zanotti 1990).

	Goldsaat GK 240 NHD	Granifrigor KK400	Grain Cooler 8000	Uniblock 10000
Chilling Capacity [t/day]	270	335	350	350
Airflow at 2000 Pa [m^3/h]	8,300	16,300	16,250	17,000
Evaporator Capacity [kW]	96.5	107.0	107.0	110.0
Connected Load [kW]	32.0	54.0	55.0	50.2

It is obvious that with the exception of one manufacturer (i.e. Fritz Döring) the performance characteristics of the chilling units are similar. This generally holds true for the entire line of chiller models offered. Burrell (1982) considered the main design parameters of chilling units to be (1) operating time, (2) airflow rate, and (3) refrigeration capacity. In his opinion the seasonal operating times of cooling units vary from 700 hours to several 1,000 hours. The airflow rates required to chill grain range from a low of 600 volumes of air per volume of grain to a high of 1,400. A value of about 900 volumes of air per volumes of grain calculated for the commercial chilling units in Table 3.3 using an airflow rate of 16,000 m^3/h, a daily chilling capacity of 350 tonnes, and a small-grain bulk density of 772 kg/m^3, fall within this range of values. With respect to refrigeration capacity Burrell (1982) stated "Because of the high variations in heat load from day to night, low temperatures can be achieved in one of two ways. Either the refrigeration unit must be highly powered to cope with the highest heat load or, alternatively, the airflow through the unit must be governed." Every current commercial chiller manufacturer uses motorized dampers to control the airflow through the evaporator and provide a constant cold air temperature into the bin. Figure 3.2 shows a modern grain chilling unit.

The treatments recommended by the end of the first commercial grain chilling decade in Germany are summarized in Table 3.4.

Table 3.4 Recommended chilling treatments of grain according to Ihne (1971).

Moisture Range [%]	Grain Chilling Treatment
12 - 15	no chilling necessary if grain temperatures are below 20°C
15 - 17	chill to 8 - 10°C once
17 - 19	chill to 8 - 10°C and rechill when grain temperature rises above 20°C
19 - 21	chill to 8 - 10°C and store up to 3 - 4 weeks
21 - 25	chill to 4 - 5°C and store up to 1 - 3 weeks
25 - 30	first dry to desired level, then chill

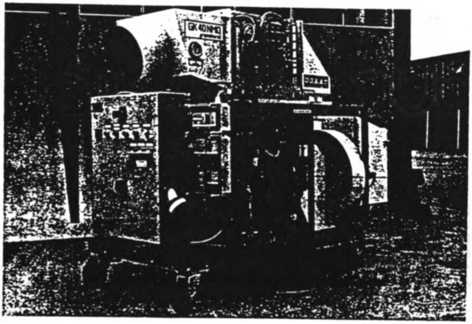


Figure 3.2 Modern grain chiller with automatic airflow and refrigeration control (Fritz Döring 1991).

In contrast, Burrell (1964) recommended the chilling of grain above 22% moisture in the UK climate only for short periods, and it was to be followed by drying. Weekly rechilling was prescribed for grain at 20 - 22 percent moisture, and bi-weekly rechilling for wet grain up to 20% moisture.

By the 1970's practical experience with grain chilling had become numerous enough to refine earlier recommendations. A summary of more current chilled aeration and storage recommendations are listed in Table 3.5.

Table 3.5 Moisture content ranges (MC), grain temperatures (θ), and allowable storage times (AST) of grains with different end uses under chilled storage conditions (Sulzer-Escher Wyss 1972[2], 1989[1]).

	Seed Grain & Malting Barley		Bread Grains		Feed Grains	
MC [%]	θ [°C]	AST	θ [°C]	AST	θ [°C]	AST
12-15[1]	9-12	perm.	10-12	perm.	10-14	perm.
15-16.5[1]	8-10	1-1.5y	9-10	perm.	10-12	perm.
16.5-18[1]	5-7	4-6 m	8-10	5-10 m	8-10	6-13 m
18-20[1]	5	2-3 m	8-10	2-7 m	8-10	3-9 m
20-22[1]	5	3-4 w	6-8	4-16 w	8-10	5-20 w
22-25[2]	5	1-2 w	5-7	3-8 w	5-8	10-25 w
25-30[2]	4-5	2-3 d	4-5	5-10 d	4-5	14-30d
>30[2]	-	-	-	-	4-5	<5 d

Note: y = years, m = months, w = weeks, d = days, perm. = permanent

The data on the relationships between moisture content, temperature and allowable storage time of small grains was based on the research work of Bewer (1957), Agena (1961), Kosmina (1956), Scholz (1962), and Jouin (1964). The chilled storage of grains above 22% moisture was still recommended in 1972, but not any longer in 1989.

The chilling of corn proved to be somewhat more complicated than the chilled aeration of small grains (Sulzer-Escher Wyss 1980). According to the recommendations, corn above 21% moisture content should only be stored short-term and under continuous chilling with cold air at 3 - 5°C without reheat. Corn with a moisture content of 19 - 21% can be stored for 3 - 6 weeks by chilling once to 8 - 10°C. At the end of the storage period the corn needs to be dried to a safe level. Corn at 17 - 18% moisture chilled to less than 10°C can be stable if during chilling the moisture content is reduced below 16%. Corn at less than 16% moisture can be safely stored long-term. The biggest benefit in corn chilling is claimed by combining it with the high-temperature drying. Less stress cracking of kernels is observed when corn is first dried to 19 - 20% and then chilled in-bin, while the corn is still hot. The evaporative cooling effect removes an additional 2.5 - 3.5% moisture, and reduces the grain temperature to a safe storage level (i.e. less than 10°C) according to Sulzer-

Escher Wyss (1980).

Also, corn should be thoroughly cleaned before filling and chilling the storage bin, or at least a grain spreader should be used to distribute the fines. Komba et al. (1987) investigated the airflow through corn with and without a spreader. Without a spreader, the airflow through the corn ranged from 0.15 m/s in the center of the bin to 1.2 m/s at the 7.5 m radius. The silo filled with a grain spreader showed an airflow rate of 0.6 to 0.87 m/s over the entire radius of the bulk. Due to the late harvest season of corn, significant condensation due to the exhaust air from the grain can occur in the head space of the bin (Sulzer-Escher Wyss 1980). During chilling a fan should be installed above the pile to exhaust at least 1.5 - 2 times the volume of the chilling air. More refined recommendations with respect to geographical location of the storage facility, rechilling needs during the storage season, and performance fluctuations due to ambient conditions are generally not found in the commercial grain chilling literature.

In his comprehensive state-of-the-art review, Burrell (1982) summarized the main uses of grain chilling as (1) the reduction of power consumption by storing higher moisture content grain in temperate climates, and (2) the protection of grain from insect infestation by storing cooler grain in tropical and subtropical climates. However, he concluded that "refrigeration has so far had little worldwide impact." Although grain chilling may so far have had little impact on the grain industry, a wealth of application experiences has been reported. Many of these efforts are reviewed and summarized in the next section.

3.2 Applications of Grain Chilling throughout the World

3.2.1 Grain Chilling in Germany

In Germany, the limited capacity of available drying equipment in the 1950's sparked an interest in the commercial development of grain chilling. Traditionally, grain was delivered to the elevator between fall and spring. With the advent of the combine harvester many elevators were faced with the handling of a large variety of crops during a short harvest time. In order to manage drying operations by maximizing intervals between crop switching, grain chillers were used successfully to chill silo cells for the wet holding of grains (Anon 1979).

The temporary storage of wet grain using a refrigeration system to cool to below 10°C independent of the ambient conditions was discussed by Heidt (1963). The possibility to accomplish this task with a continuous-flow process, in-bin, and in flat storage buildings was evaluated. Heidt and Bolling (1965) published the first in-depth German study on the chilling and storage of harvest-wet wheat and corn. Seventy-five tonnes of wheat with a moisture content of 20.5% were successfully chilled to 7.8°C and stored for 20 days. Although the grain temperature increased by 7.4°C during the storage period, the baking and feeding qualities were excellent. A light musty smell disappeared after drying the wheat to 14.6% moisture. Corn at 30% moisture was chilled and stored successfully for 10 days. A difference in self-heating was noted between cleaned versus uncleaned corn bulks.

The recommended design of grain chilling systems for German conditions was based on cooling ambient air from an average summer harvest temperature of 23.5°C to 10°C. The chilled air temperature was kept constant successfully. They noted that the required airflow rate for cooling was independent of the desired grain temperature reduction. A 0.5% moisture reduction of the grain for every 10°C of chilling was determined. The expected energy consumption was 6 kWh per tonne of grain to chill to the final grain temperature of 10°C. Quality preservation was seen as the primary benefit of grain chilling. Their claim of reduced grain respiration was based on work by Scholz (1962), of the preservation of germination and baking quality was based on the works by Bewer (1957), Agena (1961) and Kosmina (1956), and of the prevention of insect development on the work by Burges and Burrell (1964).

The use of grain chillers in the preservation of malting barley had grown to about 100 units in German breweries by 1966 (Bauder 1966). For malting barley the preservation of germinability is of utmost importance. The chilled storage of barley at 18% moisture up to three months was economically attractive for breweries because drying to 14% moisture to achieve storage stability was energy-intensive. Calculations on the need to rechill barley every 25 days to 5°C was based on the self-heating data of Jouin (1964). Miller (1973) conducted an in-depth review of the cooling requirements in malting plants. In many plants and breweries grain chillers were applied in the cold preservation to replace part, or the entire drying step.

Bauder (1967a) presented thermodynamic calculations that formed the basis of the Granifrigor grain chiller design by Sulzer-Escher Wyss, Lindau, Germany. He assumed that in the cooling of large bulks of grain the air and grain temperatures equilibrate. Furthermore, he distinguished between the time for the leading edge of the cooling zone to reach the top of the bulk (i.e. the grain temperature of the top layer begins to decrease), and the time for the cooling zone to push completely through the bulk (i.e. the trailing edge of the cooling zone exits the top of the pile). A theoretical specific airflow rate was established that accounted for the evaporative cooling effect.

On the basis of field experience a multiplier for the airflow rate of 1.2 was used to account for the traverse time of the trailing edge of the cooling zone. Thus, an airflow rate of about 35 m^3/h per daily tonne was calculated to chill 20% moisture grain from 20°C to 10°C. The cold air fan was sized to allow for chilling grain in silos up to 20 m depth at 400 mm water column counter pressure, and in flat storages up to 5 m depth at 100 mm. The calculated refrigeration load was 279 W per daily tonne with a compressor size of 75 W per daily tonne.

During the 1970's the emphasis of chilling wet grain for the temporary storage before the dryer shifted toward utilizing grain chilling as a post-drying treatment. This was in part due to the rising heating oil prices. In comparison, 5 kWh per tonne of grain of electrical energy consumed during chilling versus 3 liters of heating oil per tonne of grain consumed during drying saved DM1.00 per tonne of grain in 1981 prices in Germany (Anon 1981). The break point in favor of chilling occurred at 17.5 to 18 percent moisture content. Conventional drying of grain to that level, coupled with chilling lowered the moisture to the safe storage level of 16 percent, and resulted in energy cost savings of 22.7% for small grains and 7.7% for corn (Brunner 1981). The combination of warm-air drying to lower the crop moisture content to about 18%, and subsequent chilled-air cooling to lower the crop temperature is still widely promoted in Germany as the method yielding the highest grain quality at the least risk to the processor (Skriegan 1989a).

Since the chilling of small grains and corn had become standard technology by the late 1970's, interest in the preservation of other crops began to arise. Self-heating is more pronounced in oilseeds, such as sunflower seeds and rapeseed, due to the high oil content of 40-45% (Holzinger 1989). Oilseeds are not considered stable for long-term storage at 22°C and 6-8% moisture content. Data from Kreyger (1972) shows that the allowable storage time can be extended by a factor of 10 for rapeseed stored at 10°C and 8% moisture, i.e. 160 weeks, compared to 25°C and 8% moisture, i.e. 16 weeks. Crop temperatures of 10-12°C and moisture contents of 12% are considered optimum for the safe storage of rapeseed (Skriegan 1989b). These conditions can only be assured by chilled aeration that controls both the temperature and the relative humidity of the cold air. To overcome the high airflow resistance of rapeseed, manufacturers of grain chilling equipment recommend the use of a suction fan positioned on top of the silo. This has shown to easily double the maximum piling depth of rapeseed (Skriegan 1989b).

3.2.2 Grain Chilling in the United States

In the United States conditioned-air storage to maintain grain quality found its first application in 1959 at a commercial elevator in Happy, Texas (McCune 1962). The objectives of using conditioned-air were (1) to reduce moisture losses due to ambient aeration in Texas, (2) to control insect infestation by lowering grain temperatures, and (3) to store grain at higher moisture contents for feeding purposes. McCune et al. (1963) noted that "... the aeration of grain with conditioned air in which both temperature and humidity are controlled offers a possible solution to insect control problems and the elimination of possible residue hazards." The initial field test employed a 26.4 kW (7.5 tons of refrigeration [T.O.R.]) evaporator coil, a 17.6 kW (5 T.O.R.) compressor, and a 3.7 kW (5 Hp) fan. In 1960 another 26.4 kW were added to the chilling system. The results showed that conditioned-air grain storage had good potential, and that the grain temperature could be reduced to below 10°C.

The field work was followed by detailed laboratory tests to determine the design factors, such as equipment size, operating parameters, appropriate moisture contents, and allowable storage times (McCune et al. 1963). Insulated test bins were equipped with air recirculation and humidity control. The recommended design data for chilling 17.5 tonnes (1000 bushels) of sorghum from 35°C (95°F) to 12.8°C (55°F) was (a) 6.2 kW (1.75 T.O.R.) cooling capacity and 0.12 m^3/min/t (0.12 cfm/bu) of recirculated air over 168 hours, (b) 3.2 kW (0.90 T.O.R.) and 0.12 m^3/min/t (0.12 cfm/bu) without recirculation over 168 hours, or (c) 1.1 kW (0.31 T.O.R.) and 0.12 m^3/min/t (0.12 cfm/bu) without recirculation over 20 days. In later work, Person et al. (1966) and Sorensen et al. (1967) described the thermodynamic considerations necessary to design chilled grain storage systems. A cooling time equation for sorghum describing the traverse time of the trailing edge of the cooling zone was established (Sorensen et al. 1967):

$$\tau = 29\ Q^{-0.65} \qquad (3.1)$$

The total cooling time, τ, is in hours, and the airflow rate, Q, is in cubic feet per minute per bushel.

Haile and Sorenson (1968) determined the effect of respiration heat of sorghum on the cooling load requirements for conditioned-air storage systems in Texas. For sorghum grain it was found that at moisture contents of less than 15% the respiration heat was negligible, while at higher moisture contents the effect was significant.

Shove (1966) proposed a process called "dehydrofrigidation" to dry grain at low temperatures in an insulated dome structure using a refrigeration system. The first phase consisted of cooling the shelled corn from its harvest temperature to -1°C to 10°C (30 - 50°F) within 24 hours. Assuming a moisture content above 22%, about 0.5 m^3/min/tonne (0.5 cfm/bu) were needed to cool the grain. No recirculation was proposed during the cooling phase since the enthalpy of the exhaust air was generally higher than the inlet air to the refrigerator. Thirty-five kW (10 T.O.R) of refrigeration were considered sufficient to cool a daily load of 102 -122 tonnes (4,000 - 4,800 bushels) in the Corn Belt of the United States. Once the grain was chilled, the drying phase began.

Shove (1966) designed a closed-system to dry corn to 15.5% moisture content by dehumidifying the air in the evaporator and reheating it slightly in the condenser to control the relative humidity. One to three kWh per bushel per 10 points of moisture removal, including cooling, was suggested. The system was limited by a small daily drying rate due to the limited allowable storage time of corn. The experimental test encountered several other problems, including molding of the grain in the top layers, and inadequate controls to properly condition the air.

In 1969, Thompson et al. compared the performance of temperature control systems for the storage of chilled, high-moisture grain. The objective of chilling high-moisture grain was to (1) maintain quality until drying was possible, (2) reduce harvest bottlenecks by extending the drying season, and (3) to hold and market grain for feed or processing purposes. Experimental data was collected for corn at 23.3 - 24.8 percent moisture content during two seasons. One bin was equipped with a standard ambient aeration system, and the second bin with a 5.3 kW (18,000 BTU/h) refrigeration system. Both bins had recirculation ducts. Four tests were performed. The first refrigerated test resulted in hot spots and mold development, including a 0.5% moisture increase in the top of the bulk after four weeks. When after nine weeks heating of the grain set in, the refrigeration unit was operated continuously. The first non-refrigerated test showed no visual signs of molding. Neither of the second tests with and without refrigeration developed hot spots. Since the tests were conducted between November and April, no significant performance differences between the systems were observed. The results were used to verify a simulation model that accounted for the dry matter loss of the high-moisture corn. It was concluded that under Midwestern conditions a system with continuous ambient aeration will perform better than a more complicated mechanical refrigeration system when storing high-moisture corn, although the continuous aeration system could not control the grain temperature and moisture content in the bulk.

Ambient and refrigerated air storage in the United States was further investigated by Tuite et al. (1970). Corn at moisture contents of 18 to 22 percent was evaluated with respect to changes in moisture content, temperature, mold population and fat acidity. Field tests were conducted between 1965 and 1969 by storing field-harvested corn in insulated 6 tonne (250-bushel) bins and aerating them at 0.5 m^3/min/tonne (0.5 cfm/bu). The treatments ranged from continuous aeration, to intermittent aeration, and to refrigerated aeration with and without recirculation. It was found that continuous aeration in order to be successful should reduce the maximum corn moisture content in the bulk to below 16% by April. Also, the maximum initial moisture content should not be higher than 21 percent. The refrigerated aeration system had several design shortcomings, including the lack of automatic de-icing of the evaporator coil. However, the system did cool the corn faster in the fall, maintained the temperatures closer to the desired level, and kept the temperatures at a lower level for 4-6 weeks longer in the spring than the ambient aeration system.

Tuite et al. (1970) noted that continuous aeration could not be relied on every year to store high-moisture corn without artificial drying below 20 - 21% moisture first. In their opinion, a refrigerated aeration system did not offer advantages commensurate with the added cost. Besides, the ambient temperatures were generally low enough during the corn harvest in central Indiana to cool grain without a refrigeration system. In the use of both systems, problems with surface molding on top of the pile due to condensation were encountered. A difference in mold development between tests with cleaned versus uncleaned grain was not detected.

Although the temporary storage of high-moisture grain in the United States continued to be of interest to researchers over the next 20 years (Thompson 1972, Stewart 1975, Felkel 1978, Friday et al. 1989, Strohshine and Yang 1990), it appears that after 1970 no additional attempts were made to store grain in the U.S. with the help of a chilled (or refrigerated) aeration system until 1988 with the start of the research project that is in part the basis of this dissertation (Bakker-Arkema et al. 1989, Maier et al. 1989).

Commercial application of grain chilling is starting to take place in a limited number of facilities in the United States; the first chillers were sold in 1991 (Hegadorn 1991). Chilled aeration in the years passed was always applied to the storage of high-moisture grain to overcome bottlenecks in drying, or to utilize wet-stored grain for feeding purposes. Today, throughout the world grain chilling is applied primarily to the storage of dry grain. The evaluation of this aspect of grain chilling for the United States' grain industry is one of the objectives of this dissertation.

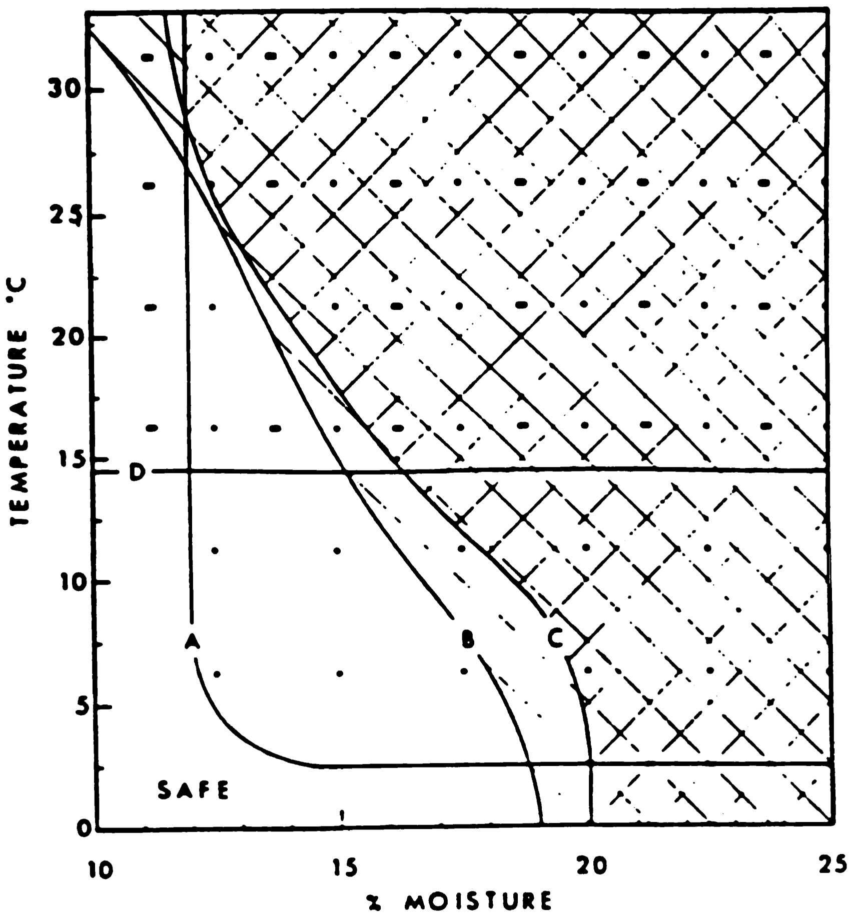
3.2.3 Grain Chilling in Great Britain

Burrell (1964) discussed the potential advantages of chilling harvest-fresh grain over traditional drying, and over storage in air-tight silos in Great Britain. Although chilling 21% moisture grain from 25°C to 5°C used less power than drying the grain to 15%, the potential savings were generally used up due to the need for frequent rechilling. Chilling of grain was beneficial for the control of insects when the grain temperatures were kept below 17°C. Labor savings were incurred by reduced handling and elimination of rewetting of the grain, i.e. of dried wheat rewetted to 16-18% moisture for milling, and of crimping and rolling damp grain for feed. As in other parts of the world, circumventing the drying bottleneck by chilling high-moisture grain was also considered advantageous in Great Britain. The capital costs of a chilling unit were estimated at about 60 percent of the costs of a new dryer. Table 3.6 is a summary of the storage temperatures considered safe by Burrell (1964). Figure 3.3 is a summary in graphical form.

Table 3.6 Recommended safe storage temperatures of grain (in °C) to prevent self-heating due to mold growth, to avoid insect development, and to maintain grain germination for eight months in the British climate (Burrell 1964).

Moisture [%]	Molding	Insects	Germination
17	13	17	10
18	11	17	8
19	9	17	7
20	8	17	5
21	6	17	-
22	4.5	17	-

Burrell (1964) recommended design airflow rates of 0.6 m^3/min per m^3 of grain (0.6 cfm per ft^3) for chilling within 24 hours, and .2 - .3 m^3/m^3/min for chilling within 3 days. In silos the grain pile was to be levelled to assure even cooling.



Effect of environmental conditions on stored cereals. Spoilage occurs more rapidly toward the top right and more slowly toward the bottom left of the diagram. • = mites breeding, − = insects breeding, /// = fungal growth, \\\ = germination loss and spoiled baking quality. Mite attack occurs to the right of and above line A; germination of barley falls to 95% in 35 weeks under the conditions described by line B; fungal heating and mold growth occur above line C. Most common stored-product insects fail to increase below line D

Figure 3.3 Recommended safe storage temperatures of grain to preserve grain quality in chilled aeration and storage systems (Burrell 1964).

Ayton and Huntley (1965) investigated the chilled storage of barley at 18 - 19% moisture for feeding and malting purposes in a flat-storage in Northeastern England. The chiller had a cooling capacity of 19.1 kW (65,000 Btu/h) at an airflow rate of 76.4 m^3/min (2,700 cfm), cooling ambient air from 21°C to 10°C without reheating. The average temperature of 450 tonnes of barley was lowered from 12.8°C to 7.2°C over a 10-day period. In a second test chilled storage of barley compared favorably with sealed grain storage and grain stored after conventional drying. The economic analysis showed savings in drying costs, avoidance of weight losses, and lower capital costs. The design recommendations included an airflow rate of about 1.1 m^3/min per tonne of grain, 3.5 kW (12,000 Btu/h) to cool 10 tonnes of grain in 24 hours, and the consideration of a recirculation system.

Munday (1965) focused on the feeding of cattle with moist barley, which had become popular and profitable in Great Britain. Barley dried to 22% moisture, was successfully chilled and stored in flat-storages. The cold air temperature had to be at least 3°C below the grain temperature for chilling to be effective, and a moisture reduction of 0.35% in barley with a moisture content of 20% was to be expected. The potential need for insulating the flat storage building to prevent the damp barley from rewarming was pointed out.

In 1965, Burrell warned British grain handlers about being too over-enthusiastic about the refrigeration of damp grain while neglecting the need for drying. Although grain chilling controlled insects, molds and mites could still attack damp, cold grain. Recommended precautions included not to chill grain above 22% moisture, to clean the grain before chilling, to rechill at least twice monthly, and to insulate metal bins to prevent heat gain due to the ambient environment.

Burrell and Laundon (1967) published an in-depth study on the first British grain chilling trials. The objective was to evaluate the interest in storing grain above 18% moisture for feeding purposes. Wheat and barley were stored in rectangular, flat-bottomed, metal silos each with about a 100-tonne capacity. A chiller equipped with a 11 kW (15 Hp) compressor and a 5.6 kW (7.5 Hp) cold-air fan was connected to the bins. Barley and wheat at 14 to 17% moisture were chilled from 20 - 25°C to 5°C in 60 hours with an average airflow rate of 0.32 m^3 (1,140 ft^3) of air per m^3 of grain. Wheat at 16 to 22.4% moisture was chilled from 17 - 21°C to 5°C in 36 hours with an average airflow rate of 0.35 m^3 (750 ft^3) of air per m^3 of grain. Since the cold air fan had no damper installed to regulate the airflow the inlet chilled air temperature ranged from -3.2 to 10°C. A moisture loss of about 0.5% was measured for every 24 hours of refrigeration. Since the cold air was saturated, rewetting of the grain around the inlet air ducts with subsequent spoilage was observed.

Burrell and Laundon (1967) made several interesting operational observations. They checked the heat exchange between the air and the grain by turning off the refrigeration unit for 20-minute intervals to see whether the thermocouple readings changed, i.e. to determine whether the thermocouple readings reflected the interstitial air temperature rather than the grain temperature during aeration. Since the readings did not change when chilling was interrupted, they concluded that the sensible heat exchange between the air and grain was essentially instantaneous. However, the latent heat exchange, i.e. the evaporative cooling effect, extended over a broad front through the grain pile. Airflow velocities through the grain were measured as 2.7 - 3.0 m per minute. They cautioned about recirculating the exhaust air since it often had a higher enthalpy than the ambient air. They recommended to start chilling tall bins with fresh air into the refrigeration unit, and later continue by recirculating the exhaust air.

Also, Burrell and Laundon (1967) observed an apparent increase in the grain temperature upon start-up of the chilling unit. This was explained by the fact that warmer layers of grain were located in-between the thermocouples scattered throughout the bulk. Rewarming of the cold, damp grain during the storage period was especially significant near the walls. At 0.15 m and 0.25 m from the wall, the grain warmed 15°C and 10°C after 5 days, respectively. At 0.31 m and 0.61 m, the grain warmed 15°C and 10°C after 13 days, respectively. Insulation of metal bins under the British climate was not considered necessary, and overall chilled aeration of damp wheat and barley for feed purposes was considered a successful application.

In England grain chilling continued to find large-scale application for storing high-moisture feed grain in metal silos (Bauder 1967b). However, Sullivan and Sebestyen (1973) noted that grain chilling in Great Britain during the 1960's could not be considered a success. By 1973 only one of the original installations still used chilled aeration. Among a number of reasons for the failure was in their opinion the attempt to replace drying with refrigeration, a "most serious mistake". They began to reintroduce grain chillers to the British Isles by stressing the effectiveness of preserving small grains and seeds, pulses and legumes, as well as feed pellets and cubes at low temperatures and low moisture contents.

In 1991, McLean and Barlett reported using grain chilling to preserve dry barley in Great Britain. A silo holding 800 tonnes of 13.2% moisture barley was chilled from 29.3°C to 13.6°C in 236 hours. The average moisture content of the barley after chilling was 12.7%. The chilled inlet air was 11.2 ± 1.4°C with an average relative humidity of 72.4 ± 5.4%. The ambient conditions ranged from 10.4 to 24.9°C with an average of 16.8°C and a relative humidity range of 33 to 100% with an average of 72.2%. Energy consumption of the grain chiller was 3.73 kWh per tonne of grain with a power requirement of 12.8 to 14.8 kW and an average value of 13.8 kW. The cooling time of the barley depended more on the ambient conditions, i.e. high ambient temperatures closed the damper on the cold air fan and reduced the airflow, than on the initial grain temperature. The average airflow rate was 709.5 m^3 per m^3 of grain.

The primary motivation for using grain chilling in Great Britain was in their opinion the fact that grain temperature and moisture content had become the major reason for the rejection of British barley by the intervention board of the European Community. In 1987/88 grain temperature was the reason for 23 out of 100 rejections and moisture content for 20 out of 100.

3.2.4 Grain Chilling in Australia

Australian wheat and barley is generally harvested in November and December with grain temperatures of 25 - 40°C and moisture contents below 12% (Sutherland 1986). Storage periods usually last between 6 and 12 months. The biggest problem in Australian stored grain is insect infestation, causing temperature rise, moisture migration, and subsequently molding and spoiling. In the early 1960's Australia almost lost major wheat-exporting markets due to the high frequency of insect infestations found in export shipments (U.S. Congress 1989b). By treating the grain with malathion, grain insects were successfully controlled (Sutherland 1986). However, by 1973 insect pests had developed resistance to the fumigant. Australia exports about 70 percent of its annual wheat crop and is bound by contract to deliver insect-free grain. Besides insect resistance to fumigants, chemical residue in grain has become a public concern.

A comprehensive summary of chilled aeration in Australia was published by Sutherland (1986). After the introduction of ambient aeration in Australia in 1959, refrigerated aeration was found necessary in areas with high ambient temperatures to achieve the same keeping quality. Since it had been well established that insect activity was greatly reduced in grain stored below 15 - 18°C, CSIRO started to conduct the first trials using chilled aeration in 1967. A unit was designed using computer simulation and was built from standard industrial parts to fit the environmental loads of Queensland (Sutherland et al. 1970). It included a motorized damper to regulate the airflow, a 2.8 kW centrifugal fan placed behind the evaporator coil, and a 3 kW compressor. The fan was sized to provide reheating of the saturated air to 10°C and lower the relative humidity to less than 80%. Five-hundred and ninety-four tonnes of wheat initially at 26.4°C and 10.8% moisture were loaded into a 24.4 m high, 6.4 m diameter concrete silo, and chilled to 10.4°C in 17 days at an airflow rate of 0.026 m^3/min/tonne (Sutherland 1986). The final average moisture content was 12.5%. A second silo cooled in parallel with 0.0086 m^3/min/tonne of airflow took nine weeks to cool from 33.0°C to 12.1°C. The average moisture content increased slightly from 10.7% to 10.9%.

During the 1968-69 season, 570 tonnes of wheat were chilled from 28.3°C to 15.5°C in 18 days with an airflow rate of 0.035 m^3/min/tonne of wheat. The average moisture content was reduced from 11.1% to 10.9%. The energy consumption was 4 kWh per tonne for the initial cool-down, but increased to 18 kWh per ton over 10 months of storage in order to maintain the grain temperature in the non-insulated silo.

Sutherland et al. (1970) concluded that insect control during both seasons was successful, however, using one initial fumigation treatment and subsequent chilling was considered preferable.

A second series of chilling trials was conducted beginning in 1973 with a concrete-walled, corrugated-iron roofed silo that was insulated with 50 mm thick polyurethane foam (Sutherland 1986). The chilling unit had 70 kW of cooling capacity, two 11 kW compressors, and recirculated the exhaust air from the head space of the silo back into the chiller. In the first season 2,390 tonnes of wheat were chilled from 29°C to 6°C in about 7.5 weeks at an airflow rate of 0.046 m^3/min/tonne. The average moisture content rose slightly from 11.0 to 11.4%. During six months of storage no insect infestation was determined. The energy consumption was 3.7 kWh per tonne per month of storage.

In the second season 5,230 tonnes of wheat were chilled from 27°C to 5°C at the same airflow rate in little over 5 weeks. The grain moisture content rose from an average of 11.2% to 11.6%. No infestation was found at the end of 9 months of storage. The energy consumption was 3.3 kWh per tonne per month. During the 1975-76 season 2,230 tonnes of barley were chilled from 26°C to 8°C with an airflow rate of 0.052 m^3/min/tonne in 6 weeks. The average moisture content increased from 11.3 to 11.7%. Insect control was excellent during the 10 months of storage. The energy consumption averaged 2.8 kWh per tonne per month. Thirty-five percent of the total capital costs was for insulation. The improved germination and malt yield of barley resulted in the continued commercial use of the system.

A third system was designed based on computer simulations in 1976 (Hunter and Taylor 1980). It incorporated recirculation of the air and insulation of the 1,700-tonne steel silo. The chilling unit had a cooling capacity of 34 kW and a 7.5 kW compressor. The 7.5 kW cold air fan delivered 138 m^3/min at 1,200 Pa static pressure. The chilling unit was equipped with an automatic control system, which turned off the compressor whenever the return air dropped to 8°C, and turned of the compressor and fan, whenever the return air and ambient air were both below 11°C. The silo was fitted with a perforated air distribution duct that was placed on the floor of the silo as closely along the silo wall as possible. The silo was 13.1 m high and 14.5 m in diameter. In the first trial 1,650 tonnes of wheat were chilled from 34°C to 9°C at an airflow rate of 0.086 m^3/min/tonne in about 5 weeks. The mean grain moisture increased from 8.8% to 9.2% at the end of the 9-month storage period. The energy consumption was 2.7 kWh per tonne per month.

The second trial chilled 1,750 tonnes of wheat from 30°C to 9°C at the same airflow rate within 6 weeks. The moisture content increased from 8.3% to 8.8% after 9 months of storage. The monthly energy consumption averaged 2.4 kWh per tonne. In each case adequate insect control was achieved at an energy cost comparable to a newly developed insecticide. However, 43 percent of the capital costs were incurred for insulation. Hunter and Taylor (1980) concluded that chilled aeration is both a practical and effective method of grain quality preservation in Australia.

A fourth system involved the fixed installation of 6 chilling units connected to a 15,000-tonne insulated flat storage (Sutherland 1986). Each unit had 30 kW cooling capacity and utilized recirculation of the exhaust air. In 1977-78, 12,160 tonnes of wheat were chilled from 32°C to 9°C at an airflow rate of 0.040 m^3/min/tonne within 12.5 weeks. The average moisture content increased from 9.9% to 11.0% over the 10-month storage period. The energy consumption was 2.6 kWh per tonne per month. Good insect control was achieved, although some infestation was noted in the peaks of the grain, which cooled slowest.

Trials in Australia with the chilled storage of high-moisture grain have also been reported (Sutherland 1986). Barley at 12 - 14 percent moisture stored well at 8 - 10°C.

The chilling of 16% moisture sorghum to below 20°C before drying came into commercial use in at least one Australian facility. Mobile grain chillers are successfully used in Australia; a 55 kW mobile chilling unit with a rated cooling capacity of 5,000 tonnes per month at 35°C ambient dry-bulb temperature and 40% relative humidity is priced at $A47,300 (about $35,000) (Elder 1991).

Sebestyen (1977) summarized the primary reasons to chill grain in tropical and subtropical countries, such as Australia, as (1) to reduce insect activity, (2) to reduce the need for fumigation, and (3) to eliminate grain respiration.

3.2.5 Grain Chilling in Israel

In Israel a number of studies were conducted with refrigerated aeration. Navarro et al. (1973a) chilled 245 tonnes of wheat in a concrete silo with a height of 19.5 m and 17.9 m^2 surface area. The average grain temperature was reduced from a range of 21 - 21.5°C to 9.9 - 12.7°C in 94 hours. The grain chiller had a cooling capacity of 49 kW and a compressor size of 14.9 kW. Since the reheater was only operated during the first 47 hours, the average moisture content increased from a range of 11.9 - 12.3% to

16% near the inlet duct. The cold air temperature was set to 5°C, and then to 7°C after 18 hours. An increase of about 2°C in the cold air temperature was recorded in the non-insulated duct between the chiller and the silo. The airflow rate was about 3,517 m^3/h, and the energy consumption 6.3 kWh per tonne. No insect infestation was discovered after one week of the end of chilling.

Navarro et al. (1973b) conducted a second chilling test on soybeans imported from the United States. The goal was to arrest self-heating in 229 tonnes of soybeans with a moisture content of 14%. The beans were stored in a concrete silo in February with an initial temperature of 15°C. After three months self-heating to 47°C at 3.5 - 4.5 m below the surface of the pile occurred. A chilling cycle was initiated, cooling the soybeans to 15 - 21°C within 4 days, except for the hot spot, which remained at 25.5°C. The cold air temperature into the silo ranged from 7.5 - 12.0°C including a 2 - 3°C increase in the duct. Over a period of 8 weeks the temperature in the hot spot location increased to 41°C.

A second chilling cycle reduced the bean temperatures to 16.8 - 22.3°C, including the hot spot, over an 8-day period. The cold air temperatures into the silo ranged from 11.0 - 13.0°C with 4 to 5°C reheating in the duct. During both cycles the reheater was turned off, which caused an increase of the soybean moisture content to 15% around the duct. The average moisture content in the rest of the pile decreased to 12.8%. The energy consumption was about 4.5 kWh per tonne per cooling cycle. In the final analysis the development of the hot spot was attributed to a high moisture content and excessive screenings in the top layers of the beans coupled with high ambient temperatures. Navarro et al. (1973b) concluded that the grain chiller was successful in preserving the soybean quality.

In a third trial, a redesigned chilling unit was used, which had the cold air fan positioned after the evaporator to lower the relative humidity (Donahaye 1974). First, 699 tonnes of wheat were successfully chilled from a range of 30 - 37°C to 18 - 19°C in 160 hours with an energy consumption of 4.65 kWh per tonne. Secondly, 863 tonnes of wheat were chilled from 42°C to 15 - 21.5°C in 236 hours with an energy consumption of 4.7 kWh per tonne. No rewetting of the grain occurred near the duct. Over a two month storage period a gradual temperature rise to 23.5 - 25.5°C occurred. Insect activity was not completely arrested. From the analysis of the chilling unit data it became obvious that placing the fan behind the evaporator was not sufficient to control the amount of reheating. There were large swings in the cold air temperature ranging from 7 - 15°C and in the relative humidity from 50 - 65%.

For the chilling of dry wheat in Israel Donahaye (1974) recommended a cold air temperature of 6 - 8°C with a relative humidity of 60 - 70%. The energy costs for chilled aeration compared favorably with ambient aeration in Israel, which consumes 2.05 to 2.77 kWh per tonne for operating times of 523 to 708 hours. The biggest advantage of grain chilling was its operation independent of the ambient conditions. An apparent increase in the grain temperatures recorded in the early stages of chilling were attributed to the heat generated by insect metabolism at depths that could not be sampled.

Ben-Efrain et al. (1985) studied the intermittent use of chilling units in Israel at times when the ambient temperature was too high for the conventional aeration of soybeans. With the combination of regular and chilled aeration, soybeans were stored successfully for four years.

3.2.6 Grain Chilling in Italy

It took about seven years from the introduction of commercial chillers in Italy for grain chilling to find acceptance in the Italian grain industry for the storage of corn, wheat, barley and rice (Baldo et al. 1987). Baldo and Brunner (1983) reported storing 2,600 tonnes of corn in a flat storage building in Northern Italy at an average of 15.2% moisture content (range 12.2 - 17.7 percent) and a grain temperature of 25 - 26°C. In the fall, the pile was chilled with 107 kW refrigeration capacity to 10°C in 282 hours. The energy consumption was 1.86 kWh per tonne. The grain rewarmed in some spots to 15°C by spring. Rechilling the grain to 10°C took an additional 260 hours. The average moisture content during unloading was 14.2%, i.e. a reduction of about one percentage point. An economic comparison of chilling versus drying corn conventionally to 13% moisture yielded a reduction of 26% in heating oil costs, a 15% increase in the dryer capacity, and a pay-back period for the chiller of 1 to 2 years.

Increasingly, refrigerated aeration is used to maintain the quality of the Italian rice crop (Finassi 1987). Drying of the paddy is stopped at 17% moisture, and chilling is used to complete the process by lowering the moisture content and the temperature. Paddy can be stored insect-free at 10°C and 14 - 15% moisture up to 6 - 8 months after cooling once in the late fall (Finassi 1987). Baldo (1987) reported on a number of field tests in which paddy was chilled immediately after the dryer versus after extended tempering. Paddy temperatures of up to 30°C were lowered to 10 - 12°C, and moistures of up to 16.8% were reduced to 15.4%. He concluded that paddy at 15 - 16% moisture could be successfully stored at low temperatures without the development of kernel rancidity. He recommended that initial chilling take place after the kernels have been sufficiently tempered, and rechilling a few days thereafter.

The chilled aeration of hard wheat in Sicily was tested by Blandini (1988). The experimental tests were performed with a mobile grain chiller. The results showed that bulk chilling was practical in Sicily and ensured good storage conditions without pest infestation. New technical developments in the cooling of cereal grains were reported by Zuddas (1986). The new systems were completely automated and designed to minimize energy consumption and grain losses. Bissaro and Bertoni (1989) reported results of the effectiveness of the refrigeration system "Frig-O-Dry F5" on the preservation of rice in silos. The primary advantages were a reduction in dry matter losses, and the prevention of mold and insect development during the storage of paddy.

3.2.7 Grain Chilling in France

Although France is considered the place where grain chilling was first applied commercially, Bauder (1967b) pointed out that negative experiences in field trials discredited grain chilling in France. The tests attempted to utilize the exhaust air from the condenser of the chilling unit to dry grain in an adjoining silo, with both systems underdesigned.

In 1988, Lasseran and Fleurat-Lessart reevaluated chilled aeration in France. They noted that despite the widespread use of ambient aeration systems in France grain spoilage still occurred due to systems that were (1) poorly designed, (2) undersized, (3) improperly operated, and (4) lacked monitoring of grain temperatures. In their study they evaluated insect and larvae mortality during the aeration of grain with cold air. Although cold night air was effective in reducing the grain temperatures and arrest insect development, they concluded that artificial cooling would have reduced the grain temperatures to the desired 5°C faster. It would have also allowed for the maintenance of the temperature over the entire storage period independent of the ambient conditions.

An in-depth study was conducted to compare ambient and chilled aeration in a commercial French elevator (Berhaut et al. 1988). Although more effective in maintaining the desired grain storage temperatures in the high concrete silos, grain chilling was found more expensive in operating costs than ambient air cooling. Artificial cooling of grains in France is mostly limited to large elevators that equip a small number of silos with refrigeration systems in an attempt to preserve poorer quality grain (Lasseran 1991).

3.2.8 Grain Chilling in Spain

In 1970, about 6,000 tonnes of harvest-fresh paddy at 20 - 25% moisture were stored in 12 octagonal silo cells of 32 m height and 20 m^2 floor area in Spain (Clapers 1970). The paddy was chilled from 25°C to 7 - 8°C in 120 hours. At a depth of 1 m from the top surface the temperature was 15°C. After two months in storage the paddy was unloaded. The temperatures had remained stable and the average moisture content was 16%. The paddy showed a 20 percent improvement in head-yield, no yellowing of the kernels was detected, and a higher milling yield was recorded. The following combination of drying and chilling of paddy was proposed:

Step 1: dry the paddy initially to 20% moisture;

Step 2: chill the paddy to 8 - 10°C after drying is complete (an additional moisture removal of about 1.5% is obtained, store the paddy up to 30 days if desired);

Step 3: dry the paddy in a second step to 17% moisture;

Step 4: chill the paddy to 8 - 10°C after drying (an additional moisture removal of about 1% is obtained);

Step 5: re-chill the paddy when the temperatures rise above 13°C (the total storage time is well over 4 months).

Conventional paddy storage in Spain used to be in sacks (Torres 1983). However, since the advent of mechanized harvesting larger bulk storage facilities took the place of sack storages. By 1975 paddy storage had expanded in one facility to 48 steel silos with about 28,000 tonnes total capacity and an additional 20,000 tonnes in flat storage space. The entire storage facility was cooled with 17 grain chillers. Torres (1983) reported that paddy was successfully stored for 3 years at 14% moisture and 12 - 14°C in a silo without turning or fumigation. An economic evaluation of Spanish paddy processing yielded an annual cost of 1.55 Pts/kg for conventional handling of paddy including dry matter loss, fumigation, and drying from 20 to 14% moisture. Chilled handling cost 1.02 Pts/kg in the first year, and 0.30 Pts/kg each year after that including capital and operating expenses, and drying from 20 to 16% moisture.

By 1984 about 80 percent of the paddy handling facilities in Spain used grain chilling technology. Torres (1985) estimated 90 chillers cooled at least 325,000 tonnes of paddy, i.e. one-third stored in silos and two-thirds in flat storages. He made the following recommendations for paddy processing in Spain:

(1) Dry paddy to at least 18% moisture, then chill to 12 - 16°C. Rechill after 3 - 4 weeks to secure safe storage of the paddy for 5 - 6 months at a recommended storage moisture content of about 15 - 16%.

(2) Put paddy up to 18% moisture into chilled storage immediately after harvest. Rechilling needs and storage times are the same as under (1).

Cleaning the paddy before storing and monitoring the paddy temperatures in the silo were considered a must in every installation.

3.2.9 Grain Chilling in Other Locations

The chilled storage of dry barley has been successfully practiced in the hot climate of Peru since 1971 (Malaga 1973). The quality of barley stored at 10 - 15°C with chilled aeration was superior to barley stored at 25°C in conventional facilities. The added electrical costs of chilling were compensated by the elimination of insect treatment with phostoxin, reduced dry matter losses, and elimination of pesticide treatment of the empty storage silos.

In Yugoslavia sunflower seeds arrive at elevators with moisture contents ranging from 6 to 26 percent (Panic 1977). High post-harvest losses were observed because of the high oil content of the seeds. If the moisture content of sunflower seeds is not lowered to 6 - 8% as quickly as possible, it turns rancid during temporary storage. The use of grain chillers was found to preserve the seed for 2 - 4 days before drying. Dried seeds were chilled and successfully stored at 8 - 10% moisture.

In Romania sunflower seeds were chilled from 38°C to 11°C within 144 hours (Thierer and Popescu 1978). The moisture content of the seeds were reduced from 12 to 9% upon completion of the chilling cycle. Over the 7-day chilling period the sunflower seeds did not turn rancid.

In order to avoid fumigation and spoilage, a grain storage was converted into a low temperature warehouse in China (Yang and Song 1980). In the winter dry, cold air was used to cool the corn and rice. In the summer, refrigeration was used to maintain the grain temperatures below 20°C. Low temperature storage was shown to maintain good grain quality and eliminate insect fumigation.

Yellowing of the kernels, insect infestation and moisture migration are common problems found in grain storages in Southeast Asia (Loo 1986). Under the hot and humid summer conditions of Thailand grain chilling has been utilized successfully in at least one rice milling facility (Tuckett 1982). With chilling, the paddy temperature was kept below 20°C. During each chilling cycle about 1% moisture was removed.

In Sri Lanka chilling units are used to lower the temperature of wheat bran pellets to prevent bridging in the holding silos (Sulzer-Escher Wyss 1983). The pellets are chilled from 30 - 31°C to 23 - 24°C in 45 m high, 7.5 m diameter silos. The initial moisture content of 12.8 to 13.4% is reduced by 0.4 - 0.6%. The pellets are preserved for six weeks before loading them onto ships.

Kennedy (1983) reported on the storage of barley in a brewery in Zimbabwe. Grain chilling improved the processing operation by (1) maintaining the viability, (2) reducing grain losses due to respiration, (3) eliminating mold and insect problems, and (4) achieving grain uniformity before malting. As a side benefit he noted that chilled barley transferred to the steep tank did not heat-up the incoming steep water, thus saving refrigeration costs in the plant.

A reduction in breakage and abrasion losses for feed pellets in Indonesian feed mills was noted by Brunner (1985). The residual heat was removed from the pellets by chilled aeration in holding silos after pre-cooling them first in conventional pellet coolers.

The concern over energy consumption in Hungary due to drying (i.e. consuming up to 88% of the energy of all handling operations) lead to the evaluation of combination drying-chilling of wheat and corn (Komba et al. 1987). A total of 10 chilling trials were reported, i.e. five in vertical and five in horizontal storages. Only four were identified in the report by the crop type. In a vertical silo, 2,080 tonnes of corn were chilled from 17 - 22°C to 6 - 8°C. The average initial moisture content was 18%. Over the 305-day storage period three additional chilling cycles reduced the corn moisture by about 2.6%. The average energy consumption was 2.15 kWh/t per cycle. A 2,000-tonne wheat silo was chilled from 24 - 26°C to 8 - 10°C. The initial moisture content was about 18%. Over the 150-day storage period one rechilling cycle was administered reducing the moisture content by 0.7%. The average energy consumption was 6.76 kWh/t per cycle. A 1,500-tonne corn silo was chilled from 16 - 22°C to 6 - 8°C within 6 days. Total cooling time over the 98-day storage period was 372 hours including one rechilling cycle. The moisture content of the corn was reduced from 18% to 17.1%.

In a 700-tonne flat storage, corn was chilled from 20 - 24°C to 6 - 8°C. The moisture content was reduced from 18% to 15.5%. During the 316-day storage period two rechilling cycles were administered. The total cooling time was 366 hours. The average energy consumption was 2.73 kWh per tonne per cycle. In order to evaluate the quality of the chilled corn, a feeding trial with poultry and pigs was conducted. The poultry showed a 2% increase and the pigs a 10% increase in the feed conversion. Komba et al. (1987) concluded that the most economical use of two-stage drying-chilling in Hungary was with corn. They recommended drying corn to 18 - 20% in a conventional dryer followed by chilling and storage at 5 - 8°C.

In Argentina the successful field trial of chilling 400 tonnes of sunflower seeds led to the construction of a 20,000-tonne chilled storage facility (Sulzer Hermanos 1983). The seeds in the initial trial were chilled from 20 - 25°C and 10.5% moisture to 16 - 17°C and 9% moisture. After storage for nine months the acidity remained at its initial value of 1.3%. The main advantages of chilled storage of sunflower seeds in Argentina were savings in labor costs, and improved quality of the processed oil. The storage capacity was subsequently tripled to 60,000 tonnes.

Bean pellets were stored in concrete silos of 4 m diameter and 14 m height in Argentina (Cunille 1988). The pellets were chilled from 35°C to 15°C in 3 days. The cold air conditions were 12 - 13°C and 60% relative humidity. The moisture of the pellets was reduced from 11 to 10%. It was found that the chilled pellets were harder, created less fines, and did not bridge in the silo upon unloading after 60 days of storage.

The successful preservation of rice seed was reported in Columbia (Gonzales 1988). The seed was chilled in flat storage buildings in bulk as well as in sacks. Grain chilling trials indicated a longer storage period, a better final seed quality for growers, and a notable reduction in pest infestation.

Chek (1989) evaluated the feasibility of combining paddy chilling with traditional drying and handling practices in Malaysia. In the first trial, paddy at 19 - 20% moisture was chilled after the initial drying pass. The paddy temperature was reduced from 30 - 31°C to 11.5 - 15.3°C over nine days with cold air at about 13°C and 65% relative humidity. Rechilling took place daily for 8 - 10 hours to keep the top and bottom of the pile below 20°C. The ambient temperatures were 30 - 31°C. After two months of storage the average paddy temperature was 15°C and 18.5% moisture.

In a second drying pass the moisture content was reduced to the desired 13.5%.

In the second trial paddy was dried in three passes from 21 - 23% to 16 - 17% moisture. Chilling over 5 days reduced the paddy temperature from 31°C to 17 - 18°C with air at 17°C and 75% relative humidity. The paddy was allowed to temper for 4 days before a second chilling cycle cooled the paddy to 16 - 17°C with air at 16°C and 76% relative humidity. Although temperature differences were noted between the wall, bottom, top and core locations in the bin, the paddy was stored successfully for 5 weeks. The final paddy moisture content was 14 - 15%. The third trial involved on-floor bulk storage of semi-dried paddy at 16 - 17% moisture. Two-stage chilling reduced the paddy temperature from 32.8°C to 20°C over 5 days (with cold air of 17°C and 65% relative humidity), and after two days of tempering to 19 - 20°C over 6 days (with cold air of 16.5°C and 65% relative humidity). The final moisture content was 13 - 14% after two weeks of storage time.

In investigating the milling quality of the chilled paddy, Chek (1989) determined a 17.4% decrease in the head yield in trial 1, a 5.4% increase in trial 2, and a "satisfactory" head yield in trial 3. No kernel discoloration was found. The energy consumption ranged from 11.6 to 32.0 kWh per tonne of paddy. He concluded that combining the drying of paddy to a higher than normal moisture content with chilled aeration (as in Trial 2) had the potential of increasing the handling and drying capacity of existing Malaysian facilities by 40 percent, and at the same time improve the head-yield recovery from the paddy significantly.

Finally, a recent study on the short-term storage of harvest-wet paddy indicates good potential for chilled aeration systems in Egypt (El-Kholy 1990).

3.3 Biological Considerations in Grain Chilling

Christensen and Kaufmann (1969) stated that "Grains and seeds are both exceedingly durable and highly perishable. If they are harvested sound and are subsequently kept at low moisture content and low temperature they may retain their original processing quality, and even their original germinability, for years or decades." Deterioration of grain begins with harvest and the rate of quality loss depends on the storage conditions (Bailey 1982). The physical parameters that control the storage conditions of grain are moisture content, temperature, and time. The biological parameters of concern in the storage of grain are germination, respiration, fungi, insects, and other pests.

The primary goal of chilled aeration is to slow the rate of grain quality loss by lowering the grain temperature in a storage with the help of a refrigeration system. The effect of low grain temperature as a function of moisture content and storage time on the biological parameters has been the subject of numerous investigations.

3.3.1 Germination

The terms "germination" and "viability" are often used interchangeably. The Association of Official Seed Analysts defines seed germination as "the emergence and development from the seed embryo of those essential structures which, for the kind of seed in question, are indicative of the ability to produce a normal plant under favorable conditions" (Copeland and McDonald 1985). Viability, on the other hand, refers more accurately to the ability of seeds "to survive as viable regenerative organisms until the time and place are right for the beginning of a new generation. Like any other form of life, they cannot retain their viability indefinitely and eventually deteriorate and die." (Copeland and McDonald 1985). Germination is important in chilled storage not only because it is crucial to the reproductive cycle of seed grain, but it is essential in several end uses of cereal grain, such as malting and brewing, distilling, and sprouting (Christensen 1982).

In 1927, Reimann noted that grain storage in Germany was worry-free between November and March. However, in April and May problems arose as the ambient temperatures surrounding the grain storage increased. He stated that minimal quality losses, i.e. germination, in the storage of bread grains could be achieved when moisture contents were below 14 percent (w.b.) and grain temperatures less than 10°C. No decrease in the viability of wheat samples stored at 5°C and moisture contents of 10 - 20 percent (w.b.) were reported by Swanson (1941). Damage to the milling and baking qualities of the wheat was not found. Carter and Young (1945) investigated the effect of moisture content, temperature and storage time on the development of "sick" wheat (i.e. brown germs). The proportion of "sick" wheat increased the higher the moisture content and temperature of the grain, and the longer the storage time. Only a small percentage of "sick" wheat developed over 32 days in wheat at 18.6% moisture stored at 5°C.

Bewer (1957) stored the seeds of the primary bread grains (i.e. wheat, oats, barley, and rye) at moisture contents ranging from 18 - 26% and temperatures of 5 to 20°C. The seed quality was tested by evaluating germination. He concluded that the higher the moisture content and temperature, the sooner spoilage would occur. His results are summarized in Table 3.7.

Table 3.7 Allowable storage time (in days) of seed grain as a function of moisture content (%,w.b.) and temperature (°C) (Bewer 1957).

	5°C	10°C	15°C	20°C
18%	80	33	25	13
20%	42	20	15	9
26%	15	8	6	4

Papavizas and Christensen (1958) evaluated viability, brown germs, and percentage of seeds invaded by fungi. They concluded that the "evidence suggests that wheat with a moisture content up to 16% may be stored without obvious deterioration for a year at a temperature of 10°C or below". Agena (1961) investigated the effect of storing higher moisture grain at temperatures of 6 to -24°C on the viability of grain and mold development. At 0°C he recommended a maximum storage time of 40 days at 26%, 60 days at 22%, and 170 days at 18% moisture content. No reduction in baking quality was observed.

Christensen and Kaufmann (1969) reported that fungi-free corn stored for two years at 18% moisture and 15°C had a germination rate of 96%; when stored at 15.6 - 15.8% moisture at 5, 10, and 15°C for two years it had a rate of

100%. However, No.2 corn stored at 12°C decreased in germination from 60% at the beginning of the test to 42% after six months, to 36% after 12 months, and to 1% after 18 months. When corn was inoculated with a mixture of *Aspergillus* species and stored at 15.9% moisture content and 15°C, it germinated at only 48% after two years. The germination of 18% moisture corn inoculated with *A.flavus* stored at 15°C over 4.5 months was 62 percent. Come (1982) noted that seed of tropical and subtropical origin preserved their viability in bulk silos maintained in a dry 5°C atmosphere.

Burrell (1974) noted that the conditions stated by various researchers on the safe storage with respect to seed germination varied considerably. Apparently, different batches of grain behave differently when exposed to the same set of storage conditions. He stated that "for the preservation of high germinability, drying is preferably to chilled storage" at cool and moist conditions. The estimated safe storage time to preserve the viability of barley at 95% as a function of temperature and moisture content is illustrated in Figure 3.4.

Generally, the lower the moisture content and the lower the temperature, the longer the seed can be stored (Copeland and McDonald 1985). The knowledge of the appropriate limits are

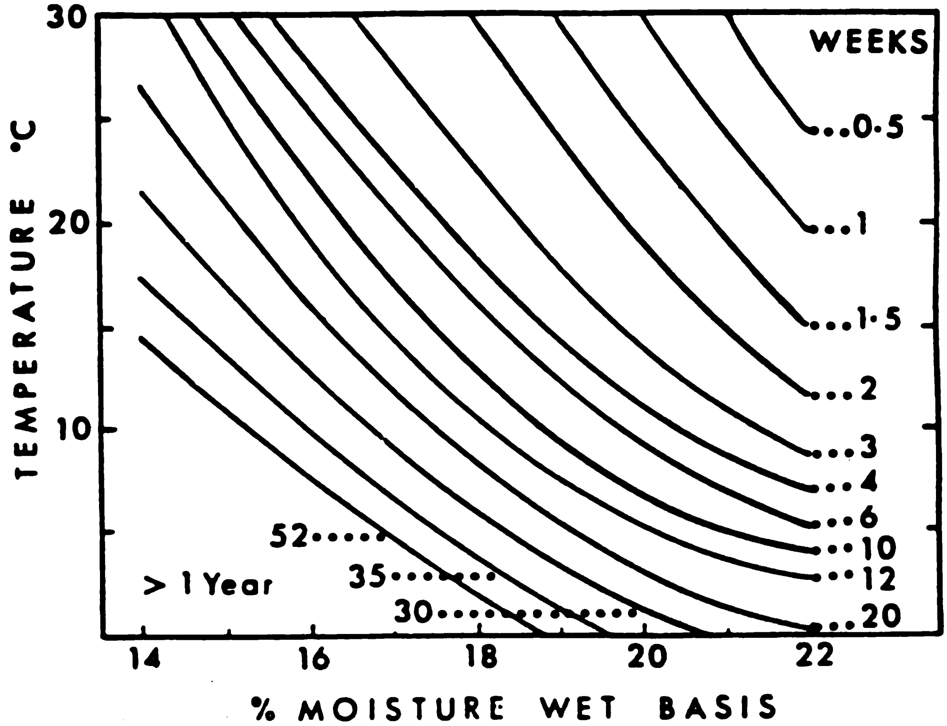


Figure 3.4 Recommended safe storage time to preserve the viability of barley (Burrell 1982).

the basis for the proper engineering design of a chilled aeration and storage system.

3.3.2 Respiration and Fungi

The losses of cereal grains, from the time they reach maturity in the field to the time of their consumption, vary for different cereal grains, varieties, geographic regions and climates from 5 to 50 percent of the production (Brooker et al. 1974). Losses during shelling, drying, and storing generally increase with an increase in moisture. An average of 4.5% cereal grain loss occurs from kernel respiration and mold damage during storage.

Respiration of carbohydrates, the primary constituent of grain kernel dry matter, is a process that produces heat, water and carbon dioxide.

The combustion of a simple sugar follows the following molecular equation (Brooker et al. 1974):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 677.2\ kcal/mole \qquad (3.2)$$

In a grain kernel, one percent dry matter loss is accompanied by the production of 14.7 grams of carbon dioxide per 1 kg of dry matter, and causes a heat development of 157.2 kJ/kg grain (Steele et al. 1969).

In the United States, much of the work on grain deterioration has focused on the dry matter loss of corn during the natural and low temperature drying operation and the subsequent storage period. In Europe, on the other hand, much of the work on grain deterioration has focused on the small grains, such as wheat, rye, and barley.

In the 1950's grain spoilage due to respiration and molding became of concern in many on-farm grain storage installations (Hall 1980). While elevators and larger-scale farm operations only held wet grain temporarily to feed their high-temperature dryers, smaller on-farm operations that dried their own shelled corn had to use unheated or low temperature air to preserve grain.

Early studies on the development of the design parameters for ambient and low temperature drying were done by Dencker et al. (1952) and Foster (1953). Dencker et al. (1952) concluded that successful drying of grain with ambient air depended on the local climate and the operational strategies employed. Foster (1953) pointed to the deterioration of grain in the top 0.3 m of the grain pile, which dried last. He used a weighted deterioration index, which increased with time, to estimate grain spoilage.

Saul and Lind (1958) developed the deterioration concept further by relating the production of CO_2 to the dry matter loss of corn due to respiration and mold development. Later, Saul and Steel (1966) proposed a relationship between the effect of temperature, moisture content, and mechanical damage on the rate of dry matter loss, which was reformulated by Steele et al. (1969):

$$AST = T_R \, m_T \, m_M \, m_D \tag{3.3}$$

The allowable storage time, AST, is in hours. The reference time, T_R, is defined as 230 hours for a 0.5% dry matter loss in corn at 15.6°C, 25% moisture content, and 30% mechanical damage. The relationships of the dimensionless multipliers, m_T, m_M, and m_D, were given in graphical form. A reference time of 58 hours was determined for a 0.1% dry matter loss, and 536 hours for a 1.0% loss. Saul (1970) expanded the results with a more accurate multiplier for grain temperatures below 15.6°C. This lengthened the allowable storage time at lower grain temperatures by a factor of about 2.

Thompson (1972) used computer simulation to investigate the temporary storage of high-moisture shelled corn under continuous aeration to predict moisture content, temperature and grain quality. The grain quality was calculated using the dry matter loss equation of Steele et al. (1969) and Saul (1970). He concluded that deterioration was minimized the higher the airflow rate, the later the harvest date, and the lower the moisture content. Although deterioration was slowed at lower initial grain temperatures, the total deterioration was about the same over the length of storage. The quality index varied by as much as two-fold in its dependence on the local, yearly weather pattern.

Kuppinger et al. (1977) compared the low temperature drying of corn in Germany at field moisture contents of 35% and corn at moisture contents of 20 - 25% after pre-drying in a high-temperature dryer. Germination, dry matter loss, and spore count of micro-organisms were determined to evaluate the quality of the corn. Germination was found not to be a good quality indicator because of its high values even after molding was already visually detected. Dry matter loss varied from 0.6 to 3.0% for corn dried from 35% moisture, while the dry matter loss of pre-dried corn was only 0.04 percent. The spore count for the micro-organism groups of harvest-wet and pre-dried corn is listed in Table 3.8.

Table 3.8 Spore count (number of spores per gram of dry matter) for bacteria, yeasts, and molds in harvest-wet and pre-dried corn (Kuppinger et al. 1977).

Microorganism	Harvest-wet at 35% w.b.	Pre-dried to 19% w.b.
Bacteria	$0.2 \cdot 10^6$ - $4.3 \cdot 10^6$	$1.5 \cdot 10^3$
Yeasts	$0.3 \cdot 10^5$ - $1.3 \cdot 10^5$	$2.1 \cdot 10^0$
Molds	$3.9 \cdot 10^3$ - $6.5 \cdot 10^4$	$3.2 \cdot 10^2$

Based on the spore counts for bacteria, yeasts and molds, ambient air drying of 35% moisture content corn was not recommended. It was concluded that based on the microbiological developments in corn, two-stage drying was preferred. The high temperatures in the continuous-flow dryer reduced the initial spore count significantly.

A similar study by Mühlbauer et al. (1981) investigated the microbiological activity during the ambient drying of wheat under German conditions. Micro-organisms, dry matter loss due to respiration, germination, and baking quality were used as quality parameters. It was concluded that wheat up to a moisture content of 22% could be dried without lowering the quality significantly. Germination of the wheat was 85%, baking quality was acceptable, and dry matter loss was 0.1% at the end of drying. However, spores of field fungi remained viable until the completion of drying, while storage fungi increased with drying time.

The onset of grain spoilage in the upper layers of the pile during ambient aeration and low temperature drying were quantified by Eimer and Morcos (1985). Drying and rewetting of wheat at 30°C aerated at 0.4 m/s, as well as the development of surface molds are illustrated in Figure 3.5 as a function of time, moisture content, and relative humidity.

Most of the molding developed at relative humidities above 85%, which is the level generally found in the upper layers of grain aerated with ambient, or for that matter chilled air, and during low temperature drying. Eimer and Morcos (1985) noted the trade-off between mold development and dry matter loss. Molding occurred earlier in non-aerated grain, while dry matter losses were higher in aerated grain. Germination decreased and spore count increased as the relative humidity of the interstitial air increased.

Friday et al. (1986) investigated the low temperature drying of different corn hybrids. They verified that so-called mold-resistant hybrids indeed were less susceptible to molding despite a higher moisture content, greater damage index and greater visual damage. Friday et al. (1989) related the mold-resistance of different hybrids to the CO_2-production of dry matter loss, and proposed to add a hybrid multiplier to the dry matter loss equation of Steele et al.

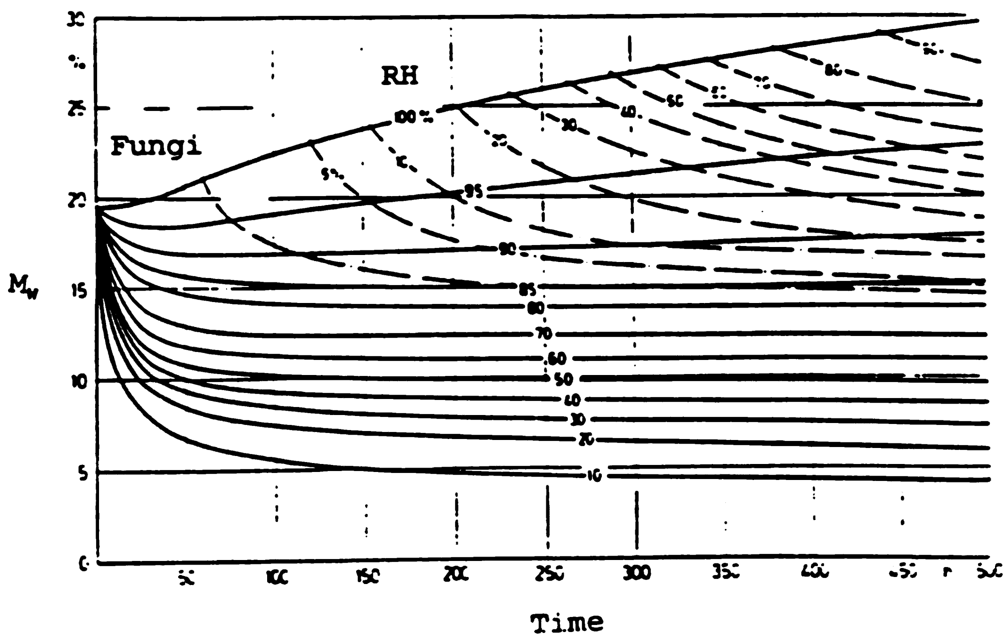


Figure 3.5 Predicted onset of spoilage in the upper layers of wheat during ambient aeration and low temperature drying (Eimer and Morcos 1985).

(1969), i.e. equation (3.3).

Coenen (1987) investigated the deterioration during the temporary cold storage of wheat. He defined allowable storage as the time until a maximum spore count of 10,000 per gram of dry matter is reached. Figure 3.6 shows the spoilage-free storage time as a function of moisture content for wheat temperatures of 5 - 15°C.

With increasing time and moisture content the spore count increases. Kernel discoloration, odor development and germination loss are less in cold, aerated storages than in warm, non-aerated storages. Figure 3.7 summarizes the specific airflow rate necessary to keep the spore count below 10,000 per gram of dry matter as a function of moisture content in aerated low temperature storages.

Mold spores develop into fungi, which cause grain spoilage. The major losses due to fungi in stored grain are (1) dry matter loss due to the conversion of starch and sugar to carbon dioxide, water, and heat, (2) oxidation of fat resulting in the production of fatty acids, (3) decrease in germination, and (4) spoilage of grain kernels due to excessive amounts of microorganisms (Kuppinger et al. 1977). "Unless the temperature or moisture content, or both, of the stored grain is lowered enough to stop the growth of storage

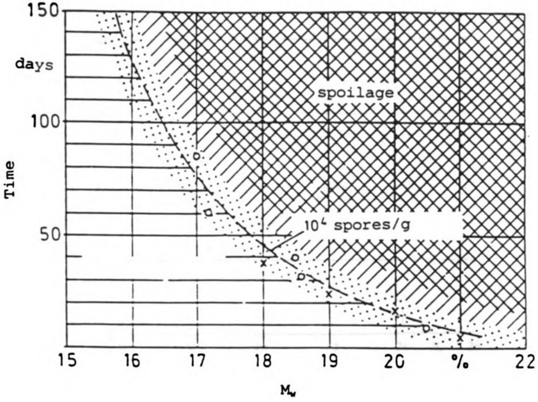


Figure 3.6 Predicted spoilage-free storage time of wheat as a function of moisture content at temperatures of 5 - 15°C (Coenen 1987).

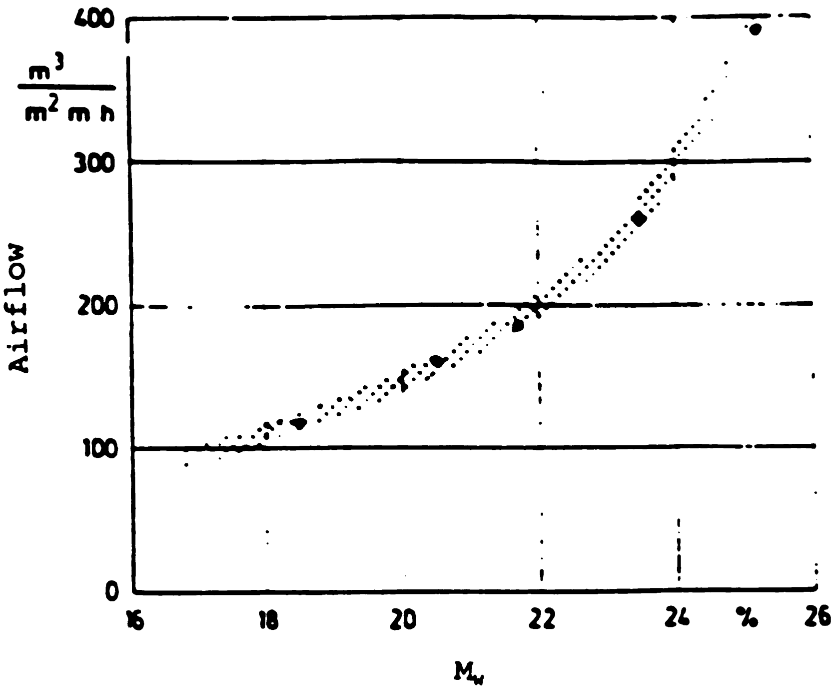


Figure 3.7 Recommended specific-airflow rate to prevent spoilage of wheat as a function of moisture content in aerated low temperature storages (Coenen 1987).

fungi, they will continue to grow..." noted Bailey (1982).

Contamination of grain due to fungi-produced toxins, such as Aflatoxin, has recently become a concern to government officials, grain merchants, grain producers, and consumers (The Wall Street Journal 1989a, 1989b). Food containing more than 20 parts of aflatoxin per billion is unsafe for human consumption under FDA rules (The Wall Street Journal 1990a). Overseas customers have complained about being shipped thousands of tonnes of aflatoxin-contaminated U.S. corn (The Wall Street Journal 1989d), resulting in farm groups calling for better inspection of U.S. grain supplies (The Wall Street Journal 1989e). Aflatoxin-tainted corn was found in Texas and the Midwest in 1989 (The Wall Street Journal 1989c), and again in Iowa a year later (The Wall Street Journal 1990b). However, there is much misunderstanding in the grain industry about the nature of fungi. In the following paragraphs some of the basic microbiological aspects of fungi are summarized.

Fungi are ubiquitous, non-photosynthetic, eukarotic organisms which primarily live on dead organic material (Nester et al., 1983). Some species are useful sources of food and industrial products, others are responsible for spoiling almost any organic material they come in contact with. The parasitic fungi live on plants and animals.

Mycelial growth is characteristic of many fungi. Fungi reproduce by asexual spores, sexual spores, or both. Fungi are found where organic materials are available as nutrients. Fungal reproductive cells, or spores, are found virtually all over the earth and in large numbers in the air. A fungal reproductive spore is typically a single cell about 3 to 30 micrometer in diameter. When a spore lands on a suitable substrate, it germinates and sends out a projection called a germ tube. This tube develops into a long, thread-like filament called a hypha. As the hypha develops, it branches into a tangle of hyphae which is called a mycelium. The white mass seen on moldy bread, for example, is mycelium.

A mycelium is well adapted to absorbing food. The thread-like hyphae are very narrow, and thus the high surface-to-volume ratio permits the surface exposed to the external food source to absorb enough to nourish the enclosed volume of cytoplasm. In addition, a hypha releases chemicals to force other hyphae to grow away from it, which in turn causes the mycelium to spread throughout the food source. Specialized hyphae ensure the penetration of the animal or plant cell walls, while others anchor the fungus to the substrate.

Yeast is the common name given to fungi that are primarily unicellular, while the term mold is given to fungi that are predominantly mycelial. Fungi are able to secrete a variety of enzymes that degrade organic materials, especially complex carbohydrates, into small molecules that can be readily absorbed. Fungal spores are generally resistant to the ultraviolet rays of sunlight. Most fungal varieties prefer a slightly moist environment with a relative humidity of at least 70% and optimal temperatures in the range of 20 to 35°C. Some species even grow at temperatures ranging from -6 to 50°C. They grow best at an acid pH of about 5.0. It has been shown that fungi do not grow in grain stored at low moisture contents and temperatures (Christensen and Kaufmann 1969). It generally stops below a relative humidity of 70% and a temperature of 0°C.

Fungi fall into two general categories: true fungi and fungi-like organisms (Nester et al. 1983). Each are subdivided in accordance with their sexual spore-forming characteristics. True fungi are terrestrial, have chitinous cell walls, and nonmotile spores. True fungi include the well known fungi *Penicillium* and *Aspergillus*, which belong to the subgroup *Fungi Imperfecti* (Deuteromycetes). They reproduce asexually by budding of conidiophores borne on conidia. Most of the fungi that are pathogenic for humans are Deuteromycetes. The best known example is the aflatoxins produced by *Aspergillus*. Aflatoxins ingested on moldy food such as grains and peanuts have been associated with a certain type of liver cancer.

Mirocha and Christensen (1982) summarized the effect of mycotoxins in the human food chain in great detail. Many of the fungi are important commercially in the production of alcoholic beverages, bread and other foods, chemicals and some antibiotics and drugs. They also are among the greatest spoilers of food products, and large amounts of food are thrown away each year because of the presence of fungi such as *Penicillium*, *Rhizopus*, and *Aspergillus*.

In order to determine the possibility of fungal development in a storage bin, the presence of fungi spores in the grain has to be determined (Raper and Fennel 1965). Samples have to be taken from the bin and individual kernels plated on a growing medium. The development of the fungi can be monitored utilizing the proper composition of the substratum, temperature of incubation, conditions of illumination, a microscope, and some basic knowledge about the characteristics of the fungi species.

Christensen and Kaufmann (1969) noted that more research was needed on the microbiology of grain stored at low temperatures in order to properly evaluate the effect of chilled storage conditions.

3.3.3 Insects and Other Pests

The quality hazards to stored grain due to insects and mites are: (1) devouring of whole kernels, (2) consuming of broken kernels and fines, (3) raising of grain temperature and moisture content, (4) contamination of the grain, and (5) aesthetical objections (Bailey 1982). Grain-infesting insects are very sensitive to temperature. Their development is slowed or even stopped below 15.6°C, and no survival is possible above 41.7°C. They thrive at about 29.4°C, and after 80 days of storage at or above 21.1°C any lot of grain is likely to be invaded by insects if no protective measures are taken. In the Southwest of the United States, wheat, rice and sorghum can have grain temperature up to 39.4°C at harvest; during the fall harvest in the Northern United States grain temperatures are still likely around 15.6°C.

A summary of the optimum temperatures for rapid insect growth and grain temperatures for a 100-day development cycle of several major grain pests is listed in Table 3.9.

Table 3.9 Optimum temperature (°C) and safe temperature (°C) of several species of grain storage pests (Burges and Burrell 1964).

Species	Optimum	Safe
Saw-toothed Grain beetle	34	19
Grain weevil	28 - 30	17
Rust-red Grain beetle	36	20
Rust-red Flour beetle	36	22
Confused Flour beetle	33	21
Khapra beetle	38	22
Rice weevil	29 - 31	18
Lesser Grain borer	34	21
Flat Grain beetle	32	19

Burges and Burrell (1964) concluded that cooling grain was not only successful in reducing grain temperatures to 17 - 22°C in the British climate, but also in preventing insects from invading and developing in the grain storage.

Burrell (1967) reported on the effect of chilled aeration on infested grain bulks. The development of an infestation was prevented in 23.2% moisture barley after chilling it from 17 - 18°C to 3 - 4°C. Although the high moisture content caused molding at the top of the pile, about 97 percent of the insects disappeared from the grain. Some insects, however, survived for six months in the cold grain. It was suggested that the stimulation for the insects to leave the grain was not only due to the coldness but also due to the movement of air.

From trials with cold-air aeration Burrell (1967) concluded that cooling was sufficient to inactivate and possibly kill insects when 140 tonnes of barley were cooled from 35°C to below 15°C. He warned, however, that cold grain was more difficult to fumigate since the added methyl bromide vaporized less readily. Also, insects showed more resistance to fumigants at lower temperatures. He recommended to fumigate first and then cool the grain.

Insect activity in Minnesota was reported as severe despite cool temperatures during much of the year (Subramanyam and Harein 1989). A survey of corn facilities in 1977 showed that 90% were infested with several adult insect species. In 1983, 43% of wheat samples, 83% of corn samples, and 60% of oat samples collected from farm storages were infested with adult insects. Samples taken from barley storages in 1985 and 1986 showed on average 85 to 100% infestation. The barley temperatures in July and August ranged from 15.6 to 35°C, and moisture contents from 11 to 20 percent.

During the months of June, July and August temperatures of non-aerated grain stored under Oklahoma conditions reached 35 to 38°C (Cuperus et al. 1986). During September, October and November grain temperatures ranged from 24 to 30°C. Those were optimal levels for stored grain insect activity, and allowed populations to reach high levels. Although aeration with ambient air was shown feasible and effective as a grain management tool, the grain temperatures were not reduced to less than 15°C before October and November. Cuperus et al. (1986) noted the mortality of insects when the grain temperatures dropped below 15°C for extended periods of time.

Epperly et al. (1987) concluded that reducing the temperatures of grain below 10 - 13°C during the early fall in Oklahoma grain storages produced an unfavorable environment for stored grain insects. By maintaining low grain temperatures through the spring and summer, stored grain insect activity was reduced. Chemical insect control was not needed in the bins with lower grain temperatures.

Metal silos with perforated floors were filled with 35 tonnes of barley at 28.1°C and 13.3% moisture content in France (Lasseran and Fleurat-Lessart 1988). In five aeration cycles with cold night air the temperature of the bulk was reduced to -1.2°C between August and the following January. Due to self-heating the grain temperature rose to 13.8°C by the following June. At the beginning of the tests, six boxes with adult insects, larvae and eggs, were placed into the grain. At the end of the storage period more insects were found in the core of the bulk than near the wall, and toward the top of the pile rather than the bottom. They observed that only 1 percent of the insects survived the cold treatment, and claimed cold treatment was superior to chemical treatment in the opinion of entomologists. It was concluded that cold-air aeration was effective in disinfecting grain, and that temperatures below 5°C over a period of at least 2.5 months can kill insects.

Increasingly customers have grown reluctant to accept commodities that contain chemical residues (Longstaff 1988a). However, not only customers should be concerned. "Persons engaged in the bulk handling and storage of agricultural foodstuffs (e.g. grains, peanuts) for human and animal consumption may incur occupational exposure associated with cancer risk..." noted Alavanja et al. (1987). There is increasing pressure on the grain industry throughout the world to reduce its dependence on chemicals in the preservation of bulk commodities. The primary methods of pest control are the application of insecticides to the grain as a bin is filled, and the control of pests by fumigating the sealed storage structure. Several investigations have shown a beneficial effect by combining the application of chemical insecticides with lower grain temperatures, which can be achieved with grain chillers independent of ambient conditions.

A simulation study by Thorpe and Elder (1980) incorporated the decay of chemical pesticides into a heat and mass transfer model. The objective was to determine the potential of reducing insecticide usage and delaying insect resistance by chilling bulk stored grain. They showed that the chemical break-down was slowed in chilled grain, and that an optimum airflow rate existed for the preservation of the pesticide. The decay rate of malathion and methacrifos was insensitive to the initial grain temperature and moisture content when the bulks were chilled quickly. Field tests later supported the observations as the break-down of methacrifos was reduced by 4 - 7 times in rapidly chilled grain (Sutherland 1986). It was proposed to use chilled aeration and low dosages of insecticides in combination to treat grain in non-insulated storages. This reduced the danger from chemical residues, as well as the capital costs of the chilled aeration-storage system. Due to the high ambient conditions in Australia chemical-free storage in combination with grain chilling was found possible only in insulated storages.

Noack et al. (1984) investigated the effect of storage temperature and ventilation rate on the break-down of phosphine. Wheat and soybeans were stored for 35 days at temperatures of -18 to 35°C. It was concluded that the temperature rise favored the break-down of phosphine, while the ventilation rate showed no effect.

As malathion was phased out in the Australian grain industry beginning in 1977, it was replaced by other chemicals (Longstaff 1988a). However, resistance continued to develop with time against the newer and more expensive insecticides. A major factor in reducing the population growth rate is the prolongation of the development period at lower temperatures. Longstaff (1988a) investigated the effect of temperature manipulation upon the spread of a resistance gene in an infested grain storage under Australian conditions. Cooling of the grain had a pronounced effect upon the generation time of the insects, and thus on the rate of spread of the resistance gene. He concluded that "combining insecticide treatment with grain cooling should slow down the rate of development and/or spread of resistance."

In a related study, Longstaff (1988b) determined that cooling grain to 15°C was not sufficient to prevent population growth. However, cooling after fumigation gave some long-term protection when the cooling rate was high. The benefit of cooling depended on the type of insecticide. With pyrethroids a beneficial effect and reduced application rate were noted. Organophosphorous insecticides, on the other hand, showed a positive temperature-toxicity relationship.

3.4 Summary of Grain Chilling Applications

The physical parameters temperature, moisture and time need to be controlled to reduce the biological risks in a chilled grain aeration and storage system. Ideally, grain should be maintained at a low temperature to inhibit insects, at a low moisture content to limit attack by fungi, mites, and respiration, and should be stored for a short time to prevent other pests to cause measurable damage. This review of the literature on grain chilling shows that the chilled aeration and storage of grains can assist in that effort. The technology allows for the controlled cooling of grain independent of the ambient conditions, and preserves the grain within its biological limits. This review has revealed a lack of research on grain chilling as part of a system; including the performance of the chilling unit, the effect of the storage structure and its geographical location, and the influence of the initial grain conditions.

4. ANALYSIS

Simulation techniques are necessary for an in-depth analysis of the chilled aeration and storage of cereal grains since it would be too expensive and time-consuming to evaluate the important parameters experimentally. The development of the simulation model involves the mathematical formulation of the physical, biological and operational parameters of the chilled aeration and storage system. Simplifying assumptions are made in order to reduce the complexity of the model equations.

The simulation model of the chilled aeration and storage system consists of three parts: (1) the chilled aeration model, (2) the grain chiller model, and (3) the chilled grain storage model. The development of each will be described and verified separately. The combined system's model will be utilized to evaluate the physical, biological and operational parameters which are significant in the chilled aeration and storage of cereal grains.

4.1 Chilled Aeration of Cereal Grains

The chilled aeration of cereal grains is a special case of grain aeration, which was discussed in detail in Section

1.3.2. It involves the artificial cooling of the air with a refrigeration system before the air enters the grain bin. The primary advantage of chilled aeration is the ability to maintain stored-grain temperatures and moisture contents independent of the ambient weather conditions.

In order to evaluate the chilled aeration of grains a mathematical model is necessary to describe the heat and mass transfer process in the grain bulk as a function of the chilled air inlet conditions. The literature on the subject is vast, and the relevant results are briefly reviewed.

4.1.1 Approaches to Aeration Modelling

In-bin aeration can be analyzed with fixed-bed models, which are divided into three mathematical categories (Bakker-Arkema 1984): (1) logarithmic, (2) heat and mass balance, and (3) partial differential equation (PDE).

Hukill (1954) assumed that the drying rate in a deep (fixed) bed is proportional to the temperature decrease of the air as it moves through the grain. The model was solved using an exponential drying rate expression. However, the logarithmic model has not been found to be accurate, and is considered ill-suited for dynamic airflow conditions, which exist in chilled aeration systems (Sharp 1982).

Bloome and Shove (1971) and Thompson (1972) developed models specifically for low-temperature and low-airflow conditions in deep grain beds by assuming equilibrium between the grain and air temperatures and humidities in a given layer of grain during a short time interval. Additionally, Bloome and Shove (1971) assumed that there is no hysteresis between absorption and desorption of moisture by the grain. Thompson (1972) accounted for evaporative cooling below the temperature of the air.

An improved equilibrium model proposed by Morey et al. (1979) accounts for (1) the prediction of moisture changes in each layer by incorporating a thin-layer drying equation, (2) the hysteresis effect between absorption and desorption of moisture in the grain kernels of each layer, and (3) the non-uniform airflow in the bin by reducing the calculated fan flow rate by 20-30%. A time step of 24-hours was found to be adequate in the Morey model. Michl (1983) used the equilibrium model approach to study the influence of seven conventional aeration strategies on the storage of soft wheat under German conditions. Modifications to the Michl model have been made by Mühlbauer (1987) and Maier (1988). Sharp (1982) noted that equilibrium conditions may not be achieved for long time intervals and high airflow rates.

Parry (1985) pointed out that "the attainable accuracy of predictions made using such models is [...] somewhat restricted by the assumptions made in their derivations."

The PDE models were originally developed to simulate the drying of grains at high temperatures (Parry 1985). They consist of four non-linear partial differential equations describing the temperature of the air and the grain, the moisture content of the grain, and the humidity of the air at any location in the grain pile as a function of time. Although four equation PDE models are considered the most accurate (Parry 1985), several simplifying assumptions can be made for low-temperature and low-airflow conditions to reduce their complexity to two partial differential equations. "Low temperature" is defined as the aeration of cereal grains using a small temperature increase (or decrease in the case of chilling) of the bin inlet air to manipulate the cooling and drying effect in the grain bin (i.e. 2 - 5°C during ambient aeration, and 5 - 20°C during low-temperature drying or chilling). "Low airflow" is defined as the aeration of cereal grains at design airflows which result in long cooling and drying periods (i.e. 0.1 m^3/min/tonne require an aeration time of 250 hours or more).

For low temperature and airflow conditions equilibrium between the grain and the air is assumed in grain aeration systems. Instantaneous thermal and moisture equilibrium implies that the resistance to the heat and mass transfer between the air and the grain is negligible. The air and grain temperatures are assumed to be equal (i.e. the heat transfer coefficient is infinite and no temperature gradient exists within the kernels) and the grain moisture content is a function of the partial vapor pressure of the air only (i.e. the mass transfer coefficient is infinite). Parry (1985) derived two partial differential equations describing the equilibrium conditions in the grain making the following additional assumptions:

(1) the volume shrinkage of the grain pile is negligible,
(2) the temperature gradient within individual kernels is negligible,
(3) the particle-to-particle conduction is negligible,
(4) the airflow is plug-type,
(5) the bin walls are adiabatic with negligible heat capacity,
(6) the heat capacities of moist air and of grain are constant during short time periods, and
(7) the moisture equilibrium isotherm is known.

Since chilled aeration utilizes a refrigeration system, the temperature and relative humidity of the bin inlet air do not change significantly over time. Thus assumptions (2), (3), and (6) are justified. Additionally, chilling

generally takes place with dried grain, thus volume shrinkage of the pile (assumption 1) is minimal. Moisture equilibrium isotherms for the major cereal grains are available (assumption 7). The most suspect are assumptions (4) and (5). It is well known that uniformity of airflow through grain depends strongly on the management practices of cleaning the grain and filling the bin. Also, since the aeration periods are comparatively long, the environmental effect on the bin may be significant in terms of warming (or cooling) the outer and top grain layers of the bulk.

Three additional assumptions are made for the chilled aeration of cereal grains to simplify the differential equations:

(8) the change of the absolute humidity of the air in a layer of grain over time is negligible compared to the change with position,

(9) the change in the temperature of the grain (and air) over position is negligible compared to its change over time, and

(10) the specific heat capacity difference of the water-vapor mixture in the air is negligible compared to the latent heat of vaporization of moisture from the grain.

Assumptions (8) and (9) are justified in the development of the grain drying PDE models and do not affect the accuracy of the solution significantly (Brooker et al. 1992). The specific heat capacity difference is multiplied by the grain temperature, and is small at the low temperatures typical of grain chilling. Thus, assumption (10) is justified.

The partial differential equations describing the chilled aeration of grain are:

$$\frac{\partial H}{\partial x} = -\frac{\varrho_p}{\varepsilon \varrho_a V_a}\frac{\partial M_e}{\partial \tau} \tag{4.1}$$

$$\frac{\partial T}{\partial \tau} = -\frac{h_{fg}}{\varrho_p c_p (1 + M_e) + \varepsilon \varrho_a (c_a + c_v H)}\frac{\partial M_e}{\partial \tau} \tag{4.2}$$

subject to the following initial and boundary conditions, respectively:

$$\begin{aligned} T(x,0) &= T_o \\ M(x,0) &= M_o \end{aligned} \tag{4.3}$$

$$\begin{aligned} T(0,\tau) &= T(\tau) \\ H(0,\tau) &= H(\tau) \end{aligned} \tag{4.4}$$

Equations 4.1 and 4.2 and the initial and boundary conditions (eqns. 4.3 and 4.4) constitute the one-dimensional equilibrium heat and mass transfer model for the chilled aeration of cereal grains.

The heat and mass balance equations presented by Bloome and Shove (1971), Thompson (1972), Morey et al. (1979), and Michl (1983) are essentially algebraic equivalents of equations 4.1 through 4.4.

4.1.2 Numerical Solution

To obtain a numerical solution of equations 4.1 through 4.4, the two partial differential equations of heat and mass transfer and the associated initial and boundary conditions must be transformed such that differentiation can be performed numerically. The derivative of a function at a given point can be represented by finite-difference approximations using a Taylor series expansion of the function about that point (Özisik 1980, Holmann 1986, Stoer and Bulirsch 1983, Press et al. 1985). This approach was used to derive the finite difference expressions for the one-dimensional grain pile shown in Figure 4.1.

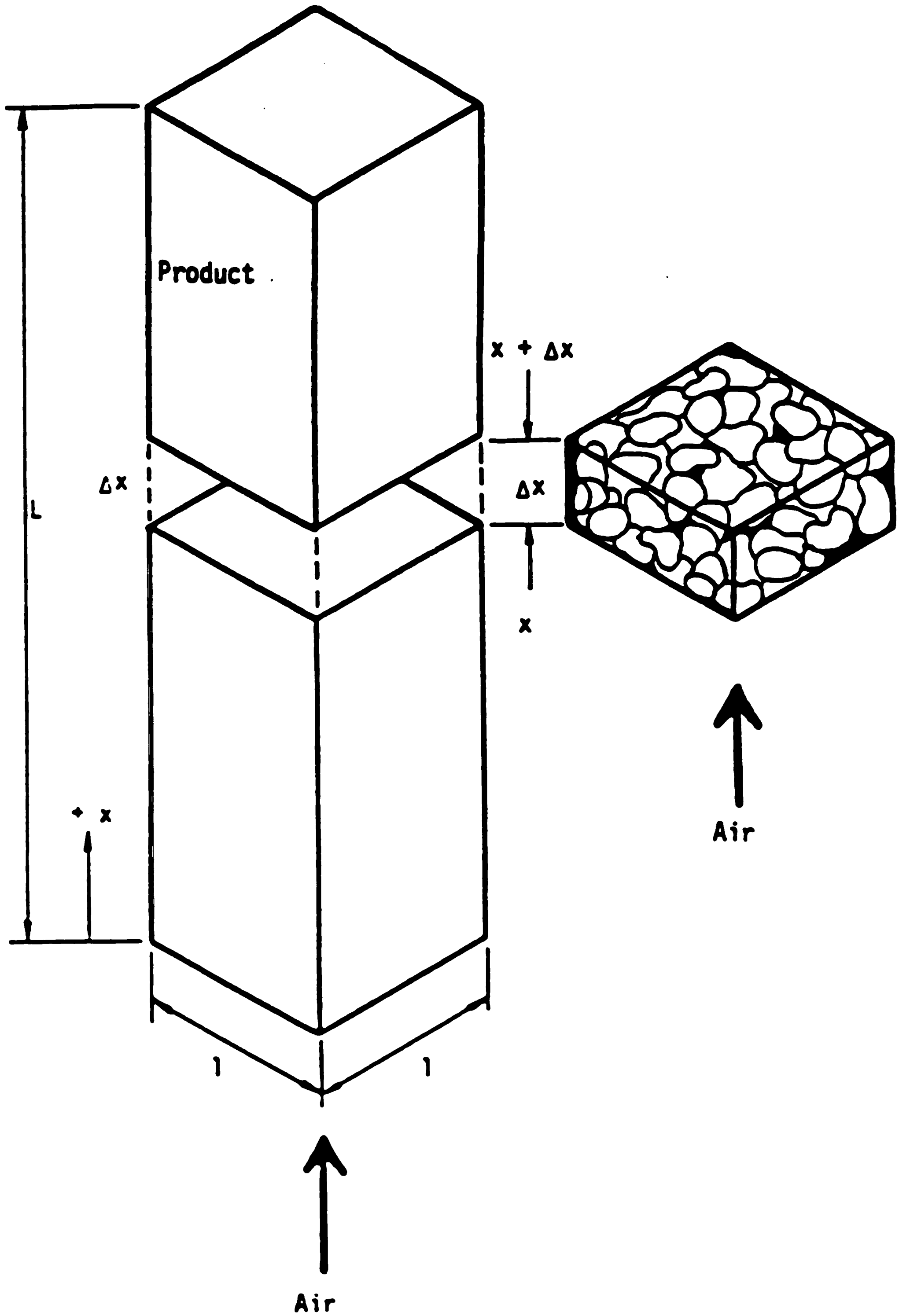


Figure 4.1 One-dimensional grid of the vertical grain pile for the simulation of the chilled aeration of cereal grains.

4.1.2.1 Nodal Equations

The forward finite difference expression of the mass transfer equation is:

$$\frac{H_{i+1}^{n} - H_{i}^{n}}{\Delta x} = -\frac{\varrho_p}{\varepsilon \varrho_a V_a} \frac{M_{e_i}{}^{n+1} - M_{e_i}{}^{n}}{\Delta \tau} \tag{4.5}$$

The forward finite difference expression of the heat transfer equation is:

$$\frac{T_{i}^{n+1} - T_{i}^{n}}{\Delta \tau} = -\frac{h_{fg}}{\varrho_p c_p \left[1 + \frac{M_{e_i}{}^{n+1} + M_{e_i}{}^{n}}{2}\right] + \varepsilon \varrho_a \left[c_a + c_v \left(\frac{H_{i}^{n+1} + H_{i}^{n}}{2}\right)\right]} \frac{M_{e_i}{}^{n+1} - M_{e_i}{}^{n}}{\Delta \tau} \tag{4.6}$$

Equations 4.5 and 4.6 are subject to:

$$T_{i}^{0} = T_{o} \qquad M_{e_i}{}^{0} = M_{o} \tag{4.7}$$

$$T_{0}^{n} = T_{inlet} \qquad H_{0}^{n} = H_{inlet} \tag{4.8}$$

The superscript n refers to the beginning of the current time step, (n+1) to the end of the current time step; the subscript i indicates the vertical coordinate of the temperature node. The air flow through the grain is assumed constant during a given time step.

To solve equations 4.5 through 4.8 numerically the algorithm needs to be initiated. A guess of the new humidity of the air at the second node for the current time step, H_i^{n+1}, starts the algorithm. The new temperature at the second node is calculated from equation 4.6:

$$T_i^{n+1} = \frac{\left(\frac{\varepsilon \varrho_a V_a}{\varrho_p}\right)\frac{\Delta\tau}{\Delta x} h_{fg}\left[H_{i+1}^n - H_i^n\right]}{\varrho_p c_p\left[1 + \frac{M_{e_i}{}^{n+1} + M_{e_i}{}^n}{2}\right] + \varepsilon \varrho_a\left[c_a + c_v\left(\frac{H_i^{n+1} + H_i^n}{2}\right)\right]} + T_i^n \qquad (4.9)$$

The new equilibrium grain moisture (i.e. at the end of the time step) at the second node is calculated from equation 4.5:

$$M_{e_i}{}^{n+1} = M_{e_i}{}^n + \left(\frac{\varepsilon \varrho_a V_a}{\varrho_a}\right)\frac{\Delta\tau}{\Delta x}\left[H_i^n - H_{i+1}^n\right] \qquad (4.10)$$

Since the humidity at the second node is an estimate, the new temperature and moisture content are also estimates. Using a grain-specific equilibrium equation (see Section 4.1.2.2), the accuracy of the estimated humidity is evaluated. The calculations for the second node are repeated until equilibrium between the air and the grain is established. The humidity of the air at the second node then becomes the initial guess for the third node. The calculations are repeated for the entire grain bulk during the particular time step. When the top layer of the pile is reached, the time is incremented and the procedure is repeated. At the end of the simulation period, the temperature and moisture profiles in the grain pile are established.

4.1.2.2 Equilibrium Humidity and Moisture

The equilibrium condition between the air and the grain is evaluated by comparing the estimated absolute humidity, H_i^{n+1}, against an equilibrium absolute humidity, H_e, which is a function of the vapor pressure of the air, P_{sat}, at the new temperature and the equilibrium relative humidity of the air, RH_e, at a particular node (Brooker et al. 1992):

$$H_e = 0.622\, RH_e \left[\frac{P_{sat}}{P_{atm} - P_{sat}\, RH_e}\right] \qquad (4.11)$$

The equilibrium relative humidity, RH_e, is grain-specific and is obtained with equation 4.12, which relates the equilibrium grain moisture content to the relative humidity and temperature of the surrounding air (ASAE 1991):

$$RH_e = \exp\left[\frac{-A}{(T+C)}\exp(-BM_e)\right] \qquad (4.12)$$

The estimated absolute humidity and the equilibrium absolute humidity must be the same. A new estimate is calculated using the Newton-Raphson root finding method (Press et al. 1985). Convergence of the solution is achieved when the difference between the estimated and equilibrium humidity is less than 0.00001 kg/kg.

Equations 4.5 through 4.12 are the numerical formulations needed to solve the heat and mass transfer between the grain and the air in the chilled aeration model.

The equilibrium moisture content of grain can also be expressed as a function of the equilibrium relative humidity and the grain temperature. The following equation is used in the chilled aeration and storage model (ASAE 1991):

$$M_e = E - F\ln[-(T+C)\ln(RH_e)] \qquad (4.13)$$

4.1.2.3 Physical Grain Properties

The numerical solution of the two partial differential equations depends on the physical properties of the cereal grain. The focus of the chilled aeration and storage analysis is on corn and wheat, and their respective properties are summarized below.

Specific Heat

The specific heat of grain, c_p, is mainly a function of the moisture content (ASAE 1991):

$$c_p = A + BM_w \tag{4.14}$$

The constants for corn and soft wheat are (Michl 1983):

	A	B
Corn	1.370	0.0272
Wheat (soft)	1.276	0.0346

Latent Heat

The latent heat of vaporizing water within and from the surface of a grain kernel, h_{fg}, is a function of the temperature and moisture content of the grain (Brook and Foster 1981):

$$h_{fg} = (2502.2 - 2.4T)\ [1 + A\exp(-BM)] \tag{4.15}$$

The constants A and B for corn and soft wheat are (Brook and Foster 1981):

	A	B
Corn	3.006	16.961
Wheat (soft)	5.896	23.628

Equilibrium Relative Humidity

The constants A, B, and C in the equilibrium relative humidity equation 4.12 for corn and soft wheat are (ASAE 1991):

	A	B	C
Corn	312.30	16.958	30.205
Wheat (soft)	726.49	23.607	35.662

Equilibrium Moisture Content

The constants E and F in the equilibrium moisture content equation 4.13 for corn and soft wheat are (ASAE 1991):

	E	F
Corn	0.33872	0.058970
Wheat (soft)	0.27908	0.042360

Constant C in equation 4.13 is the same as for the equilibrium relative humidity equation.

Bulk Density

The bulk densities, ϱ_p, of corn and soft wheat are mainly a function of the moisture content. The following range of bulk densities are commonly encountered in the chilled aeration and storage of corn and wheat, where ϱ_p is expressed in kg/m^3 (MWPS-13 1988):

M_w [%,w.b.]	Corn	Soft Wheat
11.0	684.4	750.6
13.0	700.1	767.8
15.0	716.6	786.0
17.0	733.8	804.9

Conductivity

The bulk thermal conductivity, k, of corn and soft wheat can be represented by the following equation (ASAE 1991):

$$k = A + BM_w \qquad (4.16)$$

The constants A and B for corn and wheat are (ASAE 1991):

	A	B
Corn	0.1409	0.00112
Wheat (soft)	0.1170	0.00113

4.1.2.4 Psychrometric Air Properties

In order to calculate the temperature and moisture profiles in the grain pile, the psychrometric properties of the chilling air must be known. The psychrometric equations for air were programmed by Lerew (1972) and their accuracy verified repeatedly (Bakker-Arkema 1984, Brooker et. al 1992). The equations were updated to the current ASAE Standard (ASAE 1991). The equations will not be listed here; the reader is referred to the above references.

Values for the specific heat of dry air and water vapor in the temperature range commonly encountered in chilled aeration are, respectively (Michl 1983):

$$c_a = 1.006\ kJ/kg/°C \qquad (4.17)$$

and,

$$c_v = 1.86\ kJ/kg/°C \qquad (4.18)$$

4.1.2.5 Additional Model Parameters

Besides the PDE equations, the initial and boundary conditions, the physical grain properties, and the psychrometric air properties, additional model parameters that must be specified are the time step, $\Delta\tau$, and the

vertical space step, Δx. Also needed is the pile height.

4.2 Grain Chilling Unit

In a chilled aeration and storage system the bin inlet conditions are controlled with a grain chilling unit. The development of the grain chilling technology to maintain cereal grain quality, and its world-wide application were discussed in detail in Chapter 3. Before developing the model to simulate the performance of the specific grain chiller used in this study, its design and operation are briefly discussed.

Figure 4.2 shows a typical grain chiller. Ambient air is drawn in by a centrifugal fan (13) through a filter (14), and pushed through evaporator coils (3) where the air temperature is decreased. The chilled air is reheated (4) to lower its relative humidity to or near the equilibrium relative humidity of the grain. The chilled air exits the unit (16) and is blown into a duct connecting the chiller and the grain storage bin (not shown). A manometer allows the monitoring of the static pressure at the air outlet duct (19a) and across the intake filter (19b). A hose (20) allows the condensate from the evaporator to run off.
A small axial-flow fan (31) draws ambient air across the

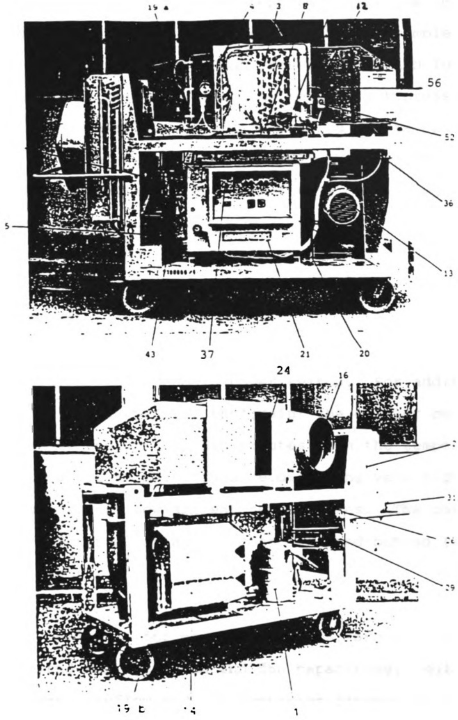


Figure 4.2 Front and rear view of a typical grain chilling unit (Sulzer-Escher Wyss 1985).

condenser coils (2). The compressor (1), the refrigerant receiver (5), and the expansion valve (8) complete the refrigeration system. High pressure (26) and low pressure (29) safety switches limit the refrigerant pressure in the system. The reheating of the chilled air is controlled by a manual valve (12), or automatically by a solenoid valve (52). The refrigeration capacity is controlled automatically by the motorized valve (43), and the airflow by the motorized flap (36) downstream from the centrifugal fan. The cold-air and reheater temperature controllers (37) are housed on the front panel of the electrical cabinet (21), together with the alarm and the operational indicators, and the main power switch. For additional safety (and to protect the grain) the chiller controller shuts-off the unit within minutes when the temperature set-point cannot be maintained, e.g. during very high cooling loads, or very low ambient temperatures. The chiller can be accessed for cleaning in front (56) and behind (24) the evaporator.

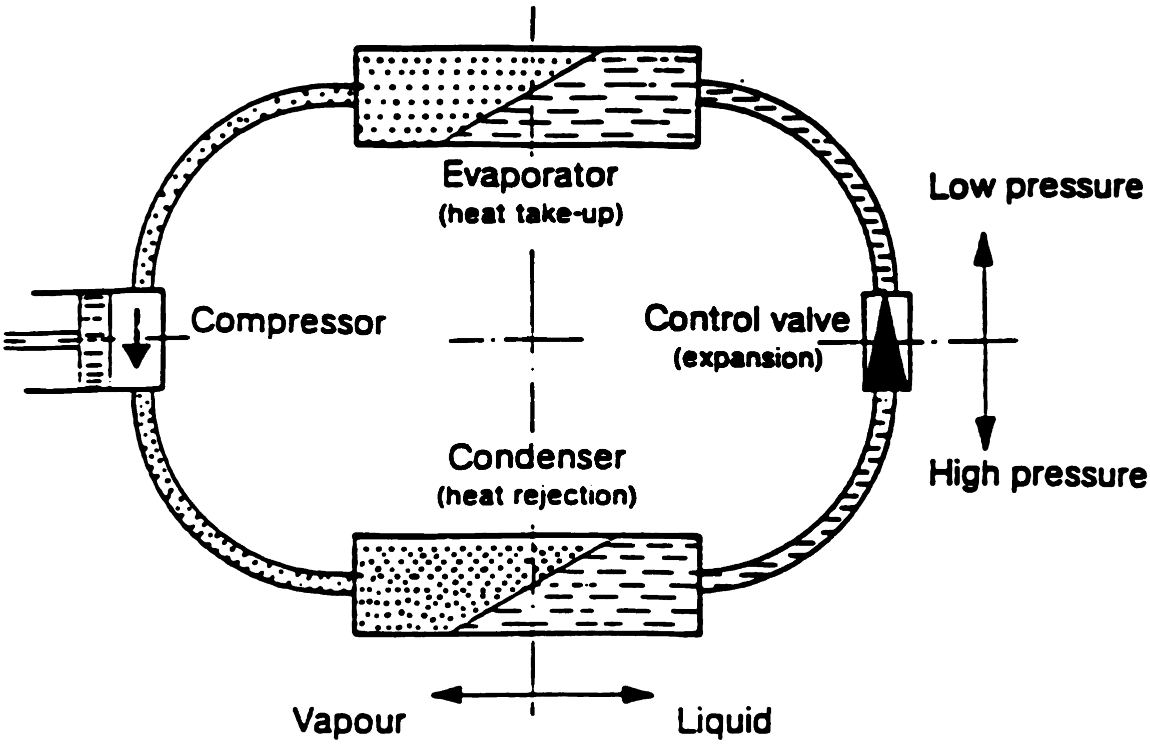
Grain chillers, for economic reasons, are not built with unlimited refrigeration and fan capacities. Models with different airflow and refrigeration capacities are available for different ambient and grain cooling requirements (see Table 1.1 for the capacities of a typical unit). In order to maintain the operator-selected cold-air and reheater temperature set-points, the electrical controller of the grain chiller varies both the refrigeration capacity and the airflow rate. For certain ambient conditions (e.g. cold spells in the early fall and spring) the set-point temperature at the chiller outlet is maintained by built-in electrical heaters. Thus, grain chilling units operate in three distinct modes: (1) maximum refrigeration during high ambient cooling load and throttled airflow, (2) maximum airflow during low ambient cooling load and throttled refrigeration, and (3) electrical heating during low-temperature conditions.

4.2.1 Theoretical Analysis of the Refrigeration Cycle

Refrigeration is defined as "the withdrawal of heat, producing in a substance [...] a temperature lower than that of the natural surroundings. Thus any methods available for lowering temperature, in the range from ambient temperature to absolute zero, involve refrigeration processes." (Threlkeld 1970). The refrigeration cycle of a commercial grain chilling unit is basically a single-stage vapor-compression system.

The mechanical compression system of a typical grain chiller uses a vapor refrigerant such as R-22 (difluoromonochloromethane or CHF_2Cl). Cooling is accomplished by evaporation of the liquid refrigerant under reduced pressure and temperature in a closed thermodynamic cycle. A theoretical single-stage compression cycle is shown in Figure 4.3. It consists of a compressor, condenser, control valve and evaporator. Electrical work is input to compress the gas mechanically from a low-pressure to a high-pressure vapor. The high-pressure vapor is allowed to condense by rejecting heat in a heat exchanger (i.e. the condenser of the grain chiller). The high-pressure liquid refrigerant is expanded through a control valve to a lower pressure. Heat is absorbed by the low-pressure liquid refrigerant in the evaporator.

The single-stage refrigeration cycle of the grain chilling unit can be modelled with steady-state internal energy balances across the compressor, condenser and evaporator. This requires knowledge of the thermodynamic properties of the refrigerant, i.e. the entropy, enthalpy and specific volume as functions of temperature and pressure, at each state point in the cycle. Also, the refrigerant mass flow rate must be known; it is a function of the design of the compressor. The internal energy and mass balances of the refrigeration system are not of direct relevance to the modelling of the chiller for the chilled grain aeration and storage system. Thus, they are not considered here.



Principle of the refrigerating system

Figure 4.3 Theoretical single-stage vapor-compression refrigeration cycle (Sulzer-Escher Wyss 1985).

In contrast, the external energy balances across the condenser, reheater and evaporator are essential for the grain aeration system, and can be established in terms of the heat transfer between the refrigerant and the air flowing across the heat exchangers. Since the airflow and the air temperature and relative humidity into the bin are of principle interest in the simulation of a chilled aeration and storage system, this approach is used in the modelling of the grain chiller.

4.2.1.1 Compressor

The principal difference between the actual and theoretical single-stage refrigeration cycles occurs in the compressor. In the reciprocating-piston compressor the pressure varies with the position of the piston (see Figure 4.4). The cylinder pressure may be less during the intake ($P_a = P_b$) than the suction line pressure (P_4), and during discharge ($P_c = P_d$) greater than the discharge line pressure (P_5). In the condenser, evaporator and piping the losses are kept small by specifically designing components for small refrigerant pressure losses and by adding insulating components to reduce heat exchange with the ambient surroundings (Threlkeld 1970).

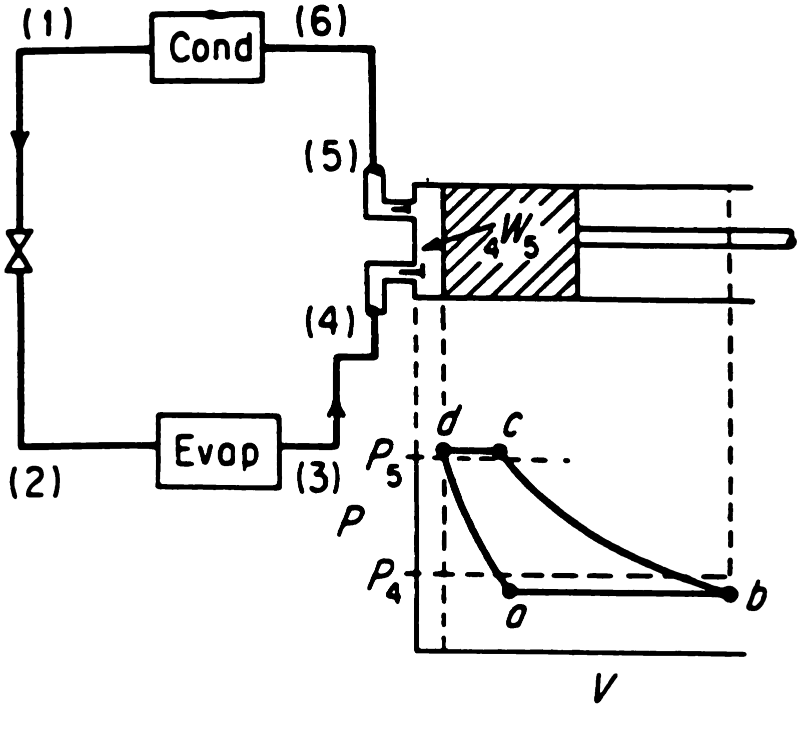


Figure 4.4 Schematic diagram describing a practical single-stage refrigeration cycle (Threlkeld 1970).

Threlkeld (1970) described theoretical compressor equations that are widely used in the design of refrigeration cycles (Cleland 1991, Rumsey 1989, Smith et al. 1987, Cleland 1983). However, characteristic performance curves of commercial compressors can only be obtained from manufacturers. Since the grain chilling unit used in this study represents an existing design, its characteristic compressor curves are used to formulate the compressor, evaporating, and condensing capacities of the refrigeration cycle.

4.2.1.2 Condenser

The condenser of the chilling unit is analyzed externally as a dry, finned-tube, cross-flow heat exchanger. The heat transfer from the chiller condenser to the externally flowing ambient air is (Holman 1986):

$$q_c = U_c A_c \Delta T_c \tag{4.19}$$

The log-mean temperature difference (LMTD), ΔT_c, is valid for cross-flow heat exchangers when one of the fluid temperatures remains constant. In the vapor compression cycle of the grain chilling unit the refrigerant condenses at constant temperature. The LMTD for the condenser of the chiller is (Holman 1986):

$$\Delta T_c = \frac{T_o - T_a}{\ln\left(\frac{T_o - T_c}{T_a - T_c}\right)} \qquad (4.20)$$

The overall heat transfer coefficient for a dry, finned-tube heat exchanger is a function of the convective heat transfer from the refrigerant to the inside tube wall, the conductive heat transfer through the tube wall and fin, and the convective heat transfer from the tube wall and fin to the air. Threlkeld (1970) developed a theoretical expression that is difficult to evaluate in practice. Thus, the overall heat transfer coefficient for the condenser of the grain chiller, U_c, is evaluated empirically. The heat transfer surface area of the chiller condenser, A_c, is known.

4.2.1.3 Reheater

The reheater of the grain chiller can be considered as a second condenser in the refrigeration cycle. It is installed after the evaporator to reheat the chilled air and lower its relative humidity to prevent water absorption by the grain. In the reheater, part of the energy previously absorbed from the air in the evaporator is returned to the refrigeration cycle.

The theoretical analysis of the reheater is similar to that of the condenser. The condensing capacity of the reheater in terms of the external heat exchange is:

$$q_H = U_H A_H \Delta T_H \tag{4.21}$$

The log-mean temperature difference of the reheater is:

$$\Delta T_H = \frac{T_2 - T_3}{\ln\left(\frac{T_3 - T_c}{T_2 - T_c}\right)} \tag{4.22}$$

The overall reheater heat transfer coefficient, U_H, is evaluated empirically for the grain chiller. The surface area of the reheater, A_H, is known.

4.2.1.4 Evaporator

The external evaporator analysis of the grain chilling unit must account for dehumidification of the air flowing across the heat exchanger. With dehumidification, the air-side surface is wetted with liquid water (or frost). The heat transfer occurs due to sensible cooling and condensation (i.e. latent cooling).

The heat transfer from the wet chiller evaporator to the externally flowing air is a function of the enthalpy difference (Threlkeld 1970):

$$q_E = U_{E_w} A_E \Delta h_E \qquad (4.23)$$

If the refrigerant temperature remains essentially constant during evaporation, as is the case in the vapor compression cycle of a grain chilling unit, and if the energy lost by the air due to condensation is assumed negligible, the following approximate log-mean enthalpy difference (LMHD) applies (Threlkeld 1970):

$$\Delta h_E = \frac{h_1 - h_2}{\ln\left(\frac{h_1 - h_{s,R}}{h_2 - h_{s,R}}\right)} \qquad (4.24)$$

The overall heat transfer coefficient for the wet evaporator of the grain chiller, U_{Ew}, is derived empirically. The evaporator heat transfer surface area, A_E, is known.

For certain combinations of cold-air set-points/ambient cooling loads, no condensation occurs in the evaporator. Then, the evaporator heat transfer analysis is similar to the condenser and reheater dry-fin analysis. The heat transfer from the dry chiller evaporator to the externally flowing air is:

$$q_E = U_E A_E \Delta T_E \qquad (4.25)$$

where,

$$\Delta T_E = \frac{T_1 - T_2}{\ln\left(\frac{T_2 - T_e}{T_1 - T_e}\right)} \tag{4.26}$$

The overall dry-evaporator heat transfer coefficient, U_E, is evaluated empirically. The heat exchange surface area for the chiller evaporator, A_E, is known.

4.2.2 Empirical Analysis of the Refrigeration Cycle

To solve the steady-state external energy balances across the condenser, reheater and evaporator, i.e. equations 4.19, 4.21, 4.23 and 4.25, the overall heat transfer coefficients must be known. Expressions for U_C, U_H, U_E, and U_{Ew} for the Granifrigor KK140 grain chiller are determined empirically from performance data made available by the manufacturer (i.e. Sulzer-Escher Wyss, Lindau, Germany). The formulation of the expressions require the analysis of the experimental data in terms of the compressor curve capacities and the psychrometric state points of the air before and after the condenser, reheater and evaporator, respectively. For reasons of confidentiality only selected data is presented. The data analysis is described in detail.

4.2.2.1 Compressor Curves

Figure 4.5 is a diagram of the characteristic performance curve of a typical compressor using refrigerant R-22. The bottom set of curves represents the cooling capacity of the refrigeration unit as a function of the evaporating and condensing refrigerant temperatures, T_e and T_c, respectively. The top set of curves represents the electrical power input to the compressor. Generally, the compressor curves include values for superheating and subcooling. The compressor of the KK140 grain chiller operates with 4°C subcooling and 10°C superheating, and is equipped to handle both 50 and 60 Hz electricity (Sulzer-Escher Wyss 1991).

The equations describing the compressor curves of the KK140 grain chilling unit were made available by the chiller manufacturer (Sulzer-Escher Wyss 1991):

For the compressor capacity:

$$W_p = g_1(T_e)\,N \tag{4.27}$$

where,

$$g_1(T_e) = f_1(T_c) + f_2(T_c)\,T_e + f_3(T_c)\,T_e^2 \tag{4.28}$$

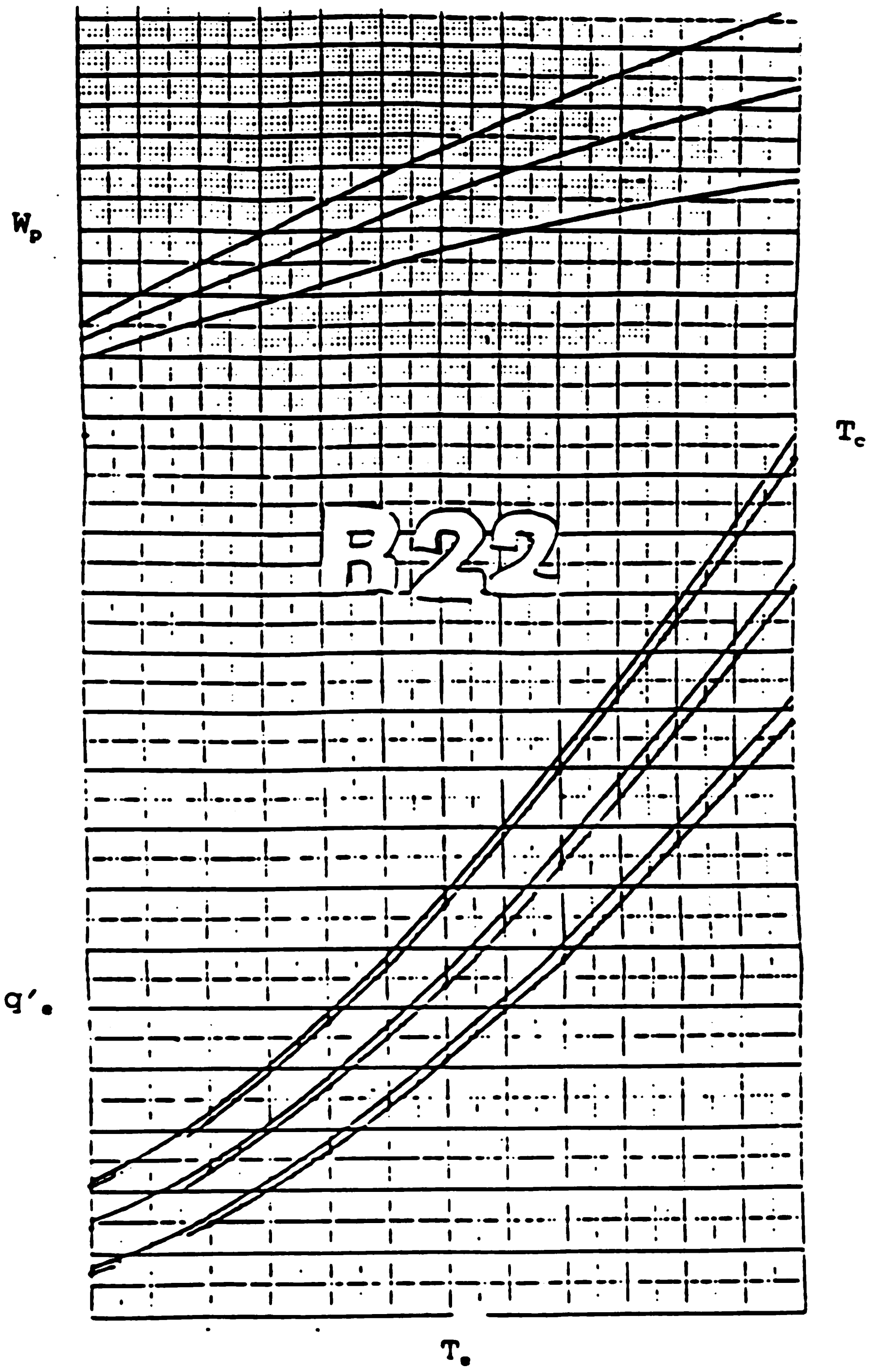


Figure 4.5 Diagram of the characteristic performance curve of a typical compressor (Sulzer-Escher Wyss 1991).

and,

$$\begin{aligned} f_1(T_c) &= a_1 + a_2 T_c + a_3 T_c^2 \\ f_2(T_c) &= b_1 + b_2 T_c + b_3 T_c^2 \\ f_3(T_c) &= c_1 + c_2 T_c + c_3 T_c^2 \end{aligned} \tag{4.29}$$

The coefficients a_i, b_i, and c_i are proprietary. They have been verified against the accompanying compressor curves, and incorporated into the grain chiller model.

For the evaporating capacity:

$$q_E' = g_2(T_e)\, N'\, F \tag{4.30}$$

The coefficient F is a design-specific loss factor to account for the suction heating and heat loss after discharge. The function $g_2(T_e)$ has the same form as equations 4.28 and 4.29. The coefficients were made available, verified against the accompanying compressor curves, and incorporated into the grain chilling model.

The total condensing capacity available in the refrigeration cycle of the chiller is:

$$q_C' = W_p + q_E' \tag{4.31}$$

4.2.2.2 Chiller Performance Data

Figure 4.6 represents experimental data collected by the chiller manufacturer during the performance test of a typical grain chilling unit. The ordinate represents ambient air temperatures. Curve 1 is the relative humidity of the ambient air measured over the temperature range. Curve 2 represents the air temperature after the centrifugal fan (and before the evaporator). Curve 3 is the cold air temperature measured after the evaporator. Curve 4 represents the temperature increase of the air due to the reheater. Curve 5 is the measured airflow to the centrifugal fan of the chilling unit for the given static pressure. Curve 6 represents the temperature of the evaporating refrigerant, and curve 7 of the condensing refrigerant. Curve 8 is the total electrical energy absorbed by the compressor, centrifugal fan, condenser fan, and the electrical controls of the chilling unit.

The test data also illustrates the two primary operating modes of the chilling unit. For high cooling loads, the airflow is throttled, i.e. the unit operates in the maximum refrigeration range. For lower cooling loads the unit throttles the refrigeration capacity and operates at maximum airflow.

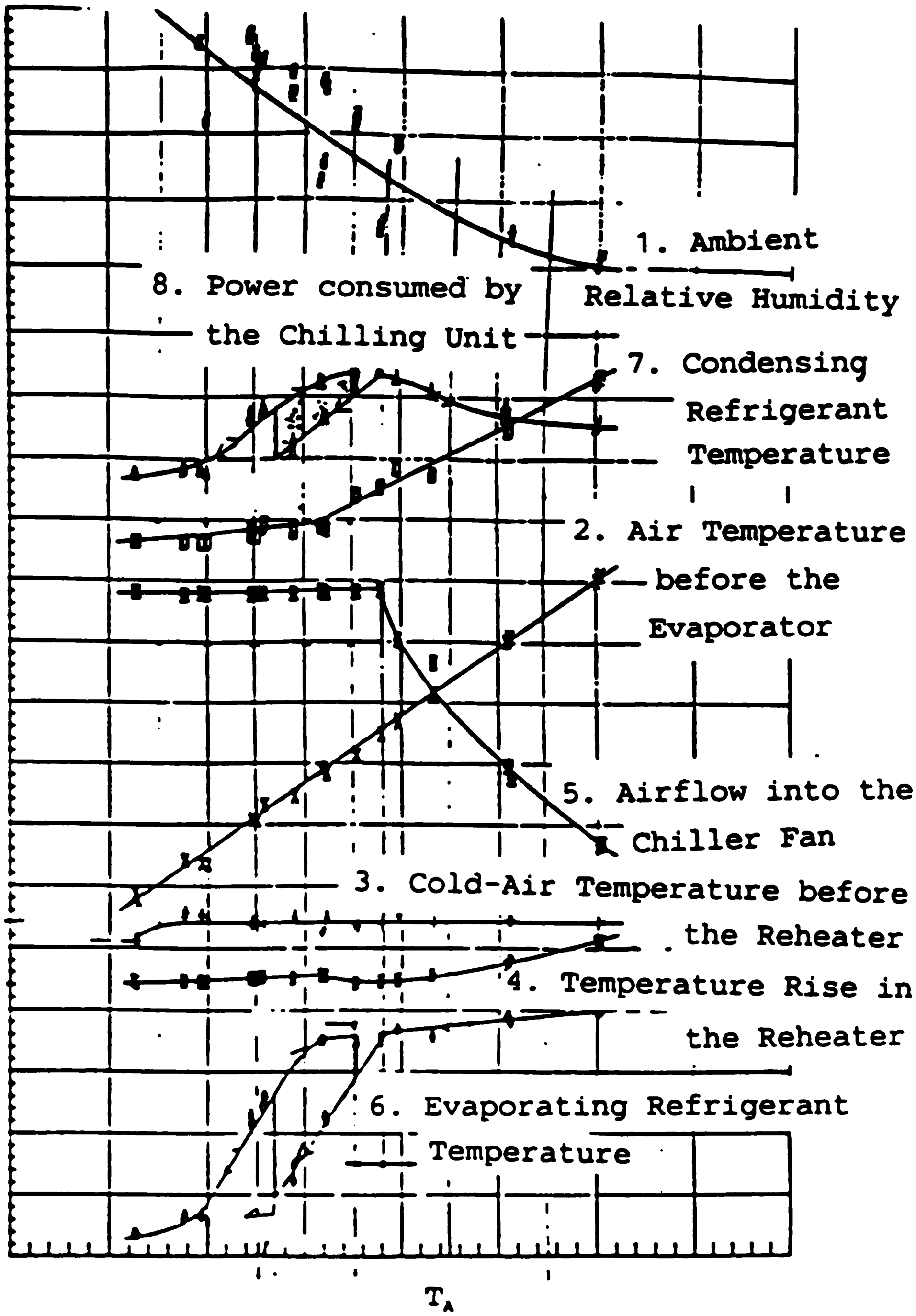


Figure 4.6 Experimental data collected during the performance test of a typical grain chilling unit (Sulzer-Escher Wyss 1991).

4.2.2.2.1 Psychrometric State Points

Based on experimental data similar to Figure 4.6 a range of psychrometric state points for the air passing through the chilling unit is established over a range of ambient cooling loads. At every state point at least two psychrometric air properties must be known to calculate the remaining properties. The psychrometric state points and air properties of interest are (refer to Figures 4.6 and 4.7):

<u>(a) Ambient Air before the Fan (Point A):</u>

The known psychrometric properties before the centrifugal fan are the ambient dry-bulb temperature, T_a (ordinate), and the relative humidity, RH_a (Curve 1). The unknown psychrometric properties needed are the absolute humidity, H_a, and the specific air volume, v_a. From the specific volume and the airflow into the fan (Curve 5), the dry mass flowrate of the air, $\dot{m}_a$, is calculated. The mass flowrate is constant through the chiller and into the bin for a given throttle position.

<u>(b) Before the Evaporator (Point 1):</u>

The absolute humidity before the fan, H_a, and after the fan, H_1, are the same. From H_1 and the air temperature after the fan (Curve 2) the specific volume, v_1, and the enthalpy, h_1, before the evaporator are determined.

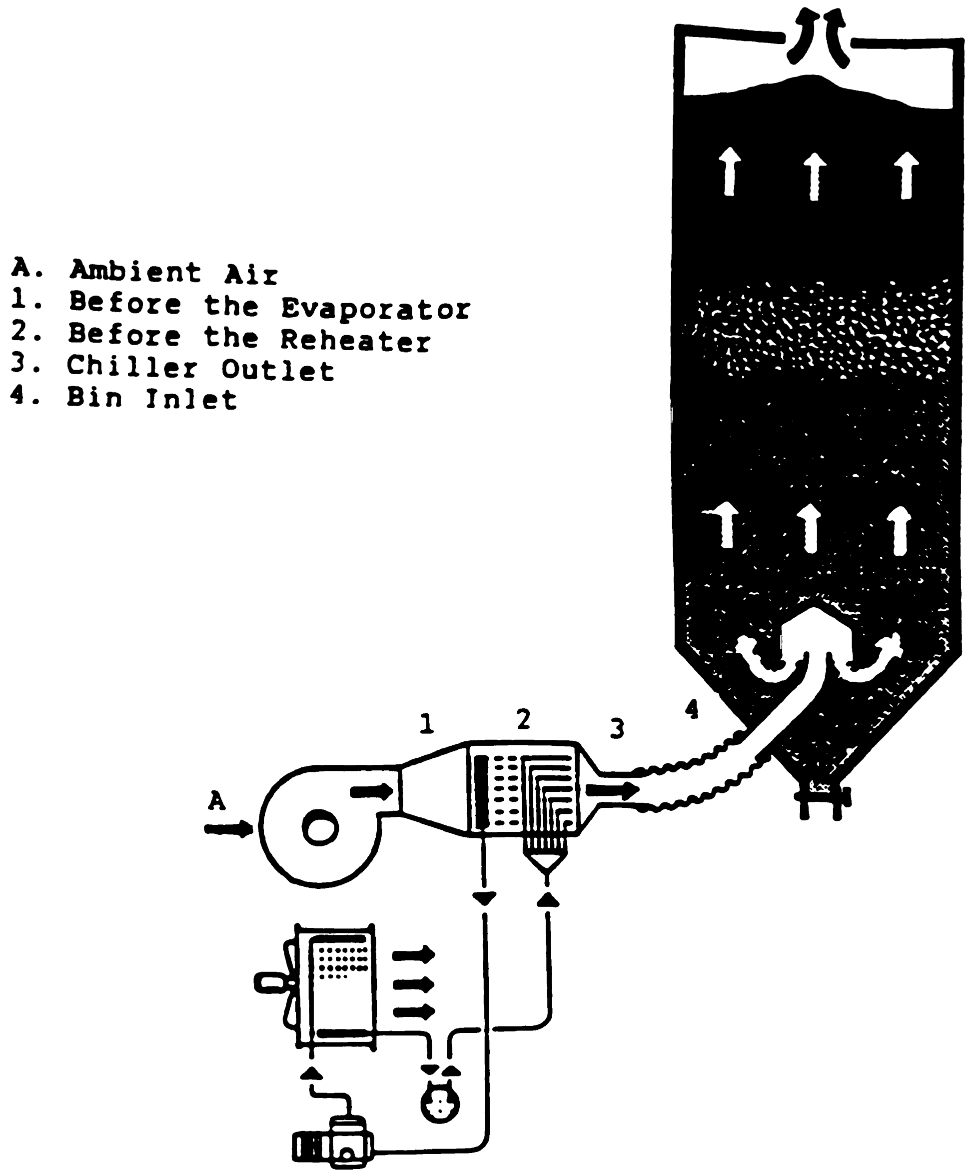


Figure 4.7 Diagram of the bin-chiller system with the psychrometric state points needed to model the chilling unit.

<u>(c) Before the Reheater (Point 2):</u>

The cold air temperature, T_2, after the evaporator is known (Curve 3). Two conditions may be encountered:

(i) <u>Wet Evaporator:</u> When dehumidification occurs the absolute humidity after the evaporator, H_2, is smaller than before the evaporator, H_1. In this case the relative humidity of the cold air, RH_2, is assumed to be 100%. From T_2 and RH_2 the absolute humidity, H_2, the specific volume, v_2, and the enthalpy, h_2, are calculated.

(ii) <u>Dry Evaporator:</u> When the evaporator is dry, the absolute humidities of the air before and after the evaporator are equal (i.e. $H_2 = H_1$). From T_2 and H_2, the specific volume, v_2, and the enthalpy, h_2, are calculated.

<u>(d) At the Chiller Outlet (Point 3):</u>

The reheater air temperature, T_3, is calculated by adding the amount of reheating (Curve 4) to the cold-air temperature (Curve 3). The absolute humidity before, H_2, and after the reheater, H_3, are equal. The specific volume, v_3, the relative humidity, RH_3, and the enthalpy, h_3, at the chiller outlet are determined from T_3 and H_3.

<u>(e) At the Bin Inlet (Point 4):</u>

If the connecting duct is long, the cold air may gain (or loose) heat between the chiller outlet (Point 3) and the bin inlet (Point 4). By specifying a temperature increase (or loss) across the duct for the chilled aeration of grain, the bin inlet temperature, T_4, can be calculated. The absolute humidity before, H_3, and after, H_4, the duct does not change. From T_4 and H_4 the specific volume, v_4, and the relative humidity, RH_4, at the bin inlet are determined. Since the chilled air into the bin is generally lower than the ambient temperature, condensation inside the duct is usually not a problem.

From the experimental psychrometric state points and the compressor curves (equations 4.27 - 4.31), expressions for the overall heat transfer coefficients of the evaporator, condenser, and reheater of the chilling unit are derived.

4.2.2.2.2 Evaporator Heat Transfer Coefficient

To calculate values of the overall wet-evaporator heat transfer coefficient equation 4.23 is solved for U_{Ew}:

$$U_{E_w} = \frac{q_E}{A_E \Delta h_E} \tag{4.32}$$

The evaporator capacities are calculated from the compressor curve (equation 4.31) as a function of the experimental evaporating and condensing refrigerant temperatures. The evaporator surface area is known. The LMHD values are calculated from equation 4.24. The enthalpies before, h_1, and after, h_2, the evaporator are calculated from the psychrometric state points. The fictitious enthalpy $h_{s,R}$ is calculated for saturated air at the evaporating refrigerant temperature.

The overall heat transfer coefficient for the wet evaporator of the grain chiller can be expressed as a function of the air flow through the evaporator coils. The face velocity at the inlet to the evaporator is:

$$V_{f_s} = \frac{\dot{m}_a v_1}{A_{f_s}} \tag{4.33}$$

Figure 4.8 shows the values of the overall wet-evaporator heat transfer coefficient, calculated from equation 4.32, versus the face velocity, calculated from equation 4.33, for a range of experimental cooling loads.

From a linear regression analysis the following equation was determined from the data (Plot-IT 1987):

$$U_{E_w} = 13.0 + 1.41 V_{f_s} \tag{4.34}$$

A statistical analysis yields an F-value of 32.91, which is significant at the 5% confidence level. The coefficient of determination is 0.69.

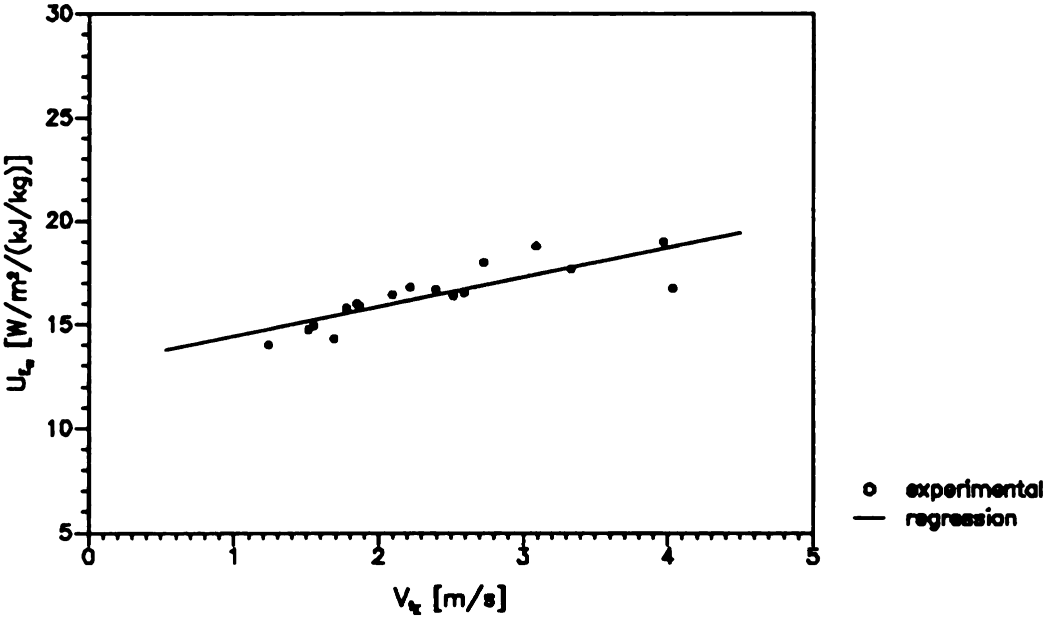


Figure 4.8 Experimental overall heat transfer coefficients and corresponding regression line for the wet evaporator as a function of the face velocity.

Figure 4.9 shows the values of the overall dry-evaporator heat transfer coefficient, calculated from equation 4.25 after solving for U_E, versus the face velocity, calculated from equation 4.33, for a range of experimental cooling loads.

From the experimental data the following equation was derived for the dry evaporator heat transfer coefficient (Plot-IT 1987):

$$U_E = 14.1 + 2.78\, V_{f_e} \qquad (4.35)$$

A statistical analysis yields an F-value of 182.6, which is significant at the 5% confidence level. The coefficient of determination is 0.93.

4.2.2.2.3 Reheater Heat Transfer Coefficient

The calculation of the reheater capacity in equation 4.21 requires knowledge of the overall reheater heat transfer coefficient. The analysis of the experimental data (see Figure 4.10) yielded the following equation (Plot-IT 1987):

$$U_H = 15.4 + 2.73\, V_{f_e} \qquad (4.36)$$

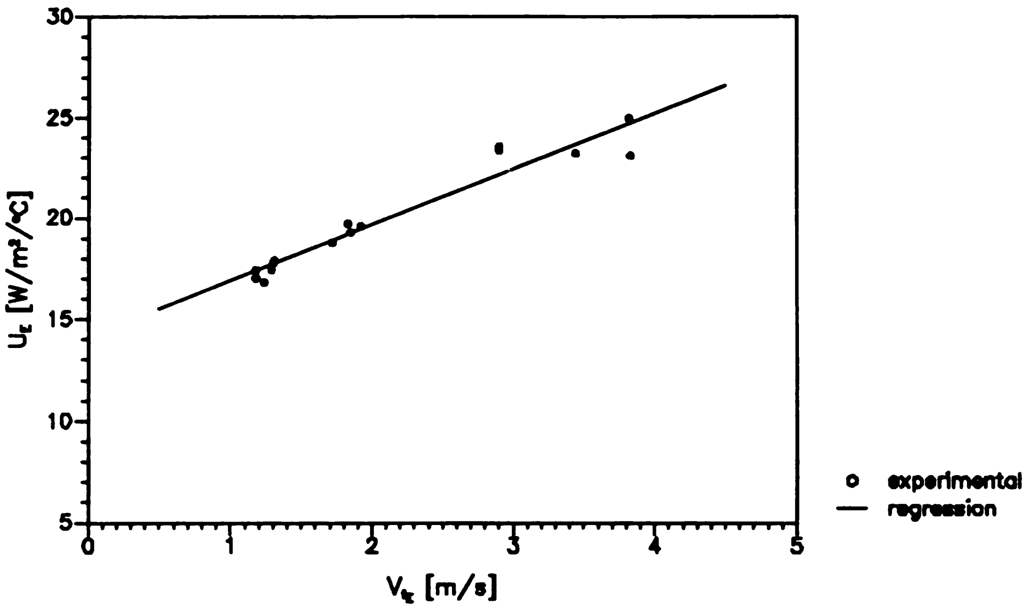


Figure 4.9 Experimental overall heat transfer coefficients and corresponding regression line for the dry evaporator as a function of the face velocity.

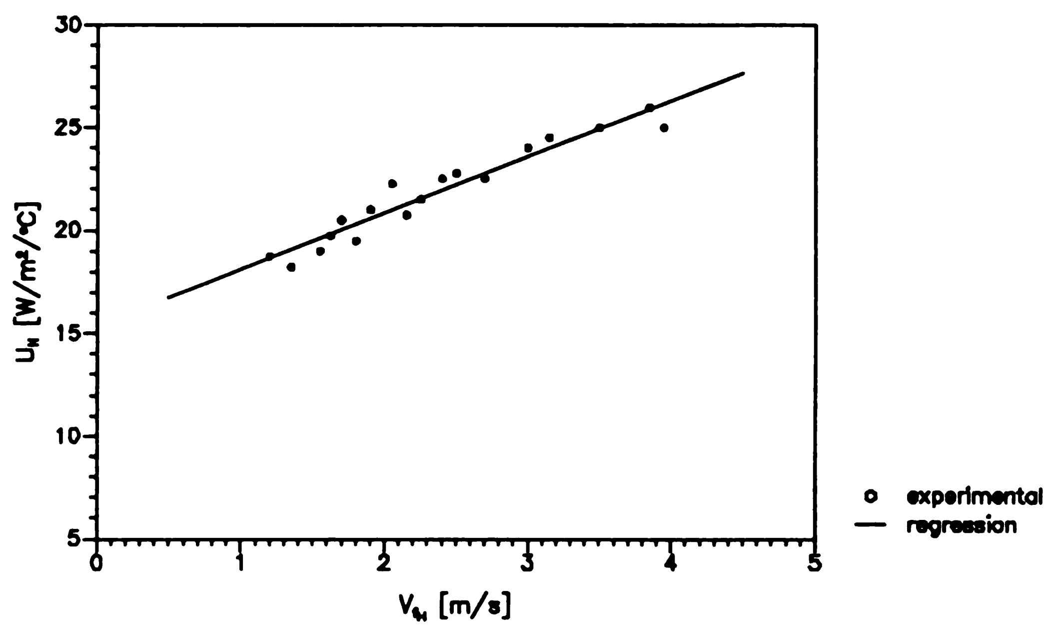


Figure 4.10 Experimental overall heat transfer coefficient and corresponding regression line for the reheater as a function of the face velocity.

The face velocity into the reheater is:

$$V_{f_r} = \frac{\dot{m}_a v_2}{A_{f_r}} \tag{4.37}$$

A statistical analysis of the linear regression yields an F-value of 218.8, which is significant at the 5% confidence level. The coefficient of determination is 0.93.

4.2.2.2.4 Condenser Heat Transfer Coefficient

The calculation of the condenser capacity in equation 4.19 requires knowledge of the overall condenser heat transfer coefficient. Since the condenser fan speed is fixed, the air velocity through the condenser is finite. Thus, the overall condenser heat transfer coefficient is constant. The analysis of the performance data yielded the following value:

$$U_C = 27.8\ W/m^2/°C \tag{4.38}$$

The face velocity into the condenser is:

$$V_{f_c} = 2.25\ m/s \tag{4.39}$$

4.2.3 Modelling the Chiller Refrigeration Cycle

By formulating external energy balances for the components of the refrigeration cycle of the KK140 grain chiller, a numerical procedure can be developed to simulate the steady-state performance under any ambient and grain cooling load. The output from the grain chilling model, i.e. the temperature, relative humidity and flow rate of the air, are the inputs to the chilled aeration model. Additionally, the total power consumption and the operating hours of the chiller are of interest in the analysis of the chilled aeration and storage of cereal grains.

The chiller equations and parameters, and the model inputs are summarized in Tables 4.1 and 4.2. The algorithm of the grain chiller simulation model differentiates between the three distinct operating modes of the chiller, i.e. maximum refrigeration, maximum airflow, and electrical heating. Each will be described separately.

Table 4.1 Summary of the equations needed to formulate the grain chiller simulation model.

Chiller Component	Parameter	Equation
Compressor	W_p	4.27 - 4.29
	q'_E	4.30
	q'_C	4.31
Condenser	q_C	4.19
	ΔT_C	4.20
	U_C	4.38
Reheater	q_H	4.21
	ΔT_H	4.22
	U_H	4.36
Evaporator (wet)	q_E	4.23
	Δh_E	4.24
	U_{Ew}	4.34
Evaporator (dry)	q_E	4.25
	ΔT_E	4.26
	U_E	4.35

Table 4.2 Summary of the chiller parameters needed to solve the equations in Table 4.1.

Chiller Parameters	Symbol	Value
Evaporating refrigerant temperature	T_e	v
Condensing refrigerant temperature	T_c	v
Ambient relative humidity	RH_a	i
Condenser:		
Surface area	A_C	f
Face area	A_{fC}	f
Face velocity	V_{fC}	f
Inlet air temperature	T_a	i
Outlet air temperature	T_o	v
Reheater:		
Surface area	A_H	f
Face Area	A_{fH}	f
Face velocity	V_{fH}	v
Inlet air temperature	T_2	i
Outlet air temperature	T_3	i
Evaporator:		
Surface area	A_E	f
Face area	A_{fE}	f
Face velocity	V_{fE}	v
Inlet air enthalpy (wet)	h_1	v
Outlet air enthalpy (wet)	h_2	v
Fictitious air enthalpy (wet)	$h_{s,R}$	v
Inlet air temperature (dry)	T_1	v
Outlet air temperature (dry)	T_2	v

f - chiller-specific fixed dimension
v - performance-specific varying dimension
i - input and set-point parameters

4.2.3.1 Maximum Refrigeration

During maximum refrigeration the grain chiller operates with a wide-open refrigeration valve and adjusts the airflow across the evaporator to match the needed cooling load with the available evaporator capacity. The following algorithm was developed:

(1) Calculate the needed evaporator capacity, $q_{E\ needed}$, to chill a given airflow, $\dot{m}_a$ (in kg/s), to the cold-air temperature set-point, T_2, from the following energy balance:

$$q_{E_{needed}} = \dot{m}_a (h_1 - h_2) \tag{4.40}$$

(2) Determine whether the evaporator is wet, or dry from the psychrometric state points (1) and (2) (see Figure 4.7):

(a) <u>If wet:</u> Solve equation 4.23 for the LMHD as a function of $q_{E\ needed}$ (eq. 4.40):

$$\Delta h_E = \frac{q_{E_{needed}}}{U_{E_w} A_E} \tag{4.41}$$

(b) <u>If dry:</u> Solve equation 4.25 for the LMTD as a function of $q_{E\ needed}$ (eq. 4.40):

$$\Delta T_E = \frac{q_{E_{needed}}}{U_E A_E} \tag{4.42}$$

(3) Calculate the evaporating refrigerant temperature:

(a) <u>If wet:</u> Solve equation 4.24 for the fictitious enthalpy of saturated moist air at the evaporating refrigerant temperature:

$$h_{s,R} = \frac{h_1 - h_2 \exp\left(\frac{h_1 - h_2}{\Delta h_E}\right)}{1 - \exp\left(\frac{h_1 - h_2}{\Delta h_E}\right)} \tag{4.43}$$

The evaporating refrigerant temperature is equal to the saturated moist air temperature and can be calculated from the steam tables as a function of the enthalpy $h_{s,R}$. A linear regression analysis of the steam table values in the range of -40 to +30°C (ASHRAE 1981) yielded the following quadratic equation (Plot-IT 1987):

$$T_e = -6.02 + 0.681\, h_{s,R} - 0.00418\, h_{s,R}^2 \tag{4.44}$$

(b) <u>If dry:</u> Solve equation 4.26 for the refrigerant temperature:

$$T_e = \frac{T_2 \exp\left(\frac{T_1 - T_2}{\Delta T_e}\right) - T_1}{\exp\left(\frac{T_1 - T_2}{\Delta T_e}\right) - 1} \tag{4.45}$$

(4) For a given condensing refrigerant temperature, T_c, and the calculated evaporating refrigerant temperature (eq. 4.44 or 4.45), determine the compressor curve evaporating capacity, q'_E (eq. 4.30).

(5) Compare q'_E to $q_{E\ needed}$ (eq. 4.40) using the false position root finding method with bracketing and a tolerance of 0.01°C on T_c (Press et al. 1985):

(a) If $q_{E\ needed}$ is greater than q'_E, the condensing temperature, T_c, is too high. Reduce T_c and go back to Step (4).

(b) If $q_{E\ needed}$ is less than q'_E, the condensing temperature, T_c, is too low. Increase T_c and go back to Step (4).

(c) If $q_{E\ needed}$ is equal to q'_E, the actual condensing, T_c, and evaporating, T_e, refrigerant temperatures have been found.

(6) For T_c and T_e calculate the compressor power, W_p (eqns. 4.27 - 4.29).

(7) Determine the total condensing capacity needed in the refrigeration cycle, q'_C (eq. 4.31).

(8) Calculate the total condensing capacity available in the refrigeration cycle of the grain chiller:

$$q_{C_{available}} = q_H + q_C \tag{4.46}$$

The condensing capacity of the reheater is calculated from equation 4.21, and the capacity of the condenser from equation 4.19. However, the LMTD of the condenser depends on the outlet air temperature from the condenser (see eq. 4.20), which is unknown. The outlet air temperature can be solved for iteratively from the following energy balance on the condenser:

$$U_C\ A_C \Delta T_C = \dot{m}_{a_c}(h_o - h_a) \tag{4.47}$$

The two unknowns are ΔT_c and h_o. The outlet air temperature is calculated using the false position root finding method using bracketing and a tolerance of 0.01°C (Press et al. 1985). The mass flow rate of the air, $\dot{m}_{ac}$, across the condenser is:

$$\dot{m}_{a_c} = \frac{V_{f_c} A_{f_c}}{v_a} \tag{4.48}$$

(9) Compare $q_{c\ available}$ (eq. 4.46) and q'_c (eq. 4.31) using the false position root finding method with bracketing and a tolerance of 10 m^3/h on the airflow rate (Press et al. 1985):

(a) If $q_{c\ available}$ is greater than q'_c, increase the airflow across the evaporator since excess refrigeration capacity is available, and go back to Step (1), or go to Step (10) if the maximum airflow is reached.

(b) If $q_{c\ available}$ is less than q'_c, reduce the airflow across the evaporator since the refrigeration capacity is insufficient, and go back to Step (1), or go to Step (10) if the minimum airflow is reached.

(c) If $q_{c\ available}$ is equal to q'_c, the refrigeration cycle is balanced and the airflow into the bin is found for the time interval.

(10) For an airflow rate outside the minimum and maximum airflow range (see Section 4.3 below):

(a) If the minimum airflow rate is understepped, the chiller is shut-off, and the airflow into the bin is zero.

(b) If the maximum airflow rate is overstepped, the chiller refrigeration cycle for the time interval has to be analyzed in the maximum airflow operating range.

4.2.3.2 Maximum Airflow

In the maximum airflow range the grain chiller operates with a wide-open fan throttle and adjusts the refrigeration capacity to match the cooling load to the available evaporator capacity.

The refrigeration capacity is controlled by throttling the refrigerant flow. To prevent the condensing refrigerant temperature from dropping too low and to maintain adequate pressure, the condensing temperature in the KK140 is kept at a minimum temperature ($T_{c\,min}$) using a hot gas loop (Sulzer-Escher Wyss 1991). In a similar manner, the evaporating refrigerant temperature is artificially raised, and not allowed to drop below a certain minimum temperature ($T_{e\,min}$). The values of $T_{c\,min}$ and $T_{e\,min}$ for the KK140 grain chiller model are set to 39°C and -22.5°C, respectively.

The following algorithm is employed:

Steps (1) and (2) are the same as for the maximum refrigeration algorithm, except the calculations are always made at the maximum airflow rate.

(3) Set T_c equal to $T_{c\,min}$.

(4) Calculate T_e as a function of T_c and $q_{E\,needed}$ from the compressor curves (eq. 4.30) using the false position root finding method with bracketing and a tolerance of 0.01°C on T_e (Press et al. 1985). If T_e is less than $T_{e\,min}$, shut-off the refrigeration cycle and try electrical heating of the air to maintain the temperature set-point at the chiller outlet, T_3 (see Section 4.2.3.3 below).

(5) For T_c and T_e calculate the compressor power, W_p (eqns.

4.27 - 4.29).

(6) Calculate the total condensing capacity available in the refrigerant cycle similarly to Step (8) in Section 4.2.3.1 (the needed and available evaporating capacities are the same in this case). The refrigeration cycle is now balanced.

4.2.3.3 Electrical Heating

Certain ambient conditions do not require the bin inlet air conditions to be maintained by the refrigeration cycle. This occurs when the cold air temperature set-point, T_2, is higher than the temperature of the air after the fan, T_1, or the minimum evaporating refrigerant temperature is understepped. In the KK140 chilling unit, three built-in 2-kW heating stages are available in the reheater to maintain the air temperature at the set-point, T_3.

The following algorithm is used:

(1) Calculate the needed electrical reheating capacity at the given airflow:

$$q_{el_{needed}} = \dot{m}_a(h_3-h_2) \tag{4.49}$$

(2) Check the available reheating capacity:

(a) If $q_{el\ needed}$ is larger than $q_{el\ max}$ (i.e. $q_{el\ max}$ = 6 kW for the KK140), reduce the airflow, $\dot{m}_a$, until the reheater is balanced. If the ambient temperature drops too low for the maximum electrical heating capacity and the airflow is minimized, the controller shuts-off the chiller and the airflow rate is zero for the time interval.

(b) If $q_{el\ needed}$ falls below the first, or between the first and second, or between the second and third heating stages, calculate the allowable airflow rate as a function of the average electrical heating capacity between two stages (e.g. $q_{el\ stage}$ = 3 kW if $q_{el\ needed}$ falls between the first and second heating stages):

$$\dot{m}_a = \frac{q_{el_{stage}}}{h_3 - h_2} \qquad (4.50)$$

(3) Check the airflow rate:

(a) If $\dot{m}_a$ is less than the minimum airflow rate, the controller shuts-off the chiller and the airflow rate is set to zero.

(b) If $\dot{m}_a$ is greater than the maximum airflow rate, reset $\dot{m}_a$ to the maximum value and assume that the electrical heaters will cycle on and off to maintain T_3.

4.3 Coupling the Grain Chiller and Aeration Models

The grain chiller operates within a certain airflow range. The minimum airflow occurs at a fully "closed" fan throttle. The "closed" position is not one of zero airflow but rather when the airflap allows 15 - 30 percent of the maximum airflow to pass (for the KK140 grain chiller model a value of 25% is used). This is a safety precaution to prevent the fan from choking off the refrigeration cycle and from overloading the fan motor. If the minimum airflow is too high for the evaporative cooling capacity, the chiller controller shuts-off the system automatically within a few minutes. The maximum airflow occurs at fully open fan throttle and is determined by the bin-chiller operating point.

As the centrifugal fan forces air through the chilling unit into the storage bin and through the grain, resistance to the airflow (i.e. pressure drop) develops as a result of friction and turbulence. The pressure drop through grain depends on the rate of airflow, surface and shape of the grain, porosity of the grain bulk, and the depth of the pile (Brooker et al. 1992).

In addition to the pressure drop through the grain, pressure drop occurs in the perforated bin floor, and in the expansion of the air from the duct into the bin. In this study, these additional losses are assumed to add 20% to the total pressure drop. The pressure drop in the chilling unit includes the resistance of the duct connecting the chiller and the bin, the reheater, the evaporator, the throttle controlling the airflow across the evaporator, and the filter screen before the centrifugal fan. The KK140 grain chiller used in this study added 1,250 Pa of pressure drop at a fully open throttle, and 200 Pa at a "closed" throttle to the total pressure drop of the system.

From the pressure drop through the grain and the additional pressure losses, a system curve of the static pressure as a function of the airflow can be established. Figure 4.11 is the open-throttle fan curve (Curve 1) of the KK140 grain chiller. [For confidentiality reasons the units are omitted.]

When plotted on the same diagram, the intersection of the system curve and the fan curve yields the operating point for the combined bin-chiller system at full throttle.

The following algorithm was implemented to determine the operating point in the chiller model (Brooker et al. 1992):

(1) Let ΔP be one-half of the upper fan pressure limit.

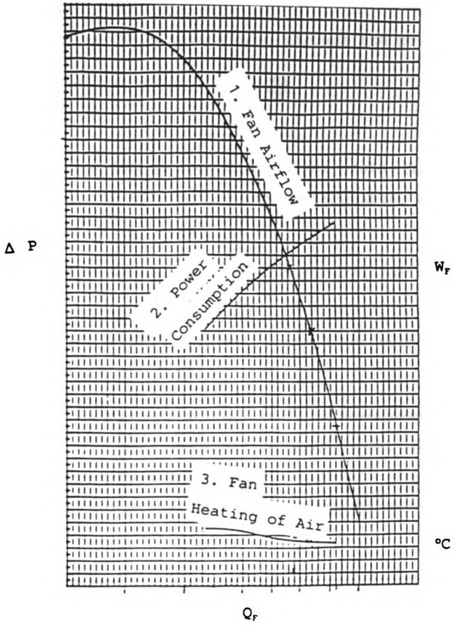


Figure 4.11 Open-throttle fan curve of the KK140 grain chiller, fan power consumption, and heating of the air by the fan (Sulzer-Escher Wyss 1991).

(2) Calculate the airflow, Q_F (in m^3/h), from the fan curve for ΔP.

(3) Determine the pressure drop through the pile as:

$$\Delta P' = \frac{\Delta P}{L} \tag{4.51}$$

(4) Calculate the airflow through the grain, Q_G, as a function of $\Delta P'$ and the bin surface area, A_{Bin} (in m^2) (Brooker et al. 1992):

$$Q_G = 3600\, A_{Bin} \exp[a + b \ln(\Delta P') + c(\ln(\Delta P'))]^2 \tag{4.52}$$

The values of coefficients a, b, and c for corn and wheat are (Brooker et al. 1992):

	a	b	c
Corn	-6.55	1.01	-0.0325
Wheat	-8.05	1.06	-0.0184

(5) Compare Q_F and Q_G (a tolerance of 100 Pa is used on ΔP):

(a) If Q_G is less than Q_F, increase ΔP, and go back to Step (2).

(b) If Q_G is greater than Q_F, decrease ΔP, and go back to Step (2).

(c) If Q_G is within a specified tolerance of Q_F (i.e. 10

m^3/h is used), the operating point of the bin-chiller system in terms of airflow and pressure drop is found.

Since the airflow through the chiller and into the bin changes as a function of the cooling load, the pressure drop through the pile at any time is calculated from the following grain-specific equation (ASAE 1991):

$$\frac{\Delta P}{L} = \frac{a V_a^2}{\ln(1 + b V_a)} \tag{4.53}$$

The coefficients a and b for corn and wheat are (ASAE 1991):

	a	b
Corn	20,700	30.4
Wheat	27,000	8.77

Figure 4.11 also contains a relationship for the electrical power absorbed by the fan (Curve 2), and the heating of the ambient air due to the cold-air fan (Curve 3). The equation for the fan power consumption from a regression analysis is (Plot-IT 1987):

$$W_F = 23.8 + 0.00743\, Q_F \tag{4.54}$$

The coefficient of determination of equation 4.54 is 0.97.

The temperature increase of the ambient air due to the fan from T_A to T_1 is calculated in the model by interpolation of the data points in Figure 4.11.

4.4 Storage of Chilled Cereal Grains

The physical, biological, and operational considerations of maintaining quality during the storage of cereal grains were discussed in detail in Chapters 1 and 3. Proper managing of a chilled grain storage facility requires the specification of the length and frequency of the chilling treatments during the storage period, and a knowledge of the required storage conditions of the grain, i.e. the grain temperature and moisture content.

In order to determine the proper chilling treatments and the optimum storage conditions, a mathematical model of the temperature and moisture content of the grain in the storage bin is necessary. The literature on the modelling of bulk-stored grain is extensive. The relevant information is considered briefly.

4.4.1 Approaches to Storage Modelling

The temperature and moisture content changes occurring in a bin containing non-ventilated grain are due to (1) conduction heat transfer, (2) natural convection heat and mass transfer, and (3) interstitial moisture diffusion.

Interstitial moisture diffusion based on Fick's law was used by Pixton and Griffith (1971), and Thorpe (1981) in one dimension, and Obaldo et al. (1989) in two dimensions to predict the moisture movement through bulk grain. Moisture changes due to diffusion were found to be extremely slow (Pixton and Griffiths 1971). Obaldo et al. (1989) noted very little evidence of moisture migration during the summer and early fall in the bulk of 58.5 tonnes of corn stored at 14 percent moisture content (w.b.) in a steel bin under Kansas conditions. The change of moisture was most pronounced at the top grain surface. Similar field results were reported by Buschermole et al. (1989) for low moisture content grain stored under Southeastern U.S. conditions. Since the time-constant of the moisture migration process is small at low grain temperatures and moisture contents (Thorpe 1981), its significance is assumed to be negligible in determining the rechilling frequency for a chilled grain storage system, i.e. storage of grain at low temperature and moisture content.

The basic laws of heat, moisture, and momentum transfer in hygroscopic porous media were employed by Beukema et al. (1983) in three dimensions, and by Tanaka and Yoshida (1984), Nguyen (1987) and Smith and Sokhansanj (1990) in two dimensions. Beukema et al. (1983) reduced the governing equations to one parabolic and one elliptic differential equation. Natural convection increased the rate of heat flow compared to conduction by changing the average bulk temperature and moving the maximum away from the core center. Nguyen (1987) solved the entire set of transfer equations numerically. He established airflow patterns, and temperature and moisture distributions in rectangular storage bins with and without headspace.

Using an approximate model by assuming the moisture flow rate negligible, Smith and Sokhansanj (1990) found natural convection to influence heat transfer significantly in the presence of moisture movement, if the resistance to airflow is low enough, and if the radius and height of the storage bin are approximately equal. The multi-differential equation models for the temperature and moisture content distributions in bulk grain due to convection appear most precise. However, due to their complexity, they require considerable computational time (Nguyen 1987). Muir et al. (1980) noted that modelling natural convection increases the computational time by a factor of 25 compared to a two-dimensional conduction model. Since the chilled storage of bulk grain is practiced over long storage periods, on the order of 6 to 12 months or more, the natural convection model approach is not used in this study for the simulation of the chilled storage of cereal grains.

The conduction heat transfer in cylindrical grain bins has been modelled one-dimensionally with one differential equation by Yaciuk et al. (1975), by Muir et al. (1980) in two dimensions, and by Alagusundaram et al. (1990a, 1990b) in three dimensions. Only the temperatures were simulated. Yaciuk et al. (1975) investigated the influence of the thermal grain properties, initial grain temperature, ambient air temperature, wind velocity, bin diameter, and bin-wall material on grain stored under Canadian Prairie conditions. Muir et al. (1980) modelled conductive heat transfer in both the radial and vertical directions of cylindrical grain storage bins; heat generation in the grain bulk was considered negligible. The Muir model was verified with experimental temperatures for rapeseed and barley, and predicts the experimental grain temperatures to within 2°C. At diameter-to-height ratios of 0.5 or less the difference between the one- and two-dimensional conduction models is negligible; for ratios greater than 1.2 the difference is more than 2°C.

Temperature distributions in the radial, vertical and circumferential directions of a cylindrical grain storage bin were simulated with both a finite difference and a finite element conduction model by Alagusundaram et al. (1990a and 1990b). The temperatures predicted by finite difference versus finite element techniques were nearly identical. The three-dimensional models predict temperatures that agree well with the measured grain temperatures in a bin of rapeseed over a 41-month storage period. Temperatures for the north- and south-facing areas of the bin are distinctly different, and cannot be predicted with a two-dimensional model. The grain temperatures in the south-facing half of the bin for three-dimensional conduction are up to 5°C higher than those calculated with the two-dimensional model. However, the difference decreases with an increase in the diameter-to-height ratio of the grain bulk. At ratios above 1.0 the temperature difference is less than 3°C.

On the basis of the above review, it was concluded that the chilled storage of cereal grains can be modelled adequately by heat conduction only. Since the storage temperatures are low, moisture migration is small, and thus the effect of natural convection currents on the temperature and moisture profiles during the storage of chilled grains is negligible.

The additional complexity of the natural convection equations does not improve the accuracy of a conduction model significantly at low grain temperatures and moisture contents. In determining the frequency of rechilling, the temperatures in the south-facing half of a cylindrical grain bin are critical. The accuracy of temperatures predicted by a two-dimensional conduction model appears adequate especially for large diameter-to-height bin ratios. Since the cylindrical steel grain bins used in conjunction with the chilled aeration and storage have regularly-shaped boundaries, the finite-difference technique is appropriate for the numerical solution of the model. Thus, the two-dimensional conduction model is chosen to simulate the chilled storage of cereal grains.

4.4.2 Two-dimensional Time-dependent Heat Conduction Model

The time-dependent, two-dimensional differential equation of heat conduction in cylindrical coordinates for the stationary, homogeneous, isotropic grain bulk without heat generation and with thermal conductivity independent of temperature is (Özisik 1980):

$$\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau} \qquad (4.55)$$

where,

$$\alpha = \frac{k}{\varrho C_p} \tag{4.56}$$

It is assumed (as explained above) that heat conduction is only significant in the radial and vertical direction in the modelling of a chilled grain storage bin.

Four boundary conditions (B.C.) exist for a grain bin symmetric about the center axis:

(1) The insulated core:

$$\frac{\partial T}{\partial r} = 0 \tag{4.57}$$

The B.C. is valid at $r = 0$ for $0 \le z \le L$ and $\tau > 0$.

(2) The convective top grain surface:

$$k\frac{\partial T}{\partial z} + h_b' T = h_b' T_b \tag{4.58}$$

The B.C is valid at $z = L$ for $0 \le r \le R$ and $\tau > 0$.

The air temperature in the headspace above the grain pile, T_b, and the convective heat transfer coefficient between the top grain layer and the air above the pile, h'_b, vary as a function of the headspace conditions.

(3) The convective bottom grain surface:

$$-k\frac{\partial T}{\partial z} + h_p' T = h_p' T_p \tag{4.59}$$

The B.C. is valid at z = 0 for $0 \leq r \leq R$ and $\tau > 0$.

The air temperature in the plenum space below the grain pile, T_p, and the convective heat transfer coefficient between the bottom grain layer and the plenum, h'_p, vary as a function of the plenum conditions.

(4) The convective and radiative wall surface:

$$k\frac{\partial T}{\partial r} + h_w' T = h_w' T_a + q_r \tag{4.60}$$

The B.C. is valid at r = R for $0 \leq z \leq L$ and $\tau > 0$.

The ambient air temperature, T_a, the convective heat transfer coefficient between the outer bin wall and the ambient air, h'_w, and the thermal radiation, q_r, are site-specific and vary as a function of the local weather conditions.

(5) The initial condition (I.C.) for the 2-D conduction

model is:

$$T = T_{initial} \tag{4.61}$$

The I.C. is valid at $0 \le r \le R$ and $0 \le z \le L$ for $\tau = 0$.

Equation 4.55 and the initial and boundary conditions (eqns. 4.57 - 4.61) constitute the two-dimensional heat conduction model for the storage of chilled cereal grains.

4.4.2.1 Numerical Solution

Equation 4.55 can be solved analytically using, for example, the separation of variables technique. For homogeneous boundary conditions, Özisik (1980) has tabulated the eigenfunctions, eigenvalues and norms for the Bessel functions in $R_i(\beta,r)$ to solve equation 4.55. A chilled grain storage bin could be represented as a solid cylinder and an analytical solution of the temperature distribution over the storage time obtained by the superposition of the elementary solutions. However, the boundary conditions at the top and bottom grain surfaces, and at the wall are non-homogeneous for the grain bin. Thus, a numerical scheme is used to solve the 2-D heat conduction equations for the chilled grain storage bin.

To obtain a numerical solution of model equations 4.55, and 4.57 through 4.61, the partial differential equation of heat conduction and the associated boundary and initial conditions are transformed such that differentiation can be performed by numerical calculation. Finite difference approximations are used to derive the expressions for the two-dimensional M by N segment for the sector of the circular grain bin shown in Figure 4.12.

4.4.2.1.1 Nodal Equations

The space derivatives of the two-dimensional heat conduction equation (eq. 4.55) are represented by the following central-difference expressions:

$$\left.\frac{\partial^2 T}{\partial z^2}\right|_{i,j}^{n} = \frac{T_{i-1,j}^{n} - 2T_{i,j}^{n} + T_{i+1,j}^{n}}{(\Delta z)^2} \qquad (4.62)$$

$$\left.\frac{\partial^2 T}{\partial r^2}\right|_{i,j}^{n} = \frac{T_{i,j-1}^{n} - 2T_{i,j}^{n} + T_{i,j+1}^{n}}{(\Delta r)^2} \qquad (4.63)$$

$$\left.\frac{\partial T}{\partial r}\right|_{i,j}^{n} = \frac{T_{i,j+1}^{n} - T_{i,j-1}^{n}}{2\Delta r} \qquad (4.64)$$

The subscripts i and j refer to the vertical and radial

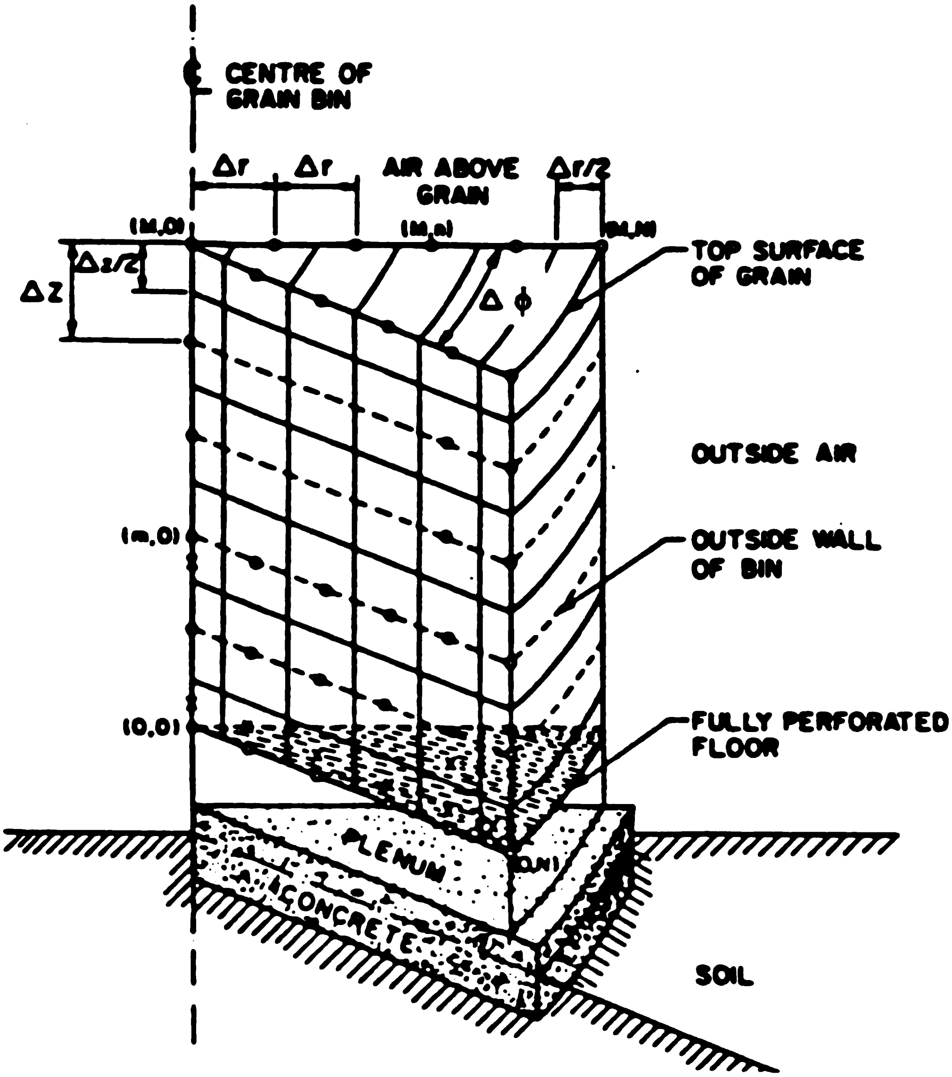


Figure 4.12 Sector of a cylindrical grain bin divided into (M + 1) vertical and (N + 1) radial elements for the two-dimensional conduction simulation of the chilled grain storage bin (Metzger and Muir 1983).

coordinates of the temperature nodes, respectively. The superscript n refers to the temperature at the beginning of the current time step.

The time derivative of the two-dimensional heat conduction equation (eq. 4.55) is represented by the following explicit forward-difference formula:

$$\left.\frac{\partial T}{\partial \tau}\right|_{i,j}^{n} = \frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta \tau} \tag{4.65}$$

The superscript (n+1) refers to the temperature at the end of the current time step.

Interior Nodes:

Inserting equations 4.62 - 4.65 into equation 4.55, replacing r with jΔr, and solving for the current temperature at an interior point (i,j) yields the following expression:

$$T_{i,j}^{n+1} = \left(\frac{2j+1}{2jU}\right) T_{i,j+1}^{n} + \left(\frac{2j-1}{2jU}\right) T_{i,j-1}^{n} + \frac{E}{U}\left(T_{i+1,j}^{n} + T_{i-1,j}^{n}\right) + \left[1 - \frac{2(E+1)}{U}\right] T_{i,j}^{n} \tag{4.66}$$

where,

$$E = \frac{(\Delta r)^2}{(\Delta z)^2} \tag{4.67}$$

and,

$$U = \frac{(\Delta r)^2}{\alpha \Delta \tau} \tag{4.68}$$

Equation 4.66 is used to calculate the interior node grain temperature in the 2-D grid shown in Figure 4.12. Eight additional finite-difference expressions are needed for the boundary condition equations (eqns. 4.57 - 4.61); four for the boundary surfaces, i.e. at the core (i.e. center column), the top, and the bottom of the pile, and the external wall surface; and four for the corner points of the grid.

Center Column Nodes:

At the center column the boundary condition of equation 4.57 applies. Since the radius, r, equals zero at the core, equation 4.55 appears to have a singularity. However, applying L'Hospital's rule yields (Özisik 1980):

$$\lim_{r \to 0}\left(\frac{1}{r}\frac{\partial T}{\partial r}\right) = \frac{\partial^2 T}{\partial r^2} \tag{4.69}$$

Then, equation 4.55 reduces to:

$$2\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial \tau} \tag{4.70}$$

Since the boundary is reflective, the finite difference expression for the current temperature of the nodes along the center column is:

$$T_{i,0}^{n+1} = \frac{4}{U}T_{i,1}^{n} + \frac{E}{U}(T_{i-1,0}^{n} + T_{i+1,0}^{n}) + \left[1 - \frac{2(E+2)}{U}\right]T_{i,0}^{n} \quad (4.71)$$

Top Surface Nodes:

At the top surface of the grain pile the boundary condition of equation 4.58 applies. The finite difference expression of equation 4.55 at the top of the pile is:

$$T_{M,j}^{n+1} = \left(\frac{2j+1}{2jU}\right)T_{M,j+1}^{n} + \left(\frac{2j-1}{2jU}\right)T_{M,j-1}^{n} + \frac{E}{U}(T_{-(M-1),j}^{n} + T_{M-1,j}^{n}) + \left[1 - \frac{2(E+1)}{U}\right]T_{M,j}^{n} \quad (4.72)$$

The temperature, $T_{-(M-1),j}$, is a fictitious node temperature outside the grid, which also appears in the finite difference expression of the boundary condition at the top surface:

$$\frac{T_{-(M-1),j} - T_{M-1,j}}{2\Delta z} + \frac{h_b'}{k}T_{M,j} = \frac{h_b'}{k}T_b \quad (4.73)$$

Solving equation 4.73 for the fictitious temperature, and substituting the resulting expression into equation 4.72, yields the finite difference expression of the current temperature for the nodes at the top surface:

$$T_{M,j}^{n+1} = \left(\frac{2B_b\Delta r}{U\Delta z}\right)T_b^n + \left(\frac{2j+1}{2jU}\right)T_{M,j+1}^n + \left(\frac{2j-1}{2jU}\right)T_{M,j-1}^n + \frac{2E}{U}T_{M-1,j}^n + \left[1-\frac{2(E+1)}{U}-\frac{2B_b\Delta r}{U\Delta z}\right]T_{M,j}^n \quad (4.74)$$

where,

$$B_b = \frac{h_b'\Delta r}{k} \quad (4.75)$$

Bottom Surface Nodes:

At the bottom surface of the grain pile the boundary condition of equation 4.59 applies. The finite difference expression of equation 4.55 at the bottom of the pile is:

$$T_{0,j}^{n+1} = \left(\frac{2j+1}{2jU}\right)T_{0,j+1}^n + \left(\frac{2j-1}{2jU}\right)T_{0,j-1}^n + \frac{E}{U}(T_{1,j}^n + T_{-1,j}^n) + \left[1-\frac{2(E+1)}{U}\right]T_{0,j}^n \quad (4.76)$$

The temperature, $T_{-1,j}$, is a fictitious node temperature outside the grid, which also appears in the finite difference expression of the boundary condition at the bottom surface:

$$\frac{T_{1,j}-T_{-1,j}}{2\Delta z} + \frac{h_p'}{k}T_{0,j} = \frac{h_p'}{k}T_p \quad (4.77)$$

Solving equation 4.77 for the fictitious temperature, and substituting the resulting expression into equation 4.76, yields the finite difference expression of the current temperature for the nodes at the bottom surface:

$$T_{0,j}^{n+1} = \left(\frac{2B_p\Delta r}{U\Delta z}\right)T_p^n + \left(\frac{2j+1}{2jU}\right)T_{0,j+1}^n + \left(\frac{2j-1}{2jU}\right)T_{0,j-1}^n + \frac{2E}{U}T_{1,j}^n + \left[1 - \frac{2(E+1)}{U} - \frac{2B_p\Delta r}{U\Delta z}\right]T_{0,j}^n \tag{4.78}$$

where,

$$B_p = \frac{h_p'\Delta r}{k} \tag{4.79}$$

<u>Top Center-Column Corner Node:</u>

At the intersection of the top surface of the grain pile with the center-column, the boundary conditions of equations 4.57 and 4.58 apply. Modifying the finite difference expression for the nodes along the center column (eq. 4.71) to account for the top center- column corner point results in:

$$T_{M,0}^{n+1} = \frac{2}{U}T_{M,1}^n + \frac{E}{U}(T_{M-1,0}^n + T_{-(M-1),0}^n) + \left[1 - \frac{2(E+1)}{U}\right]T_{M,0}^n \tag{4.80}$$

Modifying the convective boundary condition (eq. 4.73) for the top center-column corner point:

$$\frac{T_{-(M-1),0} - T_{M-1,0}}{2\Delta z} + \frac{h_b'}{k}T_{M,0} = \frac{h_b'}{k}T_b \tag{4.81}$$

Solving equation 4.81 for the fictitious temperature, $T_{-(M-1),0}$, and substituting the result into equation 4.80 yields the current temperature of the top center-column corner node:

$$T_{M,0}^{n+1} = \left(\frac{2B_b\Delta r}{U\Delta z}\right)T_b^n + \frac{2}{U}T_{M,1}^n + \frac{2E}{U}T_{M-1,0}^n + \left[1 - \frac{2(E+1)}{U} - \frac{2B_b\Delta r}{U\Delta z}\right]T_{M,0}^n \qquad (4.82)$$

<u>Bottom Center-Column Corner Node:</u>

At the intersection of the bottom surface of the grain pile with the center-column, boundary conditions of equations 4.57 and 4.59 apply. Modifying the finite difference expression for the nodes along the center-column (eq. 4.71) for the bottom center-column corner point:

$$T_{0,0}^{n+1} = \frac{2}{U}T_{0,1}^n + \frac{E}{U}(T_{1,0}^n + T_{-1,0}^n) + \left[1 - \frac{2(E+1)}{U}\right]T_{0,0}^n \qquad (4.83)$$

Modifying the convective boundary condition (eq. 4.77) for the bottom center-column corner point results in:

$$\frac{T_{1,0} - T_{-1,0}}{2\Delta z} + \frac{h_p'}{k}T_{0,0} = \frac{h_p'}{k}T_p \qquad (4.84)$$

Solving equation 4.84 for the fictitious temperature, $T_{-1,0}$, and substituting the result into equation 4.83, yields the current temperature of the bottom center-column corner node:

$$T_{0,0}^{n+1} = \left(\frac{2B_p\Delta r}{U\Delta z}\right)T_p^n + \frac{2}{U}T_{0,1}^n + \frac{2E}{U}T_{1,0}^n + \left[1 - \frac{2(E+1)}{U} - \frac{2B_p\Delta r}{U\Delta z}\right]T_{0,0}^n \qquad (4.85)$$

Wall Surface Nodes:

At the wall surface of the grain pile the boundary condition of equation 4.60 applies. The finite difference expression for the predicted temperature at the wall surface can be derived by establishing a heat balance on the exterior element of the bin grid (see Figure 4.12):

$$k\left[\left(N\Delta r - \frac{\Delta r}{2}\right)\Delta\phi\Delta z\right]\left(\frac{T_{i,N-1}^n - T_{i,N}^n}{\Delta r}\right) + k\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\right]\left(\frac{T_{i-1,N}^n - T_{i,N}^n}{\Delta z}\right)$$

$$k\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\right]\left(\frac{T_{i+1,N}^n - T_{i,N}^n}{\Delta z}\right) + h_w'[N\Delta r\Delta\phi\Delta z]\,(T_a^n - T_{i,N}^n) + q_r\,[N\Delta r\Delta\phi\Delta z]$$

$$= \varrho c_p\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\Delta z\right]\left(\frac{T_{i,N}^{n+1} - T_{i,N}^n}{\Delta\tau}\right) \qquad (4.86)$$

Solving equation 4.86 for the predicted temperature yields the finite difference expression of the current temperature for the nodes at the bin wall surface:

$$T_{i,N}^{n+1} = \left(\frac{8NB_w}{(4N-1)U}\right)T_a^n + \left(\frac{8N-4}{(4N-1)U}\right)T_{i,N-1}^n + \frac{E}{U}\left(T_{i+1,N}^n + T_{i-1,N}\right) + \left(\frac{8N\Delta\tau}{(4N-1)\Delta r\varrho c}\right)q_r + \left[1 - \frac{8NB_w+8N-4}{(4N-1)U} - \frac{2E}{U}\right]T_{i,N}^n \quad (4.87)$$

where,

$$B_w = \frac{h_w'\Delta r}{k} \quad (4.88)$$

<u>Top Wall Corner Node:</u>

At the intersection of the top surface of the grain pile with the bin wall surface, the boundary conditions of equations 4.58 and 4.60 apply. A heat balance on the top wall corner element yields:

$$k\left[(N\Delta r - \frac{\Delta r}{2})\Delta\phi\frac{\Delta z}{2}\right]\left(\frac{T_{M,N-1}^n - T_{M,N}^n}{\Delta r}\right) + k\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\right]\left(\frac{T_{M-1,N}^n - T_{M,N}^n}{\Delta z}\right) + h_b'\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\right]\left(T_b^n - T_{M,N}^n\right) + h_w'\left[N\Delta r\Delta\phi\frac{\Delta z}{2}\right]\left(T_a^n - T_{M,N}^n\right) + q_r\left[N\Delta r\Delta\phi\frac{\Delta z}{2}\right] = \varrho c_p\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\frac{\Delta z}{2}\right]\left(\frac{T_{M,N}^{n+1} - T_{M,N}^n}{\Delta\tau}\right) \quad (4.89)$$

Solving equation 4.89 for the predicted temperature yields the finite difference expression for the top wall corner node:

$$T_{M,N}^{n+1} = \left(\frac{2B_b\Delta r}{U\Delta z}\right)T_b + \left(\frac{8NB_w}{(4N-1)U}\right)T_a^n + \left(\frac{8N-4}{(4N-1)U}\right)T_{M,N-1}^n + \frac{2E}{U}T_{M-1,N}^n$$
$$+\left(\frac{8N\Delta\tau}{(4N-1)\Delta r\varrho c}\right)q_r + \left[1 - \frac{8NB_w+8N-4}{(4N-1)U} - \frac{2E}{U} - \frac{2B_b\Delta r}{U\Delta z}\right]T_{M,N}^n \tag{4.90}$$

Bottom Wall Corner Node:

At the intersection of the bottom surface of the grain pile with the wall surface, the boundary conditions of equations 4.59 and 4.60 apply. The heat balance on the bottom wall corner element yields:

$$k\left[(N\Delta r-\frac{\Delta r}{2})\Delta\phi\frac{\Delta z}{2}\right]\left(\frac{T_{0,N-1}^n-T_{0,N}^n}{\Delta r}\right)+k\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\right]\left(\frac{T_{0-1,N}^n-T_{0,N}^n}{\Delta z}\right)$$
$$+h_p'\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\right]\left(T_p^n-T_{0,N}^n\right)+h_w'\left[N\Delta r\Delta\phi\frac{\Delta z}{2}\right](T_a^n-T_{0,N}^n)+q_r\left[N\Delta r\Delta\phi\frac{\Delta z}{2}\right]$$
$$=\varrho c_p\left[\left(\frac{4N-1}{8}\right)(\Delta r)^2\Delta\phi\frac{\Delta z}{2}\right]\left(\frac{T_{0,N}^{n+1}-T_{0,N}^n}{\Delta\tau}\right) \tag{4.91}$$

Solving equation 4.91 for the predicted temperature yields the finite difference expression for the bottom wall corner node:

$$T_{0,N}^{n+1} = \left(\frac{2\Delta rB_p}{U\Delta z}\right)T_p + \left(\frac{8NB_w}{(4N-1)U}\right)T_a^n + \left(\frac{8N-4}{(4N-1)U}\right)T_{0,N-1}^n + \frac{2E}{U}T_{1,N}^n +$$
$$\left(\frac{8N\Delta\tau}{(4N-1)\Delta r\varrho c}\right)q_r + \left[1 - \frac{8NB_w+8N-4}{(4N-1)U} - \frac{2E}{U} - \frac{2B_p\Delta r}{U\Delta z}\right]T_{0,N}^n \tag{4.92}$$

Equations 4.66, 4.71, 4.74, 4.78, 4.82, 4.85, 4.87, 4.90, and 4.92 constitute the finite difference expressions needed to model numerically the temperature distribution in a two-dimensional time-dependent chilled grain storage bin. The derivation of equations 4.66, 4.71, 4.74, and 4.78 by direct substitution of the finite difference expressions confirm those presented by Muir et al. (1980), which were derived using heat balances on the grid nodes. Equations 4.87 was derived using the same approach as Muir et al. (1980) and confirms their result. Equations 4.82, 4.85, 4.90 and 4.92 have not been published in the literature.

Input Parameters:

There are a number of input parameters that must be specified to solve the 2-D model equations. Yaciuk et al. (1975) noted that some grid elements consist of more than one material, such as the bottom layer, which consists of perforated floor steel and a layer of grain, and the wall layer, which consists of corrugated sheet metal and a layer of grain. In a steel bin the wall is only a fraction of an inch thick (e.g. 18 gage sheet metal steel has a thickness of 0.0014 m). Therefore, in the 2-D simulation model for the chilled storage of cereal grains in cylindrical steel bins the effect of the thermal steel properties is negligible compared to k, c_p, and ρ_p of the grain layer.

The thermal properties of the grain storage model are summarized in Section 4.1.2.3. The dimensions of the storage bin and the grain conditions were discussed in Section 4.1.2.5. In addition to the pile height, the total bin height, the roof slope, and the plenum height need to be known. The specification of the convective heat transfer coefficients, the free-stream temperatures, the thermal radiation values, the number of grid nodes, and the dimensions of the space and time steps are discussed below.

4.4.2.1.2 Stability Criteria of the Solution

Whenever a differential equation is transformed and its solution approximated with finite differences using a Taylor series expansion, an error is introduced. Due to the cumulative effects of the rounding off and discretization errors, the solutions are not exact. In addition, the stability of a solution is related to its accuracy. Stability criteria play an important role in the finite difference solution of time-dependent heat conduction problems.

The finite difference equations of the 2-D conduction model for a grain storage bin are solved explicitly. The advantage of the explicit method is that the unknown temperature for the current time step, $T_{i,j}^{n+1}$, can be directly determined from the knowledge of the temperatures at the previous time step, $T_{i,j}^{n}$. The disadvantage of the explicit method is that once the thermal grain properties are specified (i.e. k, c_p, and ρ), the choice of the maximum space (i.e. Δr and Δz) and time (i.e. $\Delta \tau$) step sizes are restricted by stability requirements.

The bracketed terms in the finite difference equations (i.e. eqns. 4.66, 4.71, 4.74, 4.78, 4.82, 4.85, 4.87, 4.90, 4.92) must be greater than zero for the solution to be stable. For example, for the interior node the bracketed term in equation 4.66 is:

$$0 < \left[1 - \frac{2\,(E+1)}{U}\right] \tag{4.93}$$

For the solution of the interior node to be stable the following must hold true:

$$\frac{E+1}{U} < 0.5 \tag{4.94}$$

Among the nine stability criteria the most critical are (see eqns. 4.87, 4.90, and 4.92, respectively):

$$\frac{4NB_w + 4N - 2 + (4N-1)\,E}{(4N-1)\,U} < 0.5 \tag{4.95}$$

$$\frac{4NB_w + 4N - 2 + (4N-1)E + (4N-1)B_bE^{1/2}}{(4N-1)U} < 0.5 \qquad (4.96)$$

$$\frac{4NB_w + 4N - 2 + (4N-1)E + (4N-1)B_pE^{1/2}}{(4N-1)U} < 0.5 \qquad (4.97)$$

The space and time steps can be chosen too small. This increases the number of numerical calculations without improving the accuracy of the solution. For example, if α = 0.000363 m^2/h, Δz = 1.15 m, Δr = 0.72 m, $\Delta \tau$ = 3 hours, and the grid has 7 by 7 nodes, then E = 0.39 and U = 473.8, and the stability criterion for equation 4.96 is 0.039. If the time step is increased to $\Delta \tau$ = 24 hours, U = 62.1 and the stability criterion increases to 0.314. Both solutions are stable and yield a similar degree of accuracy, but the smaller time step requires 70,560 iterations over a six month storage period, compared to 8,820 calculations for the larger time step. In the numerical solution of the 2-D chilled grain storage equations in this study, the space and time steps are chosen so that the stability criteria of equations 4.95 - 4.97 are kept between 0.30 and 0.50.

4.4.2.1.3 Convective Heat Transfer Coefficients

Above the Pile:

The convective heat transfer coefficient between the top grain surface and the still air of the headspace above the pile, h'_b, was evaluated by Muir et al. (1980). They recommended:

$$h'_b = 1.0\ W/m^2/°C \tag{4.98}$$

For lack of other literature values, equation 4.98 is used in the chilled grain storage model.

Below the Pile:

The convective heat transfer coefficient between the bottom grain layer and the still air of the plenum space below the pile, h'_p, was evaluated by Muir et al. (1980). They recommended:

$$h'_p = 1.0\ W/m^2/°C \tag{4.99}$$

For lack of other literature values, equation 4.99 is used in the chilled grain storage model.

Along the Bin Wall:

Finnigan and Longstaff (1982) developed the following expression for the convective heat transfer coefficient for a vertical wall surface of a circular grain bin in ambient air.

$$h_w' = \frac{k_a Nu}{d} \tag{4.100}$$

where,

$$Nu = 0.73 Re^{0.57} Pr^{1/3} \tag{4.101}$$

The Reynolds number for the airflow around a circular grain bin with a diameter, d, is defined as (Finnigan and Longstaff 1982):

$$Re = \frac{V_{wind} d}{\nu_a} \tag{4.102}$$

The wind velocity, V_{wind}, is a function of the ambient weather conditions, which are specified in Chapter 5.

4.4.2.1.4 Free-stream Temperatures

<u>Above the Pile:</u>

Muir et al. (1980) used ambient-plus-5°C for the temperature of the air above the pile. Measurements in the experimental chilled grain storage bin (see Chapter 5) indicated significantly higher air temperatures above the pile due to solar radiation on the bin roof during the day time. Thus, a procedure similar to the evaluation of the attic temperature in buildings (ASHRAE 1981) was developed in order to estimate T_b.

The steady-state convective heat flow in the head-space above a grain pile during a specific time interval (assuming a full bin) can be expressed as a function of the heat flow from the grain, q_g, and from the roof, q_{rf}, and the heat exchange due to air infiltration, q_{vth}:

$$0 = q_g + q_{rf} + q_{vth} \qquad (4.103)$$

or,

$$0 = (UA)_g(T_g - T_b) + (UA)_{rf}(T_{rf} - T_b) + V_b c_b X_b (T_a - T_b) \qquad (4.104)$$

Solving equation 4.104 for the headspace temperature yields:

$$T_b = \frac{(UA)_g T_g + (UA)_{rf} T_{rf} + V_b c_b X_b T_a}{(UA)_g + (UA)_{rf} + V_b c_b X_b} \qquad (4.105)$$

The overall heat transfer coefficient U_g is set equal to h'_b; the grain surface area, A_g, is assumed equal to the bin area (i.e. levelled grain), and the temperature at the grain surface, T_g, is set equal to the average of the top grain temperature nodes. The recommended design volumetric heat capacity of air, c_b, is 0.335 J/m³/°C (ASHRAE 1981), and the recommended design air infiltration rate, X_b, is 0.67 volumes/hour (ASHRAE 1981).

The overall heat transfer coefficient for the bin roof is estimated by:

$$U_{rf} = \frac{1}{\frac{1}{h'_i} + \frac{t}{k_{rf}} + \frac{1}{h'_o}} \quad (4.106)$$

The convective heat transfer coefficient h'_i for stagnant air is 4 W/m^2/°C (Holman 1986). The roof thickness of a typical steel bin, t, is 0.0014 m (18 gage). The thermal conductivity of the steel roof, k_{rf}, is 54 W/m/°C (Holman 1986). The convective heat transfer coefficient h'_o for the sloped roof of a circular bin is calculated by (Finnigan and Longstaff 1982):

$$h'_o = \frac{k_a Nu}{d} \quad (4.107)$$

where,

$$Nu = 0.19 Re^{0.73} Pr^{1/3} \quad (4.108)$$

The Reynolds number is obtained with eq. 4.102.

The roof temperature, T_{rf}, is determined according to a procedure developed for flat-plate solar collectors (Duffie and Beckman 1980):

$$q_r = U_r(T_{rf}-T_a) \tag{4.109}$$

The radiative heat transfer, q_r, on the sloped bin roof is assumed to be due to solar radiation only (i.e. q_b plus q_d). It is calculated according to the procedure outlined in Section 4.4.2.1.5. The radiative top loss coefficient, U_r, is determined from (Duffie and Beckman 1980):

$$U_r = \frac{1}{\frac{1}{h_o'}+\frac{1}{h_r'}} \tag{4.110}$$

The linearized radiative heat transfer coefficient is calculated from (Duffie and Beckman 1980):

$$h_r' = \alpha_s \sigma\,(T_{rf}^2 + T_a^2)\,(T_{rf} + T_a) \tag{4.111}$$

The short-wave absorptivity, α_s, for the bin roof is equal to 0.38 (Siegel and Howell 1981). The Stefan-Boltzmann constant, σ, is 5.6697E-8 $W/m^2/K^4$. An iterative procedure is used to solve equations 4.109 - 4.111 for the bin roof temperature, T_{rf}.

<u>Below the Pile:</u>

The steady-state convective heat flow in the plenum below a grain pile during a specific time interval is evaluated similarly as the crawl space temperature under a building (ASHRAE 1981). It is expressed as a function of the heat flow from the floor of the plenum, q_{gr}, the perforated bin floor, q_{fl}, the perimeter surface of the plenum, q_{pr}, and the heat exchange due to air infiltration, q_{vtp}:

$$0 = q_{gr} + q_{fl} + q_{pr} + q_{vtp} \tag{4.112}$$

or,

$$0 = (UA)_{gr}(T_{gr}-T_p) + (UA)_{fl}(T_{fl}-T_p) + V_p C_b X_p (T_a - T_p) + (UA)_{pr}(T_w - T_p) \tag{4.113}$$

Solving equation 4.113 for the plenum temperature yields:

$$T_b = \frac{(UA)_{gr}T_{gr} + (UA)_{fl}T_{fl} + V_p C_b X_p T_a + (UA)_{pr}T_{pr}}{(UA)_{gr} + (UA)_{fl} + V_p C_b X_p + (UA)_{pr}} \tag{4.114}$$

The recommended overall heat transfer coefficient U_{gr} is 0.437 W/m^2/°C (ASHRAE 1981), the ground surface area, A_{gr}, is equal to the bin floor area, and the recommended design temperature of the deep ground, T_{gr}, is 10°C (ASHRAE 1981). The overall heat transfer coefficient U_{fl} is set equal to h'_p; the floor surface area, A_{fl}, is equal to the bin surface area, and the temperature of the floor, T_{fl}, is calculated as the average of the bottom surface grain temperature nodes. The recommended design air infiltration rate during the storage period, X_p, is 0.67 volumes/hour (ASHRAE 1981).

If the bin plenum is sealed after the chiller is disconnected, X_p becomes zero. The overall heat transfer coefficient U_{pr} is set equal to h'_w; the surface area of the plenum circumference, A_{pr}, is a function of the bin diameter and the plenum height. Typically, the plenum height in a grain bin is about 0.3048 m (1 foot), which is the value used in the grain storage model. The perimeter wall temperature, T_{pr}, is set equal to the ambient air temperature.

Along the Bin Wall:

The ambient air temperature is a function of the local weather conditions, which are specified in Chapter 5.

4.4.2.1.5 Thermal Radiation Flux

The thermal radiation component, q_r, for a grain storage bin consists of the radiative heat exchange between the ground and the bin, q_{re}, the sky and the bin, q_{rs}, the bin and the surroundings, q_{ro}, and direct (beam), q_b, and diffuse, q_d, solar radiation (Muir et al. 1980). Thus,

$$q_r = q_{re} + q_{rs} + q_b + q_d - q_{ro} \tag{4.115}$$

where,

$$q_{re} = \sigma \alpha_L F_{BE} T_a^4 \quad (4.116)$$

$$q_{rs} = \sigma \alpha_L F_{BS} T_S^4 \quad (4.117)$$

$$q_{ro} = \sigma \varepsilon_L T_{i,N}^4 \quad (4.118)$$

The longwave absorptivity, α_L, and emissivity, ε_L, of the bin wall are equal since thermal equilibrium is assumed. The value used in the storage model is 0.28 (Siegel and Howell 1981). The values suggested by Muir et al. (1980) for the ground-to-bin shape factor, F_{BG}, of 0.5, and the sky-to-bin shape factor, F_{BS}, of 0.5 are used. The temperatures in equations 4.116 - 4.118 are in degrees Kelvin. The sky temperature, T_S, is calculated from the following equation (Duffie and Beckman 1980):

$$T_S = 0.0552\, T_a^{1.5} \quad (4.119)$$

The total solar radiation (i.e. beam plus diffuse) on the wall of a vertical grain storage bin can be calculated from hourly solar radiation values on a horizontal surface. However, for most locations hourly radiation values are not available. Duffie and Beckman (1980) outlined a procedure to estimate the hourly beam and diffuse components of solar radiation from average monthly values, which are readily available for a large number of meteorological stations in North America. The procedure is used in the storage model and is outlined below.

(1) For the current month use the average daily total radiation on a horizontal surface, $\overline{H}_T$, and the average clearness index, $\overline{K}_T$, of a meteorological station near the site of the storage bin (e.g. East Lansing, Michigan for the evaluation of the experimental field tests in Chapter 5), as well as the average day for the month and the associated declination, δ.

(2) Calculate the diffuse radiation for the average day (Duffie and Beckman 1980):

$$\overline{H}_D = (0.775 + 0.00653(\omega_s - 90) - [0.505 + 0.00455(\omega_s - 90)] \cos[115\overline{K}_T - 103])\overline{H}_T \tag{4.120}$$

(3) Distribute the total, diffuse, and beam radiation for the average day into the current hour using the following expression (Duffie and Beckman 1980):

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - (2\pi\omega_s/360)\cos\omega_s} \tag{4.121}$$

where,

$$a = 0.409 + 0.5016\sin(\omega_s - 60)$$
$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \qquad (4.122)$$

The current hour angle, ω, is for the time in question (i.e. the midpoint of the hour for which the calculation is made). The current local hour is corrected for solar time.

The hourly total, I_T, diffuse, I_D, and beam, I_B, solar radiation values are:

$$I_T = r_T \overline{H}_T$$
$$I_D = r_T \overline{H}_D \qquad (4.123)$$
$$I_B = I_T - I_D$$

(4) Determine the total radiation on the sloped surface, $I_{T\,slope}$:

$$I_{T_{slope}} = I_B R_B + I_D\left(\frac{1+\cos\beta}{2}\right) + \varrho_r I_T\left(\frac{1-\cos\beta}{2}\right) \qquad (4.124)$$

The ground reflectance, ϱ_r, is 0.7 if there is a snow cover and 0.2 without snow (Duffie and Beckman 1980) (e.g. snow cover is assumed between December through February for the evaluation of the experimental chilled grain storage tests in Chapter 5).

The tilt factor, R_B, for the current hour is a function of the angle of incidence of beam radiation, θ, and the zenith angle of the sun, θ_z:

$$R_B = \frac{\cos\theta}{\cos\theta_z} \tag{4.125}$$

where,

$$\begin{aligned}\cos\theta &= \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \\ &+ \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ &+ \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{4.126}$$

and

$$\cos\theta_z = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \tag{4.127}$$

The angles are defined as follows: ϕ is the geographic latitude of the grain storage bin, and β is the slope of the receiving surface (e.g. $\beta = 0$ for the vertical bin wall). The surface azimuth angle, γ, is zero for the circular storage bin.

The average total solar radiation received by the sloped surface during the current hour is:

$$q_b + q_b = \alpha_S I_{T_{slope}} \tag{4.128}$$

The outlined procedure assumes that the average radiation for the hour is received on the entire south-facing bin wall.

4.5 Cereal Grain Deterioration

The effect of the aeration and storage conditions on the deterioration of chilled grain due to respiration and mold development is evaluated using the concept of dry matter loss, which was discussed in detail in Section 3.3. The percent dry matter loss, DM, for corn is predicted by the following equation (Thompson 1972, Brook 1987, Strohshine and Yang 1990):

$$DM = 0.0884\left[\exp\left(0.006\frac{\Delta\tau}{m_M m_T m_D}\right)-1\right]+0.00102\left[\frac{\Delta\tau}{m_M m_T m_D}\right] \qquad (4.129)$$

where,

$$m_M = 0.103\left[\exp\left(\frac{455}{(100M)^{1.53}}\right)-0.845M+1.558\right] \qquad (4.130)$$

$$m_T = a\exp\left[\frac{b(1.8T+32)}{60}\right]+c\exp\left[\frac{0.61(1.8T-28)}{60}\right] \qquad (4.131)$$

$$m_D = 1.97\exp(-0.0199D) \qquad (4.132)$$

The moisture multiplier, m_M, is valid in the 13 to 35 percent (w.b.) moisture content range. A common value used to estimate the mechanical damage level, D, is 30 percent (Strohshine and Yang 1990). The coefficients a, b, and c are:

T [°C]	M_w [% wb]	a	b	c
≤ 15.6	all	128.76	-4.68	0
> 15.6	≤ 19	32.3	-3.48	0
> 15.6	$19 < M_w \leq 28$	32.3	-3.48	$(M_w-19)/100$
> 15.6	> 28	32.3	-3.48	0.09

Morey et al. (1981) suggested the following procedure to estimate the dry matter decomposition for the deterioration of wheat:

(1) Calculate the equilibrium relative humidity of wheat as a function of the wheat temperature and moisture content (eq. 4.12).

(2) Calculate the equivalent moisture content of wheat from the equilibrium moisture content equation of corn as a function of the ERH and temperature of wheat (eq. 4.13).

(3) Use the EMC value of wheat to calculate the equivalent moisture and temperature multipliers in equations 4.130 and 4.131.

(4) Calculate the percent of dry matter loss for wheat using equation 4.129 with the equivalent multipliers.

The dry matter loss during each time interval, $\Delta\tau$, is calculated for each grid node. Over the chilled aeration and storage period the DM-loss for each node is accumulated to yield the total DM-loss in the chilled grain storage bin.

4.6 Coupling the Chilled Aeration and Storage Models

The three submodels for the chilled aeration and storage of cereal grains are integrated into a system model. Figure 4.13 shows a simplified flow chart for the algorithm. The necessary input parameters for the three submodels are specified at once. For each time step the weather data is recalled first. A control loop decides whether the chiller is to be on or off during the current time step. If the unit is on, the flowrate, temperature and relative humidity of the chilling air are determined from the grain chiller model.

The heat and mass transfer is calculated one-dimensionally for each column of nodes of the 2-D grid with the chilled aeration model. If the unit is off, the finite difference equations of the 2-D conduction model are solved for the

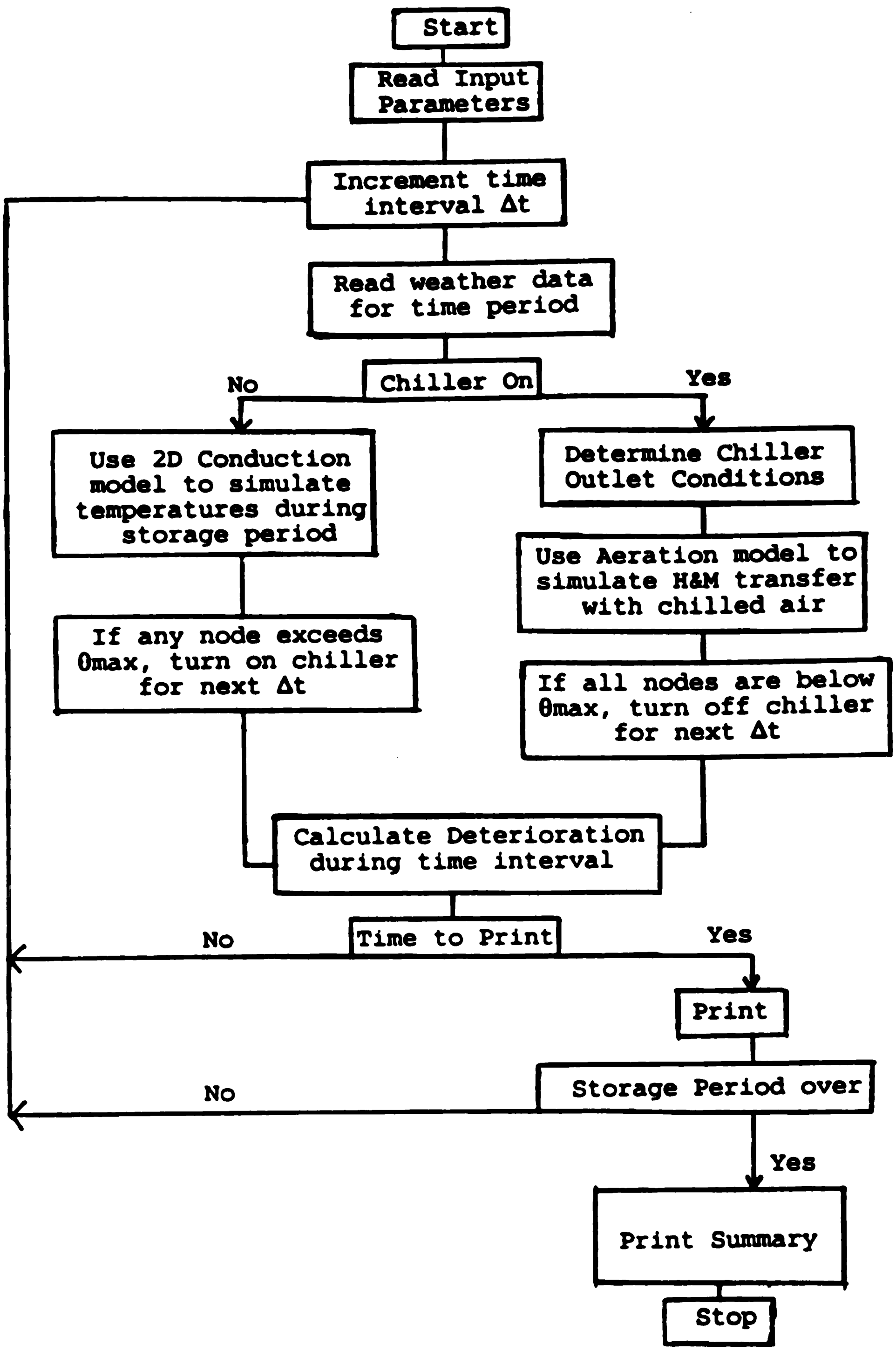


Figure 4.13 Flow chart of the system model to simulate the chilled aeration and storage of cereal grains.

temperatures of the grid nodes. At the end of the time interval the cumulative grain deterioration is updated. Printing and terminating flags are checked before the time step is incremented and the calculations are repeated until the end of the chilled aeration and storage period is reached.

THE CHILLED AERATION AND STORAGE OF CEREAL GRAINS

Volume II

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5. EXPERIMENTAL INVESTIGATION AND MODELS VERIFICATION

5.1 Experimental Tests

Field tests to evaluate the chilled aeration and storage of cereal grains under U.S. conditions were conducted over a three-year period at the Jorgensen Farm Elevator in Williamston, Michigan. Beginning in the fall of 1988, a commercial grain bin was filled each season with No. 2 grade corn. The corn was cooled and maintained over several months with a Granifrigor KK140 grain chilling unit provided by Sulzer-Escher Wyss, Lindau, Germany.

5.1.1 Instrumentation and Equipment

The grain bin used in the chilled aeration and storage tests is circular, and made of corrugated-steel. The floor is fully-perforated with an area of 79.5 m^2 and a plenum height of 0.30 m (12 inches). The bin diameter is 10.1 m (33 feet), the eaves height is 10.3 m (33 feet 9 inches), and the overall height is 13.3 m (43 feet 6 inches); the rated holding capacity is 700 tonnes (28,000 bu). The bin roof has a 30° slope and is not insulated. The bin is filled by gravity through a 0.15 m (6-inch) loading spout installed in the center of the bin roof. The bin is unloaded by gravity through two square 0.15 by 0.15 m (6 by 6 inch) ports, one installed in the center of the perforated floor, and one half-way between the center and the bin wall. Venting of the headspace above the grain pile is through three 0.30 m diameter (12-inch) vents on top of the roof, through a 0.025 m (1 inch) gap between the bin wall and roof eave, and through a 0.15 m (6 inch) diameter wind-propelled attic fan, which was installed in September 1989.

The corn used for each test was field-harvested, and dried artificially in continuous-flow, high-temperature dryers. Two cross-flow type Meyer dryers with rated capacities of 25.4 and 12.7 tonnes/h (1000 and 500 bu/hr) removing 5 percentage points of moisture, respectively, were used. After the dryer, the corn was run through a screen-cleaner, and then loaded into the bin without the use of a spreader. A core was drawn and the bin was then refilled with new corn from the dryer.

Samples of corn were collected for moisture determination during drying and loading every thirty minutes, and during unloading every fifteen minutes. Samples were also taken intermittently from the top of the pile during the storage season. The moisture contents were determined at the elevator with a Burrows digital moisture meter (Model 700), and verified in the laboratory using ASAE Standard S352.2 for corn (i.e. 103°C over 72 hours). The oven samples were weighed with a Mettler PM400 digital scale (with 0.001 g accuracy over a 400 g range).

Grain temperatures in the bin were measured with thermocouples located on four suspended, steel-reinforced cables. The layout of the temperature cables is illustrated in Figure 5.1. Each cable contains six thermocouples (TC); the TCs of Cable A are located at heights of 0.4, 2.2, 4.0, 5.9, 7.7, and 9.5 m above the floor, of Cables B and C at 1.0, 2.8, 4.6. 6.5, 8.3, and 10.1 m above the floor, and of Cable D (which was installed prior to the 1989-90 season) at 2.8, 4.6, 6.5, 8.3, 10.1, and 11.9 m above the floor. During the 1989-90 season the cables were fastened to the floor before filling the bin, thus suspending the thermocouples vertically in the grain pile. In 1988-89 and 1990-91 the bottoms of the cables were pushed toward the periphery by the corn during the loading of the bin. The bottom sensor of cables A, B, and C ended up within about 1 m of the bin wall. The sensor levels of cables A, B, and C were raised by about 0.1 m.

During the 1988-89 season, the grain temperatures sensed by the 18 TC locations of cables A, B, and C were recorded on a Hewlett-Packard 3497A Data Acquisition/Control Unit. At the

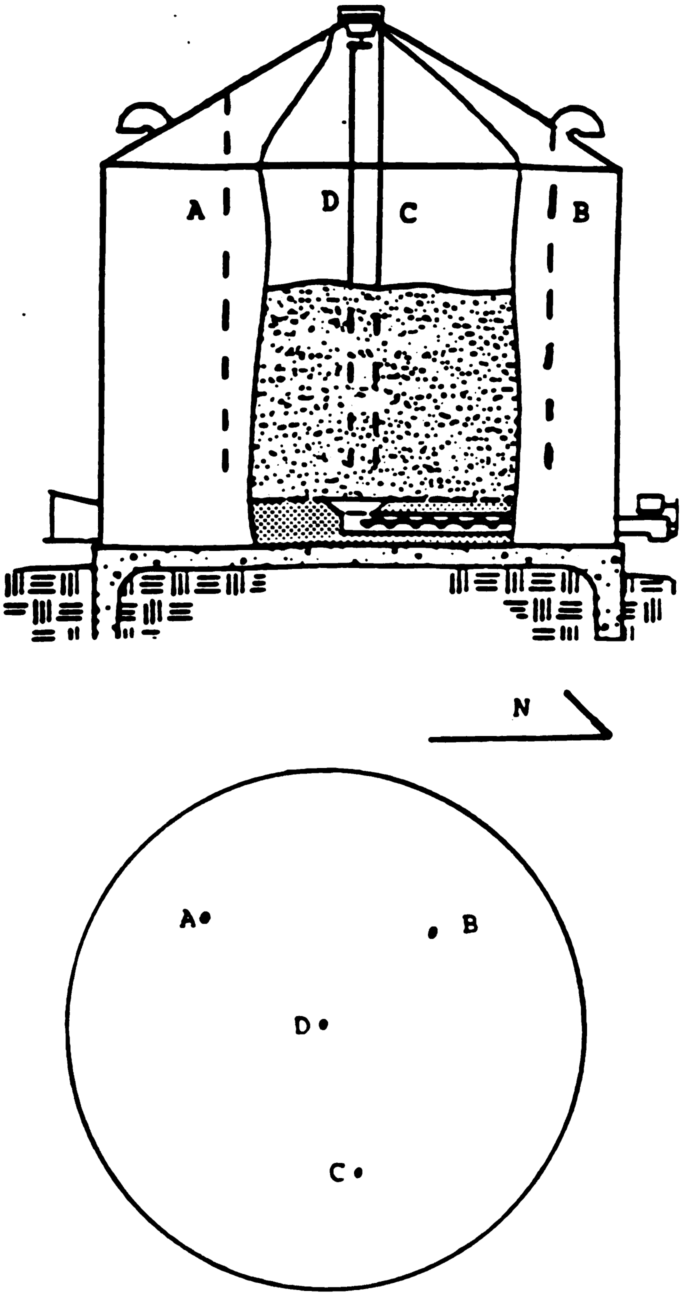

Figure 5.1 Layout of the thermocouple cables in the 700-tonne capacity bin used for the chilled aeration and storage of corn during the three field test seasons.

beginning of the 1989-90 season a Pertech Scancenter Grain Temperature and Monitoring System was installed to monitor the 24 TCs of the four bin cables. The Scancenter was connected to a Compaq Portable III computer, which recorded and processed the data using commercial and custom software. In 1988-89 and 1990-91 the grain temperatures were recorded hourly; in 1989-90 every six hours (beginning at midnight).

The grain chilling unit was connected to the bin plenum through a 0.30 m diameter and 2 m long non-insulated flexible duct. The design specifications of the Granifrigor KK140 are summarized in Table 1.1. Its performance characteristics have been thoroughly explored in Section 4.2. During the 1988-89 season the dry and wet bulb temperatures of the air reaching and leaving the grain chiller were recorded hourly with the Hewlett-Packard system. For the 1989-90 season the chiller was instrumented with a Campbell CR21 data logger to monitor the air temperatures and relative humidities at the inlet to the fan, at the outlet of the chiller, and at the bin inlet. In addition, the position of the throttle governing the airflow across the fan was measured by the data logger. The values were recorded on cassette tape every fifteen minutes. The temperature and relative humidity (RH) probes (Model 201) use Fenwal UUT-51J1 thermistors and Phys-Chemical Research PCRC-11 RH-sensors both with ±1% deviation. The throttle position was monitored with a Techmark 5K potentiometer.

The static pressure of the bin-chiller system was measured using a Dwyer Magnehelic Differential Pressure Indicating Transmitter (Model 605-10) with a range of 0 - 10 inches water column and 0.20 readability. The airflow rate through the chiller was determined from the KK140 fan curve using the measured static pressures. The run time of the chiller was monitored with a built-in hour counter; the electrical power consumption was measured with a General Electric three-phase 480 Volt wattmeter.

Spot checks of temperature, relative humidity, air flow and static pressure were made during the field tests with a Solomat MPM 500e portable multi-functional meter utilizing the following probes: 355RHX for air temperature and relative humidity, 511LPX for static pressure, 228MSX for airflow, and P101IMX for grain temperature.

In April 1989 a weather station was installed on top of the grain bin. A Campbell 21X data logger recorded the temperature and relative humidity of the ambient air with a Model 207 probe (equipped with the same sensor as the Model 201 probe), the incident solar radiation with a LI200S Silicon Pyranometer, and the wind speed with a MetOne wind-speed sensor. For the 1990-91 season a Model 207 probe was installed to monitor the temperature and relative humidity of the headspace air above the pile. The values were recorded every thirty minutes on cassette tape.

5.1.2 The 1988-89 Season

In the first season the KK140 Granifrigor grain chiller was used to cool and maintain higher-than-normal moisture content corn in stable condition between November 1, 1988 and June 7, 1989. The total amount of corn in the bin was initially 611 tonnes. After four months of storage 180 tonnes of corn were removed from the bin.

On November 1, 1988, the first corn was dumped into the bin; the filling process was completed within 36 hours. The corn was loaded into the bin at about 18% moisture content (w.b.), and 9 - 13°C. The top of the pile was initially not leveled off.

One of the goals of the first year chilling test was to fill the bin with corn at a moisture content of 18.5% (w.b.), and by chilled aeration attempt to lower the corn moisture to 15.5% during the storage period, while maintaining the grain quality. Figure 5.2 is a plot of the moisture content of 73 samples of corn taken during loading and of 90 samples taken

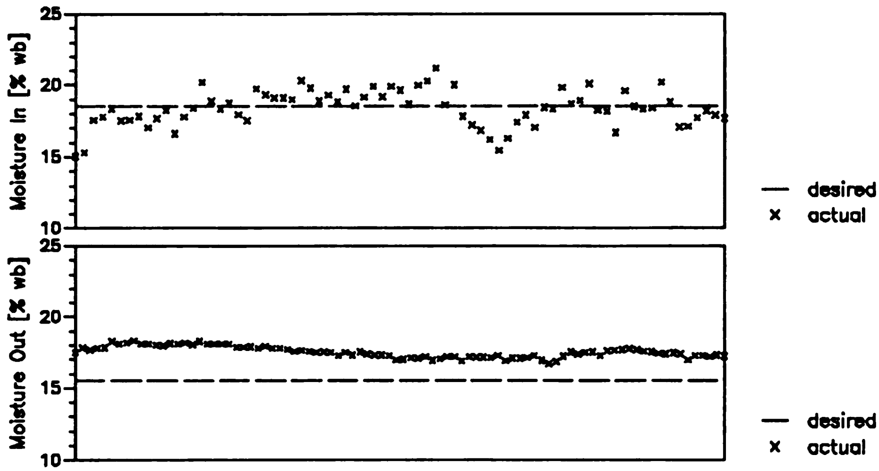

Figure 5.2 Corn moisture content (in %-wet basis) of 73 samples taken during loading and 90 samples taken during unloading of the chilled grain storage bin during the 1988-89 season.

during unloading of the storage bin. The inlet moisture content (i.e. the outlet moisture content of the two dryers) averaged 18.3%, which was slightly below the desired value; the range was 15.0 to 21.2 percent. At the end of the storage period, the moisture content of the corn was more uniform; the average was 17.5% with a range of 16.7 to 18.3 percent. However, this was two percentage points above the desired moisture content of 15.5%. The chilled aeration and storage treatment lowered the average moisture content of the corn by 0.8 percentage points and reduced the initial moisture gradient of 6.2 points to 1.6 percentage points.

The moisture content of probe samples taken periodically between December 1988 and April 1989 at 0.6 m and 1.2 m from the grain surface are shown in Table 5.1. Close to the surface the moisture ranged from 18.1 to 18.4 percent with a slight upward trend over the storage period. The corn at the 1.2 m level showed slightly lower moisture contents; the samples ranged from 18.0 to 18.3 percent. Compared to the initial average moisture content of 18.3%, the moisture of the top grain layers did not change significantly over the 3-month winter storage time despite several chilling cycles.

Table 5.1 Moisture content of corn (in % wet basis) sampled at 0.6 m and 1.2 m below the grain surface in the chilled storage bin between December 28, 1988 and April 12, 1989.

Sampling Date	At 0.6 m	At 1.2 m
12/28/1988	18.1	18.0
1/06/1989	18.2	18.2
1/17	18.2	18.2
2/07	18.3	18.2
2/22	18.3	18.2
3/07	18.4	18.1
3/29	18.3	18.0
4/12	18.3	18.3

5.1.2.1 Chilled Aeration Trial

The grain chiller was started on November 1 as soon as enough corn was loaded into the bin to cover the perforated floor to about 0.5 m depth. The variation in the corn temperature at four pile depths (i.e. Cable B, which showed the best profile) for the full bin is shown in Figure 5.3. The filling of the bin was completed by November 3, and the cool-down on November 8. The corn temperature in the full bin ranged from 2.5 to 13°C on 11/3 with the warmer grain layers toward the bottom and the cooler ones toward the top of the pile. By 11/5 the cooling front reached the 10.2 m level; the grain temperature rose to 13°C before decreasing slowly to below 5°C by 11/8. On the eighth day the corn in

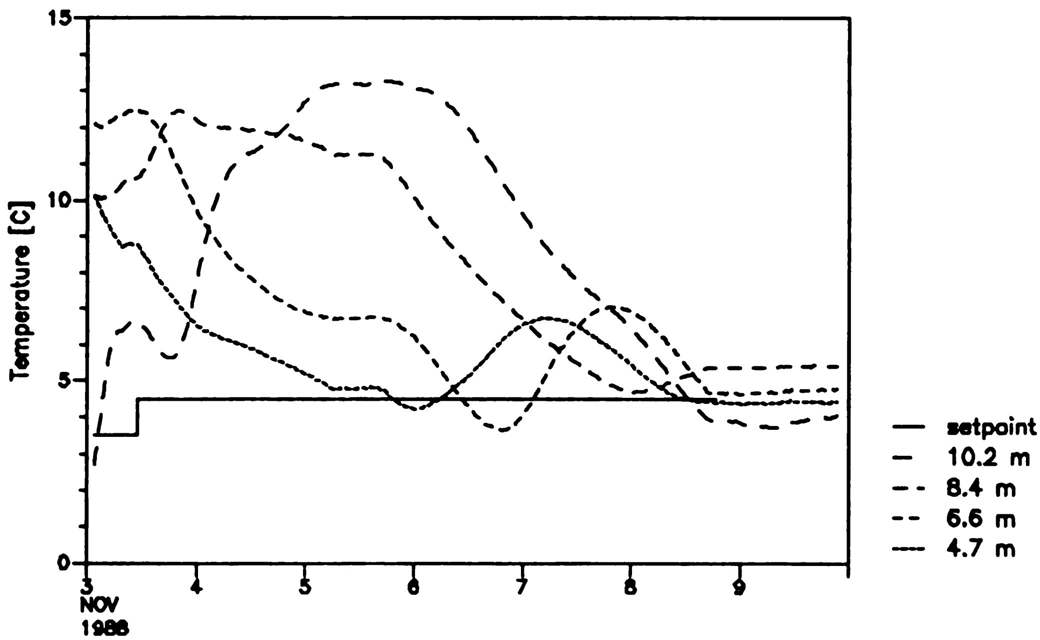

Figure 5.3 Grain temperature at four depths in the chilled storage bin, and set-point temperature of the reheated air from the grain chiller during the initial cool-down between November 1 and 8, 1988.

all layers reached a temperature range of 4 - 6°C.

On November 3 and 5 the cool-down of the corn was interrupted due to power failures at the elevator. On November 7 and 8 low ambient temperatures forced the chiller to maintain the bin inlet conditions with the built-in electrical heaters. The grain temperature in the bottom layers increased temporarily. By the end of the cool-down cycle the effect dissipated. During the 12-hour power failure on 11/5, and during the period immediately following the cool-down, the TC sensors indicated constant temperatures in the layers. This supports the assumption that the air and grain temperatures are in equilibrium during the chilled aeration period. If significant differences existed one would expect the sensors to indicate a temperature change soon after the airflow is interrupted.

During the cool-down, condensation was observed on the underside of the bin roof. The available ventilation of the headspace was not sufficient to prevent significant amounts of water dripping onto the peaked grain (particularly due to condensation inside the loading spout tube). Although the surface of the grain dried off by the end of the cool-down cycle, dampness persisted several centimeters below the surface grain layer. Several rechilling cycles were initiated starting on November 21. By December 6 self-heating was observed in the peak of the grain, which was cooled with the chiller. By December 19 a significant hot spot of about 45°C developed in the peak of the grain in an area of 1 m in diameter and 0.5 - 1.0 m in depth. A 30-tonne core was drawn to remove the spoiled grain. The core was refilled with corn from the dryer, and the pile was levelled off at 10.3 m.

After the rechilling cycle in April damp grain was found on the level surface toward the west side of the bin. Between April 17 and May 15 about 180 tonnes of grain were blended off in six unloading cycles. Visible mold damage was detected in a few corn samples. The grain surface was levelled off again before the May chilling cycle at about 7.3 m. On May 26 unloading was continued; the bin was empty by June 7, 1989.

5.1.2.2 Grain Chiller Performance

The ambient temperature during the cool-down period is plotted in Figure 5.4 along with the temperature of the air exiting the chiller. Although the ambient temperature varied between -2 and 18°C, the chilling unit maintained the air at 3 - 7.5°C. The average outlet air temperature was 4.9°C which was within 0.5°C of the reheater set-point

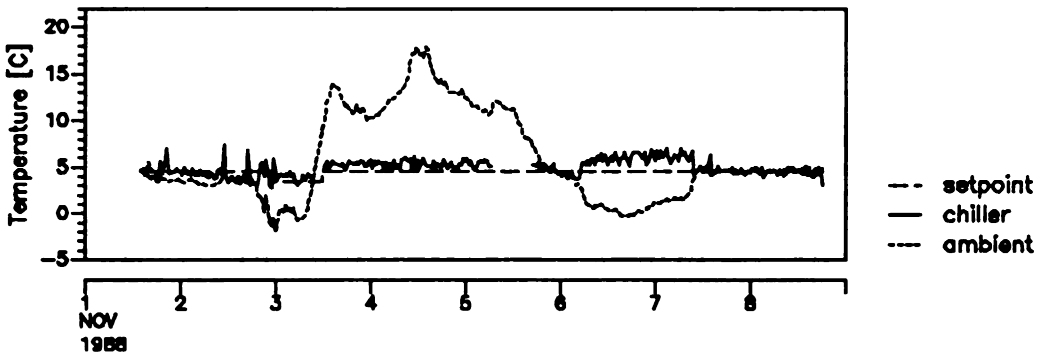

Figure 5.4 Temperature of the air into and out of the grain chiller during the initial cool-down between November 1 and 8, 1988.

temperature; the cold-air and reheater set-points were 3°C and 4.5°C, respectively (except for a brief period on 11/3). During the low ambient temperature period of November 6 - 7 the electrical heaters maintained the chiller outlet air temperature about 2°C above the set-point.

The air conditions into and out of the chiller were analyzed in detail for a five-day period of continuous operation in the late spring of 1989 (i.e. 5/20 - 5/25/1989). The results are given in Figure 5.5. Shown are the ambient inlet and chiller outlet air temperature and relative humidity. The ambient dry-bulb temperature cycled between 9.6 and 28.2°C, and the relative humidity between 24.3 and 95.9 percent. The cold-air and reheater set-points of the chiller were 4°C and 5.5°C, respectively. The air temperature at the outlet of the chiller ranged from 5.3 - 7.5°C, and the relative humidity from 84.7 - 95.0 percent (with an average of 89.3%). The average air temperature at the outlet of the chiller was 6.3°C, which was within 1.0°C of the reheater set-point. Both the temperature and relative humidity were almost held constant. The high relative humidity of the chiller outlet air was due to the small amount of reheating specified, i.e. 1.5°C. The set-points were selected to yield a bin inlet air temperature and relative humidity which matched the equilibrium conditions of the stored corn.

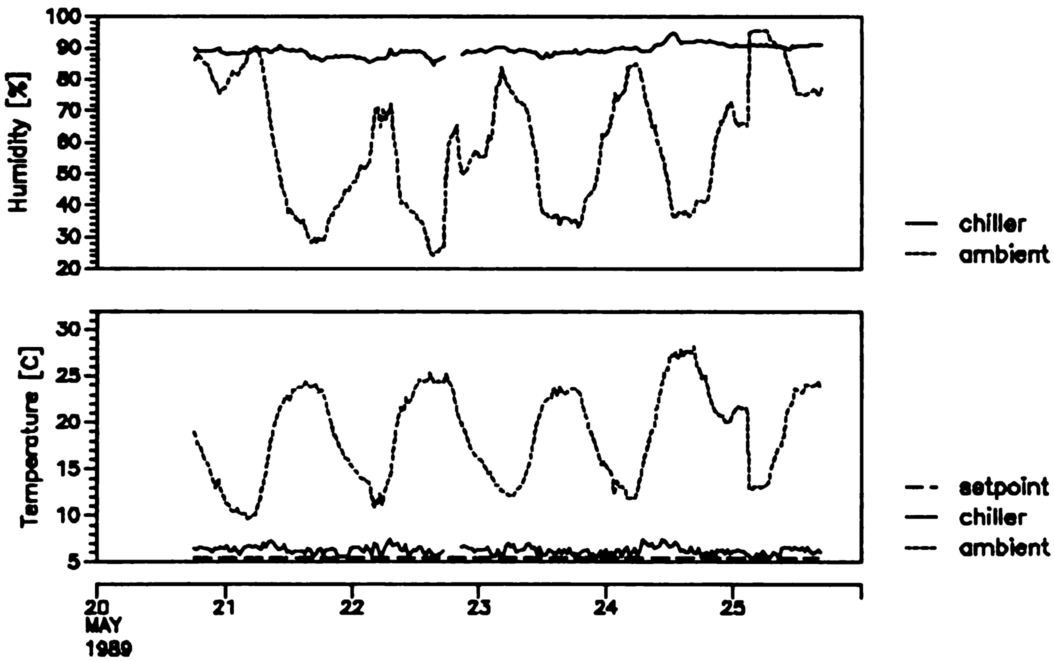

Figure 5.5 Temperature and relative humidity of the air into and out of the grain chiller over a 5-day period during rechilling between May 16 and 25, 1989.

The duct connecting the chiller and the bin is relatively short. However, some heat loss or gain occurred depending on the ambient conditions. Figure 5.6 shows the temperature and relative humidity of the air measured at the outlet of the chiller and the inlet of the bin for the same period as Figure 5.5, i.e. May 16 to 25, 1989. The average bin inlet temperature was 7.2°C with a range of 5.9 to 9.2°C. Thus, the heat gain in the duct raised the average chilling air temperature by about 1°C between the chiller outlet and bin inlet. The average relative humidity of the bin inlet air was 85.5% with a range of 76.8 to 90.8 percent, i.e. a reduction of about 4 percent. Similar observations were made during the fall when the ambient conditions were lower, thus, reducing the bin inlet temperature by about 1°C and raising the relative humidity by about 4 percent. When longer connecting ducts between the chiller and storage bin are used, the heat gain or loss can be expected to be greater, especially if the duct is not shaded. At the site of the test bin the connecting duct was not exposed to direct sunlight.

The electrical power consumption and run time of the chiller for the six cooling cycles during the 1988-89 season are summarized in Table 5.2.

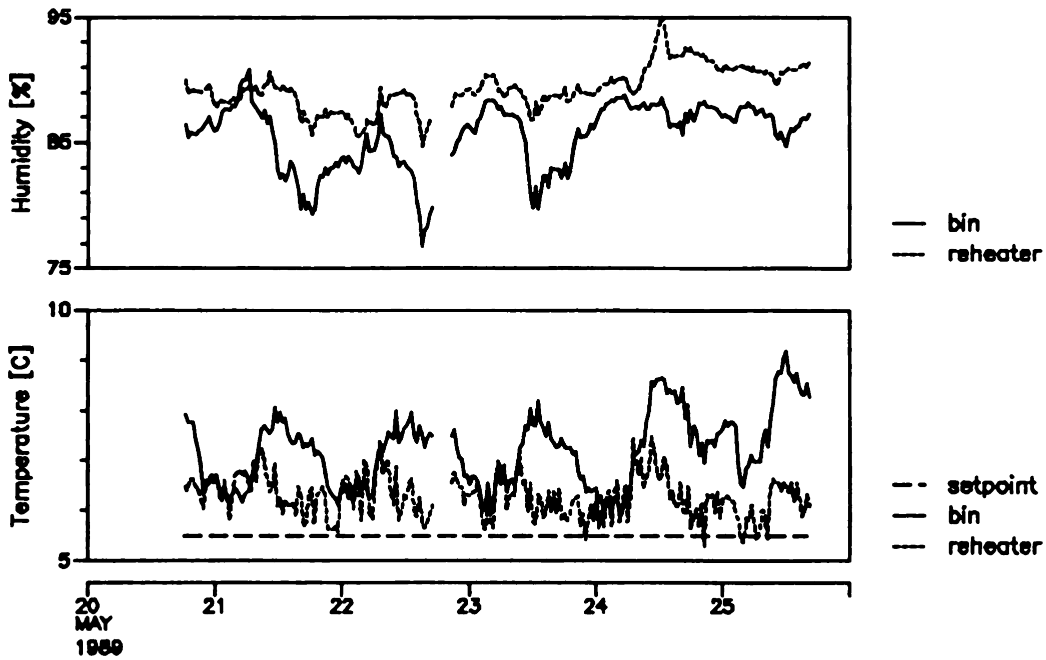

Figure 5.6 Temperature and relative humidity of the air out of the grain chiller and into the chilled grain storage bin over a 5-day period during rechilling between May 16 and 25, 1989.

Table 5.2 Power consumption and run time of the KK140 chiller during the 1988-89 storage season.			
Cycle	Period	Power Consumption [kWh]	Run Time [h]
1	11/01 - 11/08/1988	1,770	158.9
2	11/21 - 11/23	363	41.1
3	12/06 - 12/09	673	60.8
4	12/19 - 12/22	274	38.5
5	4/03 - 4/12/1989	1,957	179.4
	Total:	5,037	478.7
6	5/16 - 5/25	1,884	147.6
	Total:	6,921	626.4

In 1988, the chiller was turned on for rechilling purposes on 11/21, 12/6, and 12/19, and in the spring of 1989 on 4/3, and 5/16. The rechilling periods varied from 38.5 to 179.4 hours. The variation in chilling times reflects the degree of recooling which was required in the opinion of the operator. Cycles 2 and 3 were intended to off-set the effects of grain heating in the peak of the pile under the loading spout; the set-point temperatures were 3 and 4.5°C for cycle 2, and 3.5 and 5.5°C for cycle 3 for the cold-air and reheater temperatures, respectively. Cycle 4 was run to equalize the grain temperature in the bin after the spoiled grain was unloaded from the bin in December; the unit was operated in the fan-only and fan-plus-2kW electrical heating modes. During cycle 5 the grain was slowly rewarmed to 7 - 10°C in an attempt to remove additional moisture from the grain; the set-point temperatures of the cold-air and the reheater were 3.5 and 5.5°C, respectively. Cycle 6 was run to equilibrate the temperature in the bin after the depth of the corn was lowered from 10.3 m to 7.3 m.

The initial chilling cycle lasted 173.3 hours with 158.9 hours of actual operating time and 14.4 hours off-time (due to two power failures at the elevator site). The power consumption was 1,770 kWh, or 2.90 kWh per tonne of corn. The rechilling cycles between 11/21 and 12/22/1988 required a total of 139.9 hours, consuming 1,307 kWh , or 2.15 kWh/tonne. During the April rechilling cycle the grain chiller operated 179.4 hours, consuming 1,957 kWh, or 3.2 kWh/tonne. Various temperature set-points were employed. For most of the operating period the cold-air was set at 3.5°C and the reheated air at 5.5°C. Between 11/1/88 and 4/12/89 the chiller operated 478.7 hours, consuming 5,037 kWh of electricity, or 8.28 kWh per tonne of stored corn.

After the bin was partially unloaded (i.e. about 431 tonnes of corn remained in the bin), a final chilling cycle of 147.6 hours was administered between May 16 and 25, 1989, consuming 1,884 kWh of electricity, or 4.39 kWh/tonne. Between May 16 and 20 the chiller was turned off at night to prevent condensation of water on the bin roof. Under these conditions a longer operating time was needed to bring the grain temperature to the desired level.

The power requirement and energy efficiency of the Granifrigor was tabulated in Table 5.3.

Table 5.3 Power requirement and energy efficiency of the KK140 chiller during the 1988-89 storage season.

Cycle	Period	Power Requirement [kW]	Energy Efficiency [W/t]
1	11/01 - 11/08/1988	11.1	18.2
2	11/21 - 11/23	8.8	14.5
3	12/06 - 12/09	11.1	18.2
4	12/19 - 12/22	7.1	11.7
5	4/03 - 4/12/1989	10.9	17.9
	Average:	10.5	16.1
6	5/16 - 5/25	12.8	29.8

During the first five cycles the average power requirement of the unit was 10.5 kW with a range of 7.1 to 11.1 kW; this is below the rated nominal connected load of 13.0 kW specified by the chiller manufacturer. During cycle 6 the power requirement was 12.8 kW. Obviously, the ambient cooling load during May required the unit to operate mostly in the maximum refrigeration range, while during the fall and spring the unit operated in the maximum airflow and electrical heating operating ranges, both of which require less power.

The average energy efficiency of the Granifrigor in terms of electrical power consumed per hour per tonne of corn between November and April was 16.1 Watts per tonne, with a range of 11.7 to 18.2 W/tonne, and 29.8 W/tonne in May. During fan-only and fan-plus-heater operation, i.e. cycle 4, the energy efficiency was 11.7 W/tonne. During refrigeration the efficiency ranged from 14.5 W/tonne in the maximum airflow operating range, to 29.8 W/tonne in the maximum refrigeration operating range.

The KK140 grain chiller developed a maximum airflow of 4,300 m^3/h at a counter pressure of 2,155 Pa in the 10.3 m corn pile, and a maximum airflow of 4,750 m^3/h at a counter pressure of 980 Pa in the 7.3 m deep pile. The airflow rate from the chiller was lower when the ambient cooling load was high. At 4,300 m^3/h the airflow through the corn was 0.12 m^3/min per tonne (0.12 cfm/bu), and at 4,750 m^3/h about 0.19 m^3/min/tonne (0.19 cfm/bu).

5.1.2.3 Chilled Storage Trial

A continuous recording of the ambient weather conditions at the bin site for the entire storage season is not available. However, periodic ambient temperatures and relative humidities measured at the Jorgensen Farm Elevator compare well with the official NOAA meteorological data for the Lansing weather station (see Appendix A.1). Figure 5.7 shows the dry-bulb temperature and relative humidity of the ambient air in the Lansing area (at 3-hour intervals) between November 1, 1988 and June 7, 1989. The relative humidity ranged from 22 to 100 percent. The air temperature ranged from a low of -22°C in late February to a high of 27°C in late May 1989.

The temperature at three bin depths (i.e. Cable B, which showed the best profile) between November 1, 1988 and June 7, 1989 are shown in Figure 5.8. The temperature remained between 4 and 6°C in the upper layers of the grain during November and December. The December 19 chilling cycle lowered the grain temperature in the bottom half of the bin (i.e. below 4.7 m) to about 1°C (since the only heat added to the air into the chiller is the fan heat or the fan heat-plus-2kW electrical heater). At the 1.1 m level the grain temperature dropped below 0°C in early January. Through March a temperature difference of about 7°C persisted

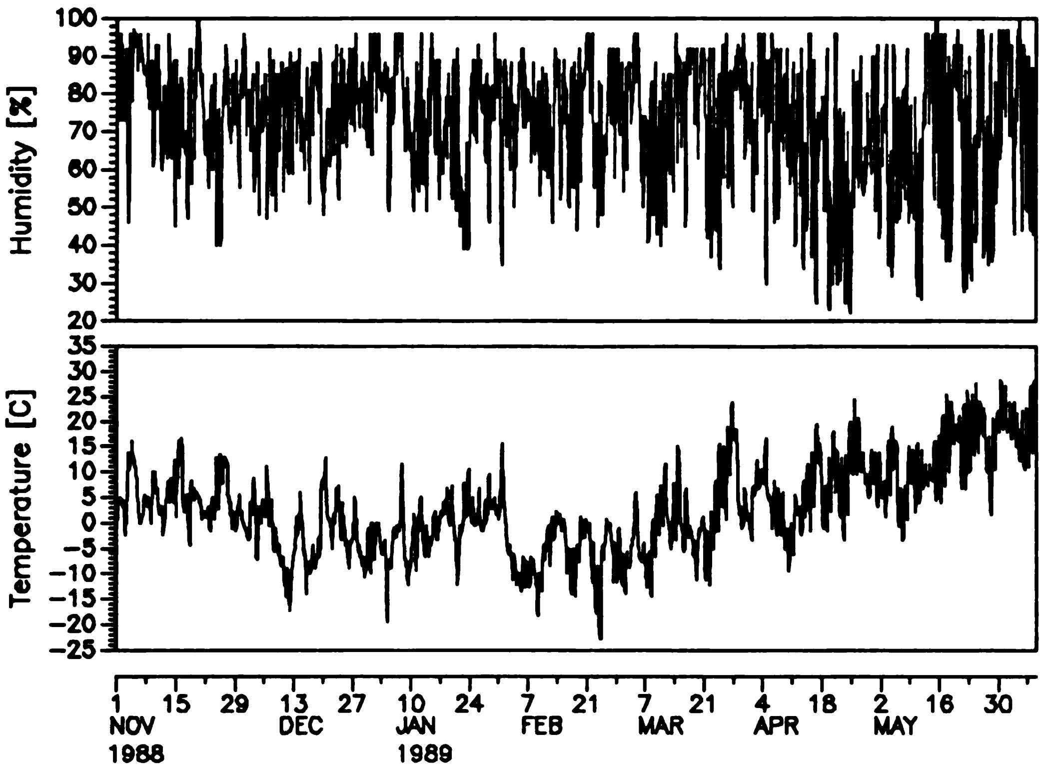

Figure 5.7 Ambient temperature and relative humidity of the air at the site of the chilled grain storage bin between November 1, 1988 and June 7, 1989.

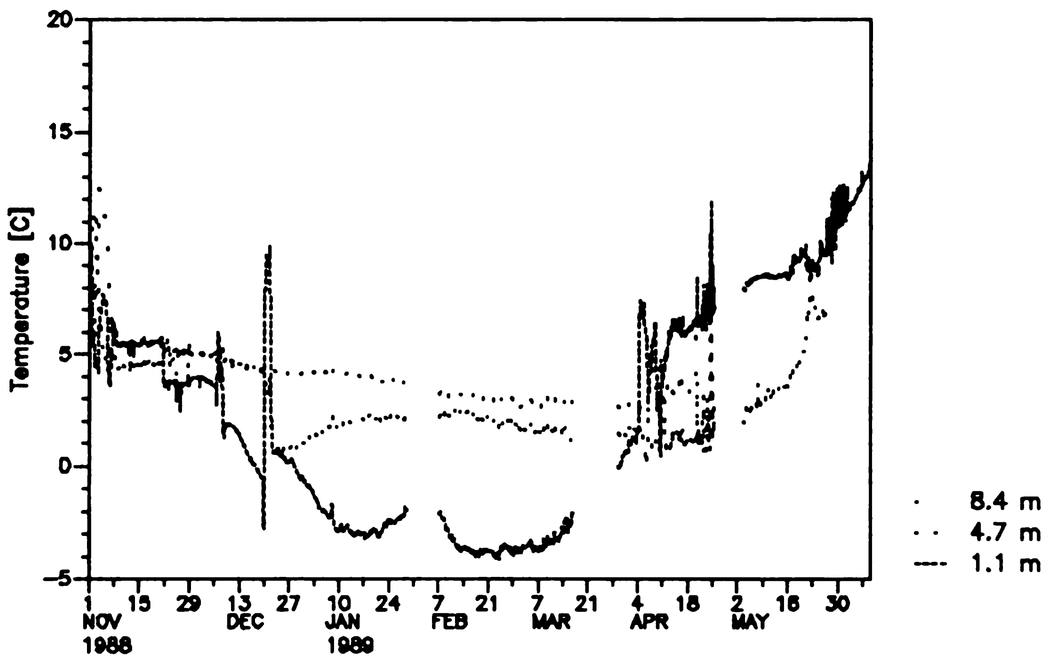

Figure 5.8 Grain temperature at three depths in the chilled grain storage bin between November 1, 1988 and June 7, 1989.

between the bottom and top layers of the bin. During the April rechilling cycle the gradient between the layers was reduced. The bottom layer remained warmest through the remainder of the storage season.

The grain temperature in the bulk (i.e. the average of all TC sensors except the bottom ones) and near the periphery (i.e. the average of the bottom TC sensors of cables A, B, and C) of the chilled storage bin are shown in Figure 5.9 between November 1, 1988 and April 18, 1989. After the fall cooling cycles the temperature of the grain bulk stayed below 5°C through April of 1989, and showed a decreasing trend; the lowest bulk temperature is 2°C. The temperature near the periphery of the grain varied significantly with the ambient conditions. Starting in late December the periphery temperature decreased to a low of -3°C by March 7. Due to warmer ambient conditions the temperature in the periphery rose about 2°C before the April chilling cycle.

5.1.3 The 1989-90 Season

The KK140 grain chiller was used to cool and maintain a bin of corn for a second season between November 3, 1989 and August 25, 1990. The total amount of corn in the steel bin was initially 591 tonnes. The bin was gradually unloaded

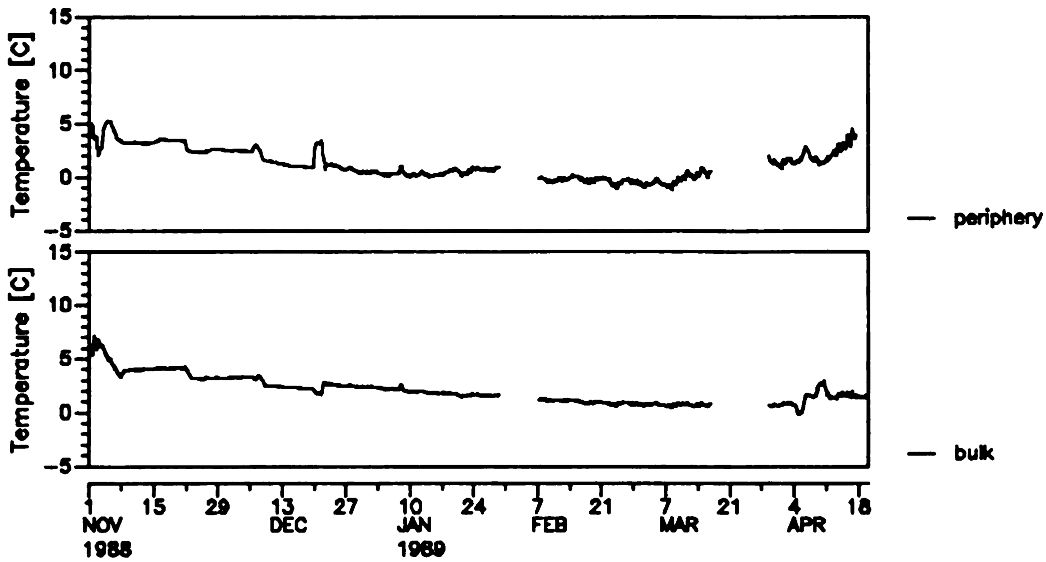

Figure 5.9 Grain temperature in the bulk and near the periphery in the chilled grain storage bin between November 1, 1988 and April 18, 1989.

over a four week period beginning on August 25 for commercial marketing.

On November 3, 1989, the first corn was dumped into the bin; the filling process was completed within 28 hours; the core was drawn on 11/7 and refilled on 11/10. The corn was dried and loaded into the bin at about 15.5% moisture content (w.b.), and 10 - 15°C. The top of the pile was leveled off to 10.3 m on April 4, 1990.

Figure 5.10 is a plot of the moisture content of 72 samples of corn taken during loading of the chilled storage bin. The average inlet moisture content was 15.6% with a range of 13.4 - 18.0 percent (the desired moisture content was 16.0%). For logistical reasons no systematic moisture sampling took place during the unloading of the bin. However, the corn was sold as No. 2 corn and samples tested between 14.0 and 14.3 percent moisture. Thus, the chilled aeration and storage of the corn lowered the average moisture content by about 1 to 1.5 percentage points during the 1989-90 chilled aeration and storage period.

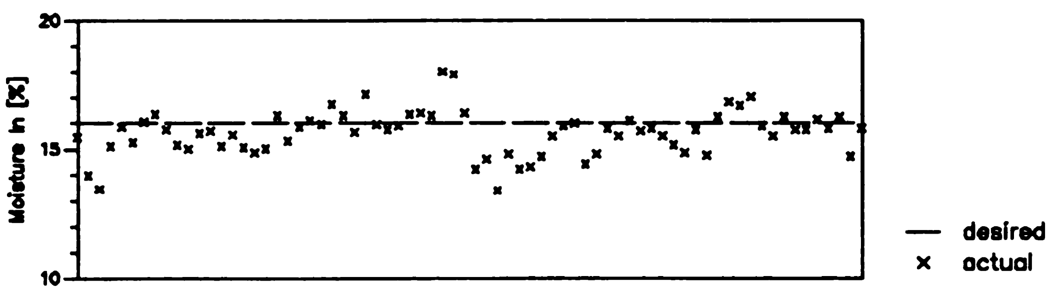

Figure 5.10 Corn moisture content (in %-wet basis) of 72 samples taken during loading of the chilled grain storage bin during the 1989-90 season.

5.1.3.1 Chilled Aeration Trial

The grain chiller was started on November 3 as soon as enough corn was loaded into the bin to cover the perforated floor. The unit was only operated during day-time hours in an attempt to prevent condensation in the headspace of the bin. Starting on 11/14 a time clock turned the unit on at 8 A.M. and off at 8 P.M. The corn temperatures at three pile depths (i.e. Cable D, which showed the best profile) between November 15 and 29 are shown in Figure 5.11 (Due to the late installation of the Scancenter monitoring system the grain temperatures before 11/15 are not available). The corn temperature in the bin ranged from about 10 to 13°C on November 15 with the warmer grain layers toward the bottom and the cooler ones near the top of the pile. At the end of the cool-down period on November 28 all bin temperatures were less than 5°C. At the 2.6 m level, the temperature dropped below the reheater set-point temperature of the air reaching a minimum of 3°C, and at the 4.4 m level a minimum of 4°C. This occurred due to a 1 - 2°C heat loss in the connecting duct because of the low ambient temperature conditions.

In May a chilling cycle raised the bin temperature from less than 5°C to about 8°C. Figure 5.12 shows that the grain temperature increased at four depths (i.e. Cable C, which

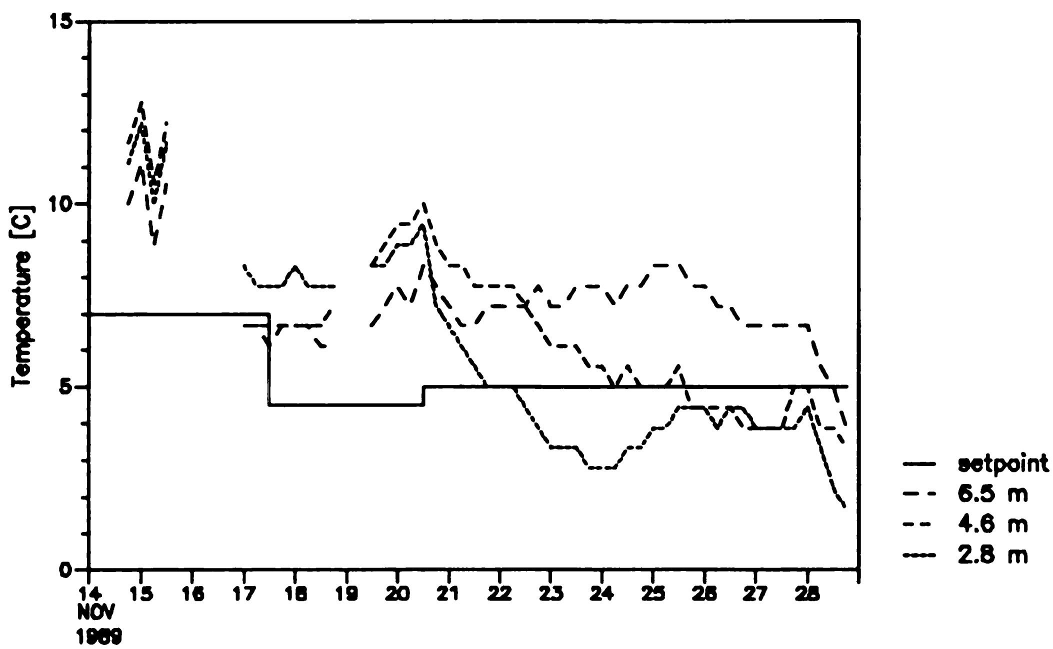

Figure 5.11 Grain temperature at three depths in the chilled grain storage bin, and set-point temperature of the reheated air from the grain chiller between November 15 and 29, 1989.

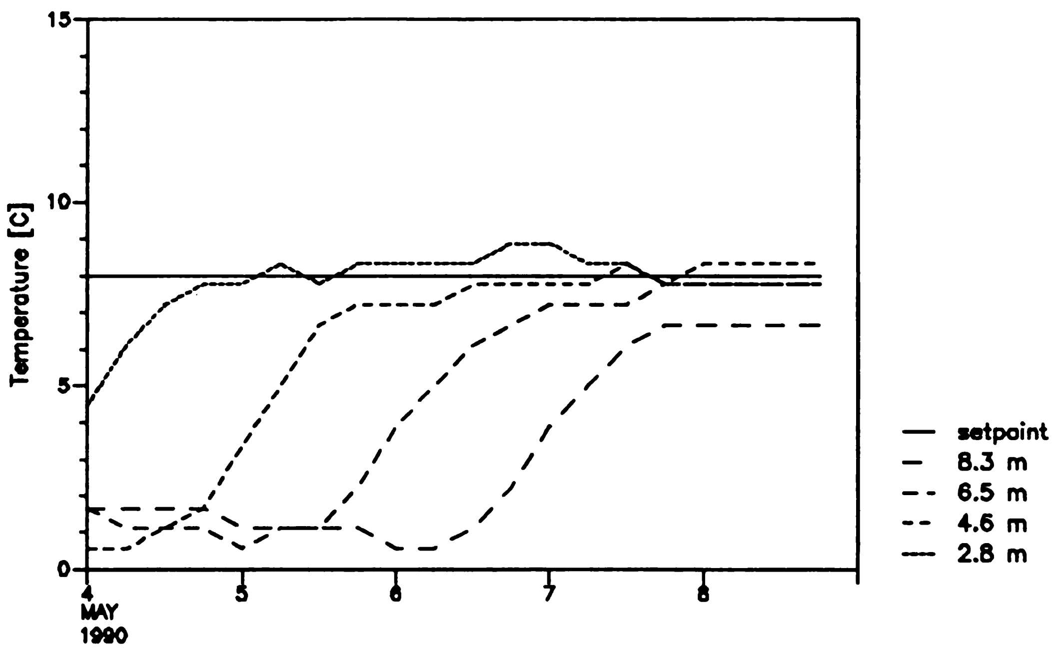

Figure 5.12 Grain temperature at four depths in the chilled grain storage bin, and set-point temperature of the reheated air from the grain chiller between May 4 and 8, 1990.

showed the best profile) over the four day chilled aeration period. The unit operated continuously. The bottom half of the bin (i.e. below 4.6 m) reached 7°C on May 5, and the top grain layers on May 8; the temperature gradient in the bin was less than 1.5°C by the end of the cycle.

Additional chilling cycles were administered between June 20 and 22, and July 18 and 26. Two days into the August 20 rechilling cycle the condenser fan of the KK140 short-circuited, and due to circumstances could not be repaired immediately. Thus, the chilled aeration and storage trial of 1989-90 was terminated at that date.

5.1.3.2 Grain Chiller Performance

The ambient temperature and relative humidity during part of the initial cool-down period is plotted in Figure 5.13 along with the temperature of the air exiting the chiller and the reheater set-point. The ambient temperature varied between 2 and 20°C while the unit was operating. The chiller maintained the air on the average within 1 - 3°C of the set-point temperature. Temperature spikes in the air from the chiller occurred throughout the operating period. They can partly be attributed to the on-off operation of the daytime-only chilling procedure. They were not observed during any

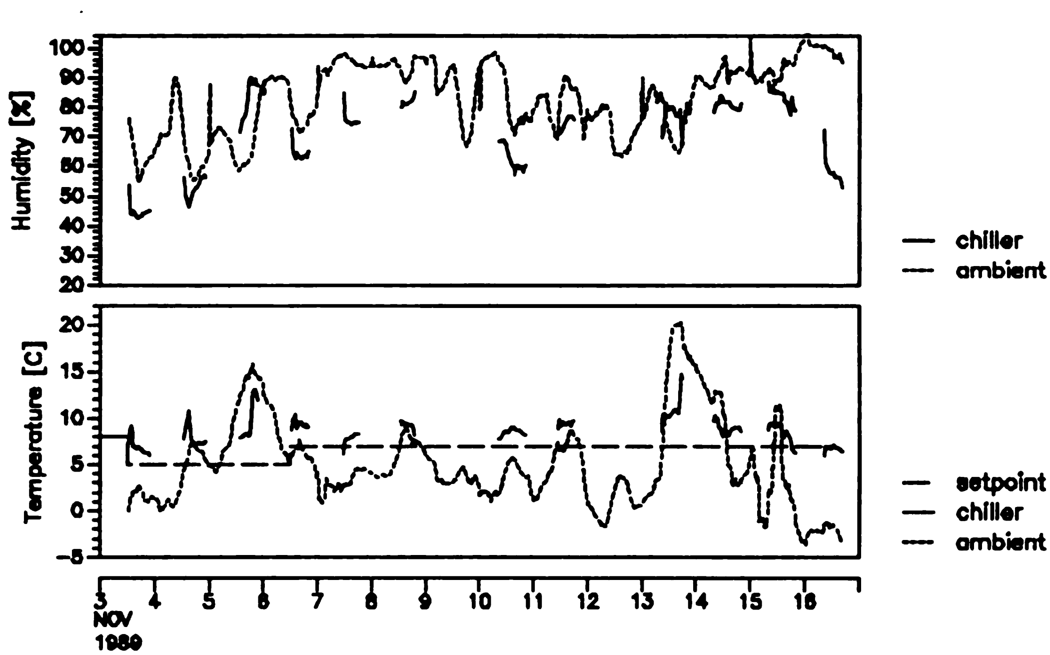

Figure 5.13 Temperature of the air into and out of the grain chiller during the initial cool-down between November 3 and 16, 1989.

other chiller operation cycle. The cold-air and reheater set-points were, respectively, 5 and 5°C between 11/3 and 11/7, 4 and 7°C between 11/6 and 11/7, 3 and 7°C between 11/8 and 11/17, 3 and 4.5°C between 11/18 and 11/20, and 3 and 5°C between 11/21 and 11/29. The settings were changed intermittently to evaluate different reheating effects at the bin inlet. The variation in the chiller settings is primarily responsible for the cycling of the temperature in the grain layers of the bin during the cool-down.

The air conditions into and out of the chiller during an eight-day period of continuous operation in July 1990 (i.e. between 7/18 and 7/26) are given in Figure 5.14. Shown are the ambient inlet and chiller outlet air temperature and relative humidity. The ambient temperature cycled between 13 and 30°C, and the relative humidity between 35 and 100 percent. The cold-air and reheater set-points of the chiller were fixed at 5°C and 10°C, respectively. The air temperature at the outlet of the chiller ranged from 10 to 13°C, and the relative humidity from 80 to 92 percent. The average air temperature at the outlet of the chiller was within 1°C of the reheater set-point. The relative humidity of the chilled air was higher than would be expected for 5°C of reheating. Assuming a temperature increase of 1 - 2°C in the duct due to heat gain, the relative humidity would be lowered to a more acceptable 70 - 80% range at the inlet to

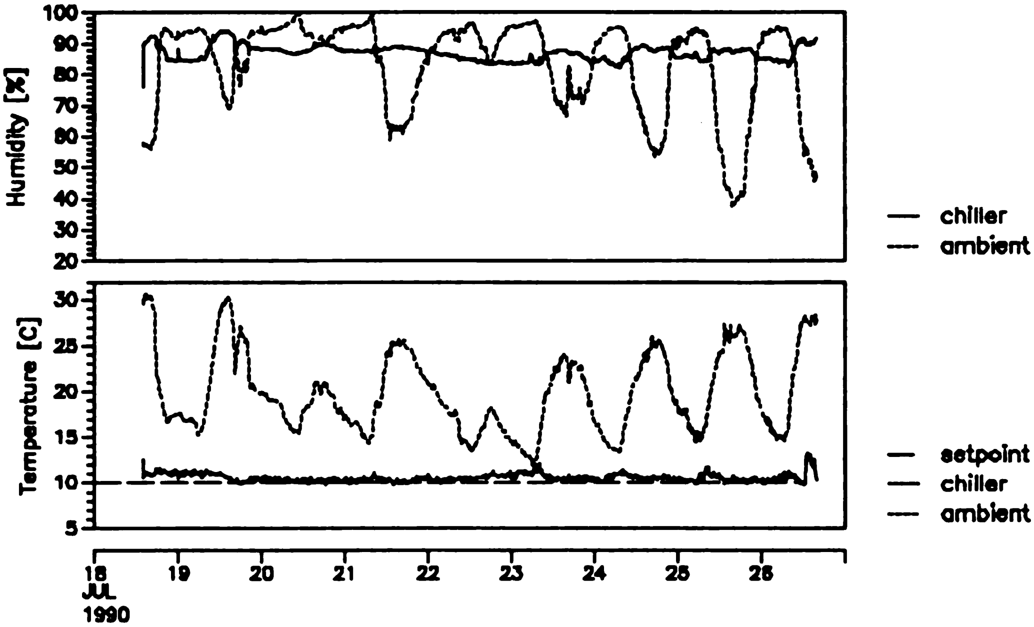

Figure 5.14 Temperature and relative humidity of the air into and out of the grain chiller over an 8-day period during rechilling between July 18 and 26, 1990.

the bin. It is possible that the relative humidity sensor at the chiller outlet was off. It was replaced for the 1990-91 season.

The electrical power consumption and run time of the chiller for the four cooling cycles during the 1989-90 season are summarized in Table 5.4.

Table 5.4 Power consumption and run time of the KK140 chiller during the 1989-90 storage season.

Cycle	Period	Power Consumption [kWh]	Run Time [h]
1	11/03 - 11/29/1989	2,242	191.8
2	5/01 - 5/07/1990	1,793	129.7
3	6/20 - 6/22	696	54.9
4	7/18 - 7/26	2,451	194.5
	Total:	7,182	570.9

The chiller was turned on for rechilling purposes in the spring and summer of 1990 on 5/1, 6/20 and 7/18. The rechilling periods varied from 54.9 to 194.5 hours. Cycle 2 was run to equalize the grain temperatures in the bin after the winter storage months, and to slowly rewarm the grain to about 8°C; the cold-air and reheater temperature set-points were 4 and 8°C, respectively. Cycles 3 and 4 were run to rechill the grain bin, especially in the periphery and near the top of the pile, which warmed due to the ambient summer conditions more significantly than the bulk of the bin. The set-point temperatures during the June rechilling cycle were 5 and 8.5°C for the cold-air and reheater, respectively.

The first chilling cycle lasted 627.7 hours with 191.8 hours of actual operating time, and 435.9 hours of off-time. The cool-down consumed 2,242 kWh, or 3.79 kWh per tonne of corn. The three rechilling cycles required a total of 379.1 hours with a power consumption of 4,940 kWh, or 8.43 kWh/tonne.

The power requirement and energy efficiency of the Granifrigor is tabulated in Table 5.5.

Table 5.5 Power requirement and energy efficiency of the KK140 chiller during the 1989-90 storage season.

Cycle	Period	Power Requirement [kW]	Energy Efficiency [W/t]
1	11/03 - 11/29/1989	11.7	19.8
2	5/01 - 5/07/1990	13.8	23.5
3	6/20 - 6/22	12.7	21.7
4	7/18 - 7/26	12.6	21.5
	Average:	12.7	21.6

During the cool-down cycle the average power requirement of the unit was 11.7 kW; this figure is below the rated nominal connected load of 13.0 kW specified by the manufacturer.

During the rechilling cycles the power requirement ranged from 12.6 to 13.8 kW. Obviously, the ambient cooling loads in the spring and summer required the unit to operate predominantly in the maximum refrigeration range, while during the fall and spring the unit operated mostly in the maximum airflow and electrical heating operating ranges. The energy efficiency of the chiller in terms of electrical power consumed per hour per tonne of corn ranged from 19.8 Watts per tonne in November 1989 to 23.5 W/tonne in May 1990, which is within the efficiency range determined during the 1988-89 season, i.e. 14.5 - 29.8 W/tonne.

The KK140 grain chiller developed a maximum airflow of 4,200 m^3/h at a measured static pressure of 2,115 Pa and a 10.3 m corn pile. At half-open throttle the chiller developed 3,700 m^3/h at 1,095 Pa, and at "closed" throttle 1,400 m^3/h at 340 Pa. The airflow through the corn was 0.12 $m^3/min/tonne$ (0.12 cfm/bu), 0.11 $m^3/min/tonne$ (0.11 cfm/bu), and 0.04 $m^3/min/tonne$ (0.04 cfm/bu) at airflow rates of 4,200 m^3/h, 3,700 m^3/h, and 1,400 m^3/h, respectively.

5.1.3.3 Chilled Storage Trial

The official NOAA meteorological records for the Lansing area are shown in Figure 5.15 (at 3-hour intervals) between

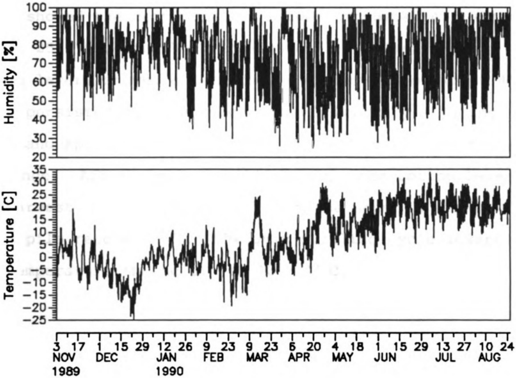

Figure 5.15 Ambient temperature and relative humidity of the air at the site of the chilled grain storage bin between November 3, 1989 and August 25, 1990.

November 3, 1989 and August 25, 1990. The relative humidity ranged from a low of 25 to a high of 100 percent. The air temperature ranged from -25°C on December 24, 1989 to 33°C on July 4, 1990.

The grain temperatures at three bin depths (i.e. Cable C, which showed the best profile) between November 4, 1989 and August 25, 1990 are shown in Figure 5.16. The top and bottom layers showed a temperature difference of about 4°C, which persisted from December through February. During March and April the temperatures in the bin were within a 2°C range. After the May chilling cycle the bottom layer was warmest. By the middle of July the upper layer of the grain pile reached 13°C. The July chilling cycle lowered the temperature in the bin to 10 - 11°C.

The grain temperature in the core (i.e. the average of the 2.6 and 4.4 m levels of cable D) and in the bulk of the chilled storage bin are shown in Figure 5.17 between November 4, 1989 and August 15, 1990. After the initial cool-down the temperature in the core remained below 5°C until the middle of March, and never rose above 10°C until the July chilling cycle. The bulk of the grain stayed below 5°C until the May chilling cycle, and remained between 8 and 13°C until the rechilling in July.

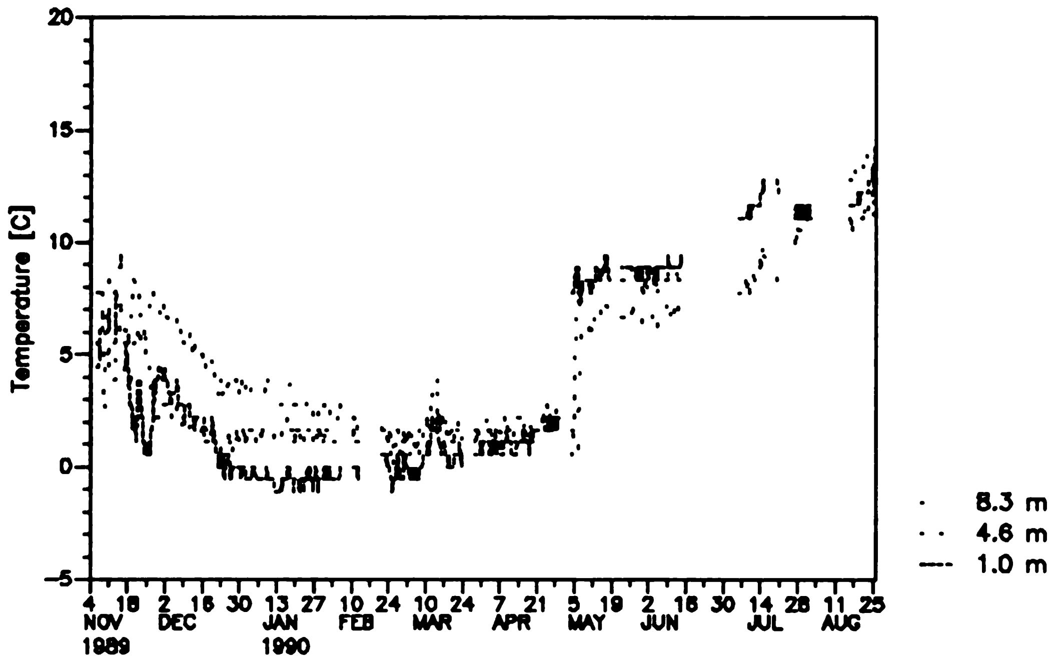

Figure 5.16 Grain temperature at three depths in the chilled grain storage bin between November 4, 1989 and August 26, 1990.

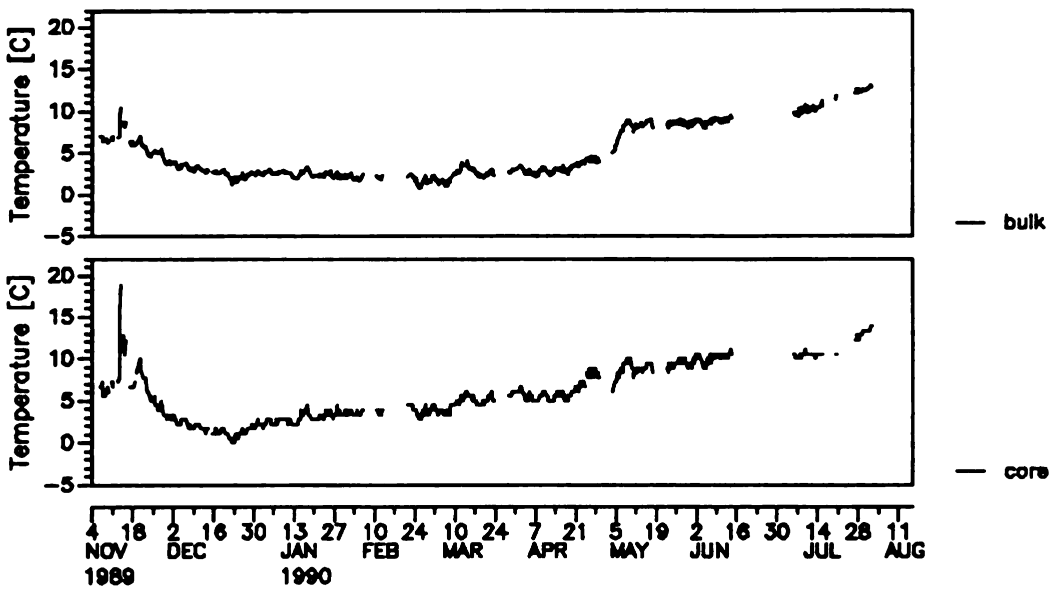

Figure 5.17 Grain temperature in the core and in the bulk of the chilled grain storage bin between November 4, 1989 and August 26, 1990.

5.1.4 The 1990-91 Season

The KK140 grain chiller was used to cool and maintain a bin of corn for a third season between October 31, 1990 and July 3, 1991. The initial amount of corn in the steel bin was 597 tonnes. Part of the grain was unloaded in early January, i.e. about 489 tonnes remained in the bin at an average grain level of 8.5 m. The bin was completely unloaded for commercial marketing starting on June 28.

On October 31, 1990 the first corn was dumped into the bin; the filling process was completed within 29 hours; the core was drawn on 11/6 and refilled on 11/9. The corn was dried and loaded into the bin at a grain temperature of 24 - 33°C.

Figure 5.18 is a plot of the moisture content of 132 samples of corn taken during loading and 126 samples taken during unloading of the chilled storage bin. The average inlet moisture content was 16.4% moisture content with a range of 10.0 - 27.5 percent (the desired moisture content was 16.5%). The average outlet moisture content was 15.0% with a range of 12.4 - 16.3 percent (the desired moisture content was 15.5%). During the chilled aeration and storage the average grain moisture in the bin was lowered by 1.4 percentage points, and the initial moisture content gradient of 17.5 points was reduced to 3.9 percentage points.

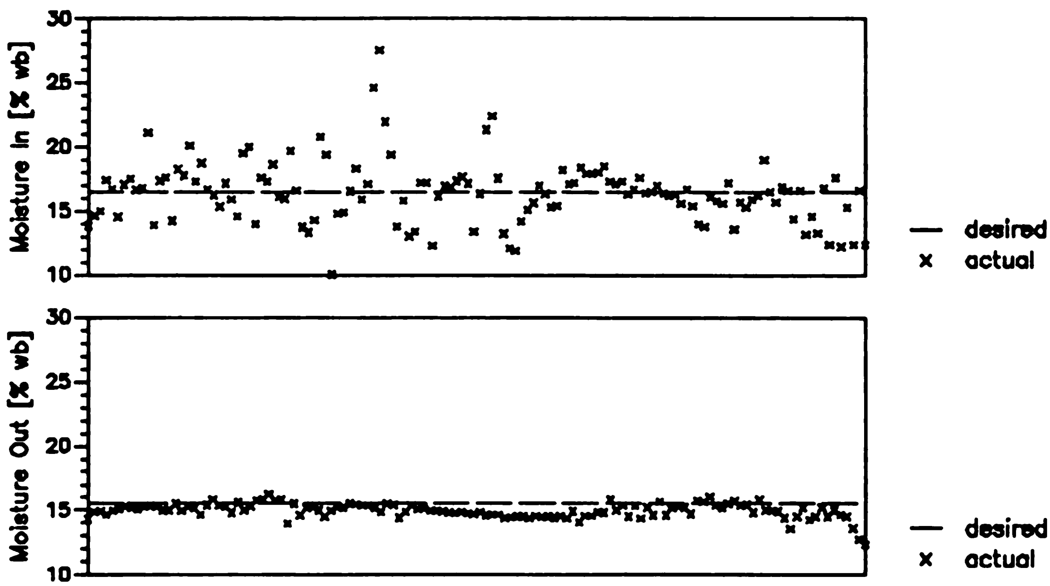

Figure 5.18 Corn moisture content (in %-wet basis) of 132 samples taken during loading and 126 samples taken during unloading of the chilled grain storage bin during the 1990-91 season.

5.1.4.1 Chilled Aeration Trial

The grain chiller was started on November 1 after the bin was fully loaded. The cool-down proceeded in three steps (to lower the grain temperature gradually) by manipulating the set-point temperatures of the KK140. The corn temperature at four pile depths (i.e. Cable C, which showed the best profile) between November 1 and 10 is shown in Figure 5.19 (on 11/6 and 11/7 the data recording device failed). The corn temperature in the bin ranged initially from 24 to 33°C with the warmer grain layers near the bottom and the cooler ones toward the top of the pile. At the end of the cool-down cycle on November 10 the temperatures in the pile were less than 6.5°C. At the 1.1 m level, the temperature dropped below the reheater set-point on 11/2, 11/5, and 11/8 (reaching a minimum of 3°C), and at the 2.9 m level on 11/5 and 11/8 (reaching a minimum of 4°C). This effect was attributed in part to the heat loss in the non-insulated duct connecting the chiller and the bin.

The corn temperature after the dryer was unusually high during the filling of the bin, due to a combination of warm weather and a high dryer throughput. On November 4 the ambient temperature dropped sharply, causing a significant condensation problem in the headspace of the bin due to the high humidity of the exhaust air from the pile. On November

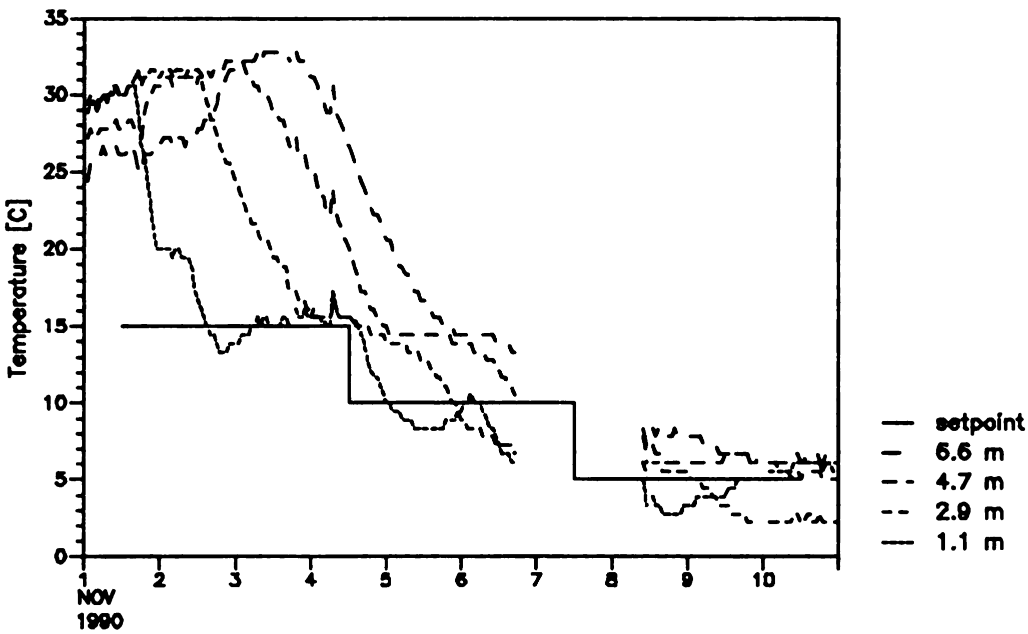

Figure 5.19 Grain temperature at four depths in the chilled grain storage bin, and set-point temperature of the reheated air from the grain chiller between November 1 and 10, 1990.

5 a temperature of 43°C with a relative humidity of 78% was measured in the headspace (see Table 5.6). The installation of a 0.5 m diameter fan in the open manhole helped to exhaust the headspace. By November 7 the high temperature and relative humidity conditions of the exhaust air subsided. By November 10 the headspace condition was measured as 10.5°C and 70% relative humidity, and the grain surface was dry.

Table 5.6 Temperature and relative humidity of the exhaust air above the pile during the initial cool-down period of the 1990-91 season.

Date		Temperature [°C]	Relative Humidity [%]
11/5/1990	6:45 A.M.	43.0	78
11/6	9:00 A.M.	32.0	84
	12:14 A.M.	41.0	82
11/7	6:50 A.M.	14.8	78
	10:15 A.M.	11.8	80
11/8	9:25 A.M.	11.0	78
11/9	8:28 A.M.	8.4	77
11/10	10:45 A.M.	10.5	70

Table 5.6 indicates that the high temperature and humidity exhaust conditions lasted about two days. Assuming an airflow rate of 4,000 m^3/h and exhaust conditions of 40°C and 80% relative humidity, about 150 kg of water were removed from the corn every hour. Over a 48-hour period

this resulted in a water removal of 7,200 kg, which translated into a moisture reduction of the 597 tonnes of corn from 16.4% to 15.4%. At the end of the 1990-91 chilled aeration and storage season the moisture content was 15.0%. Thus, it appears the primary moisture reduction for the chilled aeration of grain occurred during the first phase of the initial cool-down cycle. Furthermore, the high exhaust air temperature indicated that some of the grain in the pile exceeded 33°C (which was the highest temperature indicated by a thermocouple sensor during the cool-down cycle). Both observations are important to the simulated evaluation of the chilled grain aeration and storage system (see Chapter 6).

Apparently the dampness persisted several centimeters below the surface layer of the peaked grain. A hot spot developed by December 31 and was countered with a chilling cycle on January 1, 1991. By January 9 the grain at the top had cooled off. However, about 128 tonnes of corn were unloaded. The core was not refilled or levelled off. The average pile depth was 8.5 m for the remainder of the storage season.

In late May a chilling cycle was administered to raise the bin temperature from 3 - 7°C to about 14°C. Figure 5.20 shows the grain temperature increase at three depths (i.e.

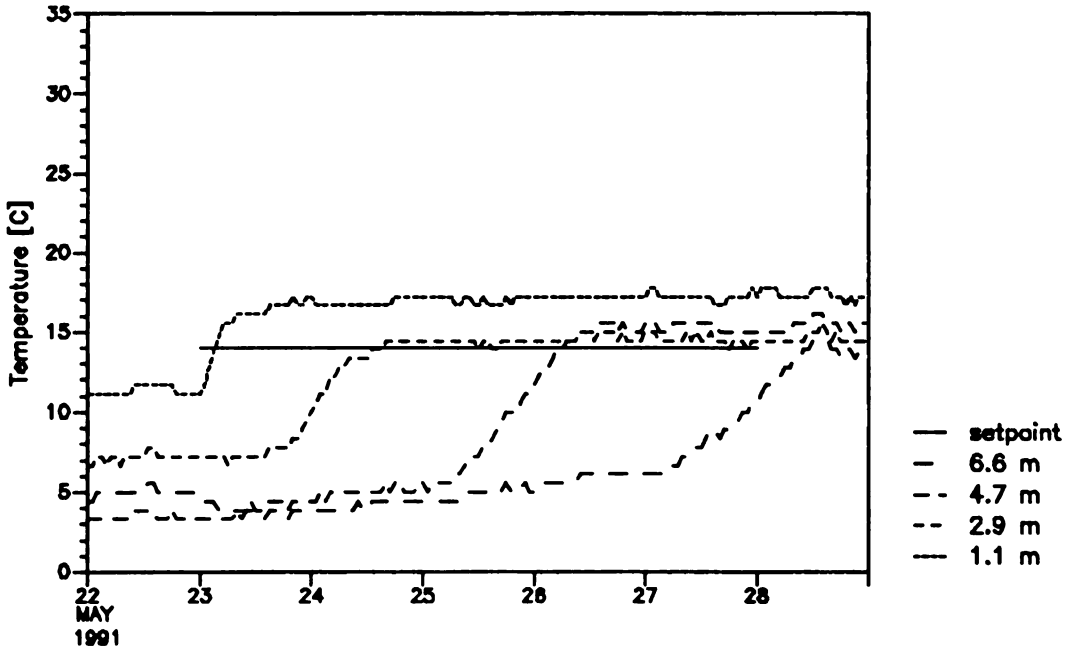

Figure 5.20 Grain temperature at three depths in the chilled grain storage bin, and set-point temperature of the reheated air from the grain chiller between May 22 and 28, 1991.

Cable B, which showed the best profile) over the six-day chilled aeration period. The unit operated continuously. The layers in the bottom half of the bin (i.e. below 4.4 m) reached 14°C by May 24, and the top grain layers by May 28; the temperature gradient in the bin at the end of the chilling cycle was about 2°C.

An additional chilling cycle was administered between June 7 and 12, 1991 to counter a rising thermocouple temperature at the 2.9 m level of Cable C. Although the temperature was reduced from 27°C to less than 15.5°C, the same thermocouple indicated a second temperature rise by June 27, and thus it was decided to unload and sell the corn. During unloading very little visible mold damage was detected in the 126 corn samples collected. The thermocouple on Cable C was checked after the bin was unloaded; it was clean and appeared functional.

5.1.4.2 Grain Chiller Performance

No data on the ambient temperature and relative humidity during the step-wise cool-down of the grain in the fall of 1990 is available. The cold-air and reheater set-points were, respectively, 10 and 15°C between 11/1 and 11/3, 6.5 and 10°C between 11/4 and 11/7, and 3.5 and 5°C between 11/8 and 11/10.

The air conditions into and out of the chiller during a six-day period of continuous operation between May 22 and 28, 1991 are given in Figure 5.21. The ambient temperature cycled between 18 and 30°C, and the relative humidity between 60 and 90 percent. The cold-air and reheater set-points of the chiller were fixed at 9 and 14°C, respectively. The air temperature at the outlet of the chiller ranged from 15.5 to 18°C, and the relative humidity from 70 to 85 percent. The average air temperature at the outlet of the chiller was about 2.5°C above the reheater set-point. This was the highest difference measured during any of the chilling cycles for the three storage seasons. The grain temperature increase at the 1.1 m bed-depth level to over 16°C confirms this observation (see Figure 5.20).

The electrical power consumption and run time of the chiller for the cooling cycles during the 1990-91 season are summarized in Table 5.7.

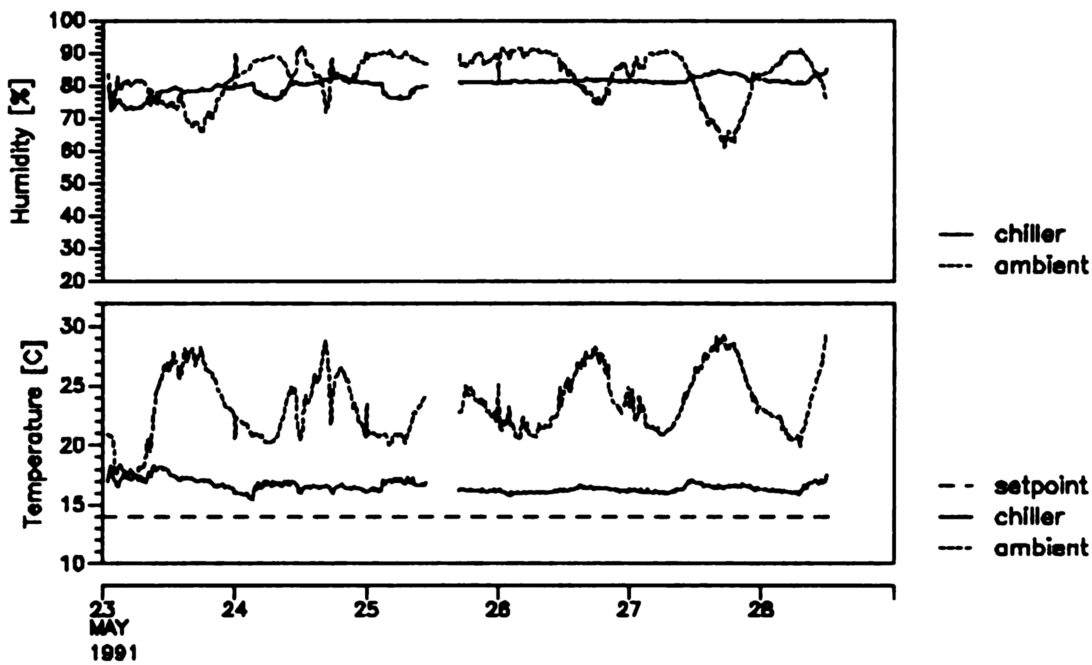

Figure 5.21 Temperature and relative humidity of the air into the grain chiller and into the chilled grain storage bin over a 6-day period during rechilling between May 22 and 28, 1991.

Table 5.7 Power consumption and run time of the KK140 chiller during the 1990-91 storage season.

Cycle	Period	Power Consumption [kWh]	Run Time [h]
1	11/01 - 11/10/1990	2,188	197.8
2	1/01 - 1/09/1991	2,013	178.3
3	5/22 - 5/28	1,891	134.6
4	6/07 - 6/12	1,701	120.6
	Total:	7,793	631.3

The chiller was turned on for rechilling purposes on 1/1/91, 5/22, and 6/7. The rechilling periods varied from 120.6 to 178.3 hours. Cycle 2 was run to counter a hot spot in the peak of the grain. Cycle 3 was intended to rewarm the grain to about 15°C. Cycle 4 was run to rechill the grain due to a hot spot developing in the bottom of the pile; the cold-air and reheater set-point temperatures were 9 and 12°C, respectively.

The first chilling cycle lasted 210.8 hours with 197.8 hours of operating time, and 13.0 hours of off-time. The cool-down consumed 2,188 kWh, or 3.66 kWh per tonne of corn. During the cooling cycle in January 2,013 kWh were consumed in 178.3 hours, or 3.39 kWh/tonne. The spring chilling cycles lasted a total of 255.2 hours with a power consumption of 3,592 kWh, or 7.38 kWh/tonne.

The power requirement and energy efficiency of the chiller is tabulated in Table 5.8.

Table 5.8 Power requirement and energy efficiency of the KK140 chiller during the 1990-91 storage season.

Cycle	Period	Power Requirement [kW]	Energy Efficiency [W/t]
1	11/01 - 11/10/1990	11.1	18.5
2	1/01 - 1/09/1991	11.3	19.0
3	5/22 - 5/28	14.0	28.8
4	6/07 - 6/12	14.1	29.0

During the step-wise cool-down cycle the average power requirement of the unit was 11.1 kW; this value is similar to that of the previous two cool-down cycles in 1988-89 and 1989-90, i.e. 11.1 and 11.7 kW, respectively. During the January cooling the electrical heaters maintained the inlet air temperature to the bin at around 5°C, while the power requirement was 11.3 kW. During the rechilling cycles in the summer, the power requirement was 14.1 kW. This was higher than during the previous two seasons, and about 1 kW above the nominal load specified by the manufacturer.

The energy efficiency of the chiller in terms of electrical power consumed per hour per tonne of corn was 18.5 Watts per tonne in November 1990, and 19.0 W/tonne in January 1991 for the full bin, and about 28.0 to 29.0 W/tonne for the partially unloaded bin during the summer rechilling. These values are similar to the range of values observed in the previous two seasons. The energy efficiencies of cycles 3 and 4 are about the same as for cycle 6 in May 1989 (i.e. 29.8 W/tonne).

The KK140 grain chiller developed a maximum airflow of 4,000 m^3/h at a static pressure of 2,239 Pa for the 10.3 m deep pile. At 8.5 m the maximum airflow was 4,200 m^3/h at 1,990 Pa. During the May and June rechilling cycles the throttle position was usually more than half closed; during this period the airflow was 2,300 m^3/h at 700 Pa. The airflow through the corn was 0.11 m^3/min/tonne (0.11 cfm/bu), 0.14 m^3/min/tonne (0.14 cfm/bu), and 0.08 m^3/mon/tonne (0.08 cfm/bu) at the airflow rates of 4,000 m^3/h, 4,200 m^3/h, and 2,300 m^3/h, respectively.

5.1.4.3 Chilled Storage Trial

The official NOAA meteorological records for the Lansing area are shown in Figure 5.22 (at 3-hour intervals) between October 31, 1990 and June 28, 1991. The relative humidity ranged from a low of 30 to a high of 100 percent. The air temperature reached a low of -22°C on December 27, 1990 and

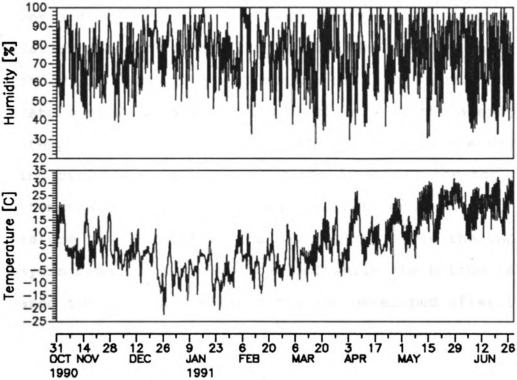

Figure 5.22 Ambient temperature and relative humidity of the air at the site of the chilled grain bin between October 31, 1990 and June 28, 1991.

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a high of 32°C on June 1, 1991.

The grain temperature at three bin depths (i.e. Cable B, which showed the best profile) between November 1, 1990 and June 28, 1991 is shown in Figure 5.23. The top and bottom layers of the grain were within a range of 3°C through November and December. After the January aeration cycle the temperature gradient in the bin was initially 8°C, ranging from 5°C at the bottom to -3°C at the top. By February the temperature gradient was reduced to about 4°C; the average grain temperature was -2°C. From Mid-March until the May chilling cycle the grain temperatures diverged; the top grain temperature rose to 5°C, and the bottom grain temperature to 12°C. After the May cooling cycle the upper bin layers remained between 14 - 16°C while the bottom layer increased to 20°C. A similar situation developed after the June rechilling cycle. The bottom layer increased from 15°C to 21°C by June 28, while the top layers increased slowly from 14°C to 16°C before unloading.

The grain temperature in the core, the bulk, and near the periphery of the chilled storage bin are shown in Figure 5.24 between November 1, 1990 and June 20, 1991. After the initial cool-down the temperature in the core remained below 5°C until January 1, and below 0°C until the middle of March. The core temperature rose due to the May chilling

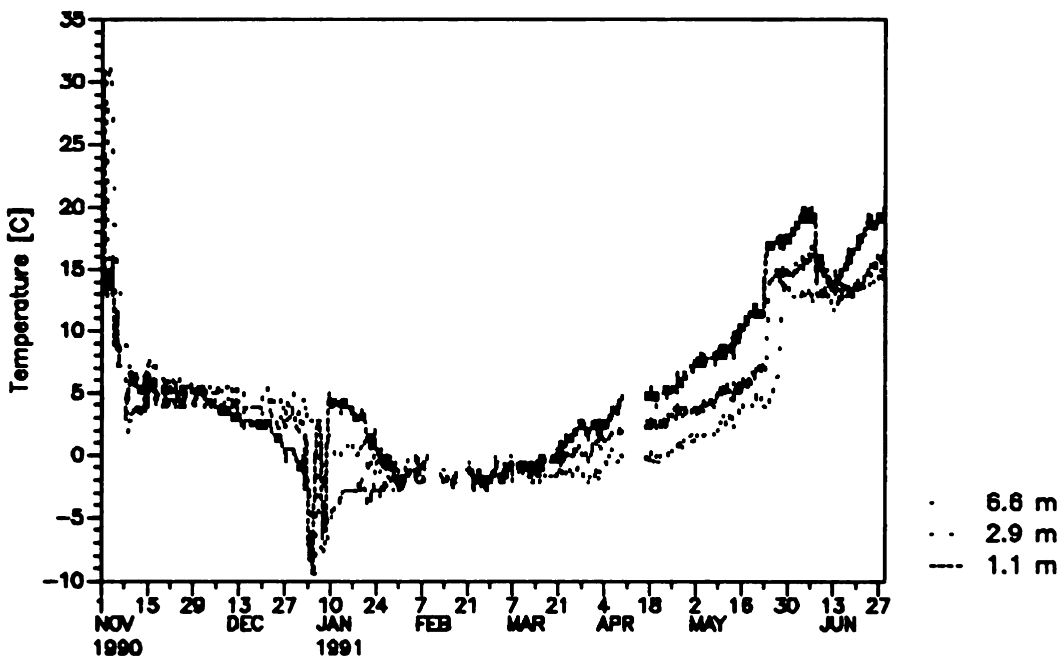

Figure 5.23 Grain temperature at three depths in the chilled grain storage bin between November 1, 1990 and June 28, 1991.

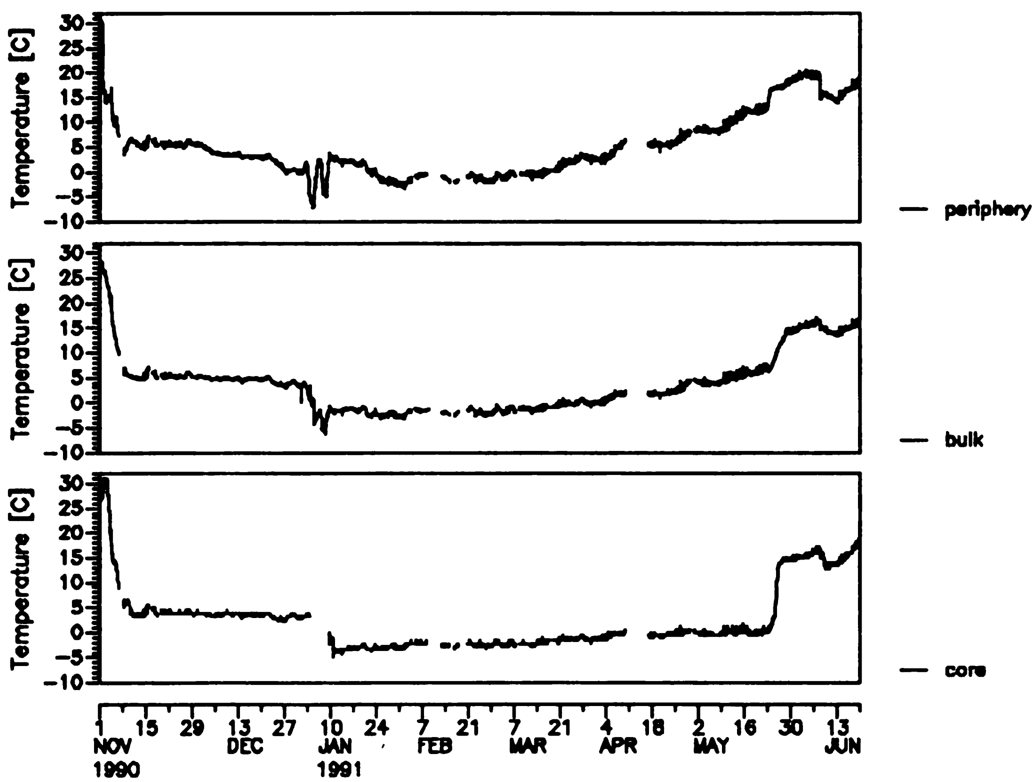

Figure 5.24 Grain temperature in the core, in the bulk, and near the periphery of the chilled grain storage bin between November 1, 1990 and June 28, 1991.

cycle to about 15°C and increased by 1°C before June. The bulk of the grain stayed below 7°C until January, and remained around 0°C until early March. A slow temperature rise to about 8°C occurred by the middle of May. After the May chilling cycle the bulk temperature rose by about 2°C to 16°C. The temperature in the periphery varied as a function of the ambient conditions. Temperatures below 5°C were not reached before the middle of December. Some cycling of the temperature was observed after the January cooling, i.e. from a low of -2°C to a high of 3°C. By the middle of March the grain temperature in the periphery rose cyclically to a maximum of 18°C before the May chilling treatment. The May cycle appeared not to affect the periphery temperature. Between May and June the temperature in the periphery reached 23°C. During the June rechilling the temperatures in the core, bulk, and periphery were reduced to 14 - 16°C.

5.1.5 Summary of Experimental Tests

The field-test results obtained during the chilled aeration and storage of corn at a commercial elevator in Michigan using a commercial grain chilling unit are summarized in Table 5.9.

Table 5.9 Summary of results from the chilled aeration and storage field tests conducted between 1988 and 1991.

Parameter	1988-89	1989-90	1990-91
Initial Cool-down Period:			
Length [days]	6.6	8.0	8.3
θ decrease [°C/day]	1.2	1.0	3.2
Efficiency [W/t]	18.2	19.8	18.5
Airflow [m^3/min/t]	0.12	0.12	0.11
Total Storage Period:			
Length [months]	7	10	9
MC decrease [points]	0.8	1.0-1.5	1.4
Bulk θ maximum [°C]	4.0	18.0	18.0
Bulk θ minimum [°C]	-1.0	1.0	-5.0
Rechilling cycles/month	0.43[1]	0.30	0.33
Power [kWh/t/month]	1.77	1.23	1.59
Power [kWh/t/cycle]	1.9	3.0	3.6

[1] counting the three fall rechilling cycles as one

Three operational chilling strategies were employed during the cool-down periods: (1) continuous, (2) daytime-only, and (3) step-wise. The run time of the cool-down cycles lasted between 6.6 and 8.3 days, and the average grain temperature reduction was 1.0 to 3.2°C per day. The step-wise strategy lasted longer partly because chilling was not started before the bin was completely full. Thus, a shorter cooling time would have resulted if chilling had been initiated as soon as the perforated floor was covered. Since the cool-down time for the three seasons is about the same, it would appear to be less dependent on the grain temperature decrease, which was different each season, than on the airflow rate through the grain, which was about the same each season.

The effect of the airflow rate on the cool-down time of corn was shown to be significant in a previous study (Bakker-Arkema et al. 1989). However, the effect of the airflow rate varying as a function of the cooling load was not investigated since a computer model of the chiller was unavailable. The relationship between the cooling time, grain temperature decrease, and the airflow cannot be assessed with the experimental results of the field tests. It will be investigated as part of the simulation study in Chapter 6.1.

The continuous chilling strategy appears to be slightly more energy efficient than the step-wise operation; both are more efficient than daytime-only chilling; a previous study supports this observation (Maier et al. 1990). Continuous versus step-wise operation of the chiller was investigated for the chilled aeration (at constant airflow) of paddy under humid tropics conditions. It was determined that cooling the paddy from the initial temperature to the desired grain temperature at a constant airflow in more than one step increased the cooling time, and thus the total energy consumption.

The chilled storage periods lasted between 7 and 10 months. The moisture content reduction during the chilled aeration and storage of the corn ranged from 0.8 to 1.5 percentage points. It appears to be primarily a function of the initial temperature reduction during the cool-down phase, rather than the length of the storage time, or the rechilling frequency. This observation will be investigated in more detail as part of the simulation study in Chapter 6.

Each season the bulk temperature was reduced to about 5°C during the initial cool-down in the fall. Storage through the winter months lowered the grain temperatures in the bulk by an additional 4 to 10°C. Chilling prevented the maximum bulk temperature to rise above 18°C in the spring and summer. However, due to the limited refrigeration capacity it was not possible to maintain the grain temperatures in the desired 5 - 8°C range during summer storage. The first cycle in the spring was utilized to reduce temperature gradients in the grain and bring the temperatures into the 8 - 12°C range. The rechilling cycles employed during the summer months maintained the grain temperatures at the 10 to 15°C level. However, rewarming the grain in the spring, as was the case in the field tests, appears to be undesirable.

The rechilling frequency and its effect on the stored grain quality are investigated in Chapter 6.3 in more detail.

The number of rechilling cycles in addition to the initial cool-down ranged from 0.30 to 0.43 cycles per storage month. This indicates about 3 to 4 rechilling cycles over a 12-month storage period for corn under Michigan conditions for this bin-chiller system configuration. The total power consumption for chilled aeration (cool-down plus rechilling cycles) ranged from 1.23 to 1.77 kWh per tonne per storage month, or about 14.8 to 21.2 kWh per tonne over a 12-month chilled aeration and storage period.

It is common in the grain chilling literature to specify the power consumption in terms of kWh per tonne of grain or in kWh/t per chilling cycle. However, this is somewhat misleading. The 1988-89 season yielded a power consumption of 1.9 kWh/tonne/cycle compared to 3.0 kWh/tonne/cycle in 1989-90 and 3.6 kWh/tonne/ cycle in 1990-91. The total storage time in 1988-89 was shorter than in the other two seasons, and most of the chilling cycles took place during the fall. Thus, the power consumption is more appropriately evaluated in relation to the storage period, i.e. kWh/t/month. The field tests indicate that the longer the storage period, the lower the monthly power consumption per tonne.

Proper ventilation of the headspace is critical to prevent condensation during the cool-down of corn in the fall. This is a concern especially when corn at a higher initial grain moisture content and temperature is chilled. Without the severe condensation problem in the top of the bin, the grain in the peak of the pile would most likely not have spoiled so quickly in 1988 and 1989. For example, at a moisture content of 18% and a temperature of 5°C, sound corn can have a storage life of up to 288 days, or 9.6 months (MWPS-13 1988). The condensation problem in the test bin was compounded by cold ambient temperatures during the cool-down cycle in the fall, and insufficient exhaust area from the bin.

Levelling the top of the pile is inconvenient from a management point of view, but it is important to assure uniform airflow through the grain (Komba et al. 1987). If a spreader is not available during the loading of the bin, coring is an alternative method to redistribute the fines in the corn pile. Preferably a screen-cleaner should be used to remove fines and broken kernels before loading the bin. Leveling, spreading/coring, and screening improve the passage of the chilling air and reduce the potential for spoilage of the grain.

Over the three chilled aeration and storage seasons the

KK140 grain chiller operated a total of 1,829 hours consuming 21,896 kWh of electricity. With the exception of the failure of one manual motor starter caused by a short-circuiting worn wire on the condenser fan, the chiller performed flawlessly. Each season it was left in the field connected to the storage bin and exposed to Michigan winters and summers without special protection, yet it started up every time it was turned on. The operational indicator and alarm lights are simple and clear to understand. The safety shut-off activated whenever the bin inlet air conditions could not be maintained to prevent chilling outside the set-point temperature range.

The grain chiller did not require much operator expertise, nor supervision during its operation. Temperature cables to monitor the progress of the cooling front while the chiller is operating, and to indicate when to rechill the grain, should be available. A daily check of the temperatures during chilling, and a weekly to bi-weekly check during the storage period should be routine. The selection of the cold-air and reheater temperature set-points is confusing; the procedure should be modified. A possible controller strategy is suggested in Chapter 6.3.6.

The chiller maintained the average air temperature at the chiller outlet within 0.5 to 1.5°C of the set-point reheater temperature (with the exception of the May 1991 chilling cycle, which may have been due to a bad sensor). The chiller outlet relative humidity was maintained within a 5 to 10% range. The bin inlet temperature was within about ± 1 - 2°C of the chiller outlet temperature, depending on whether the chilled air gained or lost heat in the connecting duct. The bin inlet relative humidity changed accordingly, i.e. increased ± 4 - 8 percent in the duct. For long connecting ducts, the temperature sensors for regulating the chiller set-points should be placed at the bin inlet, or in the plenum.

5.2 Models Verification

Before a simulation model can be used it must be validated against experimental results. The semi-theoretical models developed in Chapter 4 to simulate the chilled aeration of grains, the grain chilling unit, and the storage of chilled grains will be verified using the experimental field test results presented in Chapter 5.1. In addition, the grain chiller model is validated using performance data supplied by the manufacturer of the chilling unit.

To evaluate the degree of accuracy of the predicted values compared to the observed ones, the following statistical measures are utilized: (1) the average absolute difference (AAD), which is the sample mean of the absolute differences calculated for each pair of simulated and experimental values; and (2) the sample standard deviation (SSD), which is calculated as follows (Bhattacharyya and Johnson 1977):

$$SSD = \sqrt{\frac{\sum_{i=1}^{n} (X_i - AAD)^2}{n-1}} \tag{4.1}$$

where n is the number of sample points, and X_i are the absolute differences between the simulated and experimental values.

5.2.1 Grain Chiller

For the grain chiller model to be valid it must (1) adjust the airflow rate entering the bin dependent upon the ambient cooling load, (2) maintain the desired temperature and relative humidity of the air, (3) predict the evaporating and condensing refrigerant temperatures, and (4) predict the evaporating and compressor capacities.

The validity of the chiller model will be tested with experimental performance data supplied by the manufacturer of the chiller. The type of data made available for the validation was described in the theoretical development of the model in Chapter 4. Due to the proprietary nature of the test data, the results are presented as dimensionless curves.

Two sets of test data are employed. One set was collected at a high static pressure, and a second one at a low static pressure. The data sets represent ambient cooling loads in both the maximum airflow and the maximum refrigeration operating modes of the chiller. The model is validated by simulating the performance of the chiller both as a function of an increasing and a decreasing cooling load.

Airflow

The airflow at the low static pressure is significantly higher than at the high pressure when the chiller operates in the maximum airflow mode (see Figure 5.25). In the maximum refrigeration operating mode the airflow rates are similar given the same ambient temperatures. The airflow decreases continuously as the ambient cooling load is increased. The jump in the airflow rate at the low pressure is caused by an increase of the relative humidity in the test chamber, and thus changes the relative cooling load. The chiller model predicts the change accurately by adjusting the air throttle after the fan. The average absolute difference in the relative airflow rates for the

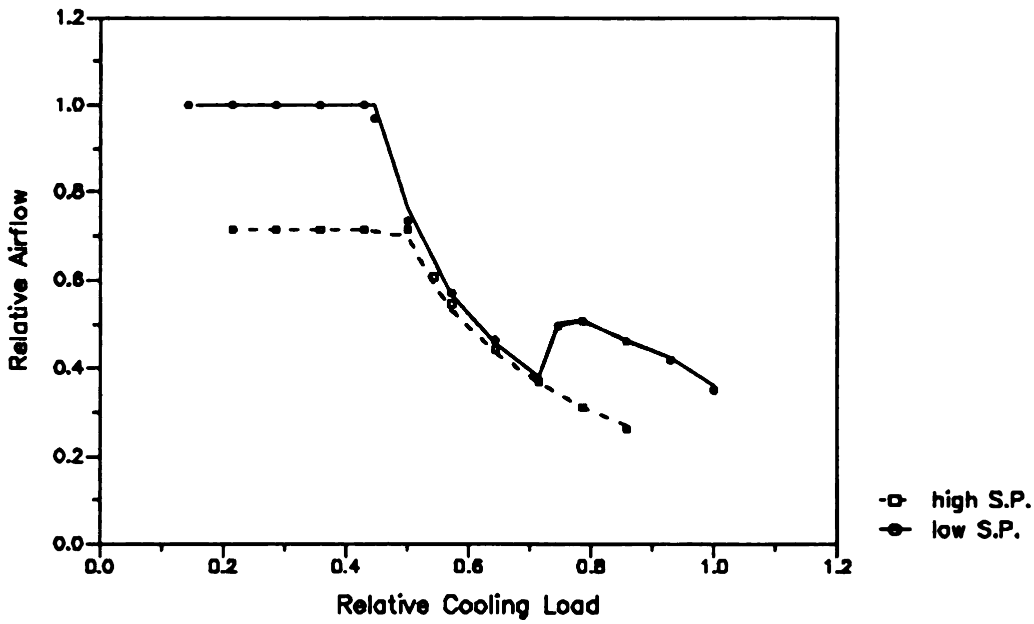

Figure 5.25 Simulated (lines) and experimental (symbols) air flow rates as a function of the relative ambient cooling load for the KK140 at a high and low fan static pressure.

combined set of test data is 44.78 m^3/h with a sample standard deviation (SSD) of 48.69 m^3/h, which is about 1 - 2 percent of the maximum airflow the unit develops. Thus, the model predicts the airflow rate into the bin accurately.

Refrigerant Temperature

The experimental and simulated evaporating and condensing refrigerant temperatures for the two sets of test data are shown in Figure 5.26. The predicted values follow the observed values closely. The break in the curves indicate the transition from the maximum refrigeration to the maximum airflow operating modes. There is no significant effect of the fan static pressure on the refrigeration cycle. The AAD of the evaporating temperatures is 1.10°C with a variability of 1.21°C; and 1.19°C and 0.73°C for the condensing temperature, respectively. Thus, the simulated refrigeration cycle of the chilling unit is accurately balanced for the given ambient cooling loads and set-point temperatures.

Capacities

Figure 5.27 shows the predicted and observed evaporating and compressor capacities of the Granifrigor KK140 at the high and low fan static pressures. The compressor capacity is maximum at the highest cooling load and decreases steadily as the cooling load is decreased. The evaporating capacity

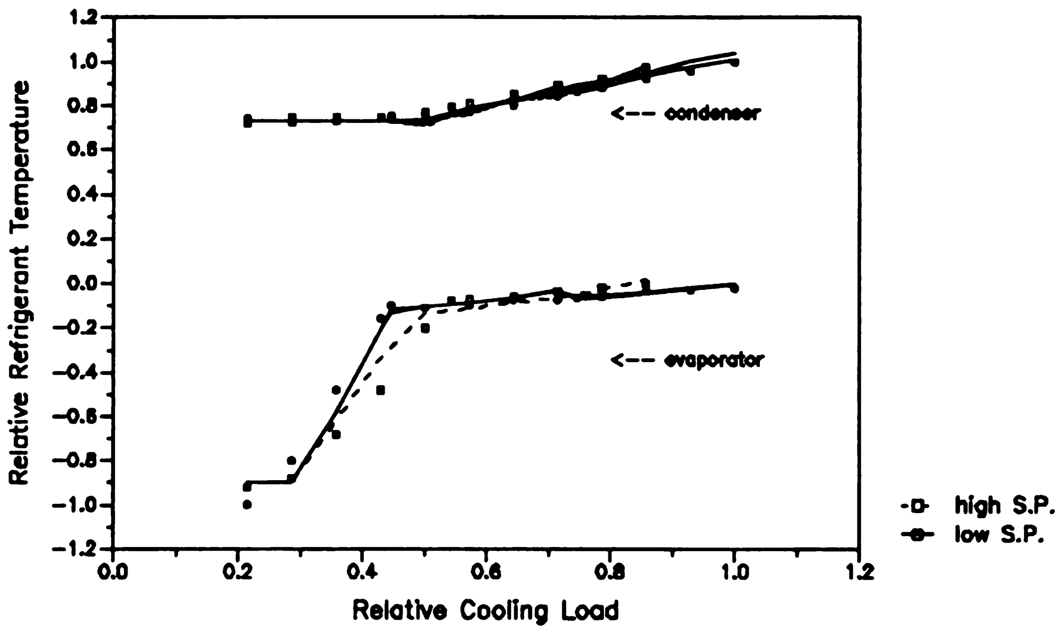

Figure 5.26 Simulated (lines) and experimental (symbols) evaporating and condensing temperatures of the refrigerant in the refrigeration cycle of the KK140 at a high and low fan static pressure.

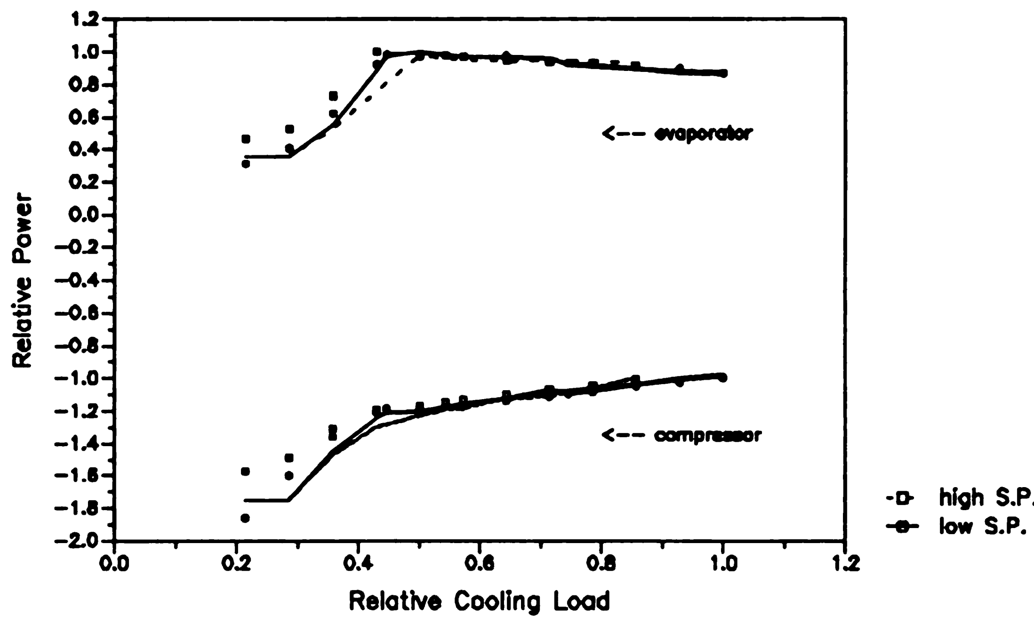

Figure 5.27 Simulated (lines) and experimental (symbols) evaporating and compressor capacities of the refrigeration cycle of the KK140 at a high and low fan static pressure.

increases with decreasing cooling load until the breakpoint between the maximum refrigeration and airflow operating modes. The evaporating capacity is both a function of the cooling load and the airflow rate. At the maximum airflow rate the evaporating capacity is reduced sharply. The compressor capacity decreases less dramatically. In the maximum airflow range the capacity is underpredicted. The evaporating capacity AAD for the two data sets is 1.02 kW with a variability of 1.52 kW. The AAD for the compressor capacity is 0.35 kW with a variability of 0.28 kW.

Summary

Using experimental performance data, the simulation submodel of the commercial grain chiller was validated. The predicted airflow rates, refrigerant temperatures and refrigeration capacities are sufficiently accurate to use the algorithm in the chilled aeration and storage system model.

5.2.2 Chilled Aeration

The chilled aeration submodel simulates the heat and mass transfer in the grain pile and is coupled with the grain chiller submodel, which calculates the inlet conditions to the grain bin. In the resulting model it is assumed that the bin inlet temperature is constant during the chilling cycle, and that the airflow and relative humidity vary as functions of the cooling load imposed on the refrigeration cycle of the chiller. A time step of 1 hour and a grid spacing of 0.9 m are used in the verification. Both were selected to reflect the experimental data collection parameters, i.e. the experimental temperatures in the bin were collected hourly (in two of the three seasons), and the thermocouples were about 1.8 m apart (in Chapter 6.1 a grid spacing of greater than 1 m was found to be undesirable).

In order to be valid the coupled model must predict with an acceptable degree of accuracy: (1) the temperature pattern in the grain bin, (2) the chilling/rechilling time of the cooling cycle, (3) the variation in the airflow and relative humidity of the bin inlet air, and (4) the power consumption (and efficiency) of the grain chilling unit. From the experimental data presented in Chapter 5.1 two representative cool-down and two rechilling cycles were selected to validate the chilled aeration model.

Fall 1988 Cool-down Cycle

Figure 5.28 shows the simulated and experimental temperatures of three grain layers for the continuous cool-down cycle of November 3 through 8, 1988. The initial grain temperatures are 10.1°C, 12.1°C and 10.1°C at 4.7 m, 6.6 m

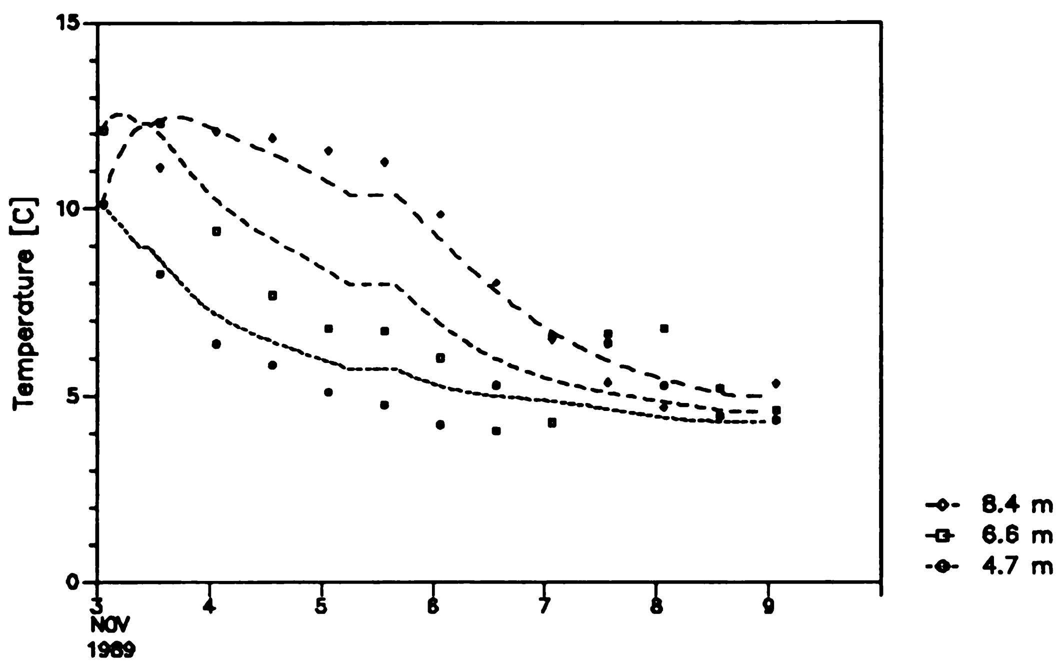

Figure 5.28 Simulated (lines) and experimental (symbols) grain temperatures at three depths in the chilled grain storage bin during the initial cool-down between November 3 and 8, 1988.

and 8.4 m above the perforated bin floor, respectively. To simulate the observed temperature rise at the 6.6 m and 8.4 m levels, layers of warmer grain must exist between the thermocouple sensor locations. In the simulation a temperature of 9°C at the 3.8 m depth, and 14.5°C at the 5.7 m and 7.5 m depths were assumed at the beginning of the cycle. The power outages on 11/3 and 11/5 were simulated by assuming the grain temperatures did not change during the brief non-ventilated periods.

The simulated temperature pattern follow the experimental profile well. At the 4.7 m pile depth the predicted and observed layers show the same cooling rate for the first two days, but diverge slightly beginning on 11/5. The 6.6 m simulated layer cools slower than the experimental one between 11/3 and 11/6. The 8.4 m layer shows the slowest cooling rate. The simulated layer predicts initially faster warming, but subsequently lags the experimental temperatures until 11/6. On 11/6 the 4.7 m and 6.6 m experimental layers indicate an intermittent temperature rise, which is not predicted in the simulated layers, since the chilling unit model is assumed to provide a constant average inlet temperature to the bin. At the end of the cool-down cycle the simulated and experimental temperatures differ by 0.1 to 0.3°C. The final simulated temperature range of the grain is the same as observed experimentally, i.e. 4.5 to 5.5°C.

Table 5.10 gives an indication of the difference and variability between the simulated and experimental temperature values.

Table 5.10 Average absolute difference (AAD) and sample standard deviation (SSD) between the simulated and experimental temperature values for the initial cool-down cycle in the fall of 1988 (in °C).

	4.7 m	6.6 m	8.4 m	Overall
AAD	0.85	1.16	0.54	0.85
SSD	0.49	0.61	0.39	0.57

The 8.4 m layer shows the smallest average absolute difference (AAD) and sample standard deviation (SSD) between the simulated and experimental values; the 6.6 m pile depth the largest. For the three layers the overall average absolute difference is less than 1°C with a standard deviation of 0.57°C. Since the thermocouple sensors have an accuracy of 0.5°C and the airflow through the grain bin is not perfectly plug flow, the accuracy of the chilled aeration simulation model in predicting the temperature profile of the experimental cool-down is considered acceptable.

The cool-down time is judged by the last grain layer (i.e. the top) to reach a desired final temperature. The 8.4 m experimental layer reached 6°C after 101 hours of chilling the full bin compared to 88.5 hours in the simulated run, i.e. a difference of +12.5 hours, and the experimental layer reached 5.5°C after 107 hours compared to 121.5 hours in the simulated test, i.e. a difference of -14.5 hours. Thus, the experimental and predicted cooling times for the slowest layer are within about ± 13 hours, or about 10 - 15%. Considering the inherent variability in the experimental cooling time, the predicted cooling time is considered acceptably accurate.

Figure 5.29 shows the simulated operation of the KK140 grain chiller during the cool-down cycle under the ambient conditions between November 3 and 8, 1988. The cold-air and reheater temperatures for the grain chiller model are the same as in the field test, i.e. 3 and 4.5°C, respectively. The chiller outlet temperature is assumed to be the same as the bin inlet temperature. The maximum airflow rate in the simulated chiller is set to 4,300 m^3/h, which is the value measured experimentally. The run time of the unit is the same as in the field test, i.e. 124 hours for the full bin condition.

Initially the ambient temperature is lower than the chiller cold-air temperature set-point, and the bin inlet conditions are maintained by electrical heating of the air. The temperature difference is small enough to allow the maximum

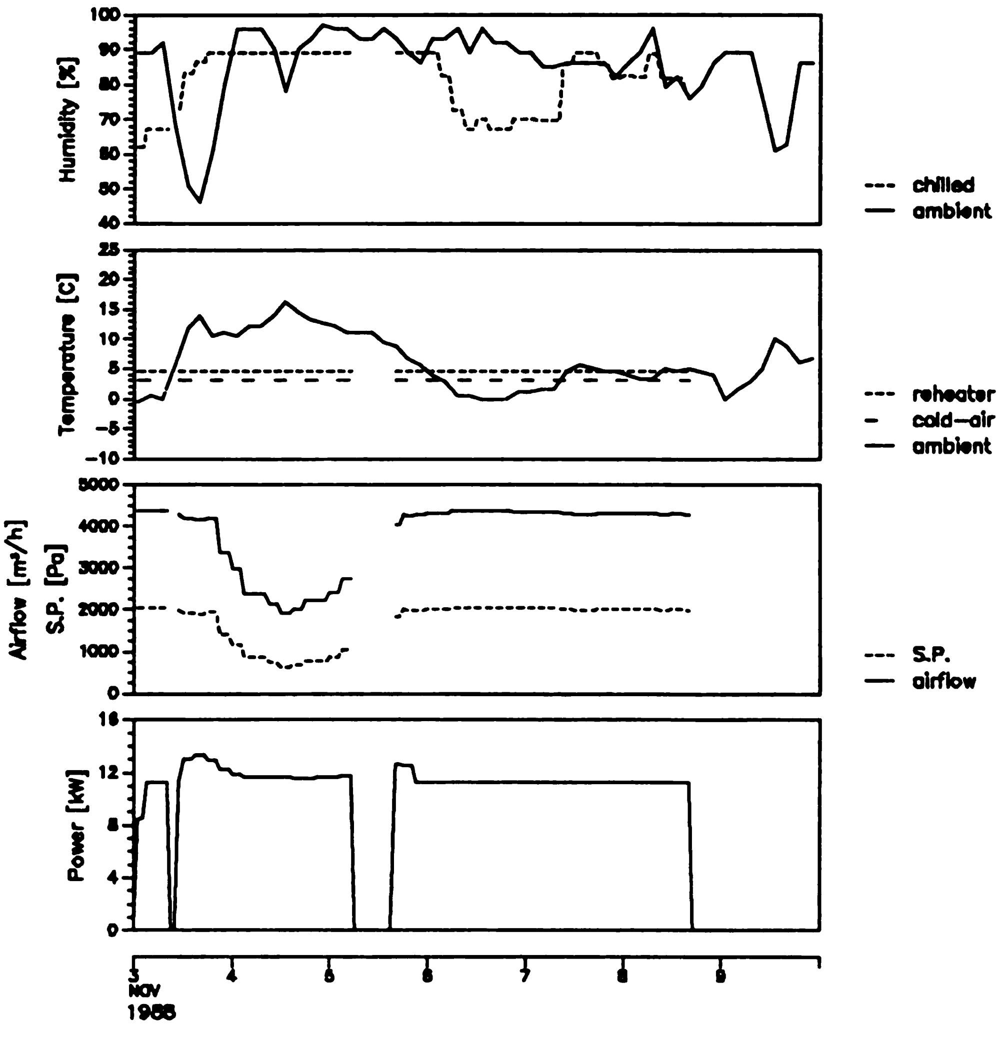

Figure 5.29 Simulated performance of the KK140 grain chilling unit during the initial cool-down of the grain bin between November 3 and 8, 1988.

airflow into the bin. The relative humidity of the ambient air is reduced from 90 to 65 percent before entering the bin. As the ambient temperature increases from 11/3 to 11/5, the airflow into the bin is reduced, i.e. the unit operates at maximum refrigeration and throttled airflow, and reaches a minimum of 2,100 m^3/h on 11/4. After 11/5 the cool-down proceeds again at maximum airflow. On 11/6 an additional electrical heating cycle is employed to maintain the bin inlet conditions. The relative humidity of the chilled air is about constant at 90% during the maximum airflow and maximum refrigeration operating modes, as long as the chiller evaporator is wet.

Although no experimental airflows and relative humidities into the test bin are available to show their variability during the fall 1988 cool-down period, the chiller model does predict the correct operating modes for the given ambient conditions. During low ambient temperature periods the built-in electrical heaters maintain the bin inlet conditions, during high ambient temperature periods the maximum refrigeration mode throttles the airflow, and during intermediate periods the unit operates at maximum airflow and throttled refrigeration capacity.

The simulated chiller operation predicts a power consumption of 1,428 kWh over 124 hours, compared to 1,385 kWh measured over 123.3 hours in the field test. This results in a simulated energy efficiency of 18.9 W per tonne of corn compared to an experimental value of 18.4 W/tonne for the full bin chilling period. The predicted and measured power consumption and energy efficiency are within 3 percent.

Fall 1990 Cool-down Cycle

Figure 5.30 shows the simulated and experimental temperatures of four grain layers for the step-wise cool-down cycle of November 1 through 10, 1990. The initial grain temperatures are 30.6°C, 30.6°C, 28.3°C and 26.7°C at 1.1 m, 2.9 m, 4.7 m, and 6.6 m above the perforated bin floor, respectively. To simulate the temperature rise at the 2.9 m, 4.7 m, and 6.6 m level, layers of warmer grain are assumed to be present between the thermocouple sensor locations. In the simulation initial temperatures of 37.5°C at the 2.0 m and 5.7 m depths, and of 35.0°C at the 3.8 m depth are assumed. The power outage on 11/2 is simulated by assuming that the grain temperatures do not change during the non-ventilated period.

The simulated temperature pattern closely resembles the experimental profile, especially in the lower layers, i.e. at 1.1 m and 2.9 m. At the 1.1 m pile depth the simulated and experimental layers show the same cooling rate and fluctuation due to the step-wise operating mode of the

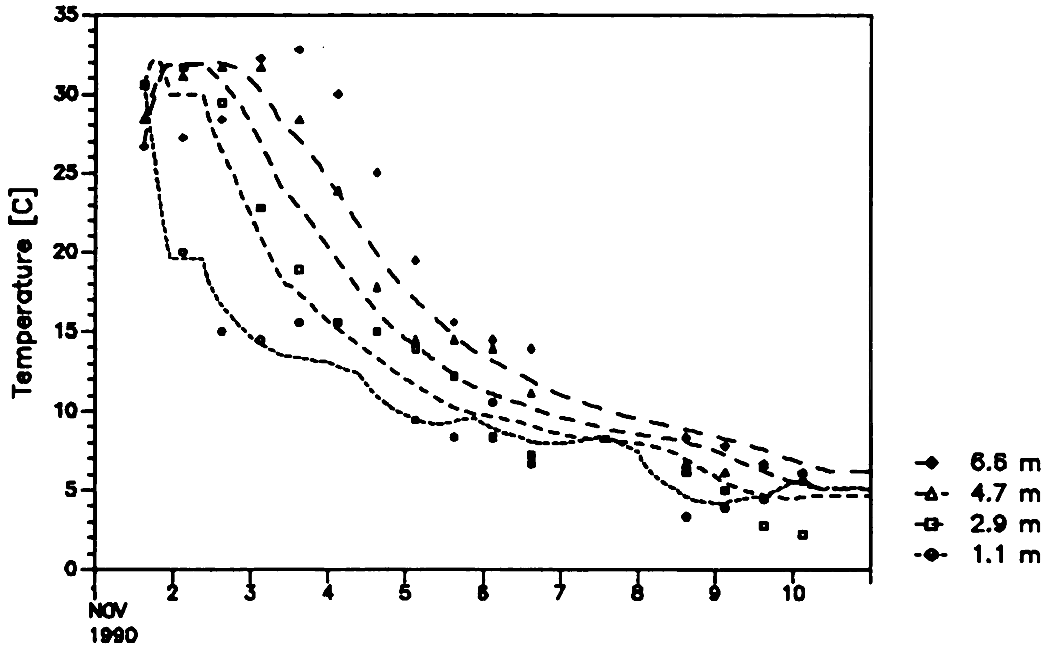

Figure 5.30 Simulated (lines) and experimental (symbols) grain temperatures at four depths in the chilled storage bin during the initial cool-down between November 1 and 10, 1990.

chiller. Some evaporative cooling of the bottom layer is observed on 11/5, 11/6 and 11/8 during which the grain temperature drops below the inlet chilled air temperature, confirming the experimental field test observations. The 2.9 m simulated layer predicts a shorter rewarming period on 11/2, and a similar cooling rate as the experimental layer between 11/3 and 11/5. After the step-change on 11/4 the simulated layer predicts faster cooling. The 4.7 m and 6.6 m simulated layers show shorter warming and faster cooling rates during the first four days of the cycle. Between 11/5 through 11/8 the simulated and experimental patterns are similar. At the end of the cool-down cycle the simulated and experimental temperatures are within 0.5° to 1.0°C. The final simulated temperature range of the grain is the same as the experimental one, i.e. 2° to 6°C.

Table 5.11 compares the difference and variability between the simulated and experimental temperature values.

Table 5.11 Average absolute difference (AAD) and sample standard deviation (SSD) between the simulated and experimental temperature values for the initial cool-down cycle in the fall of 1990 (in °C).

	1.1 m	2.9 m	4.7 m	6.6 m	Overall
AAD	1.19	1.58	2.05	2.72	1.88
SSD	1.00	0.77	1.65	2.12	1.59

The 2.9 m layer shows the smallest difference (AAD) and variability (SSD) between the simulated and experimental values; the 6.6 m pile depth the largest. For the four layers the average absolute difference is 1.88°C with a standard deviation of 1.59°C. These values are larger than for the fall 1988 cool-down validation. However, in light of the experimental variability in the field test the chilled aeration simulation model predicts the temperature profile of the experimental cool-down in the fall of 1990 acceptably accurate.

The cool-down time of the slowest grain layer, i.e. the 6.6 m level, to reach 7°C is about 201 hours in the experimental bin compared to 200 hours in the simulated bin, i.e. a difference of +1.0 hour. This is a higher degree of accuracy than during the fall 1988 cool-down validation, and it confirms the accuracy of the cooling time prediction.

Figure 5.31 shows the simulated operation of the KK140 grain chiller during the cool-down cycle given the actual ambient conditions between November 1 and 10, 1990. The cold-air and reheater temperatures for the simulated and experimental grain chiller were adjusted step-wise to 10 and 15°C on 11/1 - 11/3 (except for a brief period on 11/4 when the reheater was 13°C), 6.5 and 10°C on 11/4 - 11/7, and 3.5 and 5°C on 11/8 - 11/10, respectively. The potential heat loss or gain

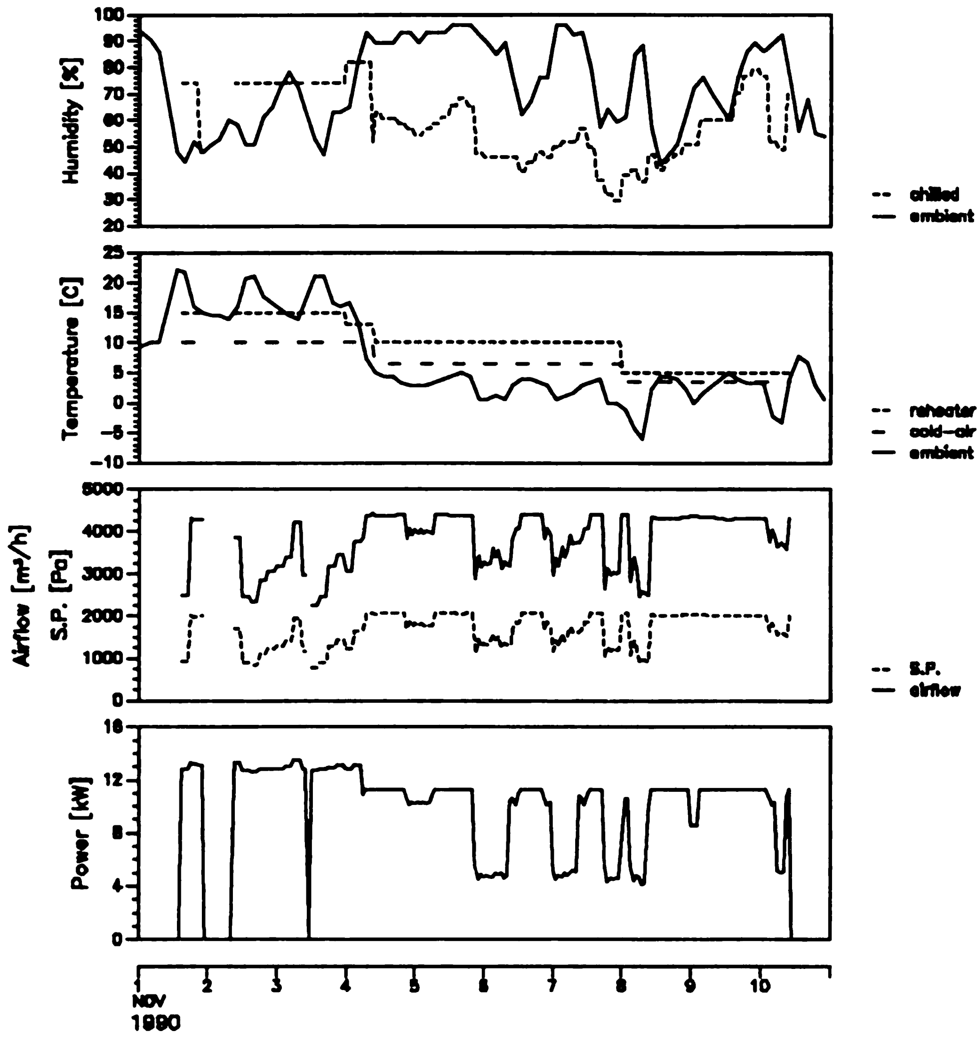

Figure 5.31 Simulated performance of the KK140 grain chilling unit during the initial cool-down of the grain bin between November 1 and 10, 1990.

in the connecting duct is considered negligible. The maximum airflow rate in the simulated chiller is set to 4,000 m^3/h, which is the value determined in the field test. The run time of the unit is the same as in the field test, i.e. 201 hours under the full bin conditions.

During the first hours of the cool-down the ambient temperature is above the chiller cold-air temperature set-point. The bin inlet conditions are maintained in both the maximum refrigeration and maximum airflow operating modes. The cold-air set-point is low enough to cause condensation in the evaporator, and thus the air before the reheater is saturated. The 5°C of reheating lowers the relative humidity of the bin inlet air to 75 percent. Simultaneously to a reduction in the set-points, the ambient temperature decreases on 11/4. Depending on warming of the ambient air in the fan before the evaporator, the inlet air to the bin is maintained by the electrical heating mode or the maximum airflow mode of the chiller. The airflow, although maximum for most of the cooling cycle, varies according to the operating mode.

During the last step in the cool-down cycle the ambient air temperature is intermittently between the cold-air and the reheater set-point temperatures. The cooling load is small enough to allow maximum airflow during most of the period.

The predicted minimum airflow rate during the fall 1990 cool-down cycle is 2,200 m^3/h. The relative humidity of the chilled air entering the bin ranges from 30 to 85 percent during the cool-down. It is constant when the cold-air set-point is low enough to cause condensation in the evaporator. Although no experimental airflows and relative humidities into the test bin are available to show their variability during the fall 1990 cool-down period, the chiller model does predict the correct operating modes for the given ambient conditions.

The simulated chiller operation predicts a power consumption of 2,083 kWh over 201 hours, compared to 2,188 kWh measured over 197.8 hours in the field test. This results in a simulated energy efficiency of 17.4 W per tonne of corn compared to an experimental value of 18.5 W/tonne for the full bin chilling period. Figure 5.31 shows the predicted power requirement of the chilling unit. On 11/6 through 11/8 the electrical heating stages are cycled on and off several times. This simulated variation between fan-only and electrical heating may be smaller than for the actual chiller, since the cycling occurs at an hourly interval in the model, while in the field the interval is likely to be much shorter. However, the predicted and measured power consumption and energy efficiency differ by only 6 percent, and thus are considered to be acceptably accurate.

Spring 1990 Chilling Cycle

Figure 5.32 shows the simulated and experimental temperatures of four grain layers for the chilling cycle of May 4 through 7, 1990. The initial grain temperatures are 4.4°C, 0.6°C, 1.7°C and 1.7°C at 2.8 m, 4.6 m, 6.5 m and 8.3 m above the perforated bin floor, respectively. To simulate the initial temperature reduction at the 6.5 m and 8.3 m level, layers of cooler grain are assumed between the thermocouple sensor locations. In the simulation an initial temperature of 0°C at the 1.9 m and 3.7 m depths is assumed.

The simulated temperature pattern resembles the experimental profile quite well. At the 2.8 m pile depth the simulated layer shows a slower warming rate on 5/4 and does not predict the maximum temperature of 9°C on 5/7 as observed experimentally. However, the simulated layer does predict a maximum of 8.5°C on 5/6 before cooling off toward the end of the cycle. The 4.6 m layer predicts a slightly faster initial warming rate before converging to the experimental values. The 4.6 m and 8.3 m levels initially reach a minimum temperature before rewarming. The simulation predicts a faster-moving warming front, especially at the 8.3 m level. However, at the end of the chilling cycle the simulated and experimental temperatures are within 0.1 to 0.3°C. The final simulated temperature range of the grain is the same as observed in the field test, i.e. 6 to 8°C.

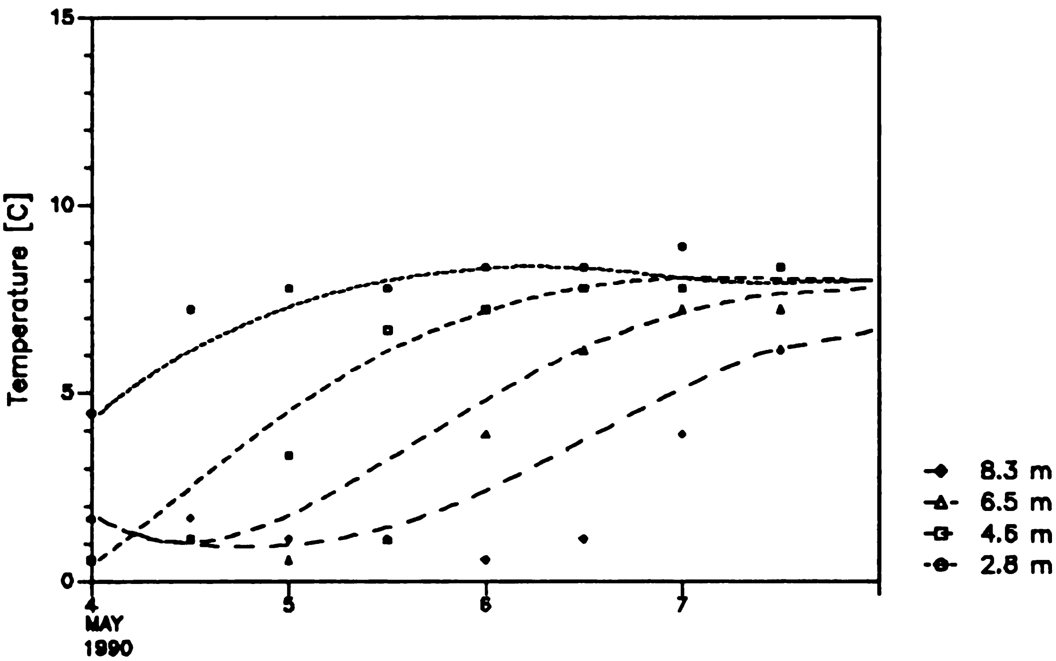

Figure 5.32 Simulated (lines) and experimental (symbols) grain temperatures at four depths in the chilled storage bin during the chilling cycle between May 4 and 7, 1990.

Table 5.12 compares the difference and variability between the simulated and experimental temperature values.

Table 5.12 Average absolute difference (AAD) and sample standard deviation (SSD) between the simulated and experimental temperature values for the chilling cycle in the spring of 1990 (in °C).

	2.8 m	4.6 m	6.5 m	8.3 m	Overall
AAD	0.44	0.53	0.56	0.90	0.61
SSD	0.38	0.53	0.68	0.90	0.66

The 2.8 m layer shows the smallest difference and variability between the simulated and experimental values; the 8.3 m pile depth the largest. For the four layers the overall average absolute difference is 0.61°C with a standard deviation of 0.66°C. These values are in the same range as for the 1988 cool-down validation. The largest absolute difference in the 8.3 m layer between the simulated and experimental values is 2.62°C; this value is fairly small in light of the variability of the grain mass.

The rewarming time of the slowest grain layer, i.e. the 8.3 m level, to reach 6.5°C is about 88 hours in the experimental bin compared to 92.5 hours in the simulated bin, i.e. a difference of -4.5 hours. This is a higher degree of accuracy than during the fall 1988 cool-down validation, and confirms the small difference observed during the fall 1990 cool-down.

Figure 5.33 shows the simulated operation of the KK140 grain chiller during the spring chilling cycle given the actual ambient conditions between May 4 and 7, 1990. The cold-air and reheater temperatures for the simulated and experimental grain chiller for the entire cycle are 4 and 8°C, respectively. To simulate the warming of the 2.8 m level above the reheater set-point temperature, a heat gain of 1°C is assumed in the connecting duct. The maximum airflow rate in the simulated chiller is set at 4,200 m^3/h, which is the value determined experimentally. The run time of the unit was the same as in the field test, i.e. 95 hours.

For the entire four-day period the ambient temperature is above the cold-air temperature set-point. The ambient cooling load is low enough between 4/5 and 4/6 for the chiller to operate in the maximum airflow range, except for two brief periods when the ambient temperature reaches 15°C on 5/5 and 5/6. On 5/7 the ambient temperature rises above 20°C and the airflow into the bin is throttled. The cold-air set-point is low enough to cause condensation in the evaporator (i.e. saturated air before the reheater) during half of the chilling period. The 4°C of reheating plus the 1°C heat gain in the duct lowers the relative humidity of the bin inlet air to 75 percent. The rest of the time the

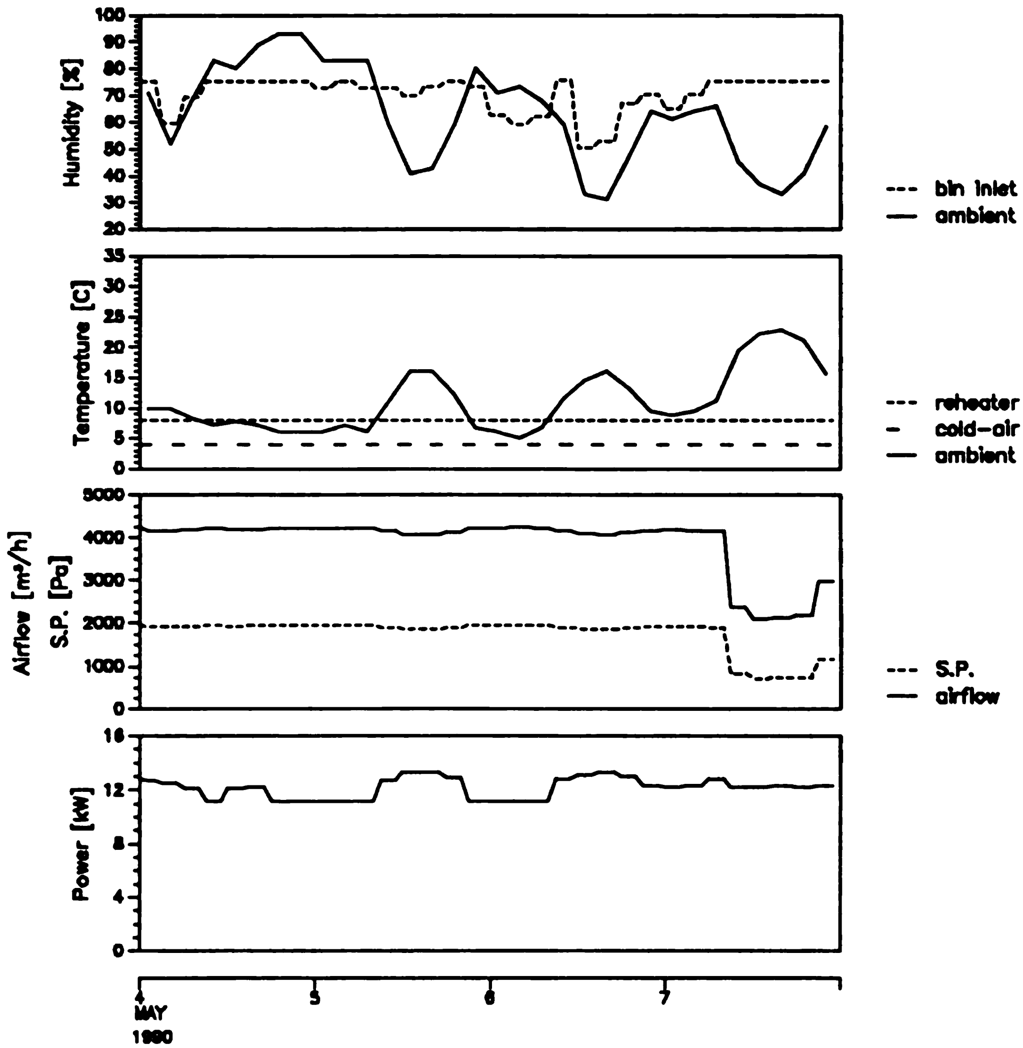

Figure 5.33 Simulated performance of the KK140 grain chilling unit during the chilling cycle of the grain bin between May 4 and 7, 1990.

evaporator is dry (i.e. the air is not saturated before the reheater) and the relative humidity of the air into the bin fluctuates between a low of 50% and a high of 75% as a function of the ambient absolute humidity and the reheater temperature. Again, no experimental airflows and relative humidities of the air entering the test bin are available. However, the chiller model does predict the correct operating modes for the given ambient conditions.

The simulated chiller operation predicts a power consumption of 1,155 kWh over 95 hours, compared to 1,282 kWh measured over the same period in the field test. This results in a simulated energy efficiency of 20.7 W per tonne of corn compared to an experimental value of 23.0 W/tonne for the full bin chilling period. The simulated power consumption and energy efficiency differ by 11 percent; this is less accurate than for the 1988 and 1990.

Spring 1991 Chilling Cycle

Figure 5.34 shows the simulated and experimental temperatures of four grain layers for the chilling cycle of May 22 through 28, 1991. The initial grain temperatures are 11.1°C, 7.2°C, 3.3°C and 5.0°C at 1.1 m, 2.9 m, 4.7 m and 6.6 m above the bin floor, respectively.

The simulated temperatures show a similar pattern as the

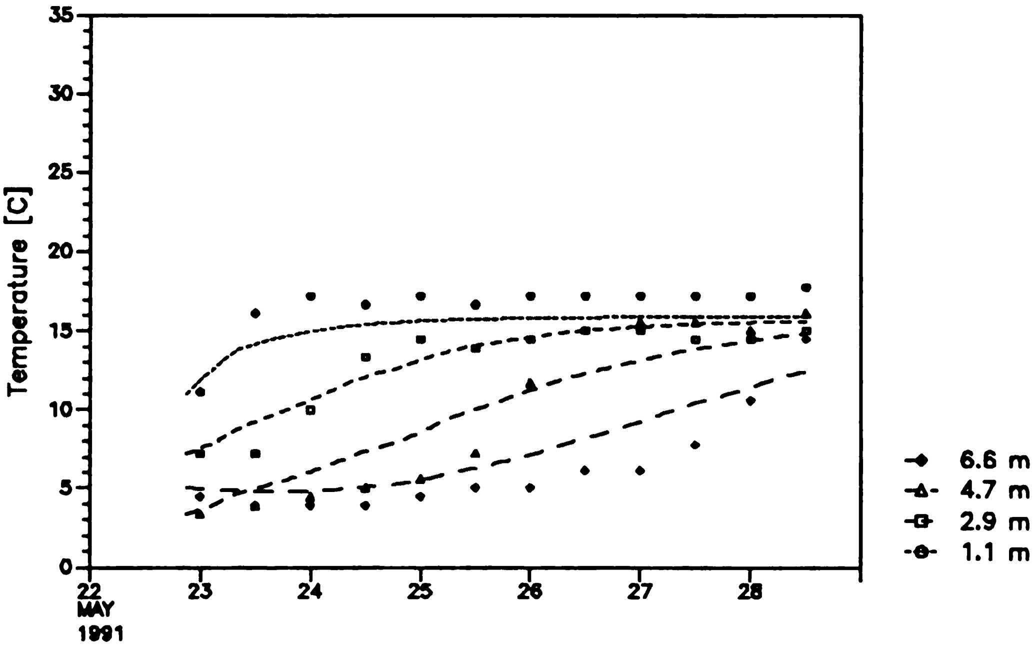

Figure 5.34 Simulated (lines) and experimental (symbols) grain temperatures at four depths in the chilled storage bin during the chilling cycle between May 22 and 28, 1991.

experimental profile. At the 1.1 m pile depth the simulated layer shows a slower warming rate on 5/23 and does not rise to the same level as the experimental layer, although 2°C of reheating are assumed in the duct. The 2.9 m level predicts initially a faster temperature rise before slowing down on 5/24. The simulated and experimental patterns compare well for the remainder of the cycle. The 4.7 m layer predicts a faster initial warming rate until 5/26 and a slower one for the rest of the cycle. The 6.6 m level shows a similar profile as the experimental layer but a temperature difference persists throughout the entire cycle. Overall, the simulated layers show flatter patterns than the experimental values. At the end of the chilling cycle the simulated and experimental temperatures are within 0.6 to 2.0°C. The final simulated temperature range of the grain is the same as observed in the field test, i.e. 12 to 17°C.

Table 5.13 compares the difference and variability between the simulated and experimental temperature values for the spring 1991 cycle.

Table 5.13 Average absolute difference (AAD) and sample standard deviation (SSD) between the simulated and experimental temperature values for the chilling cycle in the spring of 1991 (in °C).

	1.1 m	2.9 m	4.7 m	6.6 m	Overall
AAD	1.44	0.92	1.69	1.48	1.38
SSD	0.42	0.61	0.97	0.83	0.79

The 2.9 m layer shows the smallest difference and variability between the simulated and experimental values; the 4.7 m pile depth the largest. For the four layers the overall average absolute difference is 1.38°C with a standard deviation of 0.79°C. These values are higher than for the spring 1990 chilling data validation. The largest absolute difference between the simulated and experimental values is 3.2°C and occurs in the 6.6 m layer.

The rewarming time of the slowest grain layer, i.e. the 6.6 m level, to reach 12.0°C is about 126.5 hours in the experimental bin compared to 129 hours in the simulated bin, i.e. a difference of -2.5 hours. This validates the agreement observed in the spring 1990 and fall 1990 chilling cycles.

Figure 5.35 shows the simulated operation of the KK140 grain chiller during the spring chilling cycle under the ambient conditions between May 22 and 28, 1991. The cold-air and

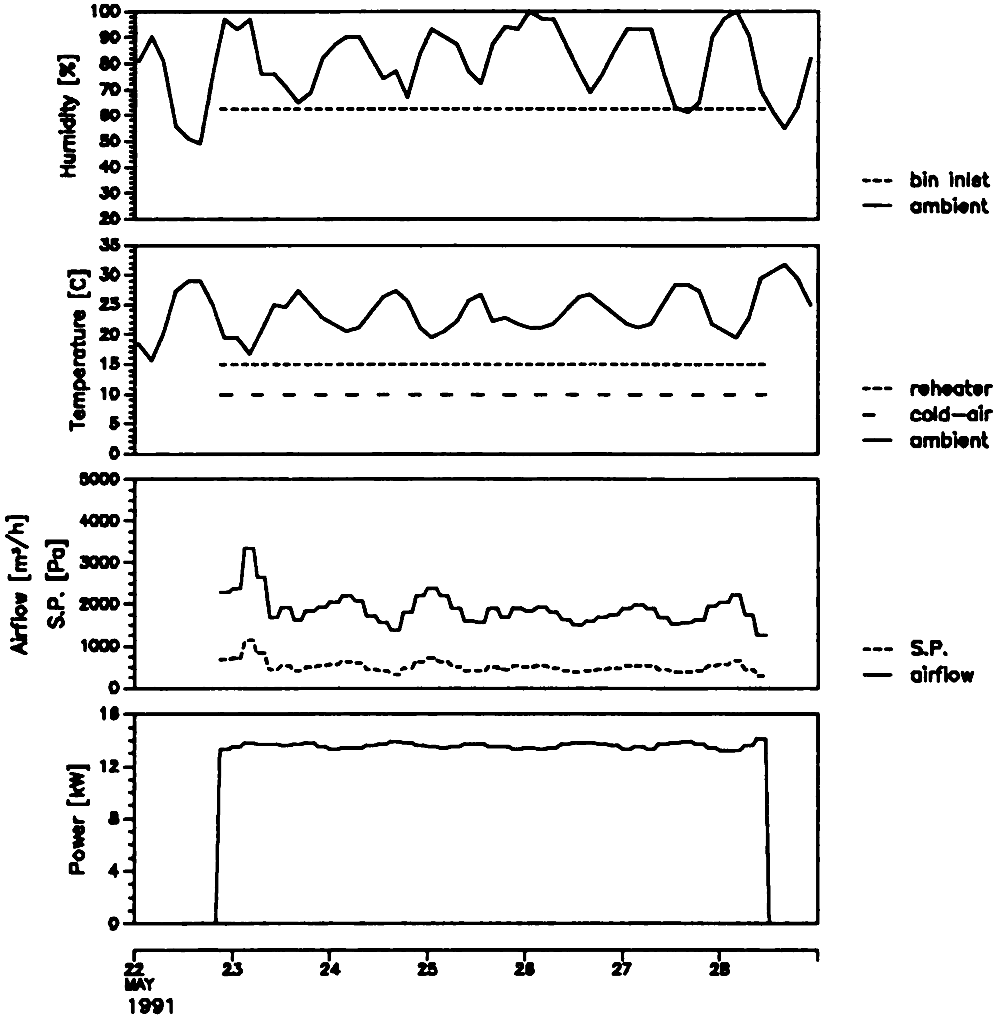

Figure 5.35 Simulated performance of the KK140 grain chilling unit during the chilling cycle of the grain bin between May 22 and 28, 1991.

reheater set-points for the experimental grain chiller was 9 and 14°C, respectively. The analysis of the chiller outlet conditions shows the outlet air from the chiller to be about 2.5°C above the reheater set-point (see Figure 5.21). To simulate this condition in addition to the warming of the grain at the 1.1 m level in the experimental bin, the simulated cold-air and reheater set-point temperatures were set at 10° and 15°C, and a heat gain of 2°C was added in the connecting duct. The maximum airflow rate in the simulated chiller was set to 4,200 m^3/h, which is the value determined experimentally. The run time is the same as in the field test, i.e. 135 hours.

For the entire six-day period the ambient temperature is above the cold-air temperature set-point. The ambient cooling load is high enough for the chiller to operate in the maximum refrigeration range, except for a brief period on 5/23 when the ambient temperature reaches 16°C. The cold-air set-point is low enough to cause condensation in the evaporator (i.e. saturated air before the reheater) during the entire chilling cycle. The 5°C of reheating in the chiller and the 2°C heat gain in the duct lower the relative humidity of the bin inlet air to a constant 63 percent. The predicted relative humidity can be compared to the experimental chiller outlet relative humidity presented in Figure 5.21. The experimental outlet relative humidity was almost constant at 80% for most of the operating period. This value is high for reheating the saturated air by 5°C and should be closer to 75%. Subtracting the effect of heat gain in the duct raises the simulated relative humidity at the outlet of the chiller to about 73%; this is close to the expected experimental value. This confirms the validity of the predicted relative humidity by the grain chilling unit. As in the previous chilling cycle validations, the KK140 simulation model predicts the correct operating mode for the given ambient conditions.

The simulated chiller operation predicts a power consumption of 1,832 kWh during 135 hours, compared to 1,891 kWh measured experimentally. This results in a simulated energy efficiency of 27.9 W per tonne of corn compared to an experimental value of 28.8 W/tonne for the chilling period. The simulated power consumption and energy efficiency differ by about 3 percent. This is within the range of accuracy predicted in the fall 1988 and fall 1990 validations. It also indicates that the spring 1991 difference of 11% between the predicted and observed value is high.

Summary

The coupled chilled aeration and grain chiller model predicts with an acceptable degree of accuracy (1) the temperature patterns during the chilling and rechilling of the grain in the experimental bin in the fall of 1988 and 1990, and the spring of 1990 and 1991, (2) the cooling time required to bring the grain temperature to the desired level, (3) the operating modes of the grain chilling unit, and thus the variation of the airflow and relative humidity of the air entering the storage bin, and (4) the power consumption (and energy efficiency) of the grain chiller. Thus, the model simulates the chilled aeration of a grain mass, employing a chilling unit, well.

5.2.3 Chilled Grain Storage

In order to be valid the chilled grain storage model, which simulates the two-dimensional conduction heat transfer in the grain bin, must with a certain degree of accuracy predict (1) the correct temperature trends in the core, bulk and periphery of the grain pile during the non-ventilated storage period, and (2) the correct temperatures at different grain depths and radial distances in the grain bin.

To verify the two-dimensional simulation model a 20 by 20 grid is used for the bin height and radius in combination with a time step of 3 hours. The effect of selecting a particular grid size and time step will be evaluated in detail in Chapter 6.2. The simulated storage periods use the following environmental inputs: (1) the ambient dry-bulb temperature for the Lansing area between October 1988 and July 1991 (see Figures 5.7, 5.15, and 5.22), (2) the daily solar flux on the vertical test bin surface for a typical year (see Figure 5.36), and (3) the average monthly wind speeds for the field test site between October 1988 and July 1991 (see Figure 5.37).

In the development of the storage submodel an initial sensitivity study was undertaken to evaluate the influence of various boundary condition parameters, i.e. the convective heat transfer coefficients, the free-stream temperatures, and the radiative flux values. It was found that the convective and the radiative heat transfer at the wall influenced the temperature profile in the bin significantly. Both boundary conditions use average monthly values, i.e. the convective heat transfer uses average wind speeds and the radiative heat transfer uses average solar fluxes. In order for the storage submodel to predict the temperatures with the given accuracy presented below, the equation of the convective wall heat transfer coefficient (i.e. eq. 4.100) was multiplied by a factor of 1.55. The effect of the boundary conditions is evaluated in more detail in Chapter 6.2.

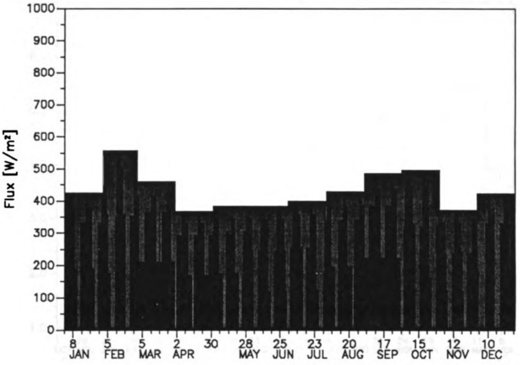

Figure 5.36 Daily solar flux on the vertical wall surface of the field test bin in Williamston, Michigan for a typical simulation year.

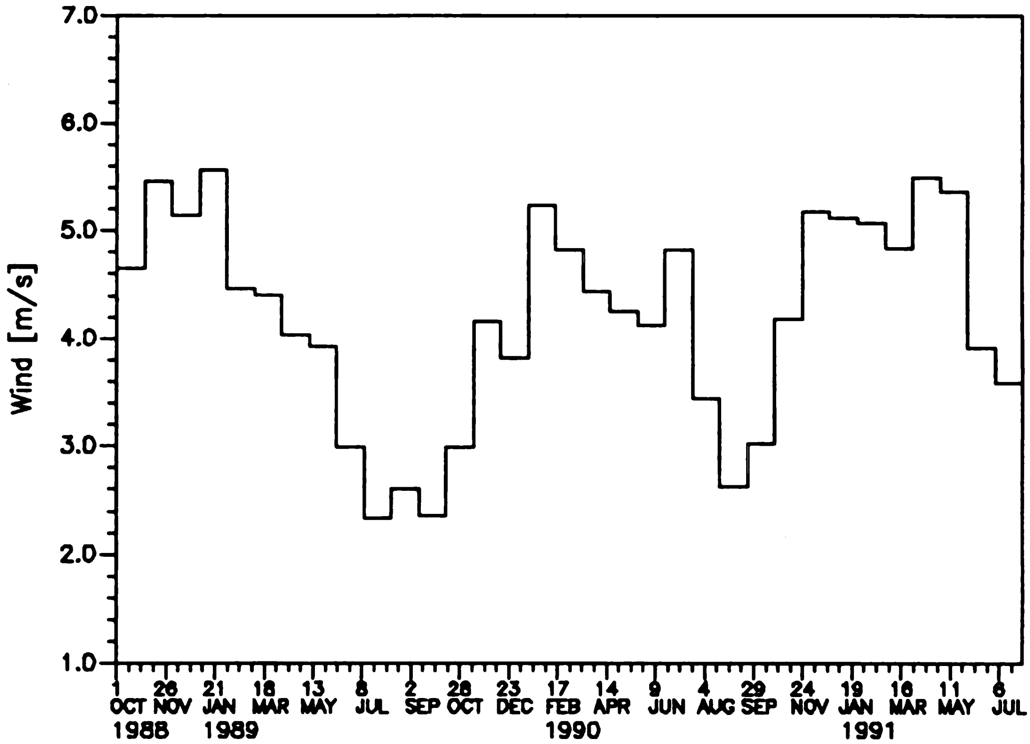

Figure 5.37 Average monthly wind speeds between October 1988 and July 1991 used in the simulation of the chilled grain storage periods for the site of the experimental bin.

The validation of the chilled storage model utilizes the limited number and selected placement of the thermocouple sensors in the experimental bin to evaluate the observed temperatures against the predicted ones. An experimental temperature in the grain bulk during the storage period is calculated as the average of all cable sensors in the grain pile (excluding the bottom sensors of each cable). The periphery temperature in the pile is calculated as the average of the bottom sensors of cables A, B and C (except for the 1989-90 season), and the core temperature of the pile is calculated as the average of the sensors on cable D at 2.8, 4.6 and 6.5 m above the floor. The simulated grain bulk is defined as 90 percent of the total bin volume. The periphery constitutes the remaining 10 percent of the grain mass, and includes the grain at the top and bottom pile surfaces, and near the wall surfaces of the bin. The core constitutes the node at the center of the grain mass.

1988-89 Storage Period

Figure 5.38 shows the simulated and experimental average bulk temperatures during the non-ventilated storage period between December 27, 1988 and April 2, 1989. The initial bulk temperature is 2.5°C, and is assumed to be uniform throughout the bulk in the simulation. The simulated and experimental temperatures follow a similar pattern in the first month before beginning to diverge slightly in mid-

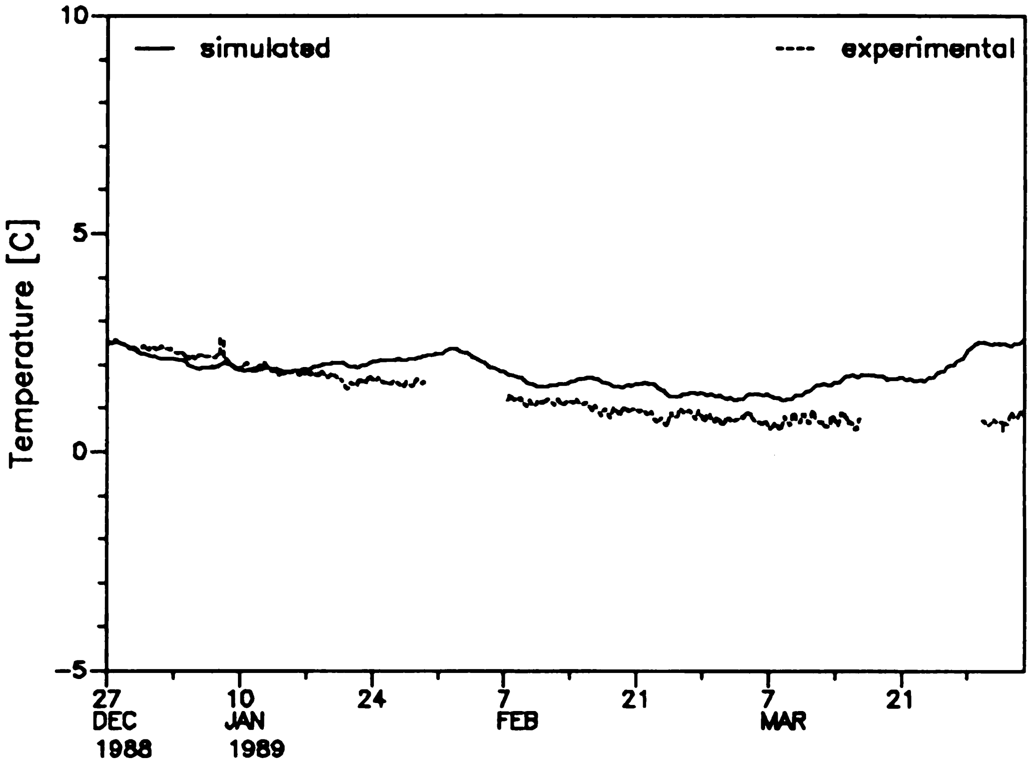

Figure 5.38 Simulated and experimental bulk temperatures in the chilled grain storage bin between December 27, 1988 and April 2, 1989.

January. The simulated bulk temperature undergoes a temperature rise to 3°C by early February while the experimental bulk temperature remains at 2°C. Both show a temperature decrease from the beginning of early February until the middle of March. The temperature difference between the simulated and experimental bulk temperature during this phase remains at 0.6 - 0.8°C. While the experimental bulk temperature does not appear to change after March 7, the simulated layer indicates a temperature rise of 1°C through April 2, 1989.

The average absolute difference (AAD) for the four-month storage period is 0.50°C with a variability (SSD) of 0.40°C. Although the bulk temperature patterns do not overlap, similar temperature changes are predicted by the simulation as measured experimentally.

<u>1989-90 Storage Period</u>

Figure 5.39 shows the simulated and experimental average bulk temperature during the non-ventilated storage period between November 30, 1989 and April 29, 1990. The initial bulk temperature is 4°C and is assumed to be uniform throughout the bulk. The simulated and experimental temperatures follow a similar pattern throughout the entire storage period. The experimental bulk temperature indicates fluctuations throughout the storage period with amplitudes

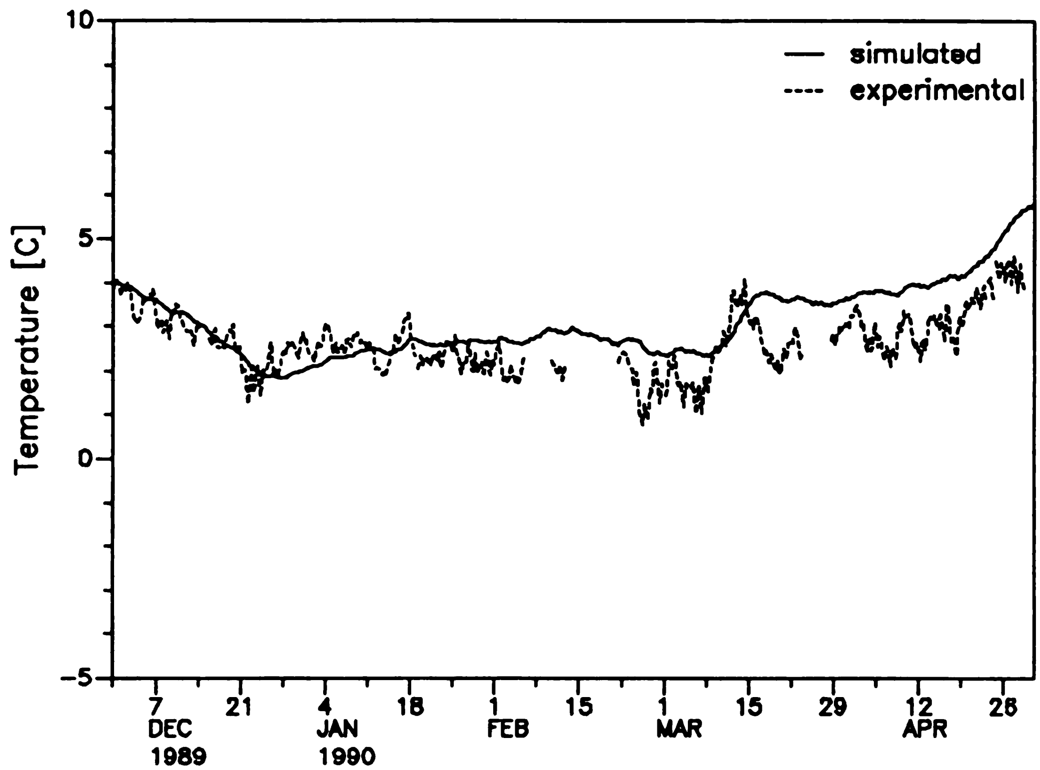

Figure 5.39 Simulated and experimental bulk temperatures in the chilled grain storage bin between November 30, 1989 and April 29, 1990.

of up to 1°C. The cooling of the bulk to 2°C due to heat conduction is shown in both cases during the month of December. During January the simulated bulk temperature increases steadily to 3°C, while the experimental pattern shows a rise through mid-January, followed by a decrease until March 1.

The simulated layer indicates a temperature decrease from the latter half of February through early March without reaching the low temperature of the experimental bulk. By the middle of March both patterns indicate rising bulk temperatures. The simulated bulk rises from 2.5°C to 4°C between March 15 and March 22, then remains level through the end of March before increasing throughout April. The experimental curve also predicts a sudden increase in the bulk temperature in mid-March but levels off at about 1°C below the simulated layer. A noticeable temperature increase is predicted throughout April as was measured experimentally.

The average absolute difference (AAD) for the five-month storage period is 0.61°C with a variability (SSD) of 0.43°C. The bulk temperature patterns overlap during most of the storage period; and the predicted and observed bulk temperatures usually agree to within less than 1°C difference.

After the early May chilling cycle a second non-ventilated storage period is shown in Figure 5.40 between May 12 and June 16, 1990. The simulated bulk temperature increases steadily from about 8°C to 10.5°C throughout the 5-week storage period. The experimental bulk temperature also increases but only by 1°C. The AAD during the period is 0.65°C with a variability of 0.39°C. The simulation model slightly overpredicts the temperature rise in the bulk of the storage bin. This is in part explained by the simulated environmental boundary condition on the southern half of the bin, i.e. the actual thermal radiation and wind speed are more pronounced than the simulated ones.

1990-91 Storage Period

Figure 5.41 shows the simulated and experimental average bulk temperatures during the non-ventilated storage period between January 10 and May 22, 1991. The initial bulk temperature is -2.5°C and assumed to be uniform throughout the bulk. The simulated and experimental temperatures follow a similar pattern throughout the entire storage period. The experimental bulk temperature indicates fluctuations throughout the storage period with amplitudes of up to 1.5°C. Both patterns show small cyclic temperature increases in January and February. By late March the simulated bulk temperature reaches 0°C, while the experimental bulk remains below 0°C until early April.

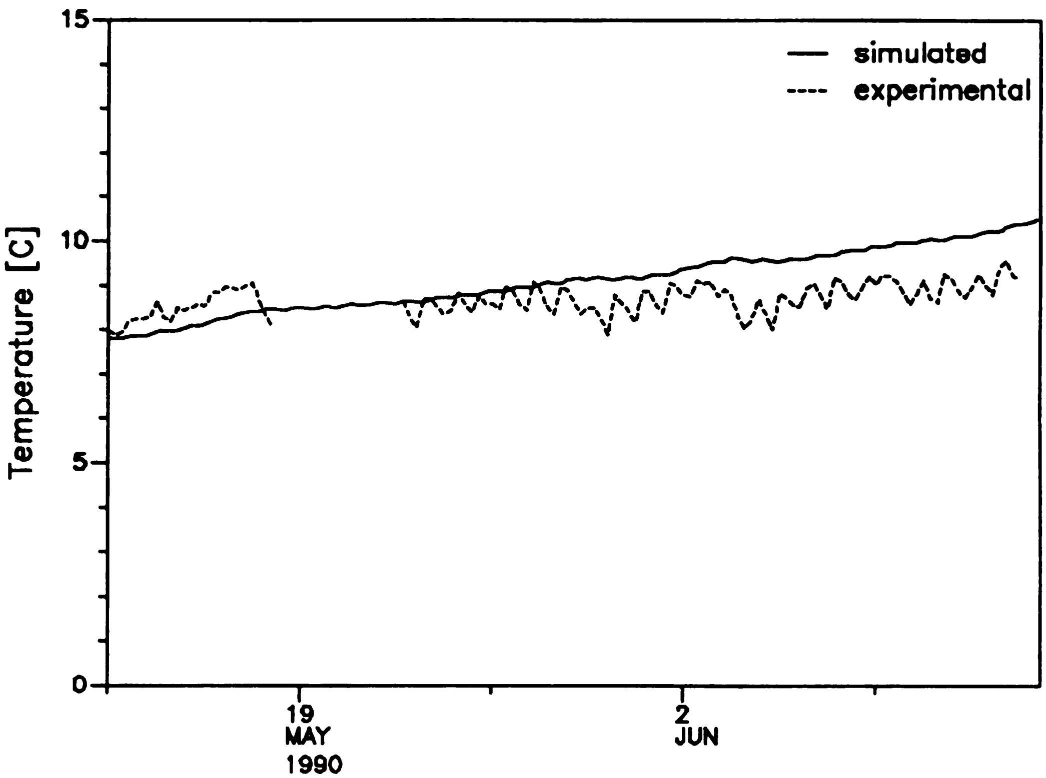

Figure 5.40 Simulated and experimental bulk temperatures in the chilled grain storage bin between May 12 and June 15, 1990.

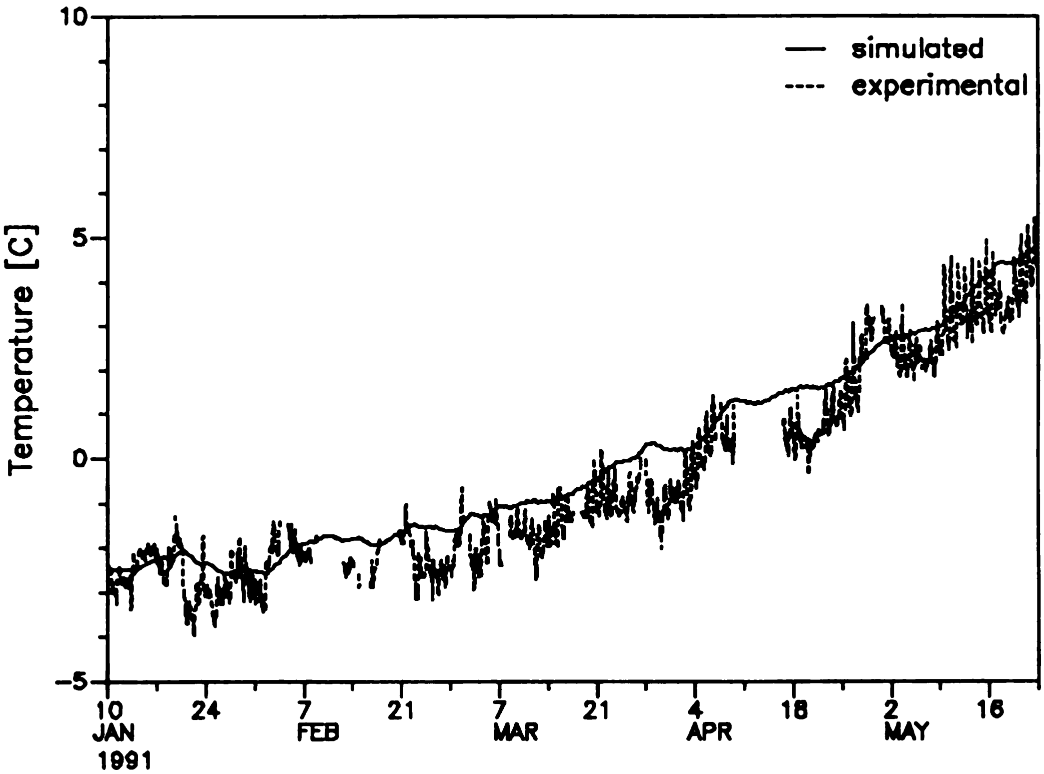

Figure 5.41 Simulated and experimental bulk temperatures in the chilled grain storage bin between January 10 and May 22, 1991.

The observed bulk temperature shows a slower rise throughout February and March, and generally remains slightly below the simulated bulk temperature. In late March and early April the patterns appear to diverge somewhat, with the simulated layer predicting a temperature rise, while the experimental bulk temperature remains fairly constant. Throughout April the experimental temperature lags behind the simulated one; the experimental temperature shows a sudden increase in late April before dropping below the simulated bulk temperature in early May. The patterns overlap throughout May. The final temperatures before the May chilling cycle is 5°C in both the observed and simulated bulks.

The average absolute difference for the four-and-a-half month storage period is 0.62°C with a variability of 0.41°C. The bulk temperature patterns overlap during much of the storage period, especially during the 4°C temperature increase between late April and May 22. The large fluctuation of the experimental bulk temperature can partly be attributed to the thermocouple sensor accuracy. It is possible that more noise was picked up by the Scancenter monitoring system during the 1990-91 season than during the 1989-90 season. The primary difference in the data logging system was that in the first season the temperatures were recorded every 6 hours while in 1990-91 they were recorded hourly. The bulk temperature in Figure 5.41 was not smoothed over time, but only averaged over several sensors.

Layers and Columns

The commercial grain bin used in the field tests was not instrumented with a large number of thermocouple sensors. Thus, temperature patterns in layers and columns of the chilled grain were not directly determined. Only single point measurements throughout the bulk, the periphery and the core of the pile were made. However, in the validation of the chilled storage model an attempt is made to evaluate the layer and column predictions of the simulated grain bin. [Grain bins instrumented with large numbers of thermocouple sensors to monitor temperature changes in vertical layers and radial columns have previously been used by researchers to establish the validity of the two-dimensional heat conduction modelling approach for the storage of grain (see Section 4.3). It was not an objective of this study to duplicate those efforts.]

Figure 5.42 shows the average temperature recorded at equal pile depths of three cables between the January 10 through May 22, 1991 storage period. The 0.9 m level, which is the average depth of the bottom sensors on cables A, B, and C, decreases from 3°C on 1/10 to about -3°C by the end of January. The 0.9 m level is the warmest throughout the remainder of the storage season and increases cyclically to

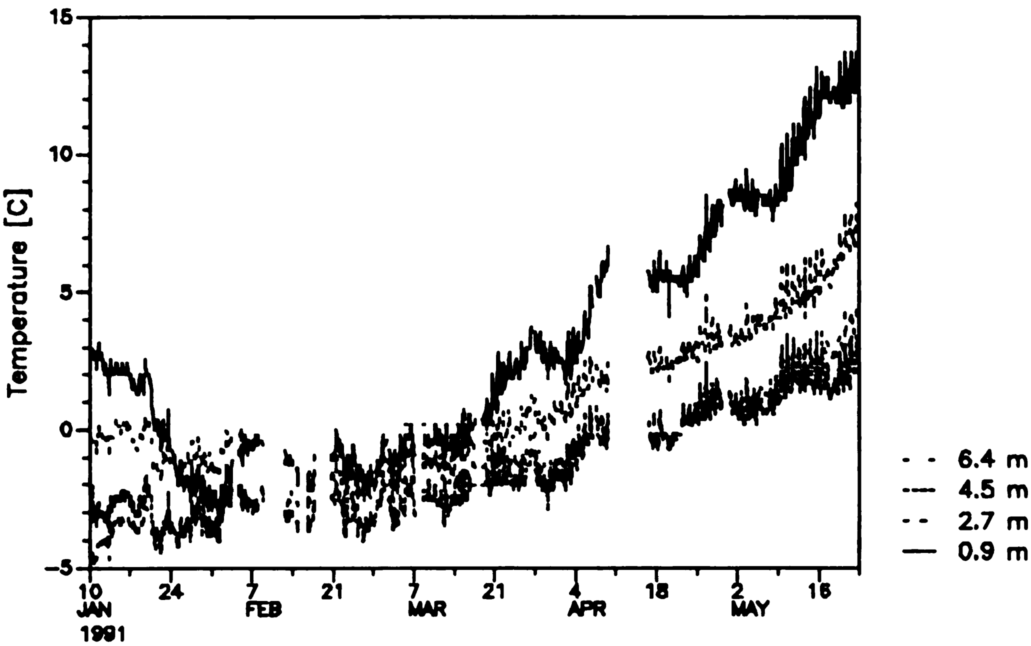

Figure 5.42 Average experimental temperature at four pile depths in the chilled grain storage bin between January 10 and May 22, 1991.

13°C by May 22. The 2.7 m level follows a similar pattern by first decreasing from initially 0°C to -2°C by mid-February, and subsequently increasing to 7.5°C by May 22. Levels 4.5 m and 6.4 m follow the same pattern. They increase cyclically from a low of -3°C and -4.5°C, respectively, to 3.5°C and 2.5°C by May 22, respectively.

The average experimental temperature patterns described in Figure 5.42 are plotted against the simulated average layer temperatures, which correspond to the respective levels in Figure 5.43 between January 10 and May 22, 1991. The simulated and experimental temperature patterns differ substantially at the 0.9 m level. At the 2.7 m level the simulated average layer temperature underpredicts the experimental pattern. However, at the higher pile levels of 4.5 m and 6.4 m the agreement between the simulated and experimental patterns is good for much of the storage period. Considering the angle of the bin cables during the 1990-91 season, Figure 4.43 appears to verify that the bottom level sensors are closer to the periphery while the upper level sensors are more in the interior of the grain bulk.

Figure 5.44 verifies the observation made in the previous paragraph. The experimental temperature patterns of Figure 5.41 are plotted against the simulated average column

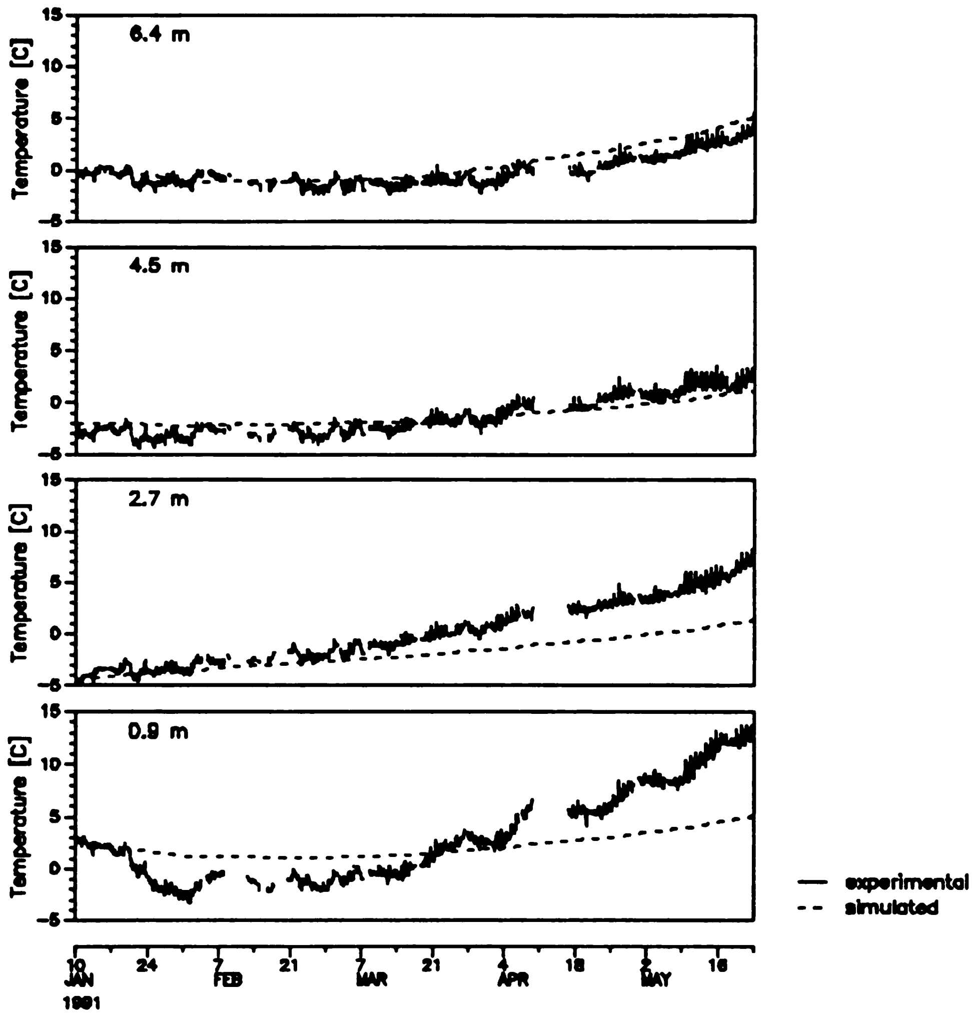

Figure 5.43 Simulated and experimental average layer temperatures in the chilled grain storage bin between January 10 and May 22, 1991.

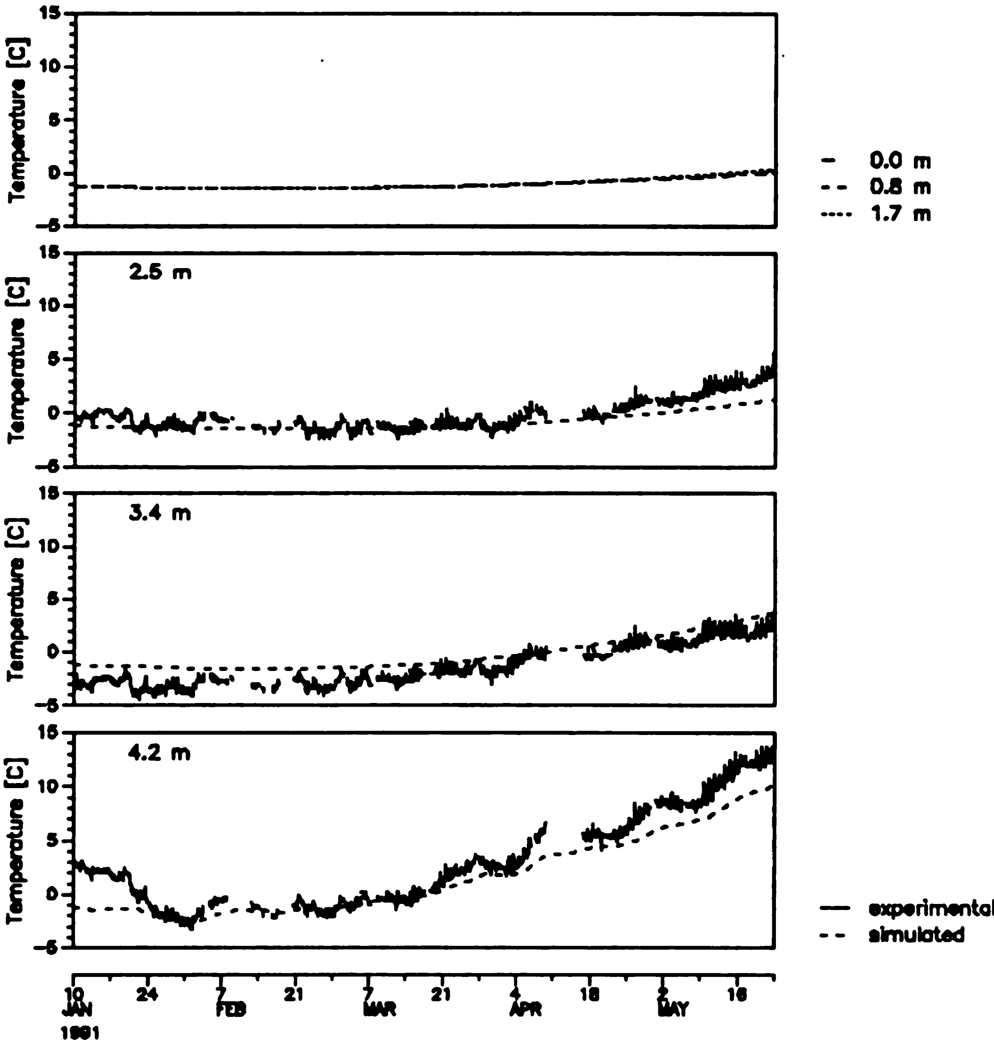

Figure 5.44 Simulated and experimental average column temperatures in the chilled grain storage bin between January 10 and May 22, 1991.

temperatures that approximately correspond to the radial distances of the cable sensors. At the 4.2 m radial distance from the core, the predicted temperature pattern follows the experimental one [which was previously labelled as the "0.9 m level"] closely except for the first two weeks. [The discrepancy is caused by specifying initially layer averages rather than radial column averages. The effect dissipates after two weeks.] At the 3.4 m radial distance the simulated average temperature is similar to the experimental pattern [which was previously labelled as the "4.5 m level"]. At the half-radius of the bin the simulated temperature pattern is similar to the experimental one [i.e. the previously labelled "6.4 m level"] through the middle of April. For the remainder of the storage period the experimental pattern increases faster. The simulated temperature patterns of the radial columns 0.0 m, 0.8 m, and 1.7 m show identical temperatures throughout the storage period. By early May a minimal difference is observed.

Figure 5.45 shows the predicted temperature in the periphery of the simulated chilled grain pile (i.e. 10% of the bin grain volume) and the observed average temperatures of the bottom sensors of cables A, B, and C between January 10 and May 22, 1991. Both curves show similar temperature patterns and increase by the same amount over the storage period. The predicted periphery temperature is slightly higher and

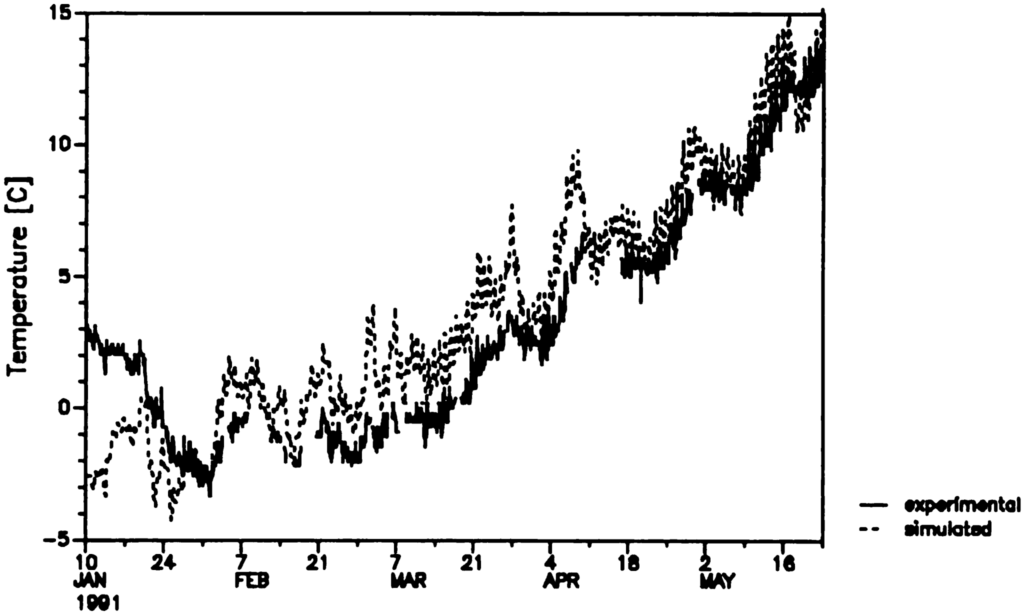

Figure 5.45 Simulated periphery temperature and experimental average periphery temperature in the chilled grain storage bin between January 10 and May 22, 1991.

shows significant fluctuations. This is not surprising since it includes the effects of the environmental boundary conditions at the top and bottom grain surfaces of the pile as well as the bin wall surface temperature.

Figure 5.46 compares the predicted average radial column temperature at the core of the pile with the observed value of the cable D core average. Although the temperature patterns are not identical, they illustrate that in the core the temperature of the grain changes very slowly during the storage period. The observed core temperature increases slightly faster than the predicted one, but at the end of the storage period they are very similar. Although the initial temperatures are not the same, the effect disappears by the end of January.

Environmental Boundary Conditions

Figures 5.36 and 5.37 show the design solar flux on the wall of the grain bin and the average monthly wind speed for the Lansing area, respectively. This data is used in the simulation of the storage of chilled grain as environmental boundary conditions. Throughout the three-year field tests intermittent environmental data was collected at the site.

Figure 5.47 shows solar flux values on a horizontal sensor mounted on the top of the test bin compared with the average

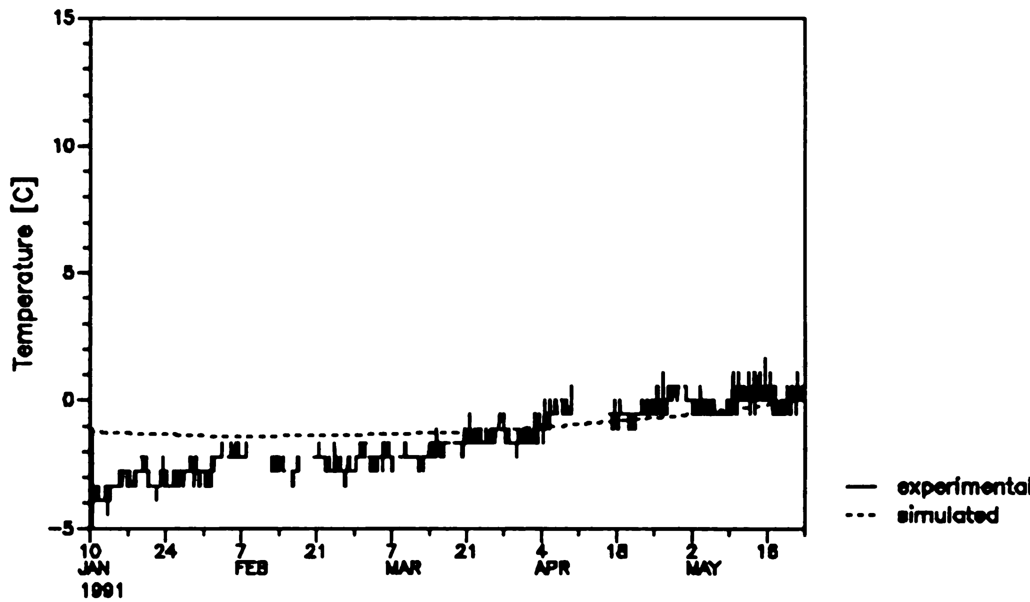

Figure 5.46 Simulated and experimental core temperatures in the chilled grain storage bin between January 10 and May 22, 1991.

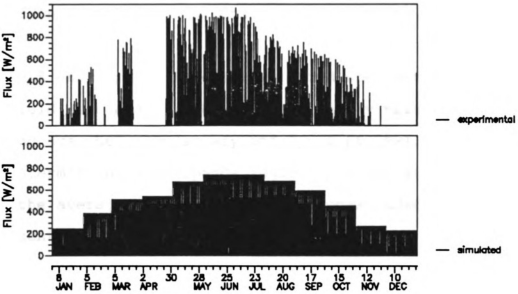

Figure 5.47 Simulated daily horizontal solar flux for a typical year and experimental flux values recorded intermittently at the site of the field test between 1989 and 1990.

daily solar flux values of the simulation model for a typical year. The simulated data, which is based on the theoretical equations presented in Chapter 4, does not predict the variation in the observed flux values. However, the simulated solar flux correctly represents the long-term average solar pattern for the Lansing area, Based on the validation of the storage periods, it appears adequate for the grain storage simulations.

Figure 5.48 compares intermittent wind speeds measured at the field site against the average monthly values for the Lansing area between January and April of 1991. Although the intermittent wind speeds indicate values as high as 12.6 m/s, the average monthly values are appear adequate to represent the local wind speeds in the chilled grain storage predictions.

The ambient dry-bulb temperature used in the validation of the simulation models between October 1988 and July 1991 is compared against the long-term temperature pattern in the Lansing area in Figure 5.49. The long-term pattern represents the 30-year temperature records between 1951-1980 (the only ones which were available from the Michigan weather bureau)(MDA 1991). The temperatures during the three storage seasons follows the 30-year average mean, minimum, and maximum band closely. Extreme high and low

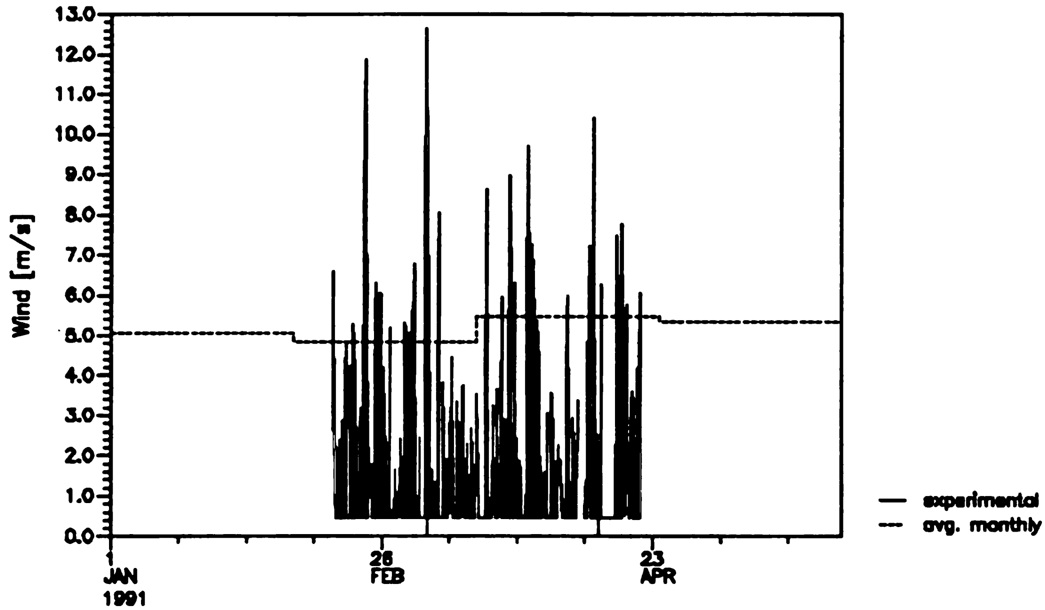

Figure 5.48 Average monthly wind speed for the Lansing area and intermittently observed wind speed at the site of the field test between January and April 1991.

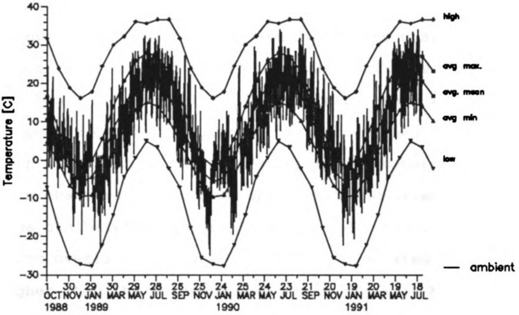

Figure 5.49 Long-term temperature pattern for the Lansing area and ambient dry-bulb temperature used in the chilled grain storage simulation between October 1988 and July 1991.

values are not observed, although several are approached (e.g. in February 1989, December 1989, and May 1991 for lows, and in October 1989, March 1990, and November 1990). Thus, the three field-test seasons appear average and thus are useful in the evaluation of chilled grain storage conditions in Michigan.

The convective boundary condition at the top grain layer of the pile is a function of the temperature in the head-space of the bin. An expression for this temperature was developed in Chapter 4. Figure 5.50 shows the temperature pattern predicted by the simulation model compared to the pattern observed in the head-space of the chilled grain storage bin between January 10 and May 22, 1991. The patterns overlap. In late January the simulated temperature is higher than the observed one, while in early May the predicted temperature is lower than the observed one. The underprediction of the temperature spikes occurs primarily during solar noon. Since the simulated headspace temperature is a function of the daily solar flux, and the experimental headspace temperature is a function of the actual solar flux on the bin roof, the discrepancy between the temperature peaks is not surprising. On the contrary, the temperature patterns indicate that the simulation model adequately predicts the headspace temperature in a grain bin during the storage season.

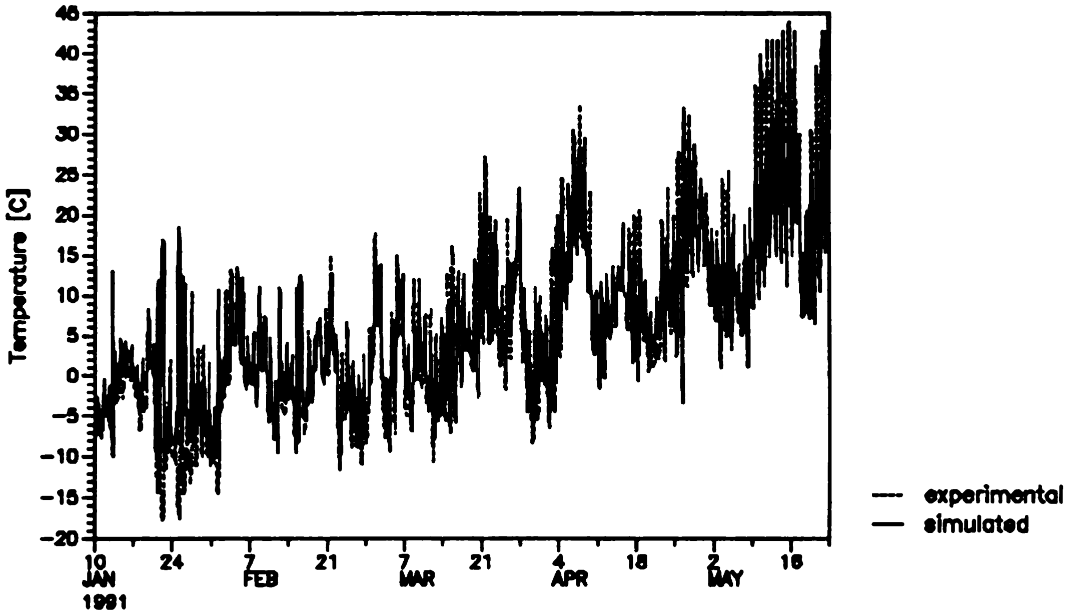

Figure 5.50 Simulated and experimental temperatures in the headspace of the chilled grain storage bin between January 10 and May 22, 1991.

Summary

The chilled storage model was found to accurately predict (1) temperature patterns in the core, the bulk and the periphery of the experimental grain pile during several non-ventilated storage periods, and (2) the temperatures in different grain layers and radial columns of the experimental grain bin. In addition, it has been shown that the methodology applied in formulating the environmental boundary conditions for the chilled grain storage bin is appropriate. Thus, the two-dimensional heat conduction model is valid for simulating the temperatures in chilled grain storage systems.

6. SIMULATION RESULTS AND DISCUSSION

The model to simulate the chilled aeration and storage of cereal grains can be used to investigate a large number of applications. For example, if weather data for a specific geographic location of an upright steel grain bin is available, the optimum storage conditions and rechilling needs for the bin could be investigated. The model can also be used to determine the performance of the chilling unit in terms of cool-down time, power consumption, and energy efficiency. The system model can be expanded to incorporate higher-capacity grain chilling units to investigate the chilling of cereal grains in larger bins. Also, optimization techniques can be incorporated to determine economic or biological aspects, and different operational strategies to chill and rechill a grain storage system. The chilling and storing of a range of additional cereal grains of economic importance in the United States, or elsewhere in the world can be investigated.

Rather than specific scenarios this chapter will address some of the basic aspects of the chilled aeration and storage of cereal grains. Specifically, (1) the chilling parameters critical in the cooling of a grain storage bin are evaluated, (2) the storage parameters critical to the successful preservation of chilled grains are investigated, and (3) an evaluation of different chilling and rechilling strategies is undertaken, including a comparison of chilled and ambient aeration.

6.1 Critical Chilling Parameters

The parameters considered critical in the chilled aeration of cereal grains are the initial grain temperature and moisture content, the inlet air temperature and relative humidity, the airflow rate, and the seasonal influence of the harvest period. Their individual and combined effects are evaluated.

Although the quantitative influence of a specific chilling parameter may vary, the qualitative influence is likely to be the same for any chiller-bin system configuration. The critical chilling parameters are analyzed for a grain bin using the simulated KK140 grain chiller under fall and summer harvest conditions for corn and wheat in mid-Michigan, respectively. Table 6.1 summarizes the values used in the simulation study.

The design airflow rate is equivalent to 0.1 m^3/min/tonne (0.1 cfm/bu), which is recommended for the aeration of cereal grains (MWPS-13 1988). The maximum airflow rate (and static pressure) is the calculated operating point for this specific chiller-bin configuration; it represents the airflow the chiller fan provides at open throttle into the level-filled bin of corn and wheat (see Chapter 4.3). The cool-down starting dates reflect the typical harvest seasons in mid-Michigan, i.e. mid-October for corn and early July for wheat (MADA 1989).

The initial temperatures are assumed to reflect ambient field conditions common in mid-Michigan during harvest. The corn initial moisture content (and bulk density) is assumed after the drying operation. It is assumed that high-temperature corn drying is stopped at 16.5% w.b. and chilling completes the process to save fuel costs and prevent excess weight loss (Maier et al. 1989). The wheat initial moisture content (and bulk density) is out of the field, or after a drying operation. The desired corn temperature is the maximum value for 12 months of corn storage (Foster and Tuite 1982). The desired wheat temperature is selected to prevent insect infestation in the grain bin during summer storage in mid-Michigan (Burrell 1982).

Table 6.1 Simulation values used to investigate the critical chilling parameters in a bin of corn and wheat under mid-Michigan conditions.

Parameter	Corn	Wheat
Bin diameter [m]	10.1	
Bin height [m]	10.3	
Mass of grain [tonnes]	597	579
Design airflow [m^3/h]	3,600	3,500
Maximum airflow [m^3/h] and static pressure [Pa]	4,200 1,930	2,900 3,500
Cool-down starting date	October 15	July 1
Initial temperature [°C]	17.0	30.0
Initial moisture content [%wb] and bulk density [kg/m^3]	16.5 729.5	14.0 708.4
Storage temperature [°C]	7.0	15.0
Cold-air setting [°C]	3.0	8.0
Reheater setting [°C]	6.0	13.0
Heat gain in the duct [°C]	0.0	1.0
Vertical step size [m]	0.74	
Time step size [hr]	3.0	

The cold-air and reheater set-point temperatures for the chilling of corn and wheat reflect the minimum cold-air temperature to prevent icing of the evaporator and the minimum reheater temperature to prevent rewetting of the grain. The heat gain in the duct connecting the chiller and the bin during the fall is assumed to be negligible, and in the summer it is assumed to account for a 1°C temperature rise of the chilled air before the inlet to the bin.

6.1.1 Grid and Time Step Sizes

Before investigating the critical chilling parameters, the validity of the simulation parameter values needs to be established. No numerical criterion exists for the finite difference solution of the two partial differential equations describing the equilibrium heat and mass transfer in the chilled aeration model. However, the selection of the grid node spacing and the time step size influence the accuracy of the solution.

Figure 6.1 illustrates the influence of the vertical grid spacing on the corn temperature in the bottom, middle and top layers of the bin, and on the average grain temperature at a time step of 3 hours. The step size is 0.29 m, 0.52 m, 0.74 m, and 1.5 m for the 10.3 m high bin. Obviously, a layer thickness of greater than 1 m predicts the temperature profiles and cooling times less accurately, especially in the bottom half of the pile. The profiles of the curves for the 0.29 m, 0.52 m, and 0.74 m node spacings are similar. The predicted cooling time for the 1.5 m layer thickness is 192 hours compared to 180 hours for 0.74 m. However, there is only a difference of 3 hours between the cooling times predicted by the 0.74 m and 0.52 m step size simulations. Similar observations are made for the chilled aeration of wheat but the figures are not duplicated here.

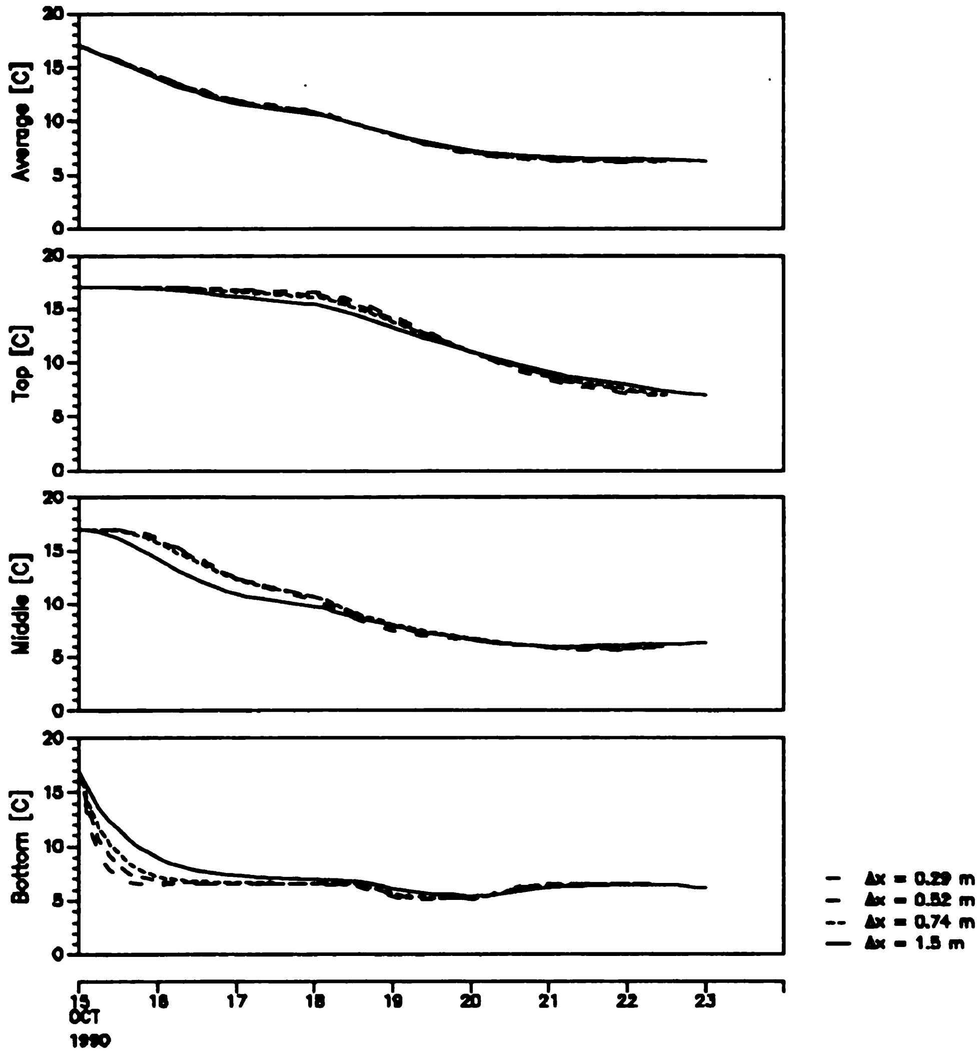

Figure 6.1 Effect of the vertical grid spacing on the temperature profile in the corn bin predicted by the chilled aeration simulation.

The radial grid size spacing is not considered since only chilled aeration is evaluated in terms of one-dimensional equilibrium heat and mass transfer.

Figure 6.2 shows the effect of the time step size on the predicted temperature profiles and cooling times at a grid node spacing of 0.52 m. The smallest time step of 3 hours corresponds to the interval of the weather data used in the simulation. The three and six hour time steps show similar patterns, particularly in the middle and top layers of the pile, and for the average temperature. The predicted cooling times are within 9 hours, i.e. 177 and 186 hours, respectively, compared to 204 hours for the 12-hour time step. Similar observations are made for the chilling of wheat but the figures are not duplicated here.

Figure 6.3 illustrates the reason behind the poorer prediction for the 12-hour time step. The airflow rate during the first two chilling days is underpredicted by about 700 m^3/h, which has a significant effect on the length of the relatively short cool-down cycle. The underprediction is due to the assumption that the airflow through the chiller is constant for a given time interval. Also, some of the variations in the relative humidity of the bin inlet air and the power consumption of the chiller are not predicted as accurately as the smaller time steps.

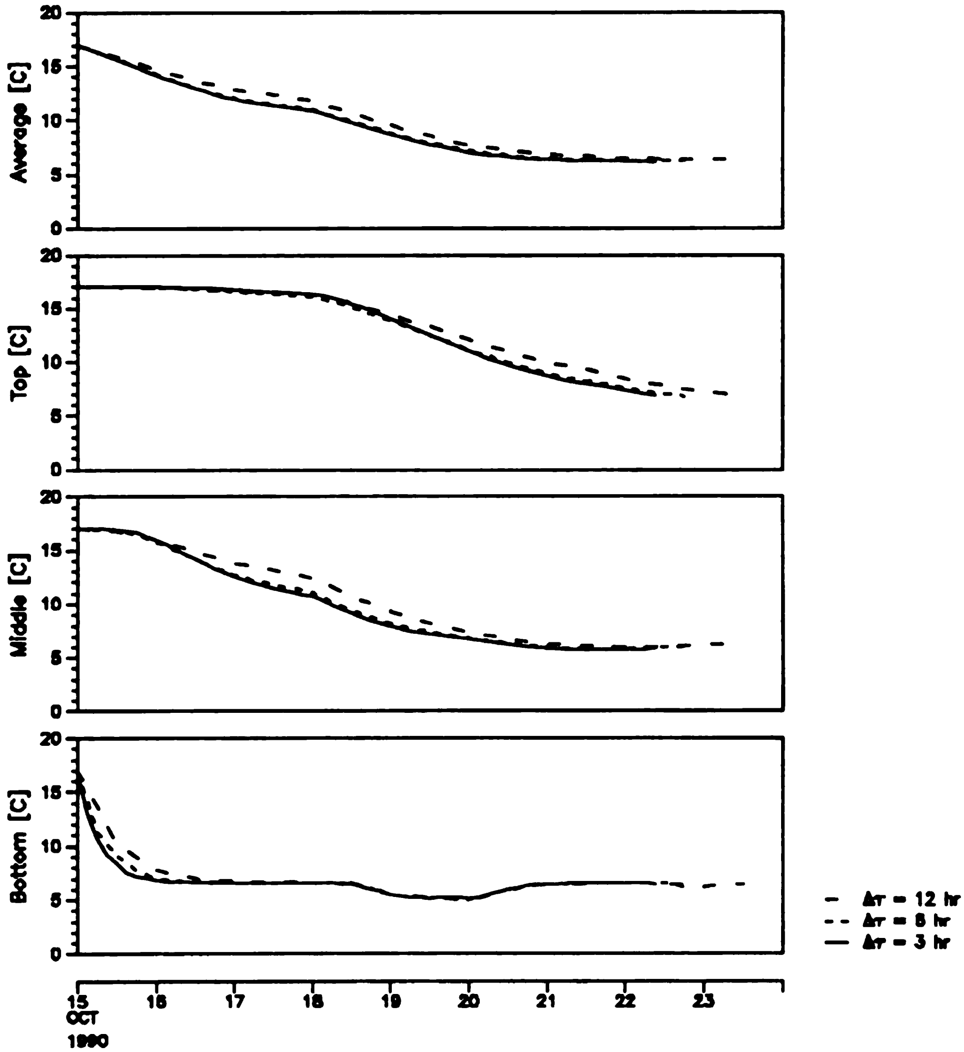

Figure 6.2 Effect of the time step size on the temperature profile in the corn bin predicted by the chilled aeration simulation.

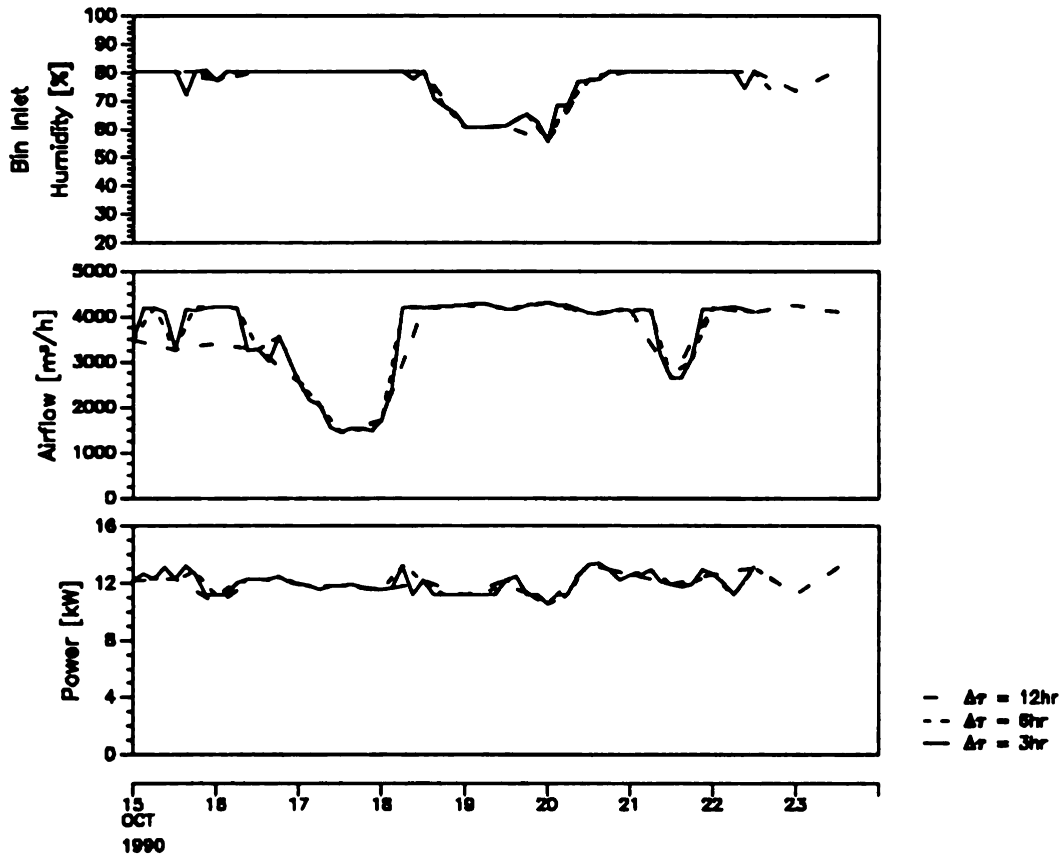

Figure 6.3 Effect of the time step size on the airflow rate, power consumption, and bin inlet relative humidity predicted by the grain chiller simulation.

Based on the above observations a vertical grid spacing of 0.74 m and a time step of 3 hours are used in the remaining chilling simulations for corn and wheat.

6.1.2 Seasonal Influence

6.1.2.1 Fall Cool-down

The simulated cool-down of a bin of corn is compared in Figure 6.4 for the 1988 through 1990 seasons. The temperature profiles and the lengths of the cool-down cycle are obviously influenced by the year-to-year variation of the ambient conditions. In October of 1988 it requires 195 hours to chill the corn from 17°C to below 7°C (i.e. resulting in a cooling rate of 1.2°C/day), compared to 180 hours in 1990 (i.e. 1.3°C/day), and 162 hours in 1989 (i.e. 1.5°C/day). Associated with longer cooling times are higher energy costs. In addition, managing the cool-down is critical since the bins are filled in rapid sequence during the fall harvest, and sufficient cooling capacity has to be available to keep up with the harvest rate. The temperature profiles indicate evaporative cooling effects, i.e. the grain temperature drops below the inlet air temperature, in the bottom and middle layers during each season. This indicates sufficient reheating of the bin inlet air to

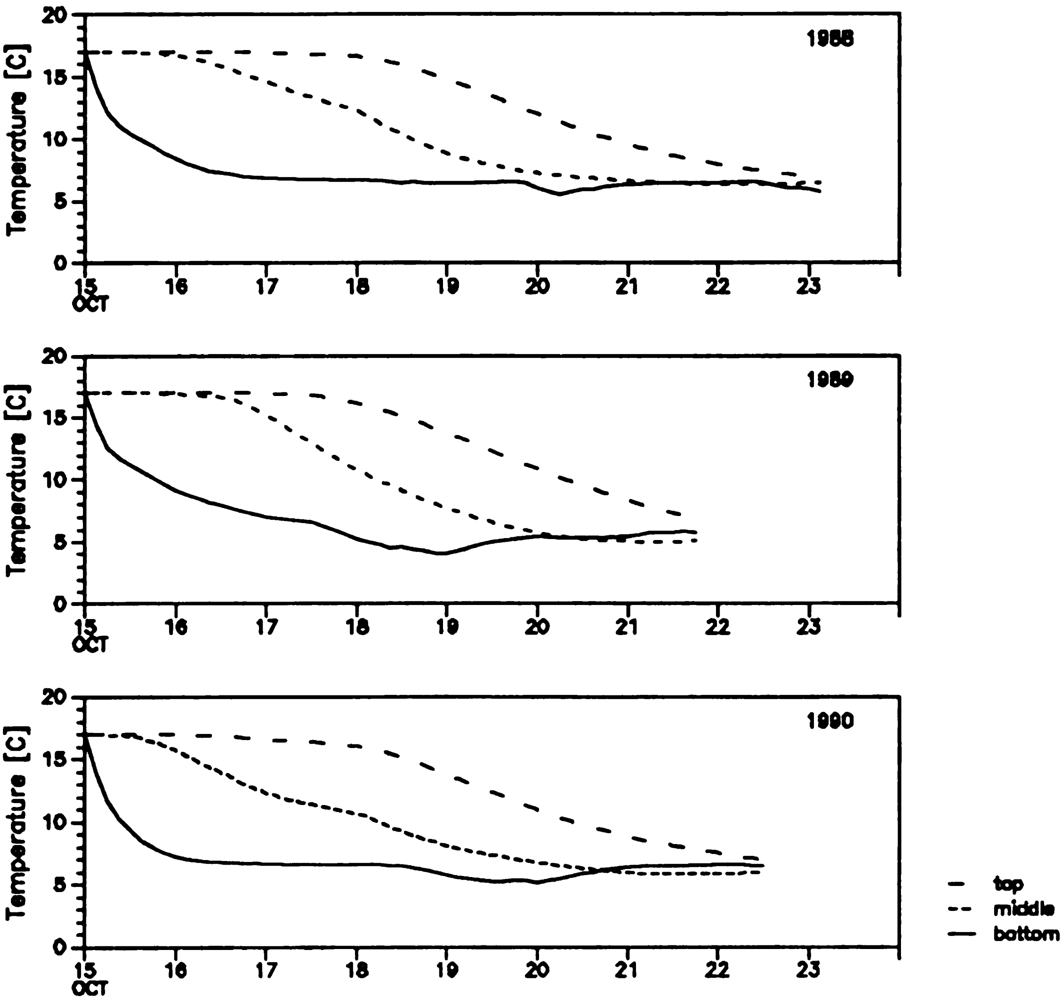

Figure 6.4 Seasonal influence on the temperature profile predicted for the chilled aeration of corn during the initial cool-down in 1988, 1989 and 1990.

remove moisture from the corn during the chilling operation.

The first three days of the 1988 cooling cycle are marked by high ambient temperatures, which reduce the airflow from the chiller and lengthen the cool-down time in the bin (see Figure 6.5). The cooling front requires three days to travel through the pile and reach the top layer. In 1989 cooling is very slow during the first two days when the KK140 is throttled due to high ambient cooling loads (see Figure 6.6). The cooling front takes about two days to reach the top layer. In 1990 the corn bin cools very fast in the early part of the cycle since the grain chiller operates mostly at the maximum airflow rate during the first 1.5 days (see Figure 6.7). The ambient temperature increases on the third day thereby slowing the progress of the cooling front [which reaches the top layer after about 2.5 days].

The maximum relative humidity of the bin inlet air, which occurs during high ambient temperature and relative humidity periods, is 80% at the 3°C cold-air set-point and 6°C reheater set-point resulting in an equilibrium moisture content (EMC) for the corn of 17.8% w.b. Since this value is higher than the initial grain moisture content essentially no moisture reduction takes place in the bin. The final average moisture content in the corn bin is about

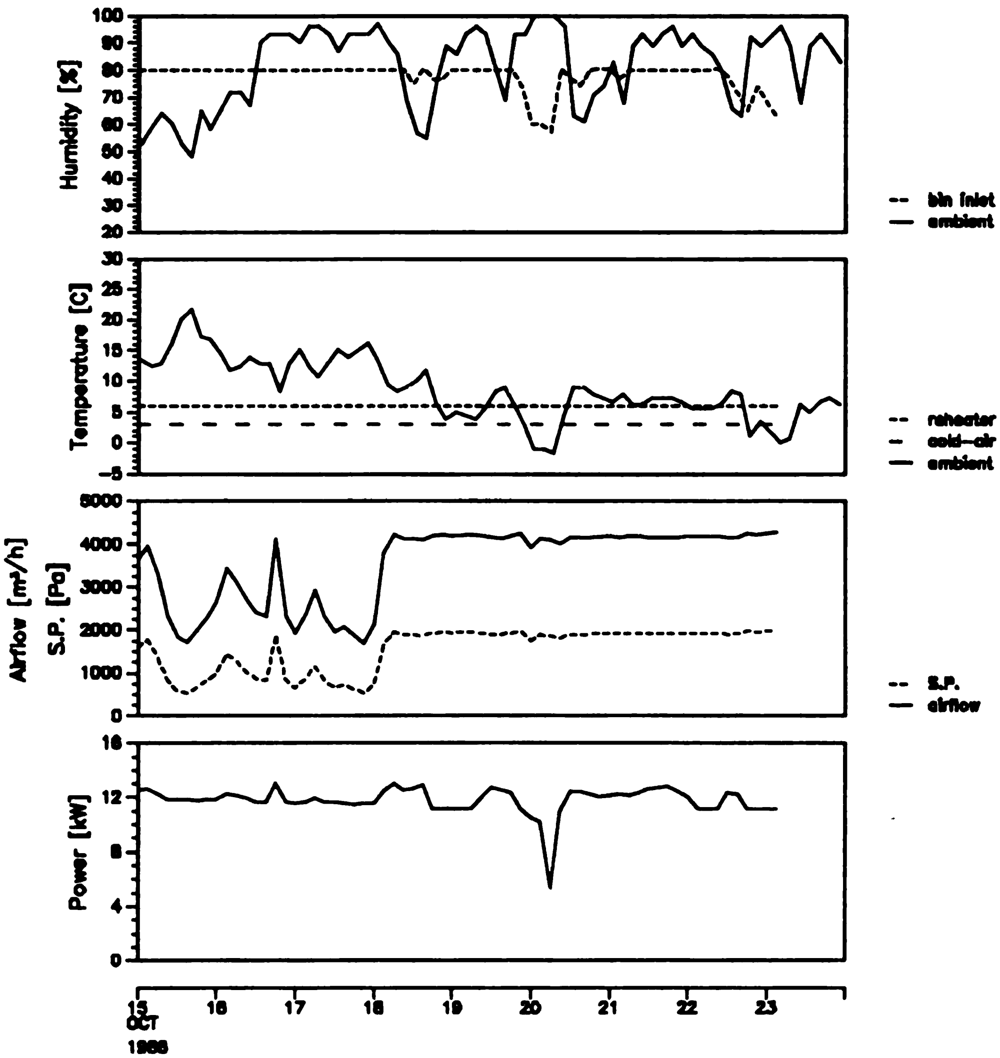

Figure 6.5 Simulated performance of the KK140 grain chiller during the initial cool-down of the corn bin between October 15 and 23, 1988.

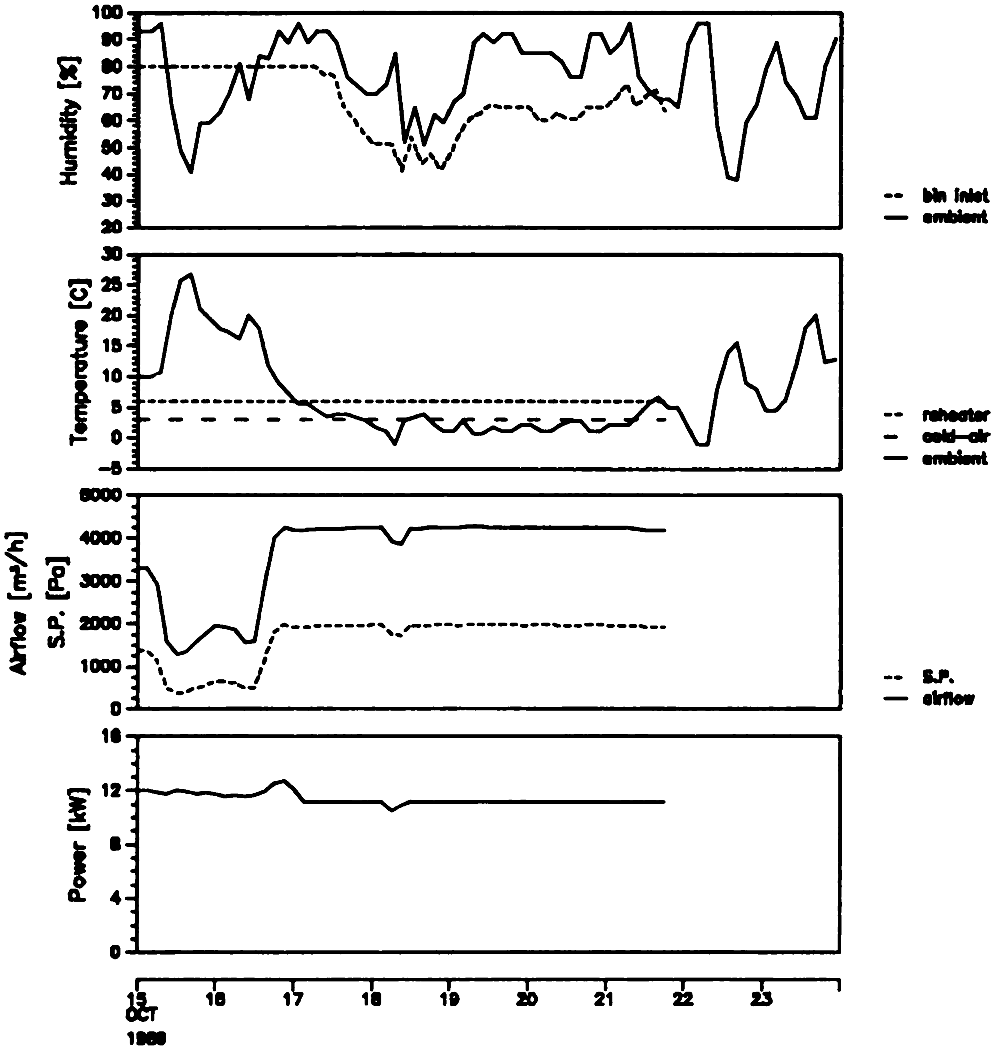

Figure 6.6 Simulated performance of the KK140 grain chiller during the initial cool-down of the corn bin between October 15 and 21, 1989.

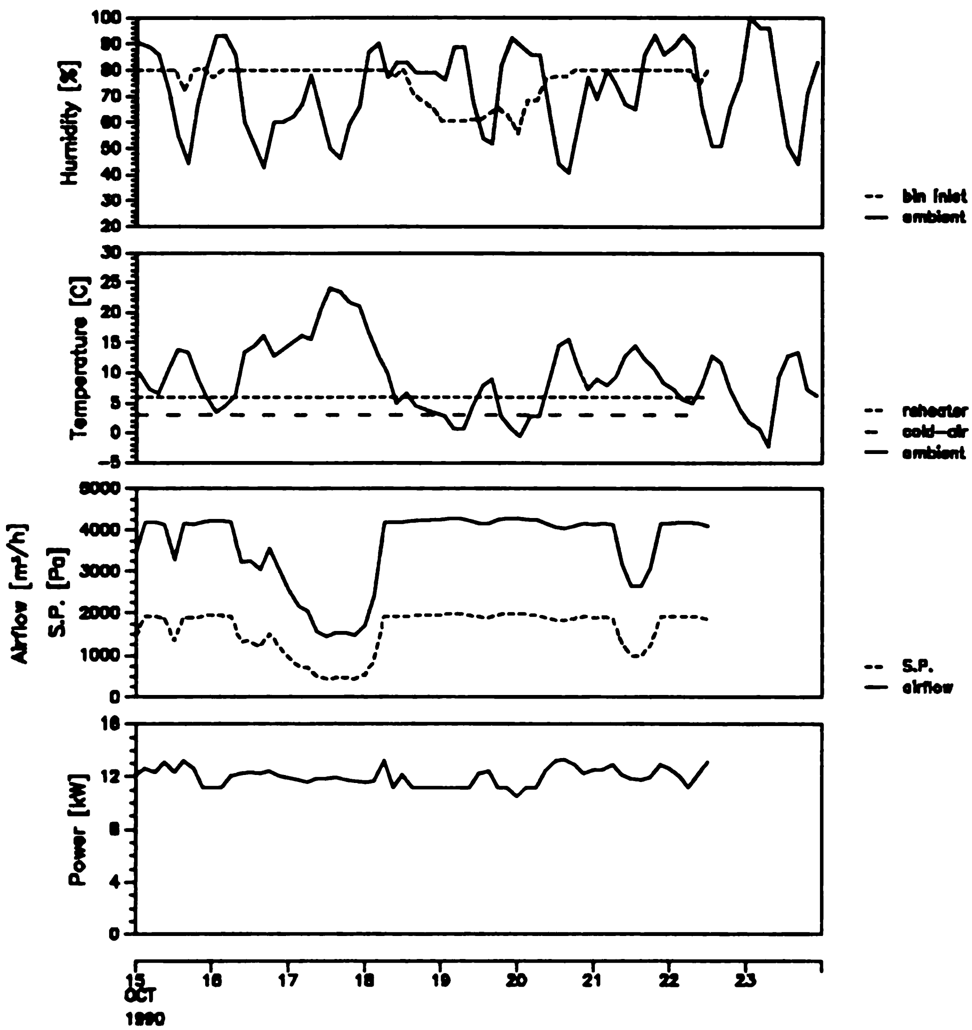

Figure 6.7 Simulated performance of the KK140 grain chiller during the initial cool-down of the corn bin between October 15 and 22, 1990.

16.2% w.b. at the end of each of the chilling periods.

The power consumption is 2,296 kWh in 1988, 1,842 kWh in 1989, and 2,157 kWh in 1990 resulting in energy efficiencies of 19.7 W/tonne of corn, 19.0 W/tonne, and 20.1 W/tonne during the three seasons, respectively.

6.1.2.2 Summer Cool-down

Figure 6.8 compares the simulated chilling of wheat during the first week of July in 1988, 1989, 1990 and 1991. Given the same grain conditions, bin dimensions, and chiller temperature settings the cooling times in the different years vary by as much as 3 days. The fastest and slowest cooling times are predicted in back-to-back years. In 1988 cooling is completed in 207 hours, and in 1989 in 270 hours, compared to 225 hours in 1990 and 258 hours in 1991. The correct management of the cool-down of multiple bins during the harvest season is critical when the cooling time of a single bin increases significantly from one year to the next.

The grain temperature profiles in the wheat bin are similar. The cooling front reaches the top layer in the bin after one day in 1988, 1.5 days in 1989, one day in 1990, and about

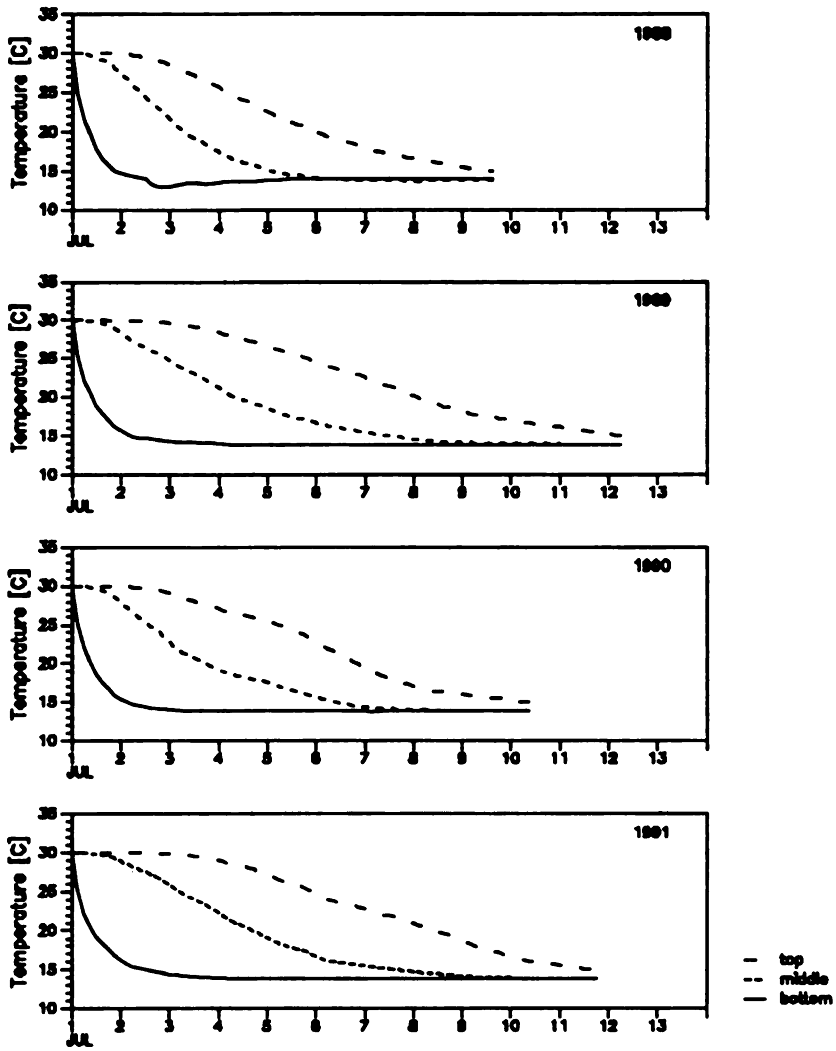

Figure 6.8 Seasonal influence on the temperature profile predicted for the chilled aeration of wheat during the initial cool-down in 1988, 1989, 1990 and 1991.

two days in 1991. In 1990 the top layer in the bin shows a low cooling rate on July 5 through 7, and in 1991 on July 6 through 8. The daily temperature reductions of 1.7°C/day, 1.3°C/day, 1.6°C/day, and 1.4°C/day are higher for wheat chilling than for the corn chilling. Despite the different cooling times the final average moisture content of the wheat is the same each year, i.e. 13.3% wet basis.

A look at the ambient conditions during each season reveals the reason for the difference in cooling times. Both in 1988 and 1990 the first 2 to 3 days are cool with night temperatures dropping to 5°C (see Figures 6.9 and 6.11, respectively). This allows the chiller to operate near maximum airflow during those periods. In 1989 and 1991 the average airflow rate is lower during the initial first days of the cool-down cycle, which results in overall longer cooling times (see Figures 6.10 and 6.12, respectively). Additionally, the bin inlet relative humidity during the first four days in the 1988 cool-down cycle ranges between 45% and 75%. Thus, evaporative cooling aids in decreasing the cool-down time. In 1989 through 1991 the inlet relative humidity of the air remains constant at 75% during the entire chilling cycle (except for a brief period on 7/6/1990).

The predicted power consumption is 2,632 kWh in 1988, 3,517

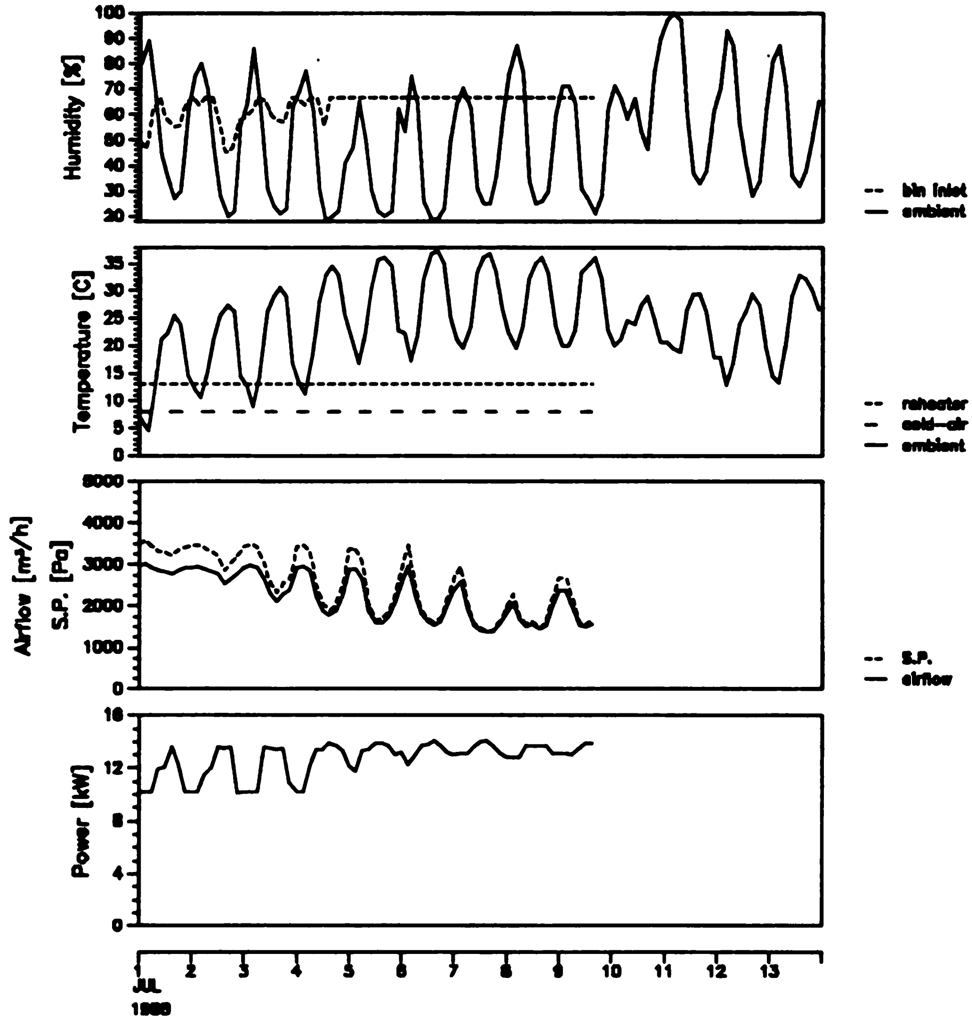

Figure 6.9 Simulated performance of the KK140 grain chiller during the initial cool-down of the wheat bin between July 1 and 9, 1988.

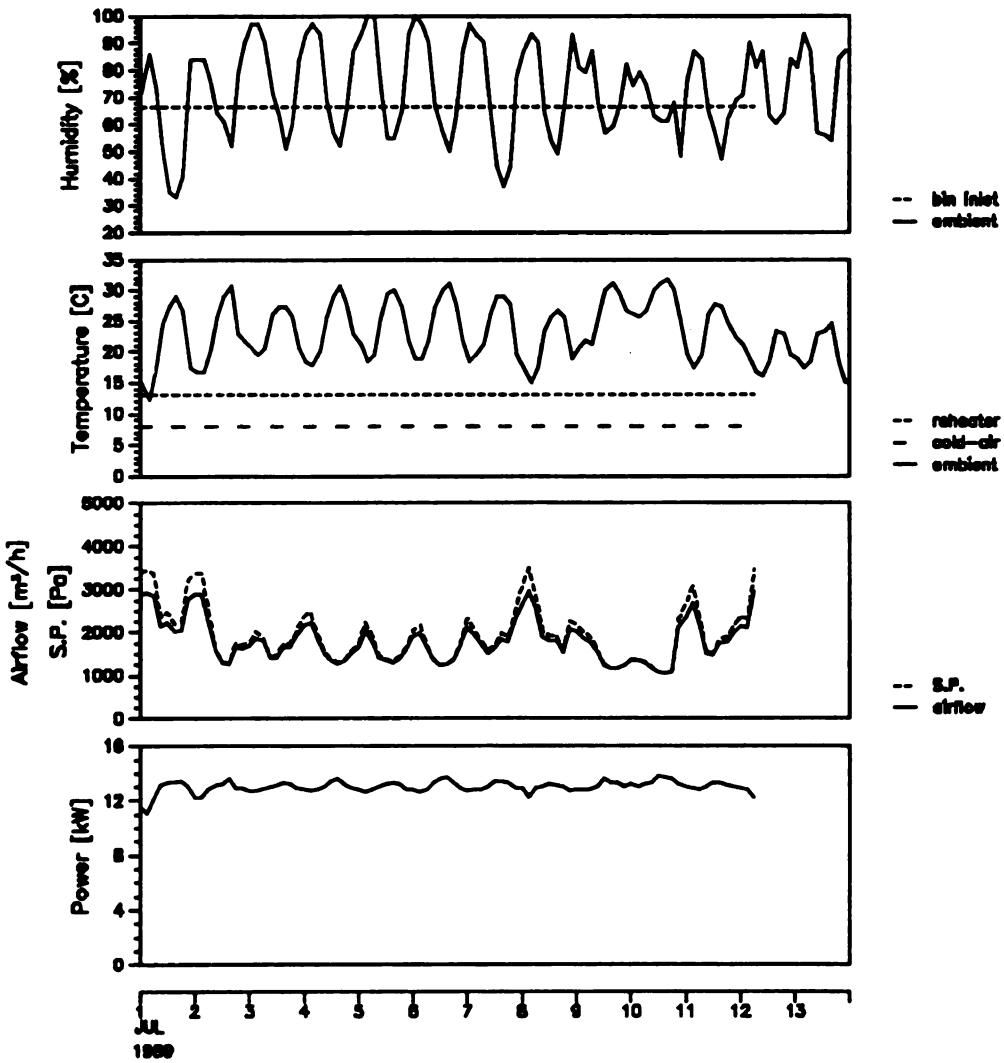

Figure 6.10 Simulated performance of the KK140 grain chiller during the initial cool-down of the wheat bin between July 1 and 12, 1989.

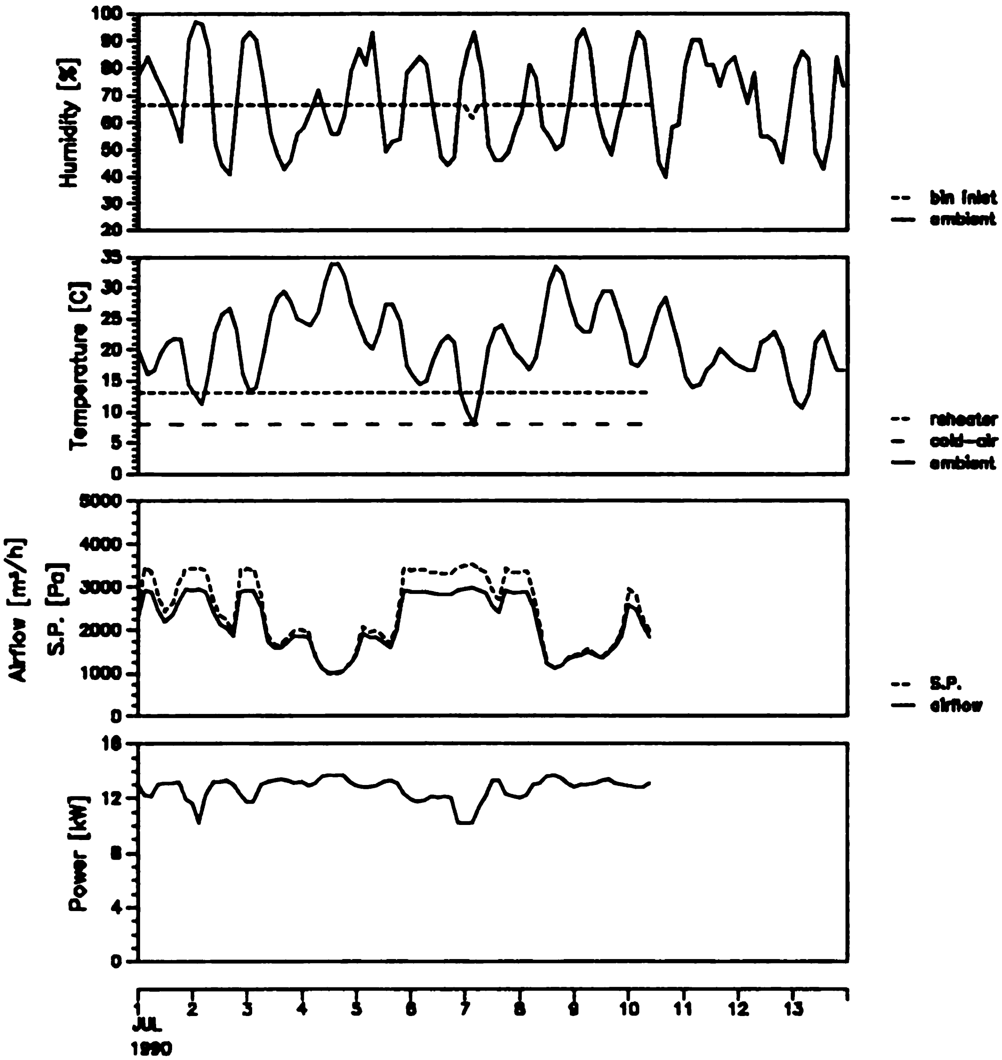

Figure 6.11 Simulated performance of the KK140 grain chiller during the initial cool-down of the wheat bin between July 1 and 10, 1990.

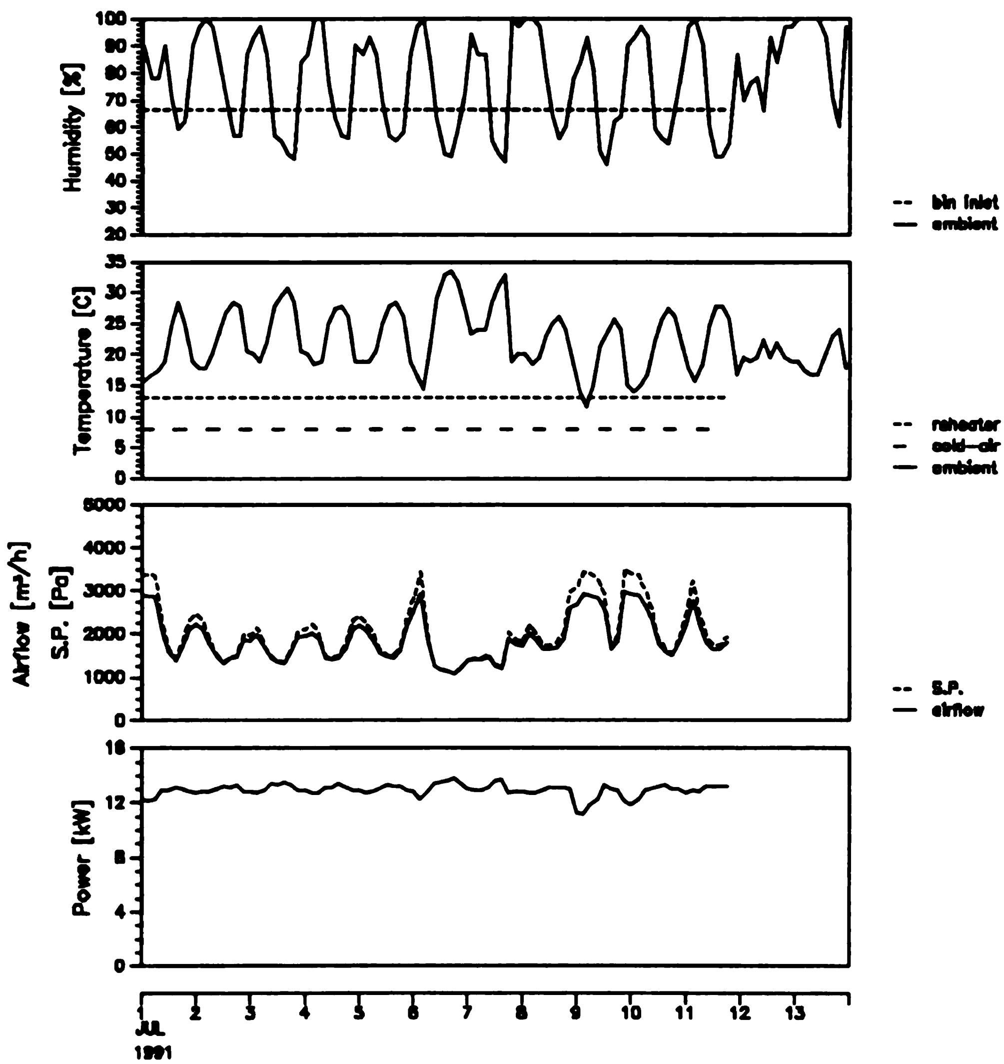

Figure 6.12 Simulated performance of the KK140 grain chiller during the initial cool-down of the wheat bin between July 1 and 11, 1991.

kWh in 1989, 2,854 kWh in 1990, and 3,335 kWh in 1991. This results in energy efficiencies for the chilling cycles of 22.0 W/tonne of wheat, 22.5 W/tonne, 21.9 W/tonne, and 22.2 W/tonne for the four seasons, respectively.

The 1990 summer and fall seasons are chosen as representative seasons in the remaining analysis of the critical chilling parameters.

6.1.3 Initial Crop Conditions

In the evaluation of the initial crop conditions, similar observations are made for the chilling of wheat and corn. Thus, only the results for corn chilling are presented here.

6.1.3.1 Temperature

The influence of the initial grain temperature on the chilling of corn is illustrated in Figure 6.13. The cooling time is 171 hours at 12°C (i.e. 0.7°C/day), 180 hours at 17°C (1.3°C/day), and 192 hours at 28°C (2.6°C/day), respectively. For the same inlet air temperature, relative humidity, and flow rate the highest cooling rate is achieved when the grain is initially at the highest temperature. In the

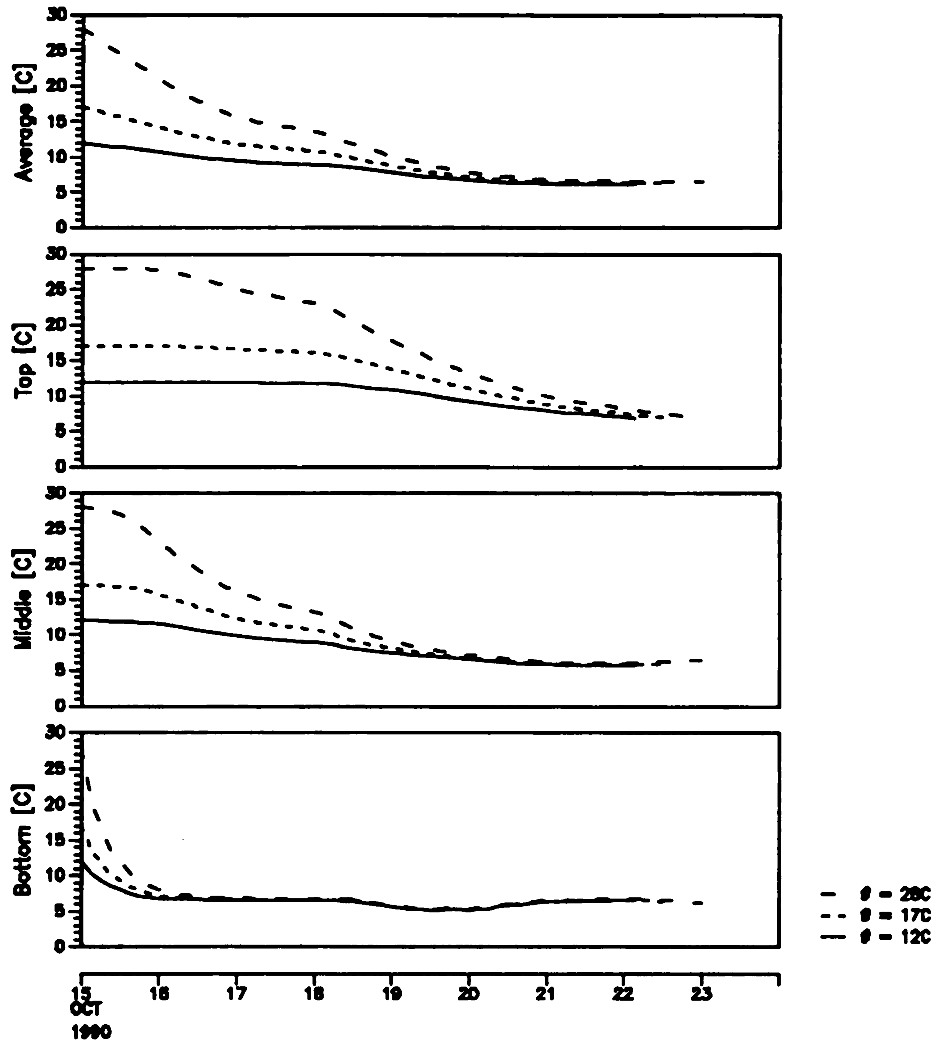

Figure 6.13 Simulated effect of the initial grain temperature on the temperature profile in the corn bin during the initial cool-down.

bottom layer the effect of the higher initial grain temperature dissipates within one day of chilling. The cooling front moves through the pile with the higher initial grain temperature within one day, in the 17°C case in two days, and in the 12°C case in three days. The cooling rate is highest during the initial phase of high airflow from the chiller (see Figure 6.7). The throttling of the airflow on the third day is reflected in the temperature profiles as a slowing of the cooling front.

The overall moisture removal during chilling is small compared to the usual drying operations. The final average moisture content of the corn initially at 28°C is 15.7% w.b., at 17°C is 16.2% w.b., and at 12°C is 16.3% w.b. (see Figure 6.14). Limited moisture removal during chilled aeration of grain has been observed in many field tests reported in the literature (Burrell and Laundon 1967, Komba et al. 1987, Skriegan 1989a). The simulations confirm these observations.

At higher temperatures the grain in the bin remains at higher levels for a longer period of time and thus a higher moisture removal from the grain is achieved due to a pronounced evaporative cooling effect. The moisture removal in the top layers is higher than in the bottom layers. The equilibrium moisture content (EMC) of the inlet chilling air

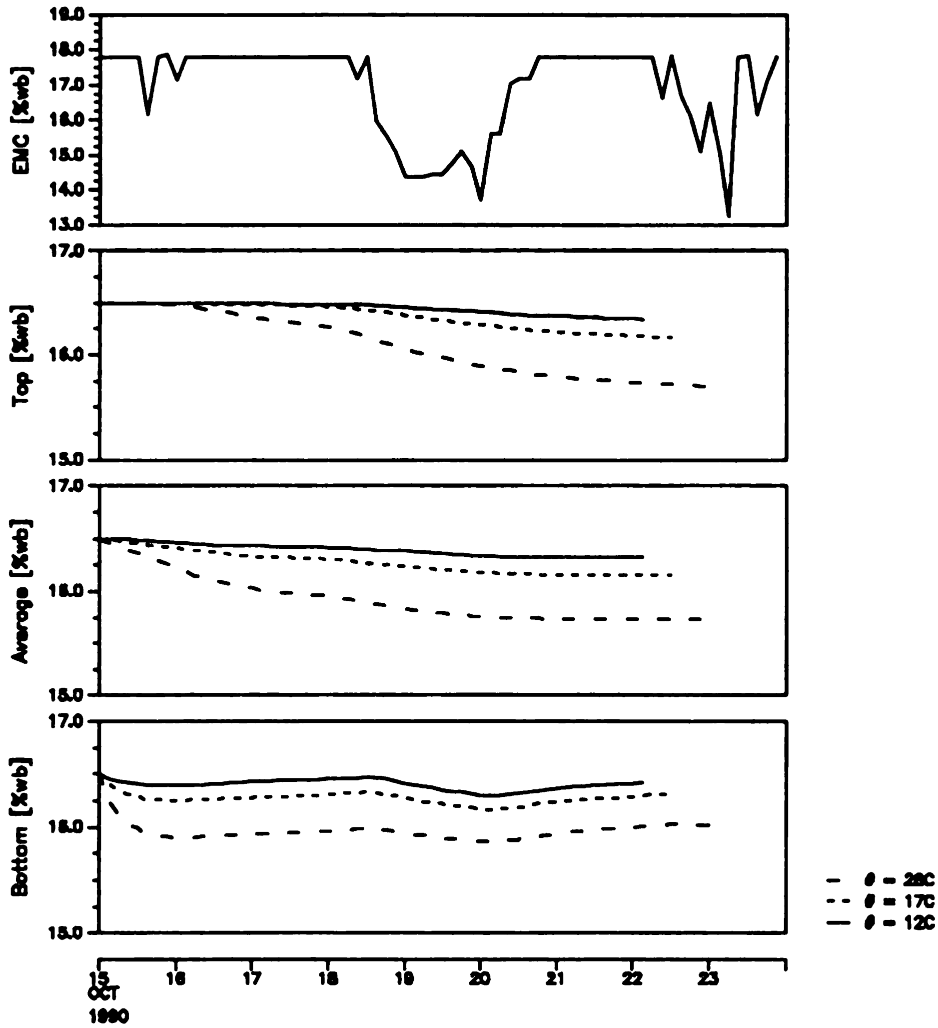

Figure 6.14 Simulated effect of the initial grain temperature on the moisture content profile in the corn bin during the initial cool-down.

is at 17.8% w.b. for most of the cooling cycle (except for a 2-day period between 10/18 and 10/21), which results in partial reabsorption of moisture in the cooled bottom layers while the cooling upper layers still loose moisture.

The higher initial grain temperature requires a longer cooling time, and thus a higher power consumption. However, due to the higher cooling rate the energy efficiency does not change, i.e. 20.0 W/tonne of corn, which is the same as for the 17°C and 12°C cases.

6.1.3.2 Moisture Content

Wet grain chills faster than dry grain. Corn initially at 18.5% w.b. cools in 171 hours compared to 180 hours for 16.5% w.b. corn (see Figure 6.15). It requires 324 hours for the 14.5% w.b. corn (the full extent is not shown). Significant differences in chilling times for the same grain type at different moisture contents is important to consider in grain storage management. A limiting condition exists, which delays the completion of cooling the drier corn. This condition is in part due to the high EMC-value of 17.8% w.b. that exists during much of the chilling period (see Figure 6.14). At the bin inlet the air conditions cause moisture absorption in the grain in the bottom layers, particularly

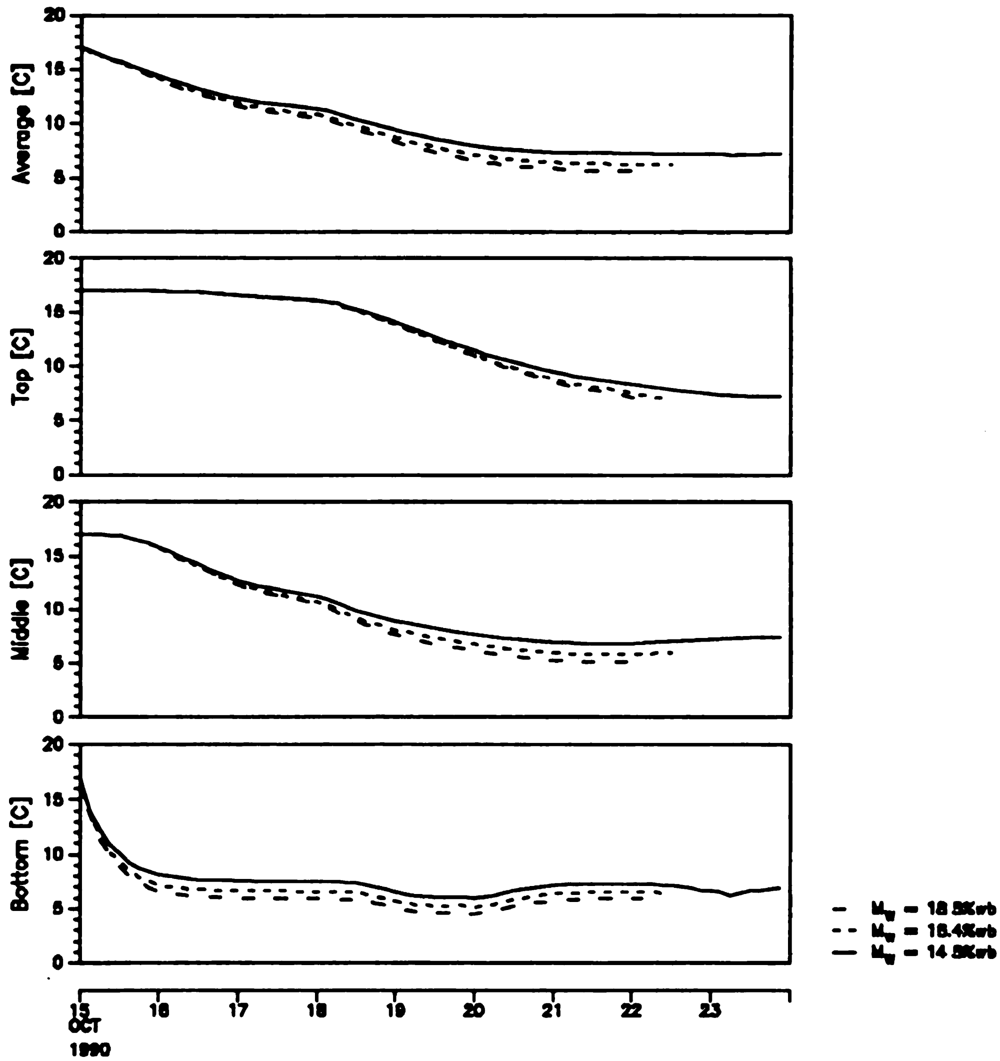

Figure 6.15 Simulated effect of the initial moisture content on the temperature profile in the corn bin during the initial cool-down.

for the corn initially at 14.5% moisture. The energy lost by the air due to moisture absorption by the grain reduces the evaporative cooling effect of the air in the upper layers of the bin.

The observation of extended cooling times for dry grain and rewetting of the grain near the inlet duct has been reported repeatedly in the grain chilling literature (Navarro et al. 1973a, Hunter and Taylor 1980, Sutherland 1986). This phenomenon is caused by certain combinations of the initial grain and air inlet conditions, and will be explored in more detail in the next section.

6.1.4 Inlet Air Conditions

In the practical operation of the grain chilling unit the inlet air conditions, i.e. temperature, relative humidity, and airflow rate, into the bin are controlled by adjusting the cold-air and reheater set-point temperatures. An adjustment of one (or both) of the set-points causes a change in at least two (or all three) of the air conditions at the outlet of the chiller. The individual effects cannot be studied separately in a field application. However, with the simulation model the individual effects of the three parameters can be distinguished. Since similar observations are made in wheat and corn only the corn results are presented here.

6.1.4.1 Relative Humidity

To evaluate the effect of the relative humidity on the cooling of the grain the simulated chilling air is dehumidified at the bin inlet by 15% and 30%, respectively (see Figure 6.16). The same inlet air temperature and airflow rate are maintained. Lowering the relative humidity of the chilling air by 15 percentage points decreases the cooling time of the 16.5% w.b. moisture corn from 180 hours to 165 hours; and lowering the relative humidity by 30 percentage points decreases the cooling time to 150 hours. Evaporative cooling is observed in the bottom layers of the bin for each inlet condition. The travel speed of the cooling front to the top layer is unaffected.

Figure 6.17 shows the effect of dehumidifying the relative humidity of the chilling air. A reduction of 15% lowers the bin inlet condition to a maximum of 65%, and at 30% less humidity to a maximum of 51%. The minimum relative humidity is reached on 10/20/1990, and is lowered from 56% to 41% and 26%, respectively, which increases the drying effect of the cold air significantly. The effect of the relative humidity

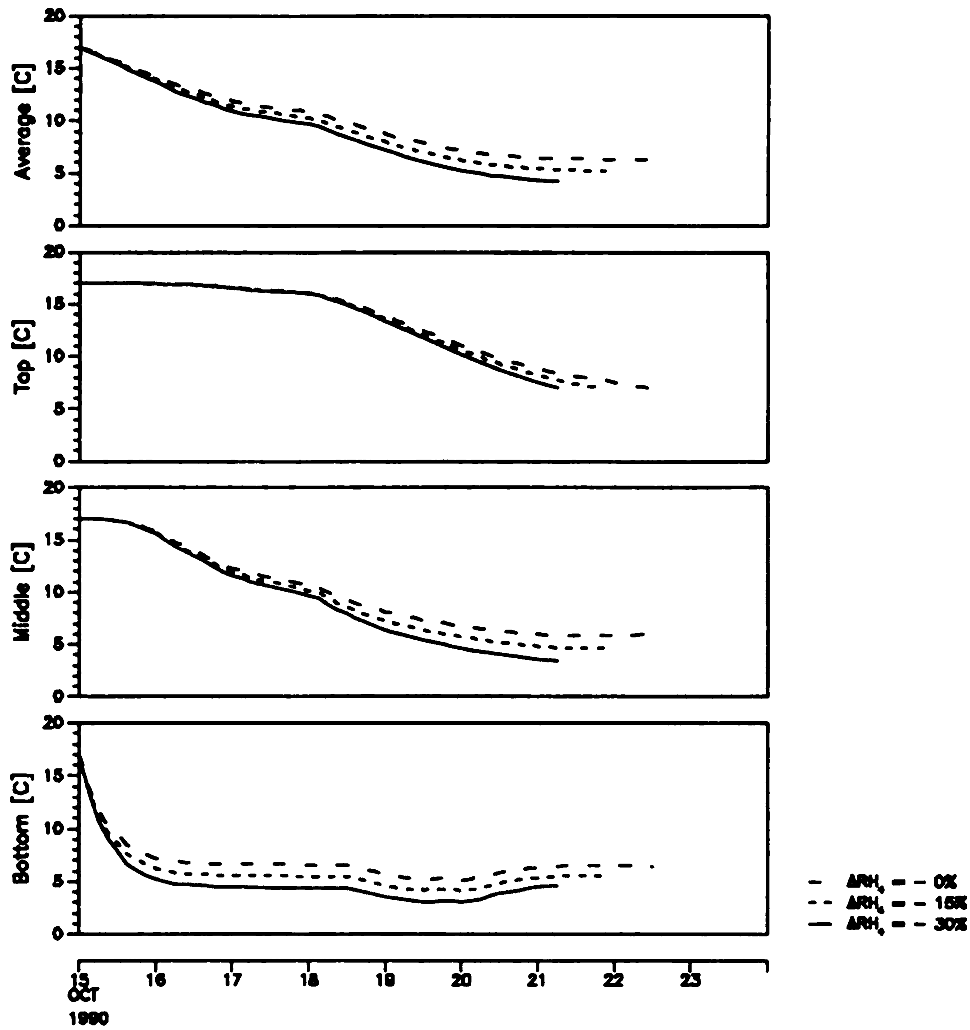

Figure 6.16 Simulated effect of the relative humidity of the bin inlet air on the temperature profile in the corn bin during the initial cool-down.

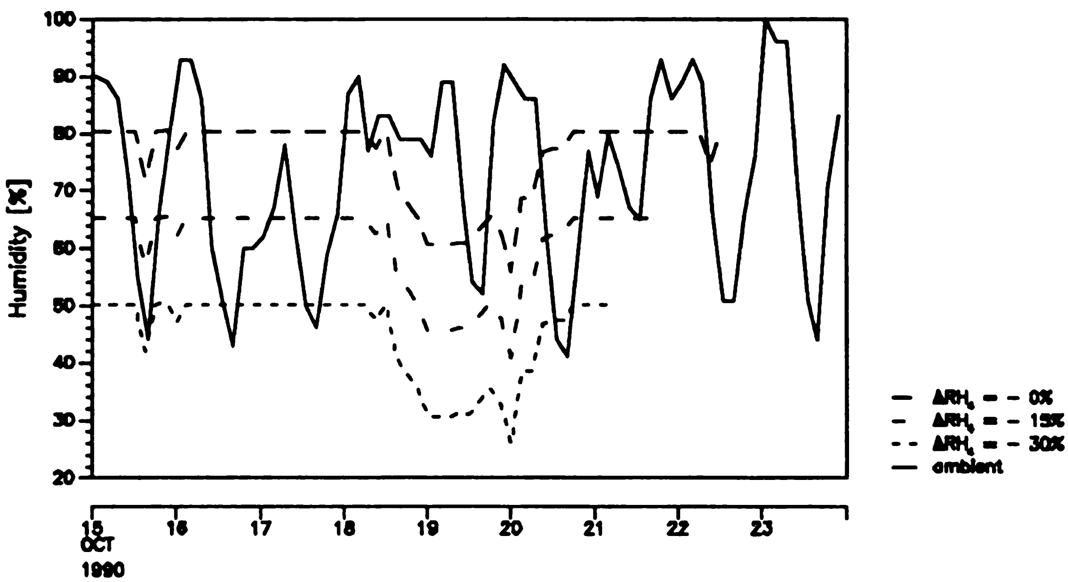

Figure 6.17 Simulated effect of reducing the relative humidity of the bin inlet air by a constant amount during the initial cool-down of the corn bin.

is obvious on the lower grain layers in the 14.5% w.b. moisture corn (see Figure 6.18). Without lowering the relative humidity the moisture content increases towards the equilibrium condition of 17.8% w.b., and the cooling time is increased significantly (the full extent of the cycle is not shown). Reducing the relative humidity by 15% maintains the moisture content in the bottom of the bin at about the initial moisture level (except for a brief drying period during the low relative humidity on 10/20), but reduces the cooling time from 324 hours to 177 hours. At a reduction in the relative humidity of 30% the cooling time reduces to 162 hours.

The bottom corn layers loose up to 1.0 percentage points of moisture in the 30%-case. However, the average moisture in the pile decreases by only 0.4 points. No moisture reduction is observed in the top layers until the fourth chilling day. The final moisture content of the grain in the top layer is about the same in each relative humidity case. This indicates that the air is near saturation when it is exhausted from the top of the grain pile. Thus, dry grain can be chilled within similar time periods as higher moisture grains if the relative humidity of the chilling air is sufficiently low.

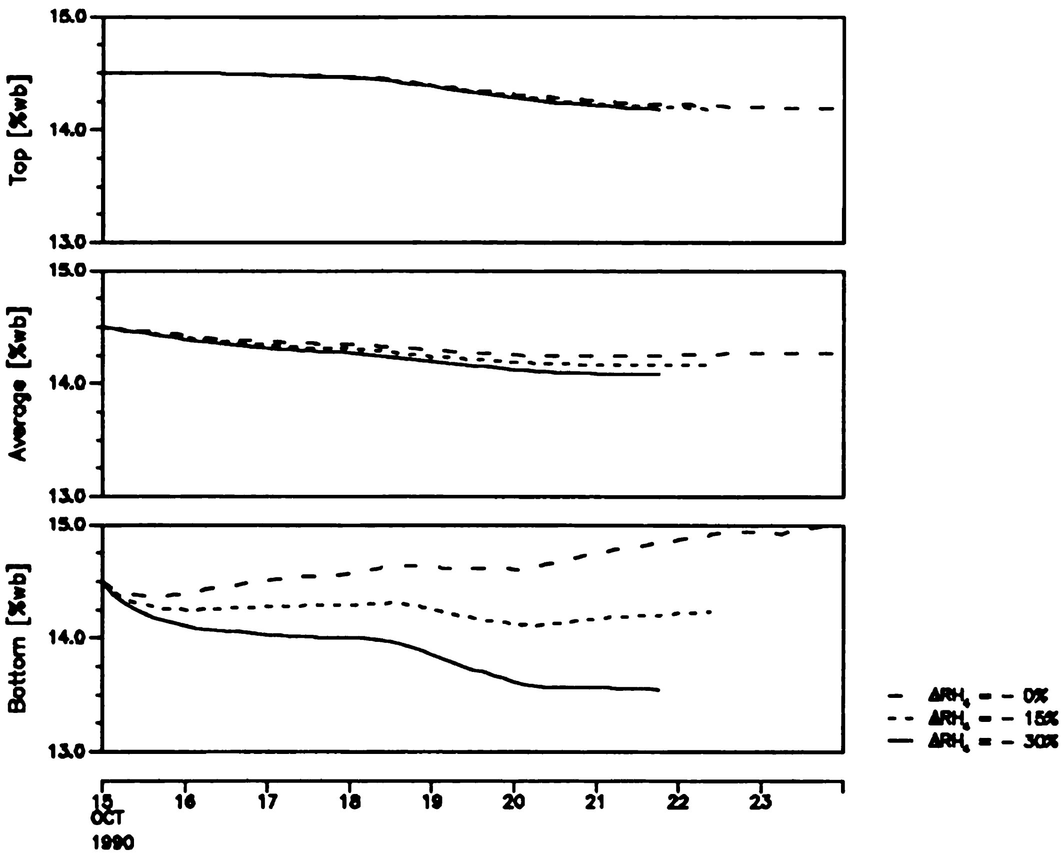

Figure 6.18 Simulated effect of the relative humidity on the moisture content profile in the corn bin initially at 14.5% w.b. during the initial cool-down.

6.1.4.2 Temperature

The effect of the bin inlet air temperature is evaluated by adjusting its simulated value while maintaining the same relative humidity and airflow rate into the bin. The desired grain temperature is within 1°C of the inlet air temperature.

At an inlet temperature of 3°C the grain cools from 17°C to 4°C in 198 hours at a cooling rate of 1.6°C/day (see Figure 6.19). At 6°C, the cooling time is 180 hours to reach a final temperature of 7°C (i.e. 1.3°C/day). At 9°C the cooling time is 162 hours to cool to 10°C (i.e. 1.0°C/day), and at 12°C it takes 141 hours to cool to 13°C (i.e. 0.7°C/day). The evaporative cooling effect is evident in the bottom layer for each of the inlet air temperatures investigated. The cooling front reaches the top layer in about the same amount of time for each case.

The effect on the moisture profile is not large; the average moisture removal ranges from 0.1 to 0.25 points (see Figure 6.20). For each of the inlet air conditions some moisture reabsorption occurs in the lower layers of the grain pile after a decrease during the first two days of the cooling cycle. Lower relative humidities of the chilling air on the fifth day dissipate the moisture absorption in the bottom of

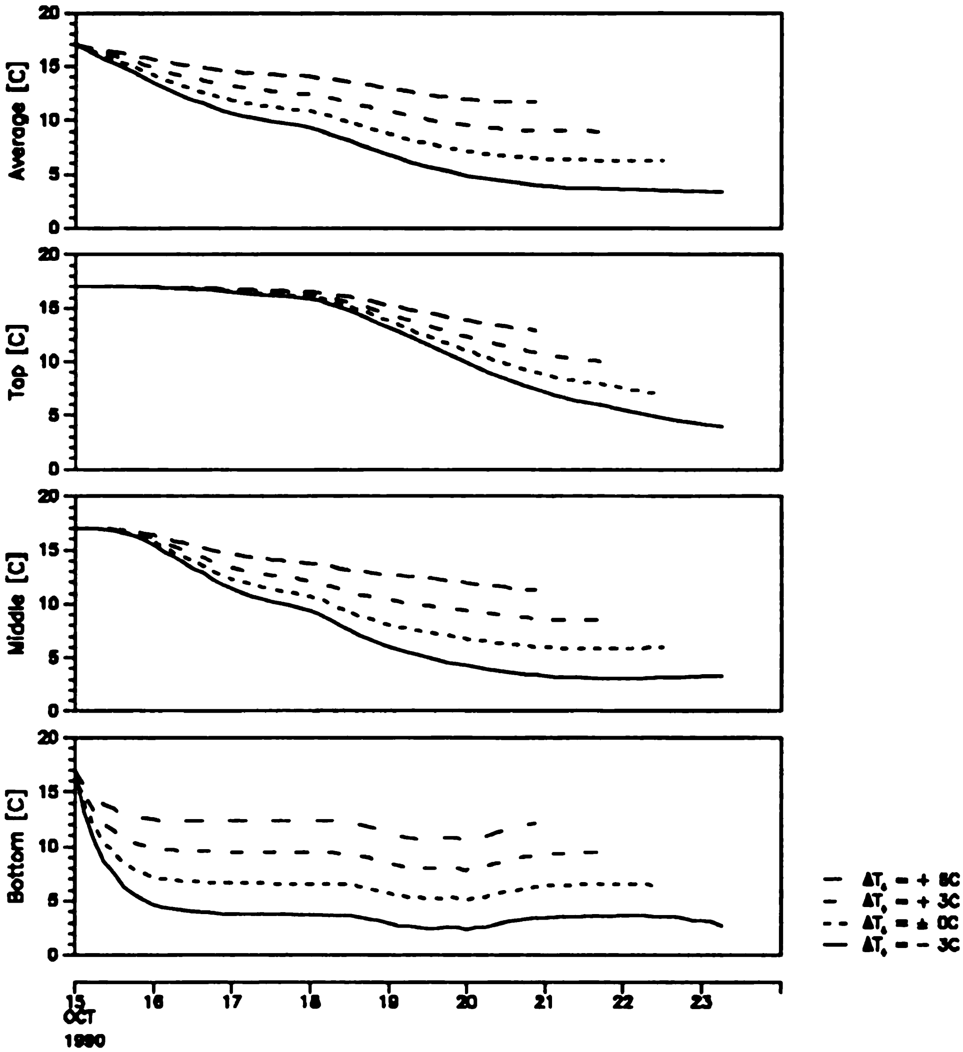

Figure 6.19 Simulated effect of the bin inlet air temperature on the temperature profile in the corn bin during the initial cool-down.

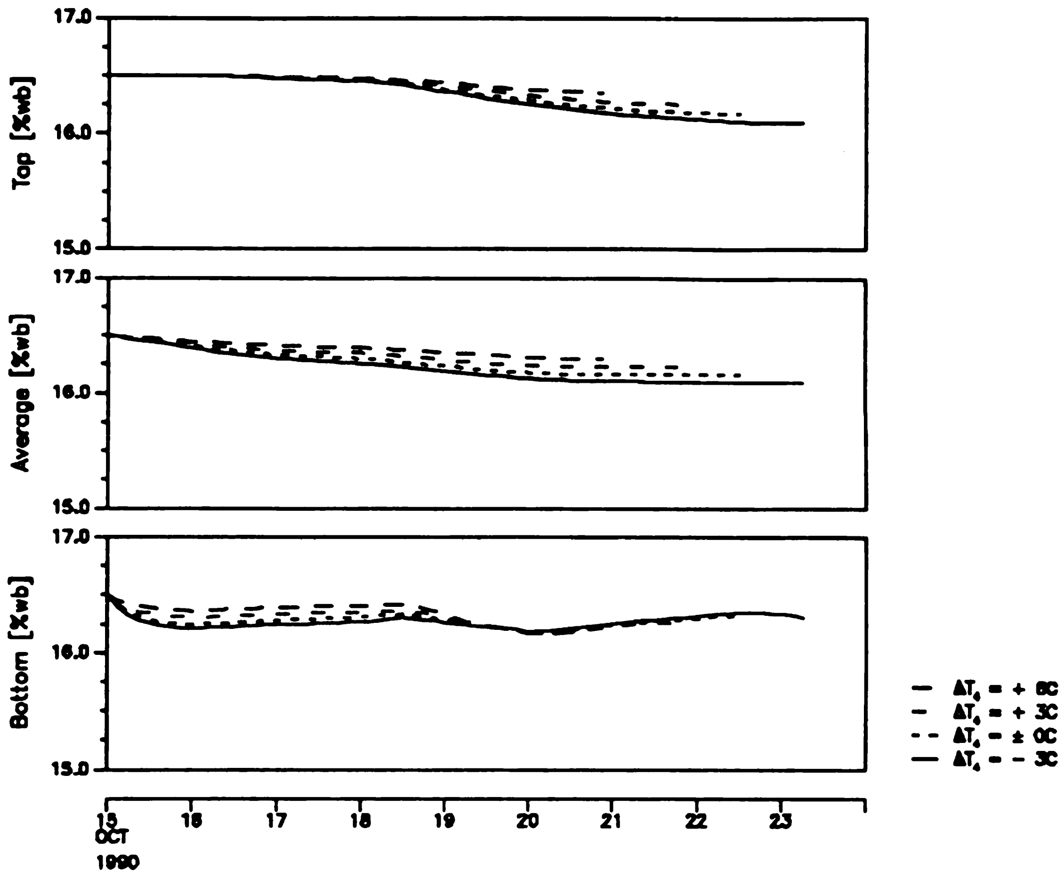

Figure 6.20 Simulated effect of the bin inlet air temperature on the moisture content profile in the corn bin during the initial cool-down.

the pile.

The cooling rates observed by changing the inlet air temperature can be compared to the cooling rates observed by increasing the initial grain temperature (see Figure 6.13). In both situations the relative humidity of the air from the chiller has the same pattern. Table 6.2 summarizes the cooling rates. They are related to the final grain temperature reduction and are independent of the initial and final grain temperatures (if the relative humidity profile of the chilling air are the same). Large cooling rates of the grain correspond to large temperature reductions in the grain pile due to chilling.

Table 6.2 Initial and final grain temperatures, overall temperature reduction, and cooling rates for the inlet air and initial grain temperature conditions.

Initial Grain Temperature [°C]	Final Grain Temperature [°C]	Reduction [°C]	Cooling Rate [°C/day]
28	7	21	2.6
23[1]	7	16	2.1
17	4	13	1.6
17	7	10	1.3
17	10	7	1.0
12	7	5	0.7
17	13	4	0.7

[1] not shown in Figure 6.13

6.1.4.3 Airflow Rate

Doubling the airflow rate into the grain bin does not cut the cooling time in half (see Figure 6.21), but reduces it by 38%, i.e. from 180 hour to 111 hours. If two identical grain chillers were connected to the same bin and operated in parallel, the airflow rate through the grain would be less than double since the operating point of the bin-chiller system changes non-linearly. The total energy consumption would increase by more than 22%, i.e. from 2,157 kWh used over 180 hours for one unit to more than 2,640 kWh (two times 1,320 kWh) for two units operating more than 111 hours each. Thus, it is more economical to operate each unit on a single bin, as long as shorter cooling times are not needed to arrest grain heating or insect infestation.

Halving the airflow rate through the grain increases the cooling time by 82% from 180 hours to 327 hours (the full extent of which is not shown). If one chiller was connected to two identical bins, the airflow rate through the grain would be more than half [since the system curve is non-linear]. The total energy consumption would reduce by more than 12%, i.e. from 2,157 kWh for a single bin to less than 1,907 kWh used for two bins at half the airflow. Again biological factors such as spoilage and insect infestation need to be considered. In wet grain the temperature should

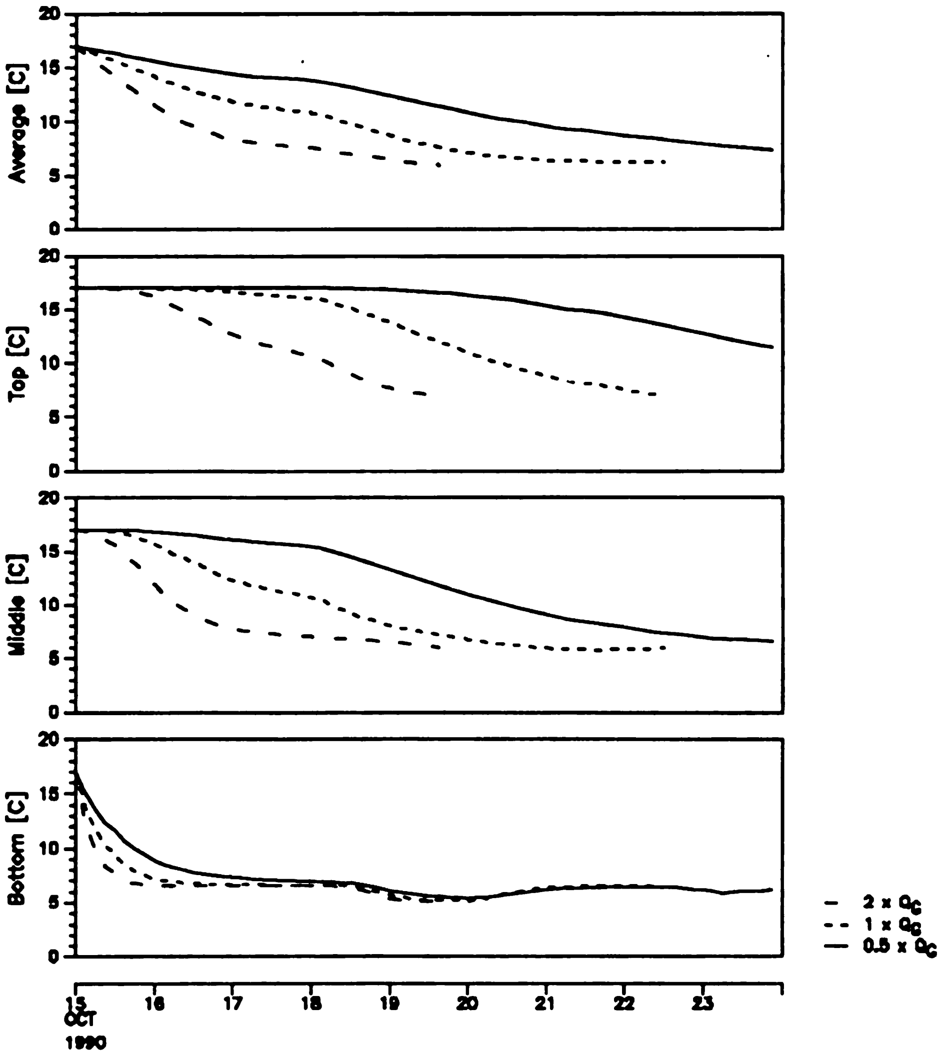

Figure 6.21 Simulated effect of the airflow rate on the temperature profile in the corn bin during the initial cool-down.

be reduced as quickly as possible to prevent molding, and in dry grain to prevent insect infestation (Christensen and Kaufmann 1969). The preferred approach from an engineering point of view is to match-up the capacity of the chilling unit (i.e. fan and refrigeration capacity) with the desired grain chilling requirements (i.e. design airflow rate and desired grain temperature).

The cooling rate at double the airflow is 2.2°C/day compared to 1.3°C/day at the standard airflow, and 0.7°C/day at half the standard airflow. Also, the cooling front reaches the top layer of the grain pile in less than one day compared to two and four days for the lower airflow rates, respectively.

The doubling and halving of the airflow rate at the bin inlet is illustrated in Figure 6.22. The airflow ranges from 3,100 m^3/h to 8,300 m^3/h at double the airflow, and from 900 m^3/h to 2,100 at half the standard airflow. The effect on the moisture content (not shown) is not significant. However, at the high airflow rate higher reabsorption rates are observed in the bottom layers of the grain during periods of high EMC values.

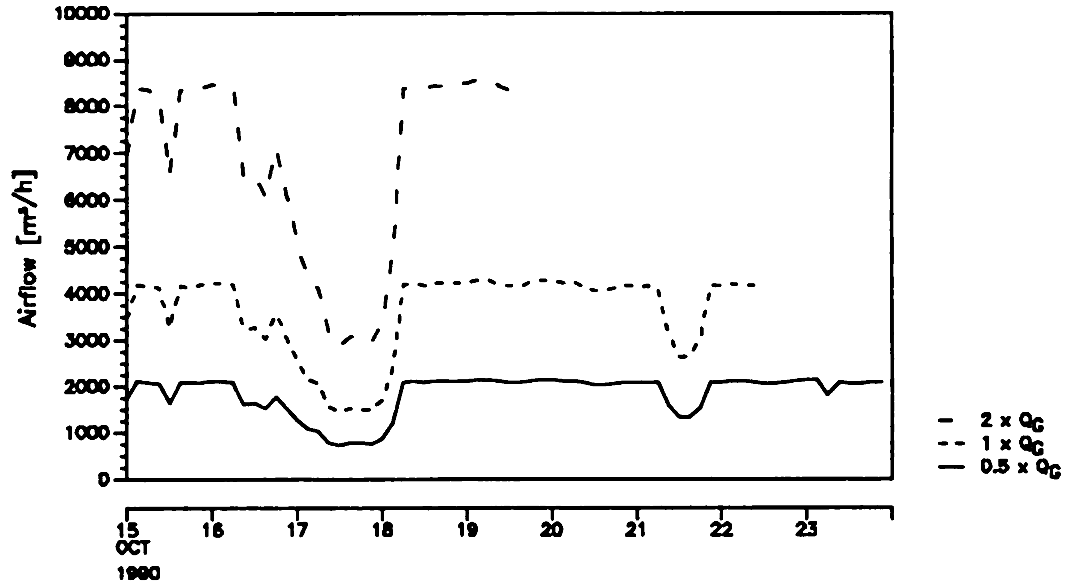

Figure 6.22 Simulated airflow rates of the KK140 grain chiller into the corn bin during the initial cool-down.

6.1.5 Chiller Controller Settings

The combined effects of the temperature, relative humidity and flow rate of the inlet air on the cooling of the grain bin are investigated for the following three scenarios: (1) changing the reheater temperature only, (2) changing the cold-air temperature only, and (3) changing both chiller set-point temperatures. If the reheater set-point is changed, while maintaining the cold-air set-point, the inlet air temperature and relative humidity are affected. If the cold-air temperature set-point is adjusted only, the airflow and relative humidity of the chilling air are affected. If both set-points are changed, and the degree of reheating is maintained, the airflow and bin inlet temperature are affected. Changing the set-point temperatures any other way affects all three inlet air parameters simultaneously.

6.1.5.1 Reheater Set-point

The combined effect of the inlet air temperature and relative humidity due to a change in the reheater temperature decreases the cooling time of the corn bin compared to the individual effects (see Figures 6.19 and 6.23). At 6°C, 9°C and 12°C after the reheater (and a constant cold-air temperature of 3°C) the cooling times are

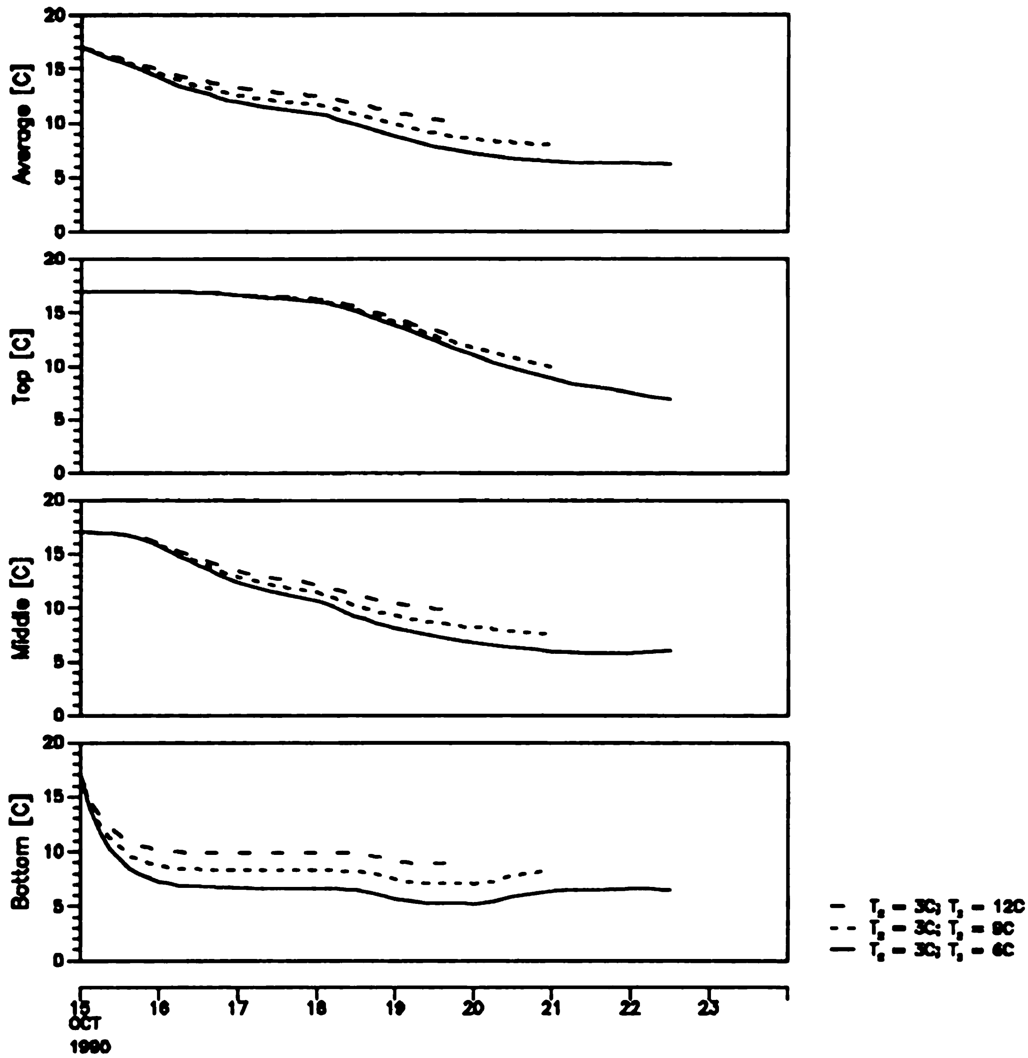

Figure 6.23 Simulated effect of adjusting the reheater set-point temperature on the temperature profile in the corn bin during the initial cool-down.

180, 144, and 114 hours respectively. Increasing the reheater temperature to 9°C reduces the maximum relative humidity into the bin to 65%. The cooling time is shortened by 18 hours compared to increasing the bin inlet temperature while maintaining a higher relative humidity range. The maximum relative humidity is reduced to 54% and the cooling time shortened by 27 hours if the reheater temperature is increased to 12°C compared to increasing the reheater temperature while maintaining a higher relative humidity.

The higher evaporative cooling effect at the higher reheater temperature combined with a lower relative humidity of the chilling air is illustrated in Figures 6.20 and 6.24. The drying effect observed in the bottom layers of the grain bin exceeds 1.0 point of moisture at 12°C reheating, and 0.8 points at 9°C reheated air. The average moisture removal is more uniform throughout the pile. Interestingly, the final average moisture content reached at the end of the chilling cycle is about the same for each setting.

The combined effect of the inlet air temperature and relative humidity is also investigated for the chilling of the wheat bin (see Figure 6.25). At a reheater temperature of 16°C the wheat cools to 18°C within 165 hours, and at a cooling rate of 1.7°C/day. At 13°C reheated air the cooling rate is 1.6°C/day for lowering the wheat from 30°C to 15°C in

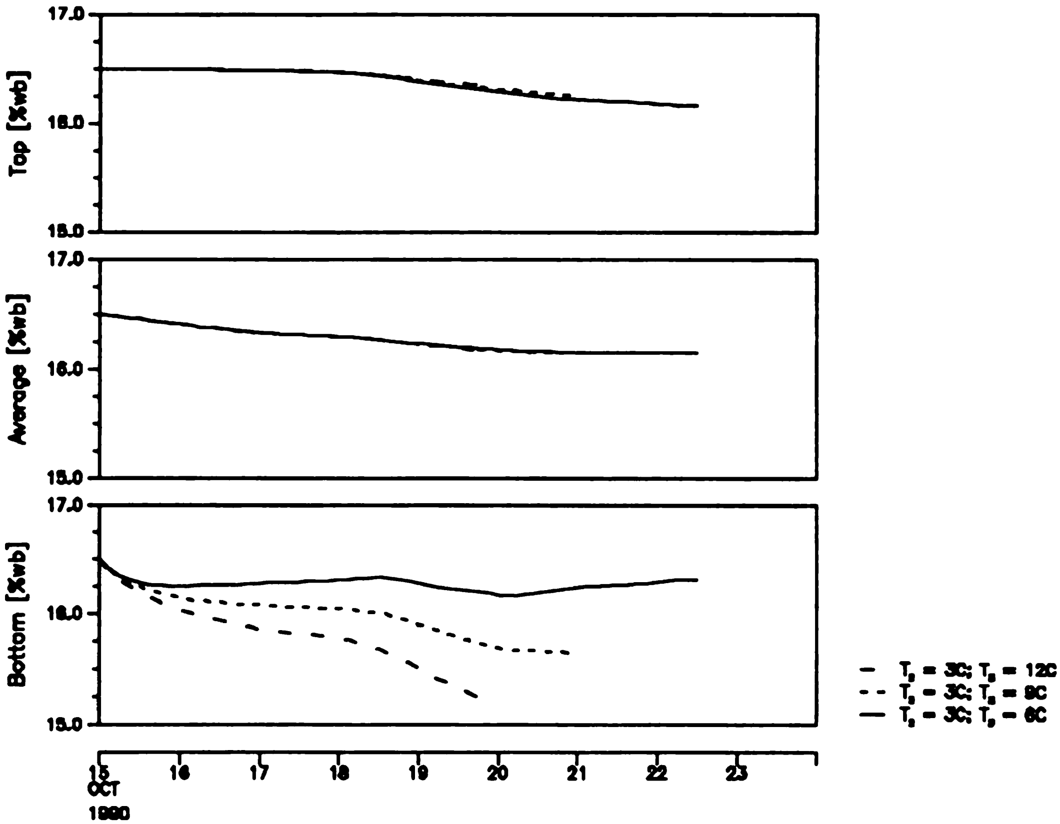

Figure 6.24 Simulated effect of adjusting the reheater set-point temperature on the moisture content profile in the corn bin during the initial cool-down.

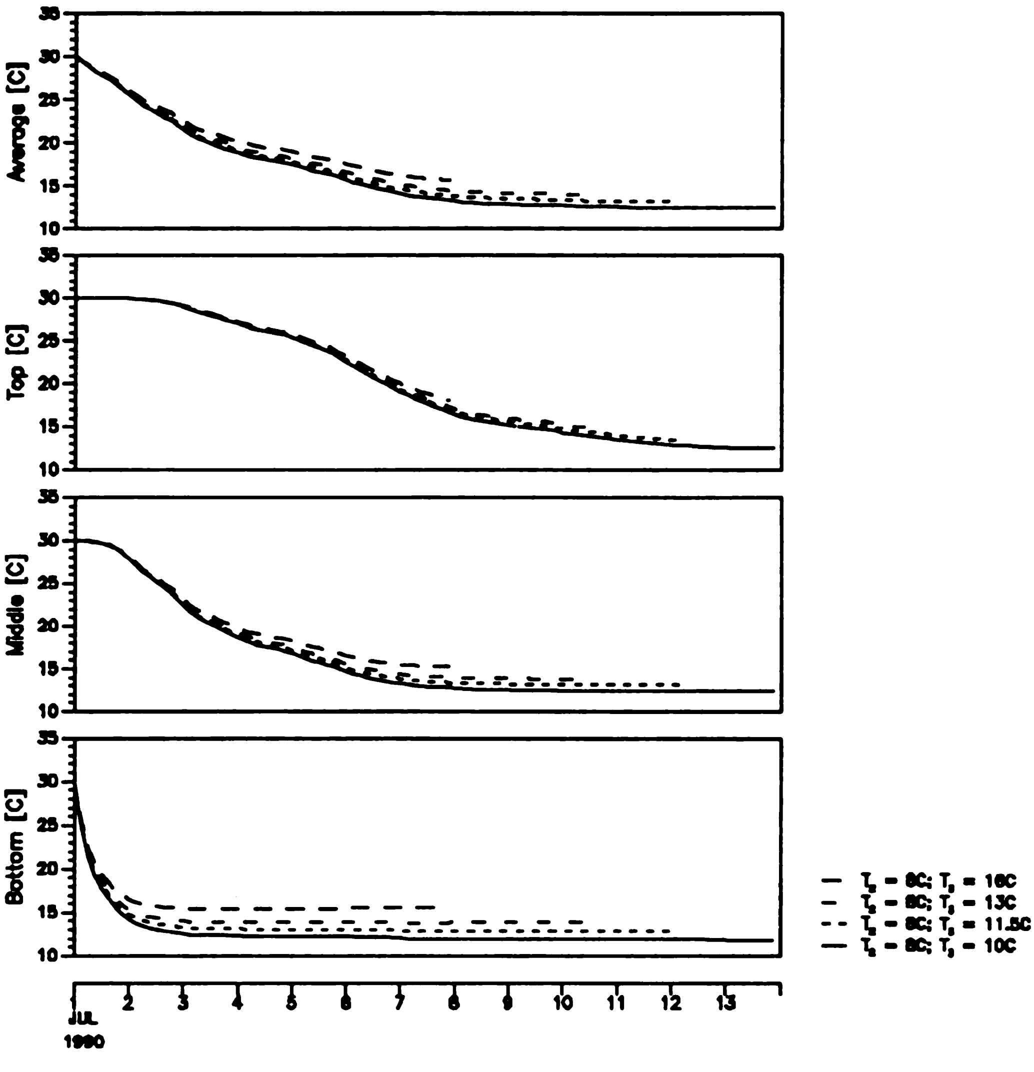

Figure 6.25 Simulated effect of adjusting the reheater set-point temperature on the temperature profile in the wheat bin during the initial cool-down.

225 hours. At a reheat temperature of 10°C (and a cold air temperature of 8°C) the wheat does not reach 12°C within the one-month run-time limit imposed on the simulation. The effect of reducing the relative humidity is obvious at a reheater set-point of 11.5°C. Sufficient reheating is available to lower the wheat temperature to 13.5°C within 267 hours at a rate of 1.5°C/day.

Initially, the bottom layers all experience a moisture reduction due to evaporative cooling in the first two days of chilling (see Figure 6.26). At 17°C inlet temperature to the bin and 55% relative humidity, the EMC-value of the air is 11.7% w.b.; at 14°C and 68% relative humidity the EMC-value increases to 13.3 w.b.%. As the EMC-value increases further, i.e. at 12.5°C and 73% the EMC-value is 14.1% w.b., the bottom layer of the pile starts to reabsorb moisture. The effect of the low relative humidity at the bin inlet dissipates in the pile. For all cases the final average moisture content is about 13.5% w.b. The same phenomenon is also observed in the corn bin, as was discussed in detail Chapter 6.1.4.1.

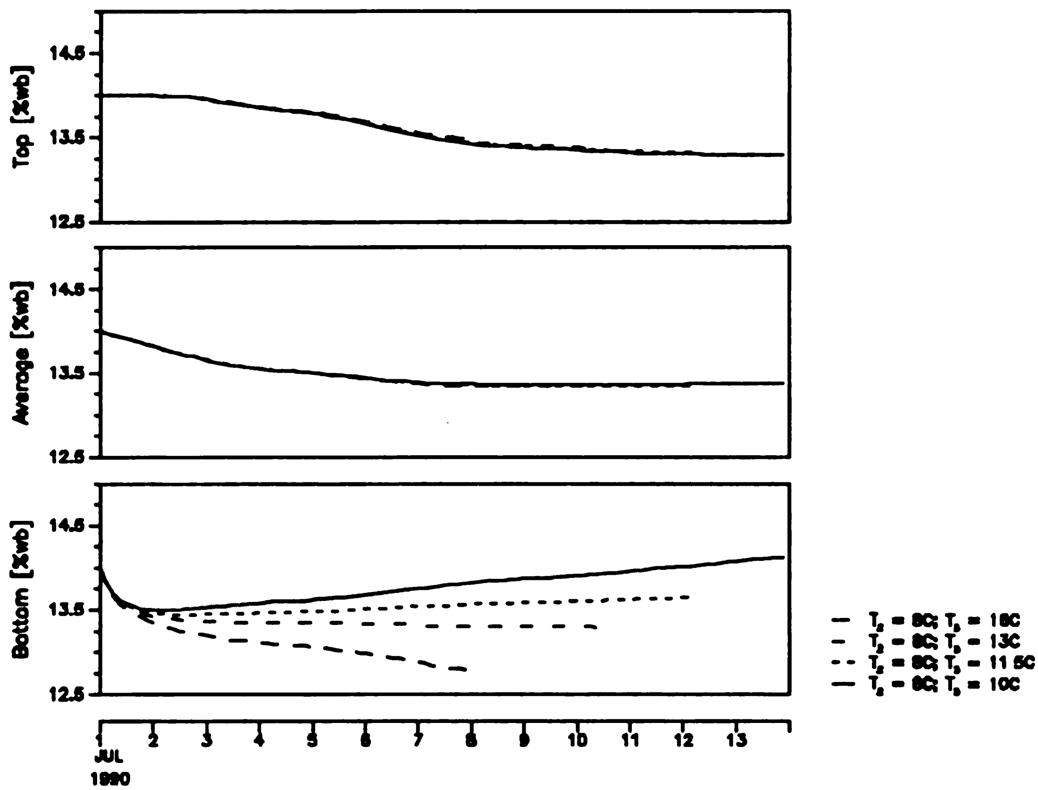

Figure 6.26 Simulated effect of adjusting the reheater set-point temperature on the moisture content profile in the wheat bin during the initial cool-down.

6.1.5.2 Cold-air Set-point

The combined effect of the airflow rate and relative humidity of the bin inlet air (by changing the cold-air temperature set-point) is illustrated in Figure 6.27. At 9°C cold-air and 12°C reheater set-points the cool-down time is 111 hours. Decreasing the cold-air set-point to 6°C does not change the cooling time. An additional decrease in the cold-air temperature increases the cool-down time slightly to 114 hours. Thus, a change in the cold-air temperature set-point does apparently not influence the cool-down time of the corn bin. The temperature profiles show similar evaporative cooling effects in the first 36 hours of chilling. On the third and fourth day of the cycle the bottom layer is rewarmed by as much as 2.5°C at the higher cold-air temperature setting. The effect on the middle and top layers in the pile is negligible. The average temperature profiles are nearly identical for the different set-point combinations.

Figure 6.28 shows the airflow rates during the 5-day chilling cycle. The airflow rate is lowest for the lowest cold-air set-point temperature, and highest for the highest set-point temperature during most of the cycle. Although a large difference in the cooling time may be expected, the effect of the higher airflow rate is off-set by the effect

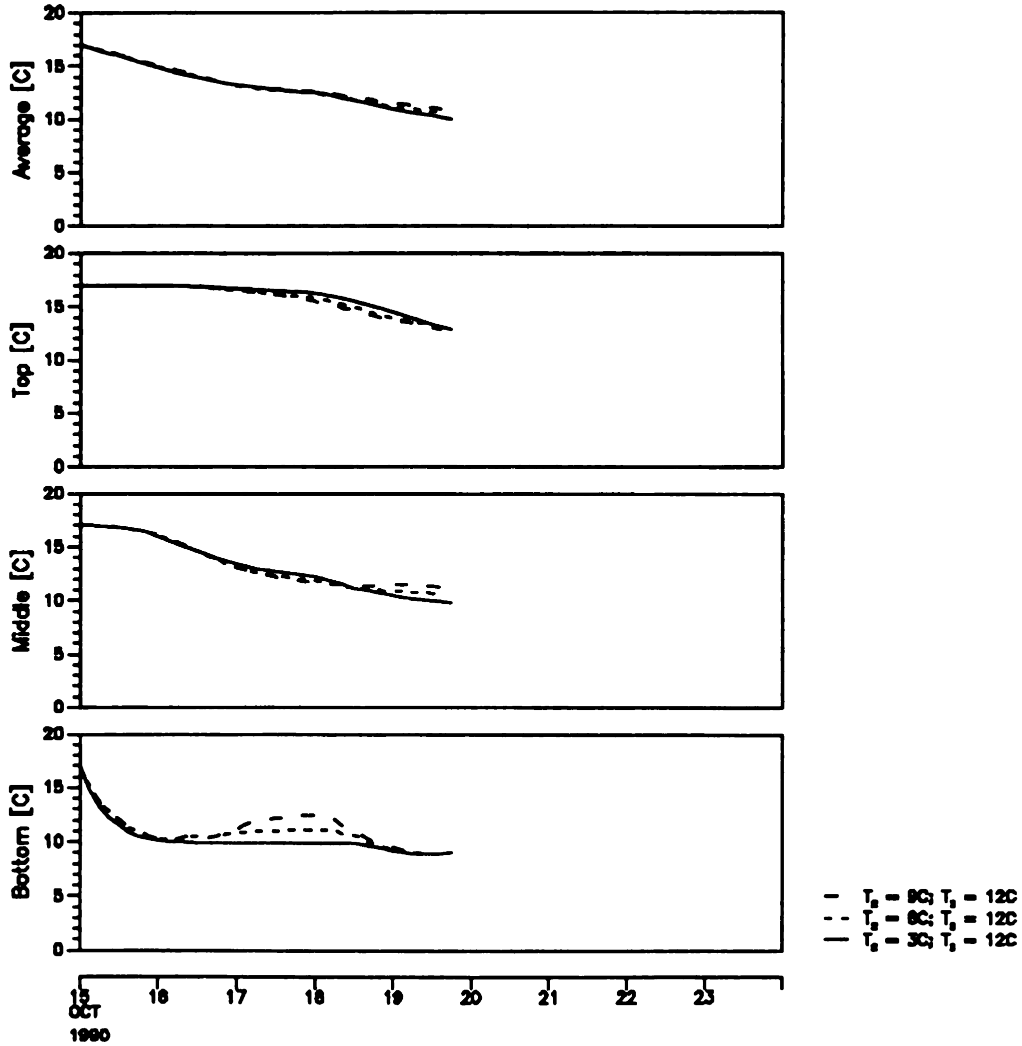

Figure 6.27 Simulated effect of adjusting the cold-air temperature set-point on the temperature profile in the corn bin during the initial cool-down.

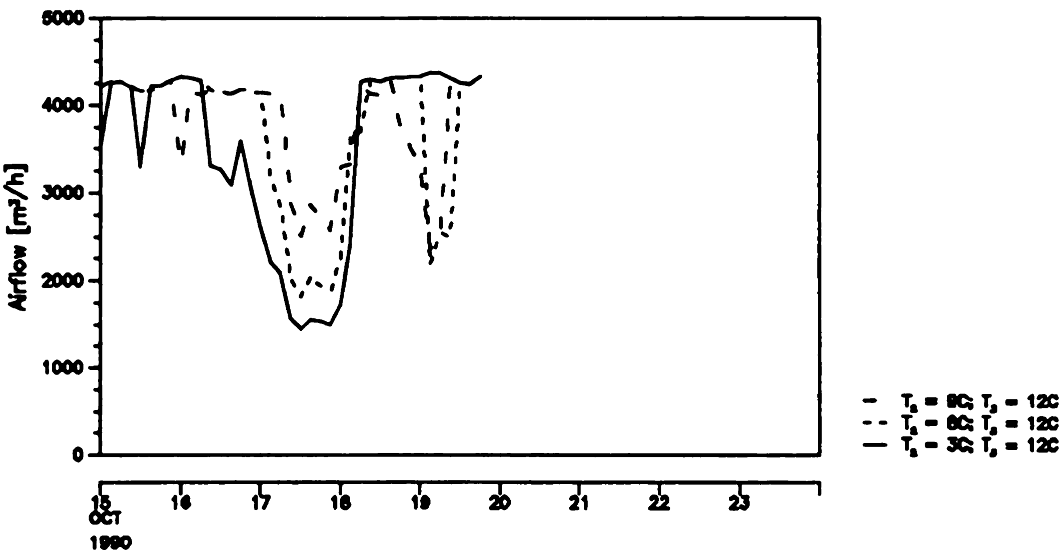

Figure 6.28 Simulated airflow of the KK140 grain chiller for different cold-air set-point temperatures during the initial cool-down.

of the higher relative humidity of the bin inlet air. Figure 6.29 shows that at a cold-air temperature of 3°C (and a reheater temperature of 12°C) the moisture content of the grain is lowest in the bottom layer of the bin. The effect is noticeable in the average moisture content. Lower relative humidity values have previously been shown to significantly affect the cooling of the grain (see Chapter 6.1.4.1).

One significant exception in the airflow rate occurs on the fifth day. The airflow rate at the 3°C cold-air is at a maximum, while at 6°C and 9°C the airflow rate is reduced to about 2,200 m^3/h (see Figure 6.28). The chiller performance curves presented in Figure 6.7 show that the ambient temperature reaches a low of 1°C during that day. The built-in electrical heaters maintain the reheater set-point temperatures for the 6°C and 9°C cold-air cases but at reduced airflow rates. For the 3°C cold-air set-point the refrigeration cycle operates at maximum airflow (and reduced refrigeration capacity), since the fan heat added to the ambient air raises the air temperature before the evaporator high enough. Thus, only supplemental electrical heating is needed since enough condensing capacity is available in the reheater to maintain the set-point temperature.

Under the summer chilling conditions of 1990 the cooling

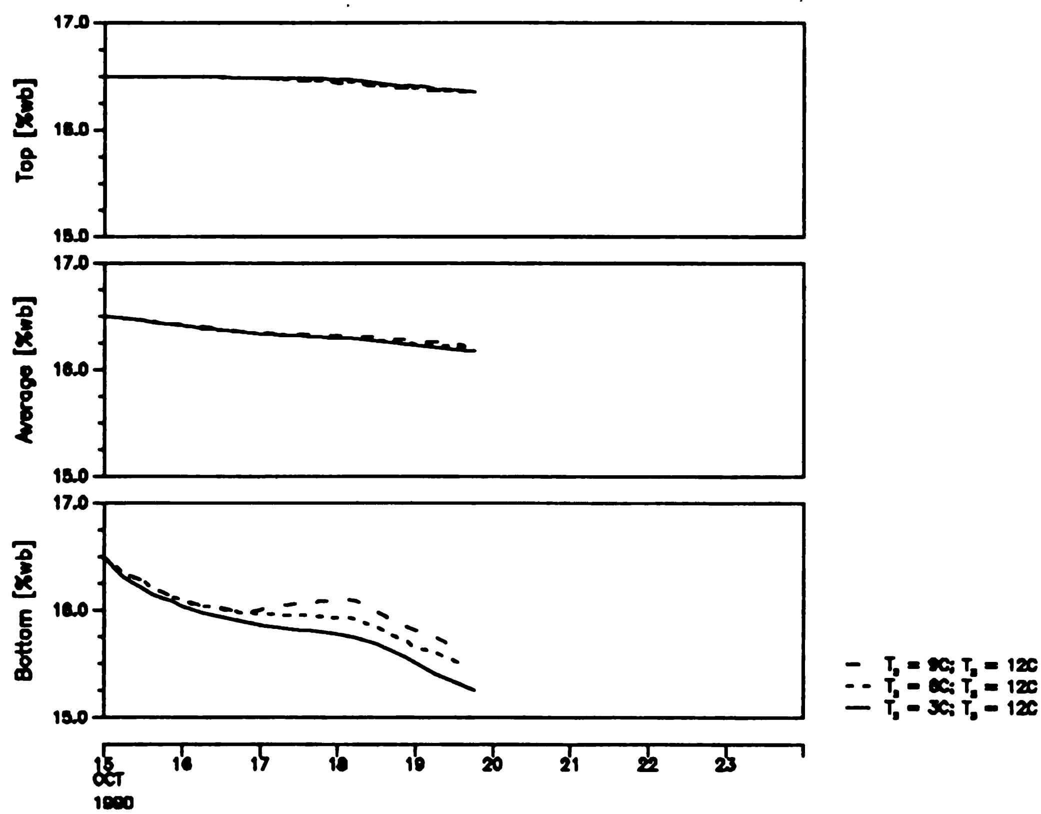

Figure 6.29 Simulated effect of adjusting the cold-air temperature on the moisture content profile in the corn bin during the initial cool-down.

time for wheat is the same at cold-air settings of 11°C and 8°C, while at 5°C the cooling time increases from 165 hours to 198 hours (see Figure 6.30). Obviously, the available refrigeration capacity of the grain chiller determines the lower limit of the cold-air set-point with respect to airflow. At a cold-air set-point of 5°C with 11°C reheating the airflow rate into the bin is low enough to affect the cooling time.

Although the higher cold-air temperature setting yields a higher airflow rate (see Figure 6.31), the increased cooling effect is off-set by the higher relative humidity of the inlet bin air [which is 67% maximum compared to 55% maximum at 8°C cold-air and 16°C reheated air]. Less than 6°C of reheating the air for wheat at 14% w.b. moisture content has been shown to extend the cooling time significantly (see Chapter 6.1.5.1). Figure 6.30 confirms that dry wheat can be chilled to 18°C within a reasonable length of time.

6.1.5.3 Cold-air and Reheater Set-points

Adjusting the cold-air and reheater set-points while maintaining the same amount of reheating affects the airflow rate and the bin-inlet temperature.

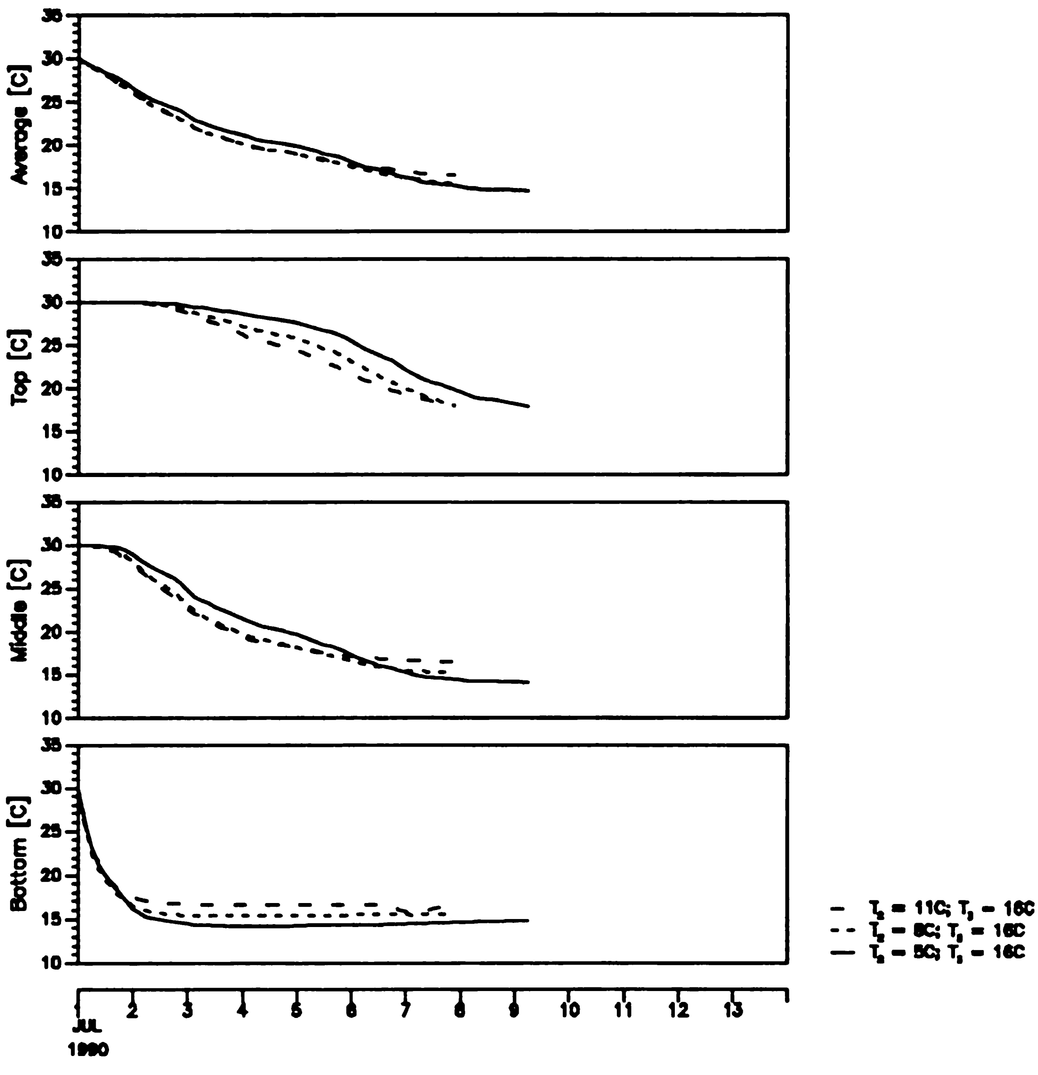

Figure 6.30 Simulated effect of adjusting the cold-air temperature on the temperature profile in the wheat bin during the initial cool-down.

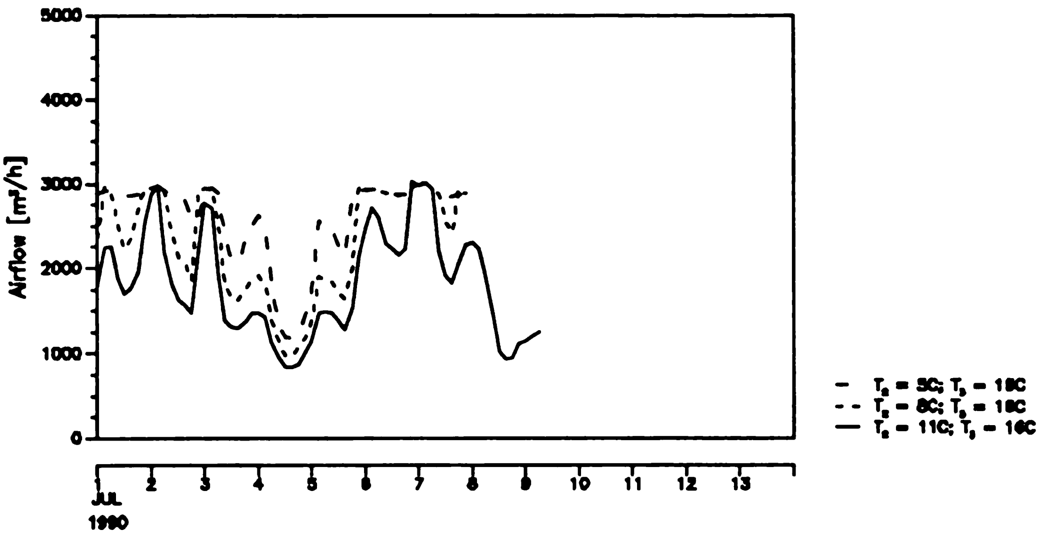

Figure 6.31 Simulated airflow of the KK140 grain chiller for different cold-air temperatures during the initial cool-down.

Increasing the cold-air set-point from 8°C to 11°C and the reheater set-point from 13°C to 16°C reduces the cooling time from 225 hours to 165 hours when cooling wheat from 30°C (see Figure 6.32). Previously it was observed that for high grain temperature reductions high cooling rates are achieved. For equal reheating at different set-points this does not occur. At a cold-air set-point of 8°C and a grain temperature reduction of 15°C, a cooling rate of 1.6°C/day results. Increasing the cold-air temperature to 11°C and the reheater to 16°C reduces the grain temperature by 12°C but increases the cooling rate to 1.8°C/day. Decreasing the cold-air to 5°C and the reheater to 10°C increases the temperature reduction to 18°C but decreases the cooling rate to 1.4°C. Thus, keeping the amount of reheating constant while increasing both set-points increases the airflow rate sufficiently to raise the cooling rate in a grain bin.

Since the same degree of reheating is used for each set-point combination, the EMC-value at the inlet to the bin is about the same, i.e. 13.3% w.b. The moisture profiles in Figure 6.33 confirm this observation. In the bottom layer the drying effect of about 0.5 percentage points is the same in each case. The average final moisture is slightly higher for higher inlet temperatures. This may be partly due to the smaller temperature reduction.

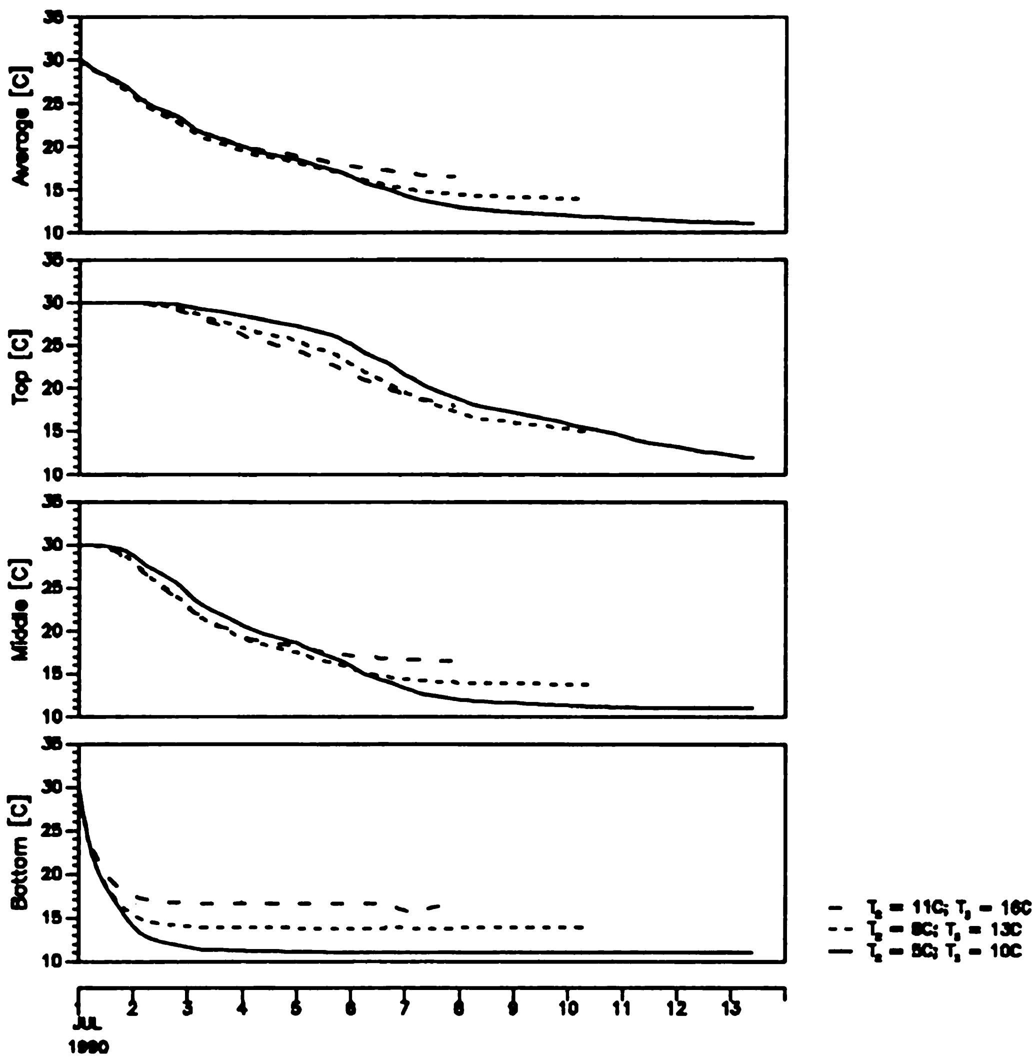

Figure 6.32 Simulated effect of adjusting both the cold-air and reheater temperatures on the temperature profile in the wheat bin during the initial cool-down.

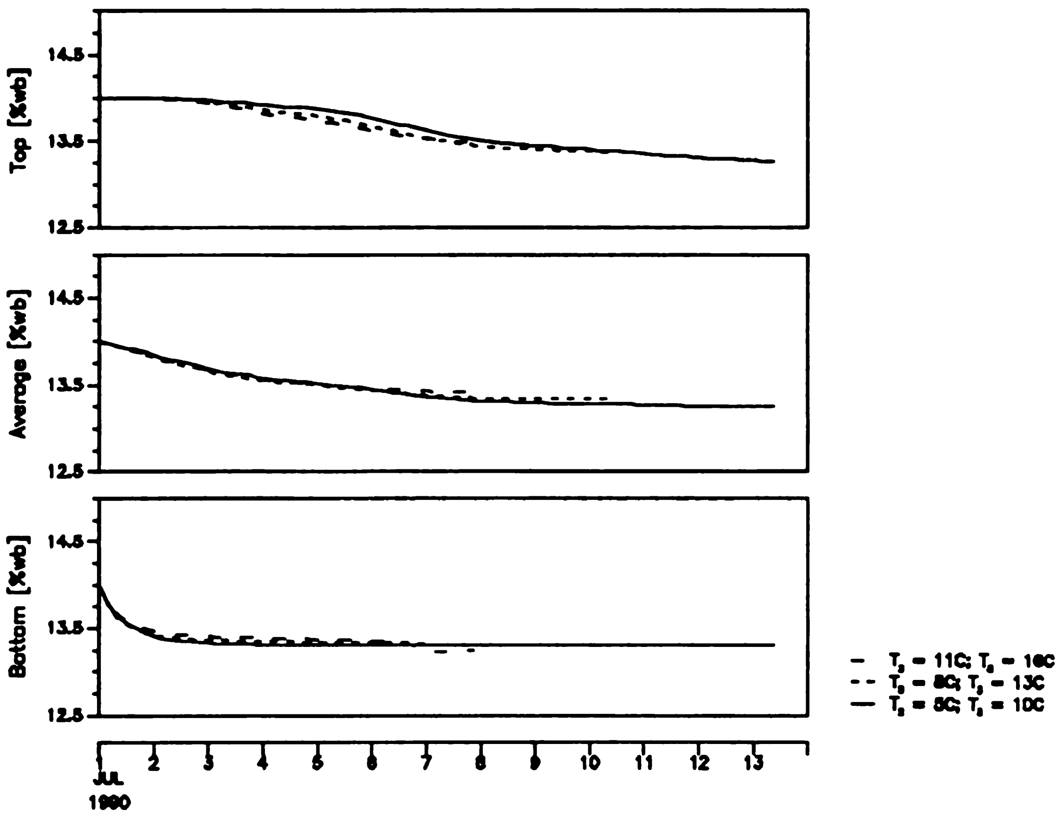

Figure 6.33 Simulated effect of adjusting both the cold-air and reheater temperatures on the moisture content profile in the wheat bin during the initial cool-down.

The above observations are different for corn chilling in the fall of 1990. Due to the low ambient cooling load toward the middle of the chilling cycle the relative humidity of the bin inlet air is not constant since the electrical heaters kick-in. Thus, this case is not further considered here.

6.2 Critical Storage Parameters

The parameters critical to the successful storage of chilled grains are the bin dimensions, grain properties, and boundary conditions (i.e. thermal radiation, free-stream temperatures, and heat transfer coefficients). Their influence is investigated with the two-dimensional heat conduction submodel, which is part of the chilled aeration and storage system model. The quantitative influence of a specific storage parameter varies for different configurations. However, the qualitative influence should be the same regardless of the configuration. The critical storage parameters are evaluated for a bin of corn and of wheat under the weather conditions for mid-Michigan between 1988 through 1991. Table 6.3 summarizes the values used in the simulation runs.

The bin dimensions are the same as for the chilled aeration study (see Chapter 6.1). A level fill of the bin to the sidewall height is assumed. The starting and ending dates represent the beginning and end of the simulated storage period. The initial grain temperature assumes that the corn and wheat in the bin are cooled by chilling (or with ambient air) uniformly before the storage period is initiated. The storage moisture contents are the ones recommended for long-term grain storage in the Midwestern U.S.A. (MWPS-13 1988). The bulk densities of the grains are a function of the grain moisture content.

Table 6.3 Simulation values used to investigate the critical storage parameters of a bin of corn and wheat under Mid-Michigan conditions.

Parameter	Corn	Wheat
Bin diameter [m]	10.1	
Bin sidewall height [m]	10.3	
Bin overall height [m]	13.3	
Bin roof angle [°]	30	
Amount of grain [tonnes]	573	628
Starting date	October 1, 1988	
Ending date	July 31, 1991	
Initial temperature [°C]	5.0	
Initial moisture content [%wb] and bulk density [kg/m^3]	13.0 700.1	13.0 767.8
Vertical step size [m]	1.5	
Radial step size [m]	0.72	
Time step size [hr]	6.0	

6.2.1 Grid and Time Step Sizes

The selection of the vertical and radial grid node spacings, and the time step size is governed by the stability criteria of the finite difference solution of the two-dimensional heat conduction equations (see Chapter 4.4.2.1.2).

Figure 6.34 illustrates the effect of the simulation parameters on the profile of the bulk and periphery grain temperature over the 3-year storage period. The bulk temperature profiles are almost identical. The 7 by 7 grid (i.e. Δr = 0.72 m, Δz = 1.5 m, $\Delta \tau$ = 6 hours) predicts lower temperatures in the winter periods by about 1°C, and higher temperatures in the summer time by about 2°C compared to the finer grid of 20 by 20 nodes (i.e. Δr = 0.25 m, Δz = 0.51 m, $\Delta \tau$ = 2 hours). The predicted temperature profile in the periphery by the 7 by 7 grid shows a narrower bandwidth and slightly smaller amplitudes compared to the finer 20 by 20 grid.

Although the temperature profiles are slightly different, the qualitative effects of the various storage parameters can be compared with either grid and time step combination. Both combinations predict similar off-set periods between the temperatures in the bulk versus the periphery. To save computer time the coarser grid and larger time step are used

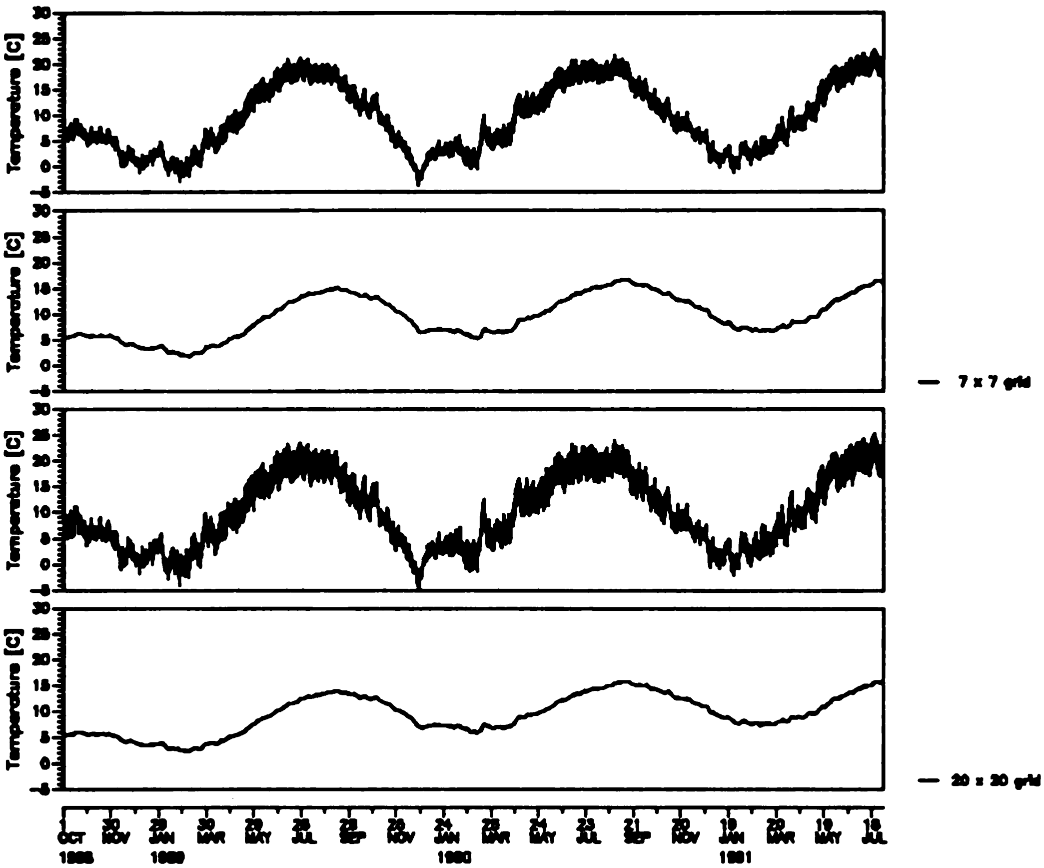

Figure 6.34 Effect of the vertical and radial grid spacing and the time step size on the bulk and periphery temperature profile in the corn bin predicted by the 2-D storage simulation.

in the evaluation of the remaining parameters. [Two exceptions: the stability criteria dictate a time step of 2 hours for the 5.0 m bin diameter, and a time step of 3 hours for the doubled wall heat transfer coefficient in order to maintain the 7 by 7 grid].

6.2.2 Bulk versus Periphery Volume

Throughout the analysis of the critical storage parameters the bulk of the grain is defined as 90% of the amount of grain in the bin. The periphery volume is assumed to completely envelop the bulk of the grain; it includes a layer of grain at the top and the bottom of the bin (each of equal thickness) plus a layer along the inside wall of the bin of twice the thickness of the top and bottom layers. The grid of the two-dimensional storage submodel is interpolated so that the average bulk temperature represents 90% of the grain volume in the bin, and the periphery temperature the remaining 10%.

Figure 6.35 shows the effect of varying the definition of the bulk volume from 75% to 95%. In the early fall of 1989 the temperature difference is 0.5°C maximum between the 75% and the 95%. In late December the difference increases to about 1°C. During the cold weather period of January

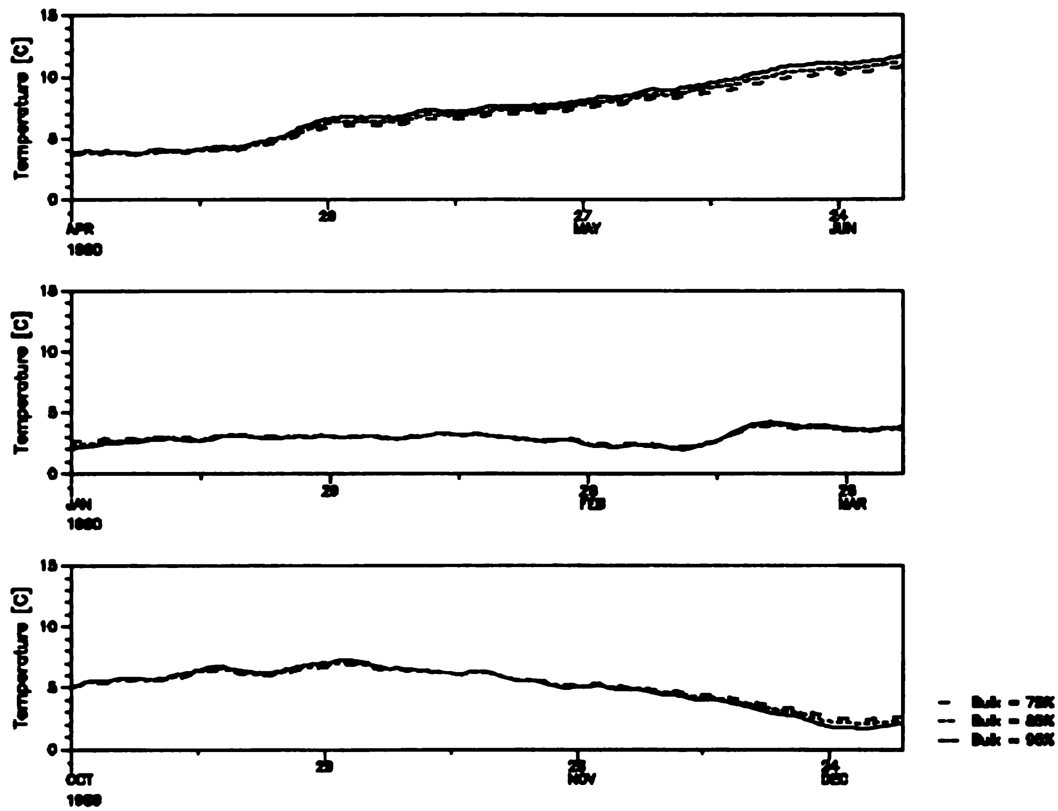

Figure 6.35 Effect of the bulk volume definition on the bulk temperature profile in the corn bin predicted by the 2-D storage model.

through March the bulk temperatures for the three cases are about equal. By late April 1990 the difference begins to develop again. By the end of June the predicted difference between the 95% and the 85% values, and between the 85% and the 75% values is about 1°C, respectively. This difference persists throughout the summer storage period (not shown). Thus, the larger bulk volume predicts slightly faster warming in the summer and cooling in the winter. However, the difference between the three definitions of bulk volume appear almost negligible.

6.2.3 Boundary Conditions

The effect of the boundary conditions on the grain temperature in the storage bin is evaluated in terms of the heat transfer coefficients in the head space and plenum of the bin, the heat transfer coefficient on the outside bin wall surface, and the solar radiation on the bin. The effects of other variables such as the free-stream temperatures in the head-space, plenum and around the bin, the wind velocity, and the radiative properties of the steel bin have similar qualitative effects, and are not presented.

6.2.3.1 Head-space and Plenum Heat Transfer

Figure 6.36 shows that the maximum and minimum bulk temperatures essentially do not change when the combined effect of the heat transfer coefficients in the head space and plenum of the bin are doubled or halved. The profile of the bulk temperature is somewhat smoother when the coefficients are halved. By doubling the values the temperature profile responds more rapidly to the daily variations of the ambient and solar conditions. Thus, the selection of the heat transfer coefficient values in the head space and in the plenum appears not to be critical in the calculation of the bulk temperature profile.

6.2.3.2 Bin Wall Heat Transfer

Figure 6.37 illustrates the effect on the bulk temperature of the heat transfer coefficient acting on the outside of the bin wall. Halving the value shifts the bulk temperature upward and increases the amplitude of the profile. For example, the bulk temperature predicted in August 1989 is about 3.5°C higher and in February 1990 about 2.5°C higher than at double the value of h_w, i.e. 17.5°C compared to 14°C and 2.5°C compared to 1.5°C, respectively. This may at first appear to contradict one's intuition. However, the

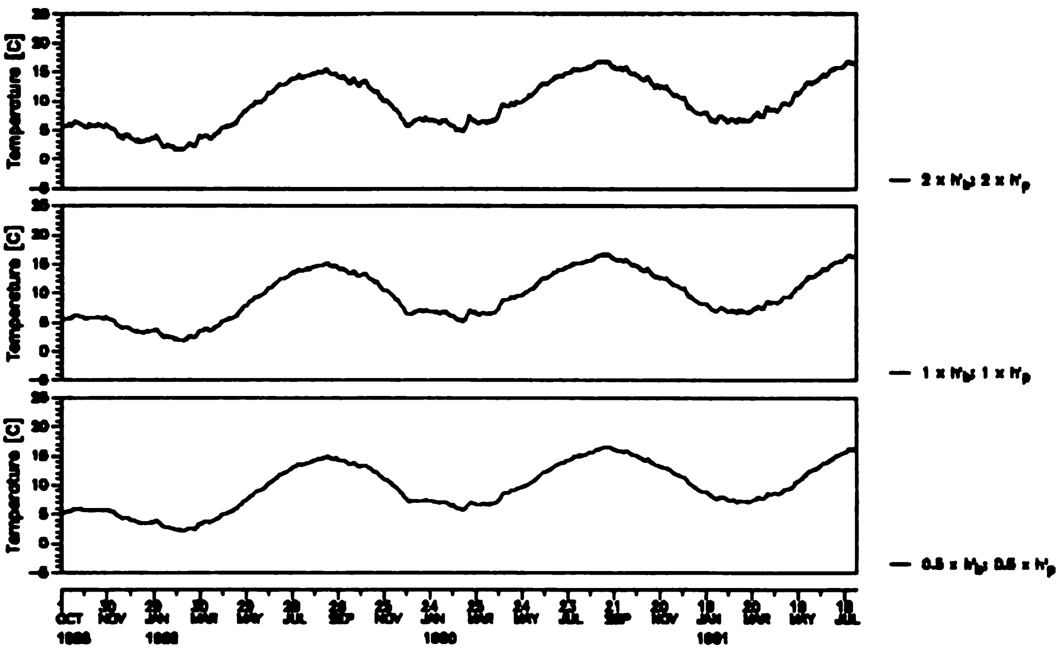

Figure 6.36 Effect of the convective heat transfer coefficient in the head-space and the plenum of the bin on the bulk temperature profile in the corn bin predicted by the 2-D storage model.

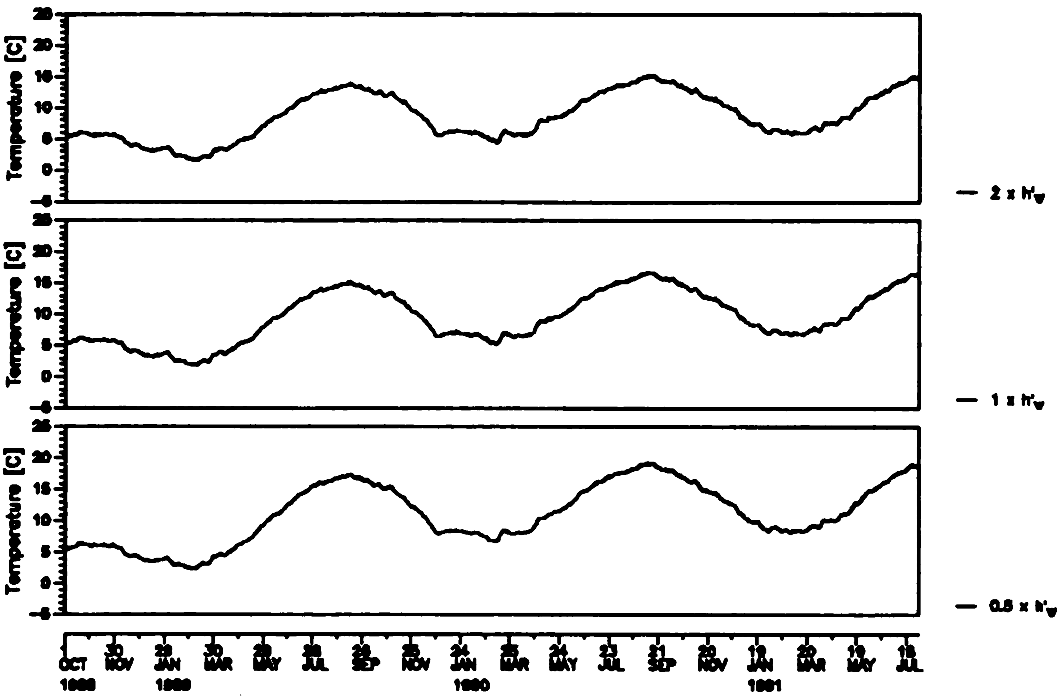

Figure 6.37 Effect of the bin wall convective heat transfer coefficient on the bulk temperature profile in the corn bin predicted by the 2-D storage simulation.

wall convective heat transfer essentially off-sets the influence of the solar radiation on the bin. The higher the coefficient the larger the convective heat exchange between the grain bin and the ambient air. A higher exchange rate maintains the grain temperature in the bulk closer to the ambient air temperature. At a lower wall convective heat transfer coefficient, the heat exchange is smaller and the effect of the solar radiation on the bin increases.

This observation in the previous paragraph justifies the choice made earlier to modify the equation for calculating the heat gain or loss at the vertical bin surface. The equation presented by Finnigan and Longstaff (1982) was adjusted by a factor of 1.55 to match the experimentally determined bulk temperatures during the chilled aeration and storage field tests between 1988 through 1991 (see Chapters 4.4.2.1.3 and 5.2.3).

6.2.3.3 Solar Radiation Flux

The solar radiation on the vertical and roof bin surfaces has the reverse effect on the bulk grain temperature than the wall heat transfer coefficient (see Figure 6.38). Doubling the solar radiation shifts the temperature upward and increases the amplitude of the profile obtained at lower

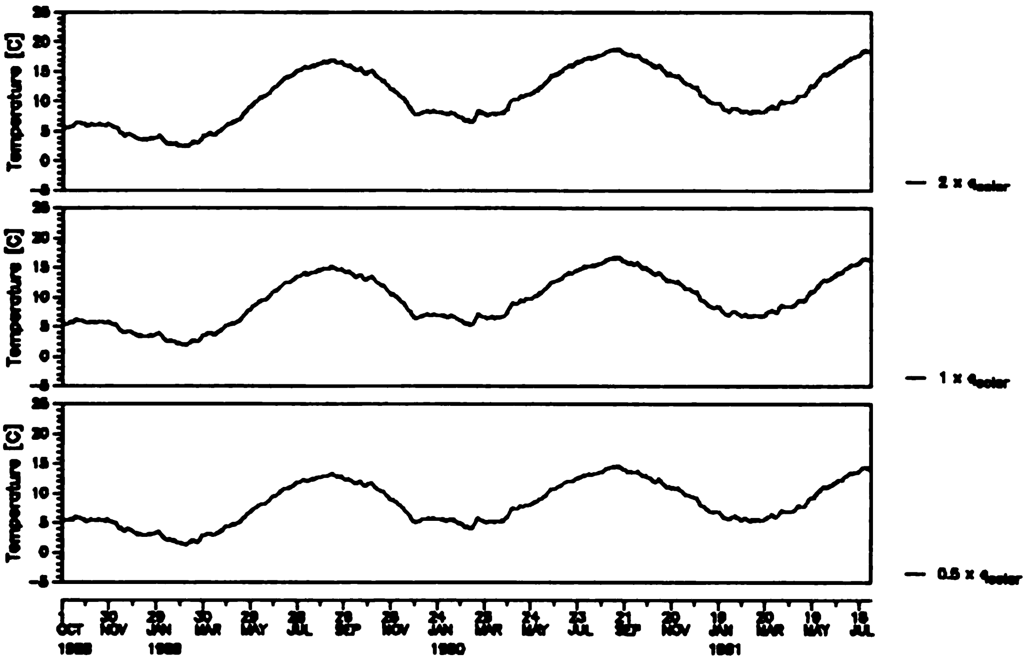

Figure 6.38 Effect of the solar radiation flux on the bulk temperature profile in the corn bin predicted by the 2-D storage simulation.

values of radiation flux. The maximum bulk temperature during the 3-year storage period is 19°C in September of 1990, compared to 17°C at the actual and 15°C at the halved value of the solar radiation. The minimum bulk temperature predicted at double the solar flux is 2.5°C in February of 1989 compared to 2°C at the actual and 1°C at the halved value of the flux.

Figure 6.39 shows the solar radiation effect on the periphery temperature of the grain pile. In addition to the temperature shift and amplitude effect, the band-width of the periphery temperature at double the solar flux is markedly wider than at the lower flux values. Since the solar radiation is mainly a function of geographic location, grain stored in bins at lower latitudes is exposed to more significant temperature variations in the periphery compared to bins in northern latitudes. Solar radiation has a significant influence on the storage temperature of cereal grains in round steel bins.

6.2.4 Bin Dimensions

The frequency of rechilling a grain bin is also dependent upon the physical dimensions of the bin. The bin dimensions are investigated in terms of the bin diameter, bin height,

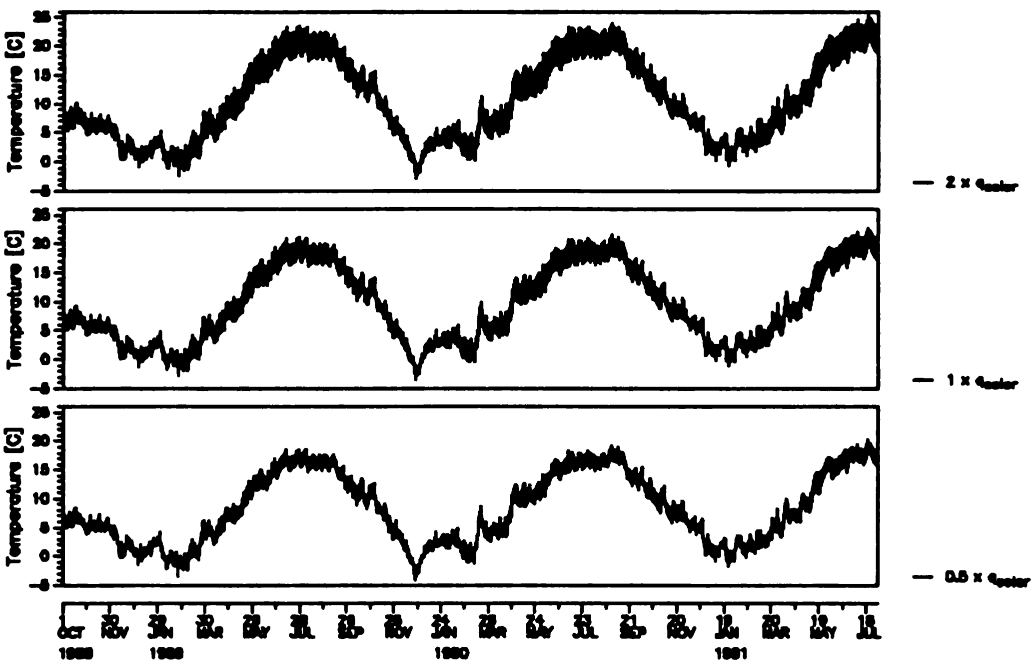

Figure 6.39 Effect of the solar radiation flux on the periphery temperature profile in the corn bin predicted by the 2-D storage simulation.

and the surface-to-volume ratio of the bin. To maintain a similar collector effect on the bin roof for different diameter bins the roof angle is maintained at 30°, and the roof height increased accordingly. This adjustment is made in the design of commercial grain storage bins for structural reasons (Chief 1986, GSI 1989). Also, the grain bulk is maintained at 90% of the bin volume for each bin dimension investigated.

6.2.4.1 Bin Diameter

The bulk temperature of a grain mass is greatly affected by the bin diameter (see Figure 6.40). At a bin diameter of 5.0 m the amplitude of the temperature profile is significantly increased compared to that of larger bins. In the 20.1 m diameter bin a difference of 8°C is predicted between the low in January 1989 and the high in August 1989, compared to 13°C in the 10.1 m and 18°C in the 5.0 m diameter bin. Thus, as expected the grain bulk temperature in smaller diameter bins changes more significantly as a function of the environmental boundary conditions than that in larger diameter bins. And, chilled grain stored in smaller diameter bins is more difficult to manage with respect to maintaining the desired storage temperature than if stored in larger diameter bins.

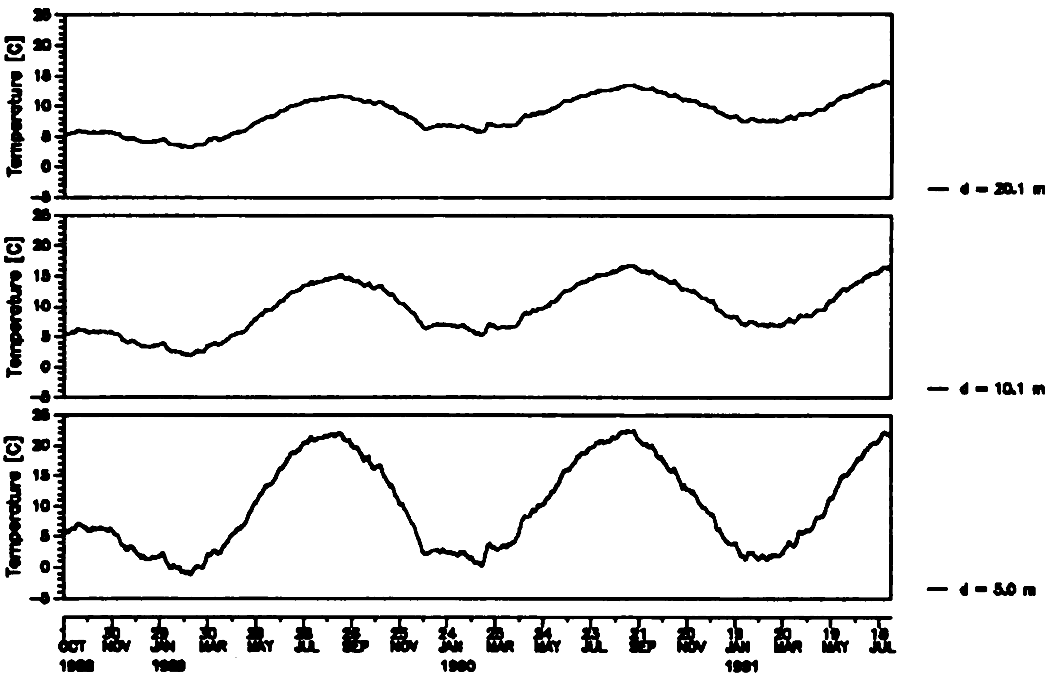

Figure 6.40 Effect of the bin diameter on the bulk temperature profile in the corn bin predicted by the 2-D storage simulation.

6.2.4.2 Bin Height

Changing the height of the grain bin at constant diameter is illustrated in Figure 6.41. At smaller heights the amplitude of the bulk temperature is increased, and larger maximum and minimum temperatures are predicted. For example, in February of 1991 the smaller height bin predicts a low of 4°C compared to 7°C in the 10.3 m and 8°C in the 20.6 m high bin. In September of 1990 a maximum temperature of 18°C compared to 16.5°C, and 16°C is predicted in the 5.2 m versus the 10.3 m and 20.6 m high bins, respectively. Thus, again as expected smaller bin heights show similar effects on the storage temperature as smaller bin diameters.

The diameter-to-height ratio is commonly used to specify the effect of the ambient boundary conditions on grain storage bins (Yaciuk et al. 1975, Muir et al. 1980, Smith and Sokhansanj 1990). However, the observation of the effect of decreasing bin height contradicts the earlier observation of the influence of the bin diameter. In both cases the diameter-to-height ratio is about 2:1, i.e. at the bin height of 5.2 m the diameter is 10.1 m, and at the diameter of 20.1 m the height is 10.3 m. Thus, the diameter-to-bin ratio is not a consistent predictor of the changes in the bulk temperature in stored grain.

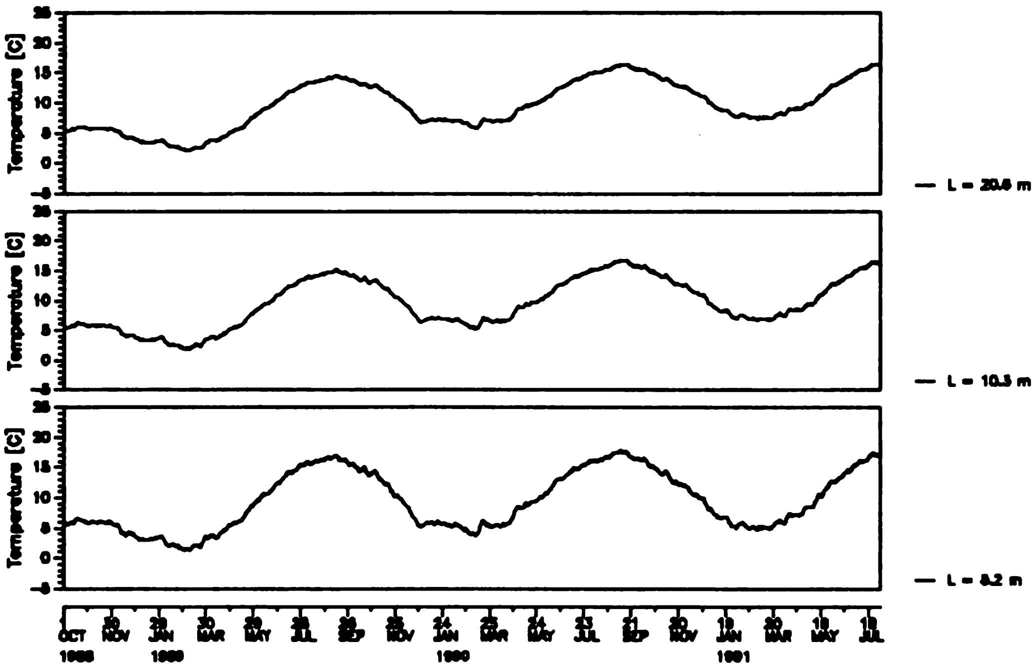

Figure 6.41 Effect of the bin height on the bulk temperature profile in the corn bin predicted by the 2-D storage simulation.

6.2.4.3 Bin Surface-to-Volume Ratio

The ratio of the bin surface area, which includes the circular side wall and the cone-shaped bin roof, to the bin volume, which includes the grain volume and the volume of the head-space above the pile, is considered in Figure 6.42. The small surface-to-volume ratio of 1:3 shows a small amplitude in the profile and a low minimum and maximum bulk temperature. As expected, an increase in the surface-to-volume ratio increases the amplitude and the extreme temperatures.

The ratios of 1:3 and 2:3 have diameter-to-height ratios of 2:1, and the surface-to-volume ratios of 1:2 and 1:1 have diameter-to-height ratios of 1:2. Thus, the bin surface-to-volume ratio is a more suitable predictor of the effect of the ambient boundary conditions on the temperature predictions in a circular grain bin than the diameter-to-height ratio.

6.2.5 Grain Crop

In Figure 6.43 the long-term storage of corn is compared to the long-term storage of wheat. Apparently, the bulk grain properties, i.e. conductivity, specific heat, and density,

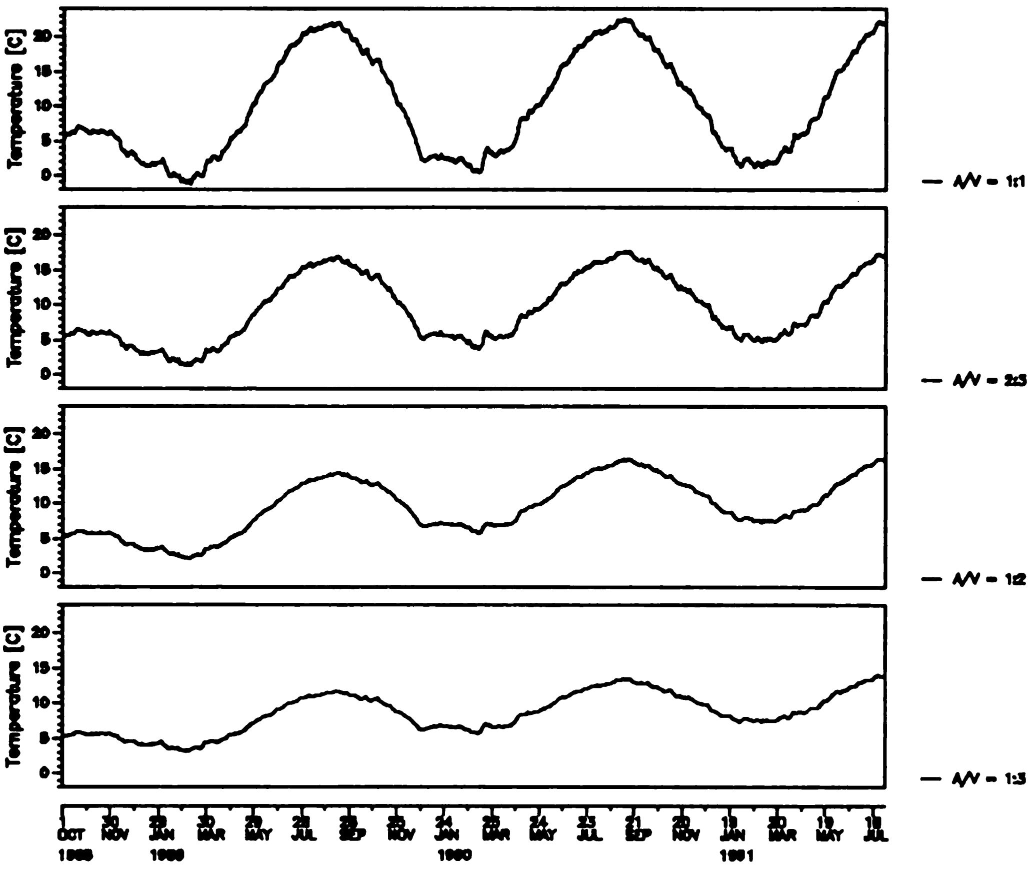

Figure 6.42 Effect of the bin surface-to-volume ratio on the bulk temperature profile in the corn bin predicted by the 2-D storage simulation.

affect the bulk temperatures. Corn reaches slightly lower temperatures during the cold ambient periods, and slightly higher temperatures during the warm periods. For example, in February of 1989 the minimum corn bulk temperature is 2°C compared to 4°C in the wheat bin; and in September of 1990 the corn reaches a bulk temperature of 17°C compared to 16°C in the wheat bin.

The three thermal properties determine the thermal diffusivity value, α, in the two-dimensional conduction equation (see equation 4.56). The physical significance of the thermal diffusivity is the speed of propagation of heat into (or out of) the grain mass during changes of temperature with time. Apparently, the thermal diffusivity of corn is higher than of wheat, since the heat propagation in the corn bin is fasterduring the storage period.

6.3 Chilling and Rechilling Strategies

One of the main objectives of this dissertation is to determine the frequency of rechilling a pile of grain during storage. A number of chilling and rechilling strategies are evaluated for corn and wheat under mid-Michigan conditions. The configuration of the bin, grain properties, ambient boundary conditions, and grain chiller are the same as in

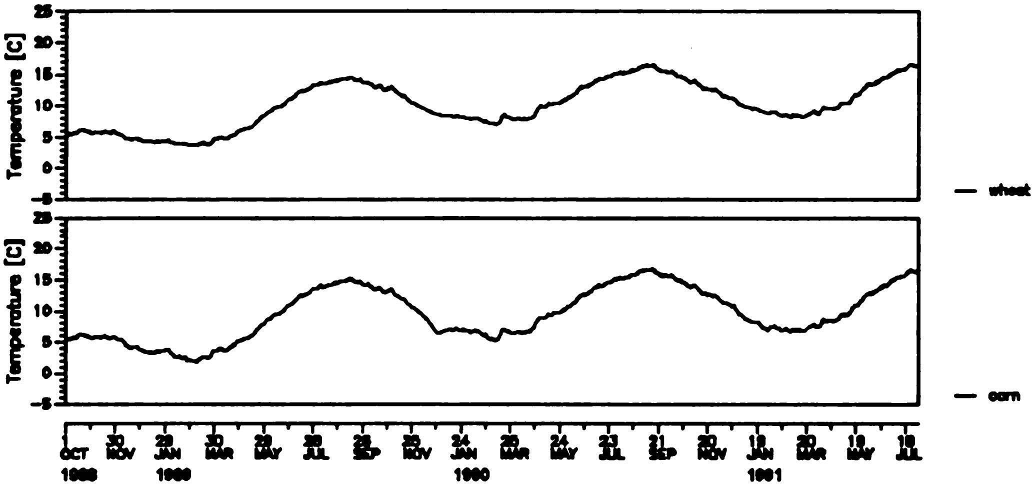

Figure 6.43 Effect of the crop type on the temperature profile in the bin predicted by the 2-D storage simulation.

the previous sections of this Chapter (see Tables 6.1 and 6.3).

The criterion in comparing various chilling and rechilling strategies is grain quality preservation, which is defined in terms of the risks of insect infestation and mold development. The risk of insect infestation (and insect activity) in grain storages is reduced when grain temperatures in a bin are less than 15 - 17°C (see Chapter 3.3.3). The risk of molding due to fungi development is reduced when moisture contents in a bin are sufficiently low (see Chapter 3.3.2). In the evaluation of different chilling and rechilling strategies the goals are (1) to lower grain temperatures in a bin immediately after filling, and maintain these temperatures below 17°C for the entire storage period, and (2) to store grain at a moisture content considered both safe for storage and desirable for marketing purposes (i.e. a dry matter loss of 0.5% is assumed to be the maximum limit).

6.3.1 Chilled versus Ambient Aeration

First, the potential benefit of using a chilled aeration system has to be demonstrated. In the northern United States ambient temperatures drop low enough in the late fall (and winter) to reduce temperatures in stored grain to safe levels. Even in the southern United States ambient temperatures usually decrease sufficiently in the late fall - early winter to achieve stored grain temperatures below 10 - 15°C with conventional ambient aeration systems (Trotter 1990, Dillehay 1990, Whitten 1990). In other parts of the country, such as the Great Plains, grain storage is frequently practiced in bins without aeration systems entirely (Yaciuk et al. 1975, Cuperus et al. 1986). There the crop is stored after the harvest and left to cool as a function of the ambient boundary conditions.

The biological hazards of mold development and insect infestation in ambient aeration and storage systems were previously discussed (see Chapters 1.3.2 and 3.3), and an in-depth evaluation of ambient aeration systems versus no aeration is not an objective of this study. However, two situations commonly encountered in the field will be discussed briefly and compared against chilled aeration, using corn and wheat under mid-Michigan conditions.

6.3.1.1 Corn Aeration and Storage

Figure 6.44 shows the predicted temperature profiles in the core, bulk, and periphery for a non-aerated bin containing

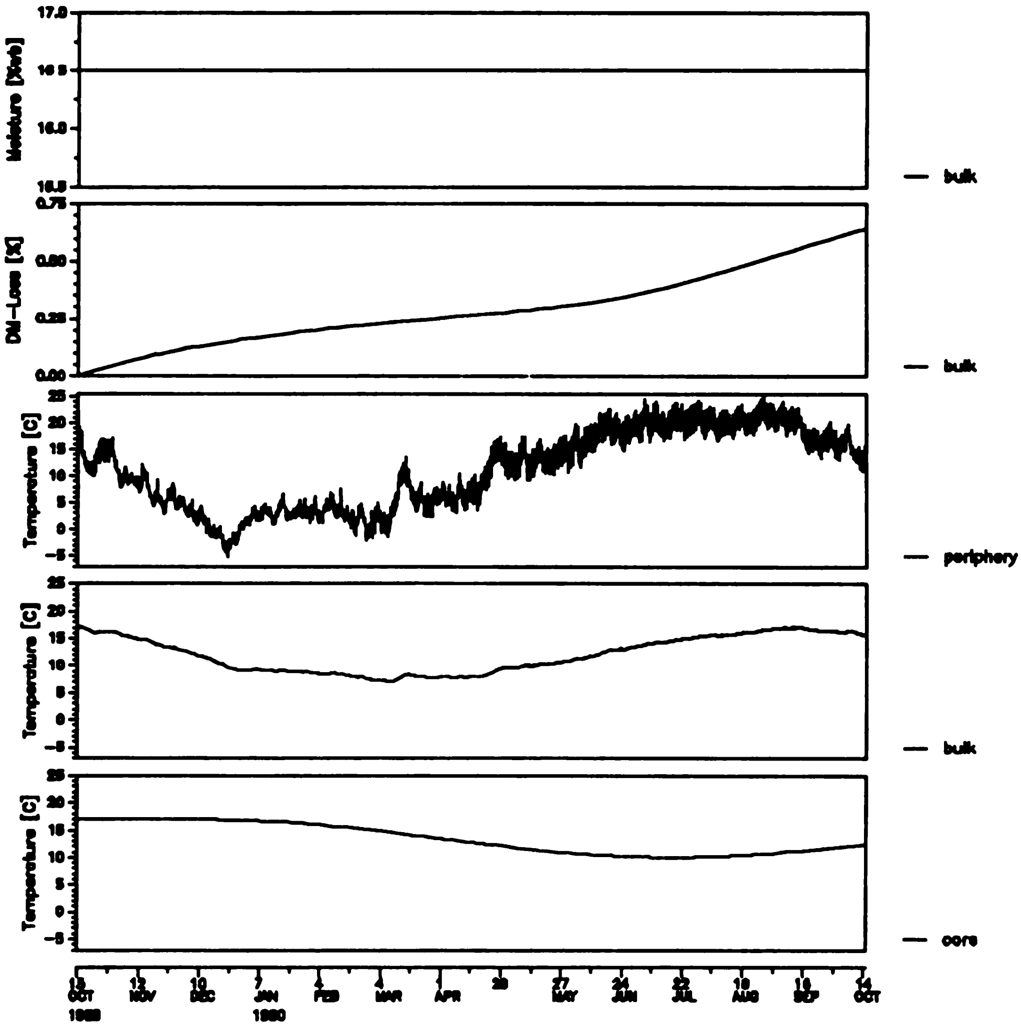

Figure 6.44 Simulated non-aerated storage of a bin of corn under Michigan conditions between October 15, 1989 and October 14, 1990.

about 600 tonnes of corn stored between October 15, 1989 and October 14, 1990 in mid-Michigan. Also shown are the average bulk dry matter loss, and the bulk moisture content profile. The initial grain temperature is 17°C, and the initial moisture content is 16.5%. The minimum bulk temperature of 7.5°C is reached after about five months of storage; after 11 months the bulk temperature increases to 17°C, which is the same as the initial temperature. The core temperature decreases to 11°C after 10 months of storage. The periphery temperature reaches a low of -5°C in December of 1989 and a maximum of 25°C in August of 1990. Since the bin is not aerated the bulk moisture content is assumed to remain constant. The average dry matter loss of the bulk over the 12-month storage period is 0.64%.

The grain temperature in the non-aerated bulk and core remain below the 17°C limit for the entire storage period. The temperature in the periphery rises above the limit after six months of storage and remains above 17°C between early June and early October. The dry matter loss limit of 0.5% is reached after 10 months of storage. It appears that the non-aerated storage of corn initially above 15°C and 15.5% moisture content in mid-Michigan is not desirable because of the risks of insect infestation and mold development.

The aeration of the corn bin at 0.1 m^3/min/t (0.1 cfm/bu) beginning on October 15, 1989 and continued until the top layer of the pile decreases below 10°C is shown in Figure 6.45. The corn is cooled within about a week and maintains good storage conditions until the following October. Initially, warmer air is moved through the bin due to higher ambient temperatures (see Figure 6.6). This increases the temperature and moisture content of the pile slightly. The core temperature remains between 4 and 5°C through June before slowly increasing to 9°C by the end of the storage period. Due to warm ambient conditions in the fall of 1989 the bulk temperature increases slightly during the first two weeks after the initial aeration cooling, followed by a conductive cooling period to 3°C. This temperature range is maintained through early March; the bulk reaches a maximum of about 16°C by early September. The periphery temperature profile is controlled only during the aeration period, and subsequently follows the same pattern as the non-aerated case for the remainder of the storage period. The bulk moisture content is reduced to 16.2% during the aeration cycle. The average bulk dry matter loss at the end of the 12-month storage period is 0.41%.

The same bin is aerated to a desired top layer temperature of 7°C beginning on the same day in the fall of 1989 (see Figure 6.46). Cooling requires about four weeks of fan operation. Two distinct cooling (and warming) and drying

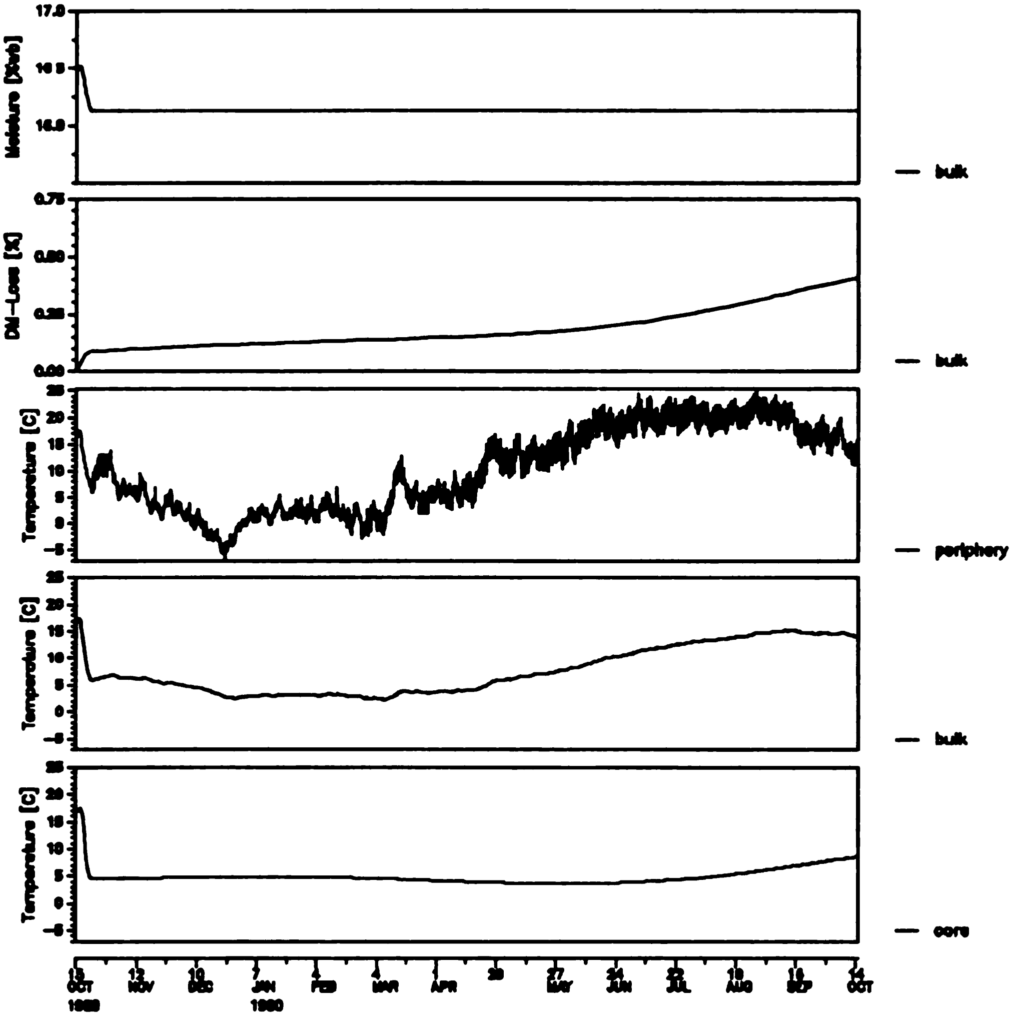

Figure 6.45 Simulated ambient aeration to 10°C and storage of a corn bin under Michigan conditions between October 15, 1989 and October 14, 1990.

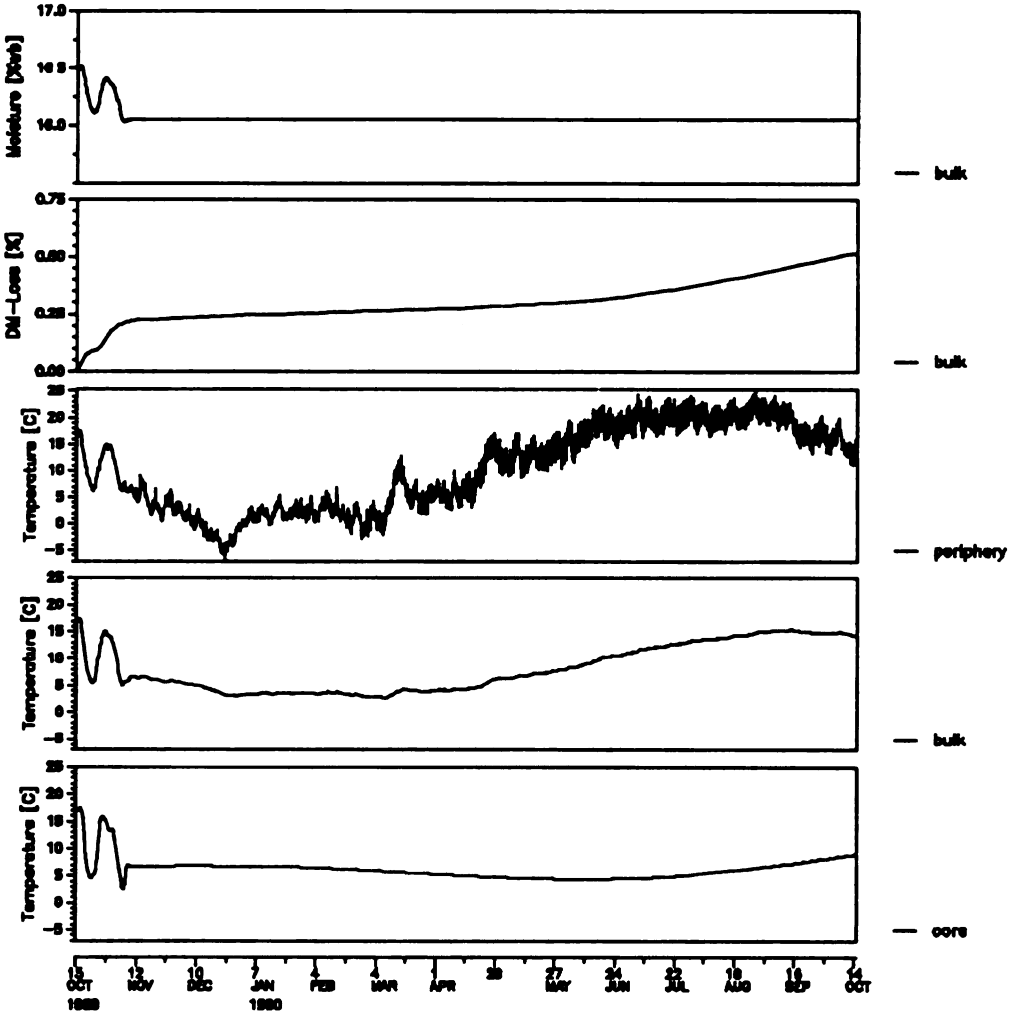

Figure 6.46 Simulated ambient aeration to 7°C and storage of a bin of corn under Michigan conditions between October 15, 1989 and October 14, 1990.

(and rewetting) cycles are observed during this period. The ambient temperature is not consistently low enough for the aeration to be completed in a comparable time as in the 10°C limit case. The cycling in the bin during the cool-down phase is reflected in an overall increase in the dry matter loss to 0.52% during the 12-month storage period.

Using a grain chiller to cool the grain bin once in the fall of 1989 to 10°C yields the same temperature and moisture profiles for the storage period as the 10°C ambient aeration case (see Figure 6.47). The final moisture content and dry matter loss are 16.2% w.b. and 0.41%, respectively. The grain chiller is operated with a cold-air set-point of 5°C and a reheater set-point of 8°C plus 1°C of rewarming in the duct. In comparison, the best storage result for the 597 tonnes of corn during the 1989-90 period is achieved by chilling the grain to 7°C at set-points of 3°C and 6°C for the cold-air and reheater, respectively (assuming no heat gain in the duct) (see Figure 6.48). Although the temperature and moisture profiles are similar (the bulk temperature rise to 16°C is delayed by only a few days in September of 1990), the dry matter loss is 0.38%, which is better than any of the previous non-aerated, ambient and chilled aeration cases.

Based on the lower core and bulk temperatures, and the

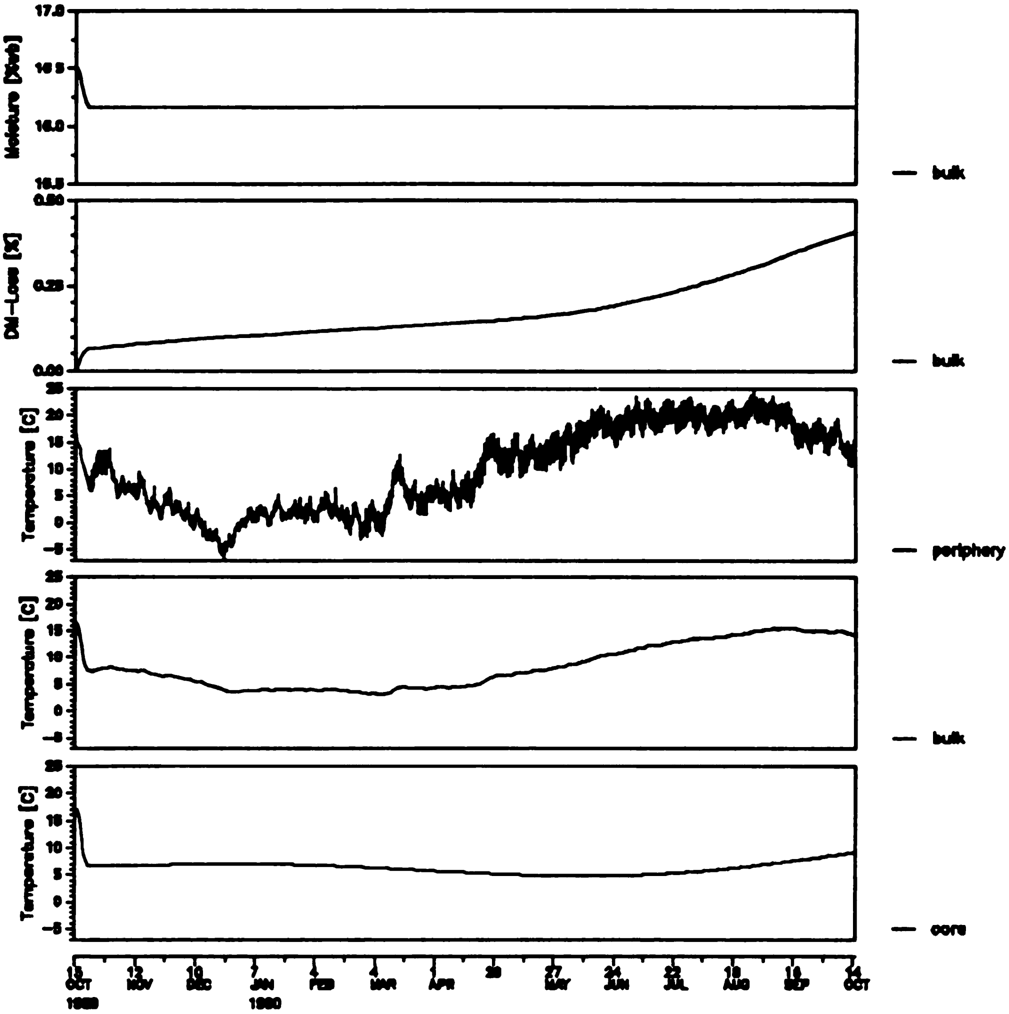

Figure 6.47 Simulated chilled aeration to 10°C and storage of a bin of corn under Michigan conditions between October 15, 1989 and October 14, 1990.

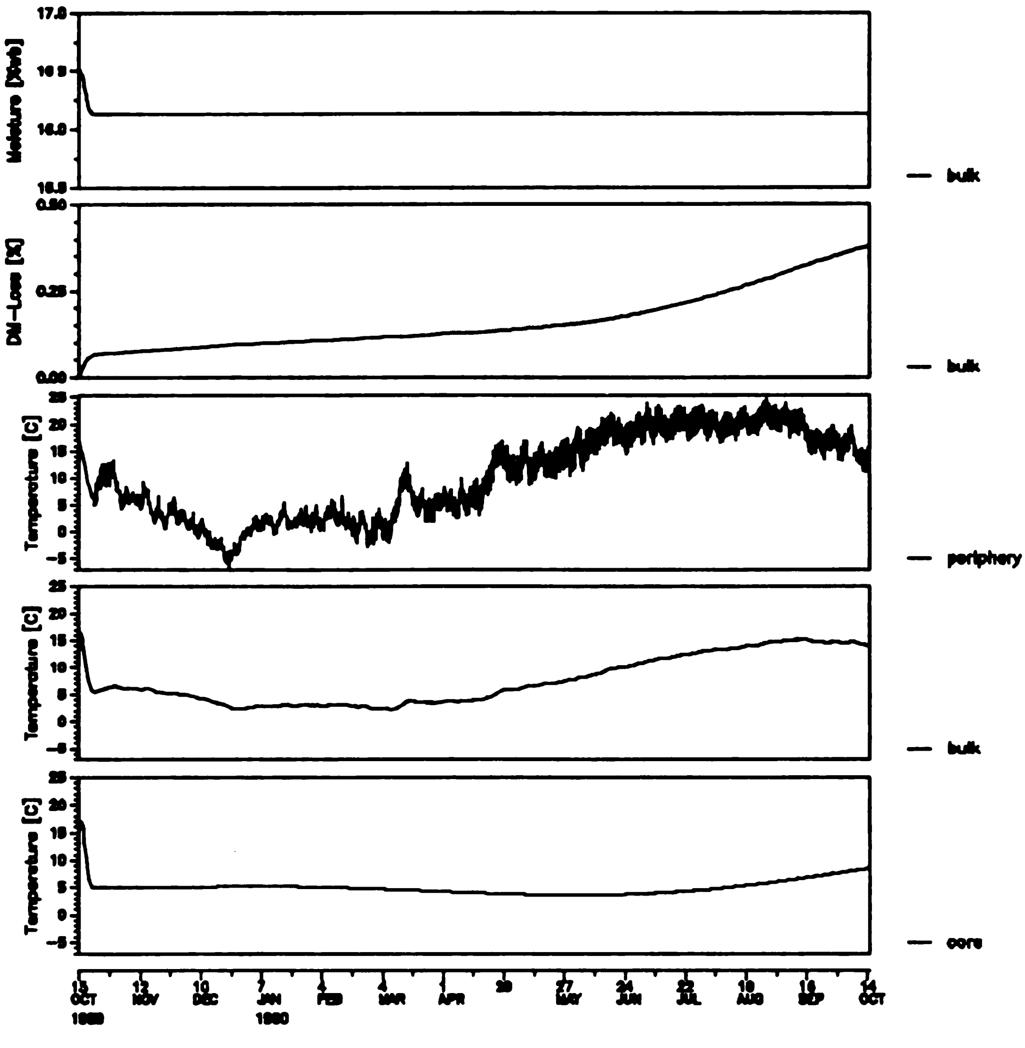

Figure 6.48 Simulated chilled aeration to 7°C and storage of a bin of corn under Michigan conditions between October 15, 1989 and October 14, 1990.

smaller dry matter losses it appears that chilled and ambient aeration systems are preferable over no aeration for the 12-month storage of corn in Michigan. Obviously, the costs of chilled versus ambient aeration have to be taken into account to make an economic recommendation of the preferred system. The operating costs for one-time chilling of a 597-tonne corn bin under mid-Michigan conditions immediately after harvest to 7 and 10°C are about 0.22 and 0.26 kWh per tonne per storage month, respectively; aerating with ambient air using a similar fan (i.e. 5.5 kW) yields about 0.11 and 0.26 kWh/t/month for cooling to 10°C and 7°C, respectively. The comparison also indicates that one-time chilling to a low of 7°C in the fall is sufficient with respect to the quality preservation of corn during the 12-month storage under Michigan conditions. Without close manual supervision, or an automatic aeration controller to selectively cool the bin, the temperature and moisture content may cycle significantly during the cool-down with ambient air. The effect of cycling appears to be more damaging to the long-term grain quality than storing at a 3°C higher grain temperature altogether. In a previous study, the cycling of the grain temperature and moisture content in bins of corn aerated under ambient Texas conditions was observed (Maier et al. 1991). Significant moisture gradients developed during the aeration period, and several warming and cooling cycles moved through the grain before a final storage temperature was reached in the fall. Thus, one-time chilled aeration of corn immediately after harvest appears to be economically attractive if operating costs and quality preservation are considered.

6.3.1.2 Wheat Aeration and Storage

Figure 6.49 shows the temperature profile in the core, bulk, and periphery, the average bulk dry matter loss, and the bulk moisture content profile for a non-aerated bin containing 579 tonnes of wheat stored between July 1, 1989 and June 30, 1990 in mid-Michigan. The initial grain temperature is 30°C, and the initial moisture content is 14.0% w.b. A minimum bulk temperature of 13°C is reached after about 10 months of storage; by the end of June the bulk temperature increases to 17°C. The core temperature decreases slowly from 30°C to 19°C over the 12-month storage period. The periphery temperature reaches a low of 5°C in early March of 1989; at the end of the storage period the grain at the periphery is at 23°C.

The temperatures in the wheat remain above the desired 17°C-limit until October in the periphery, until January in the bulk, and for the entire 12-month period in the core. Since the bin is not aerated the moisture is assumed to remain

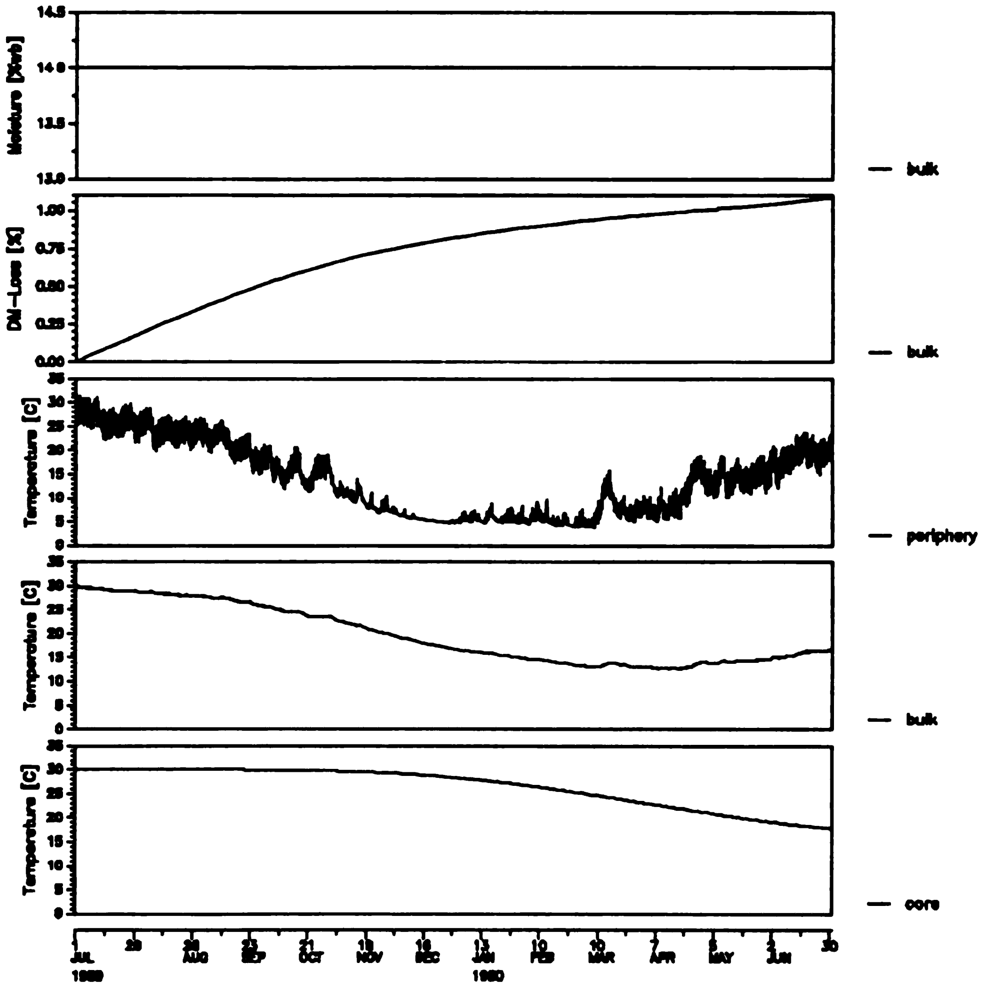

Figure 6.49 Simulated non-aerated storage of a bin of wheat under Michigan conditions between July 1, 1989 and June 30, 1990.

constant. The average dry matter loss of the bulk over the 12-month storage period is 1.1%. Thus, the non-aerated storage of wheat through the initial summer period is undesirable, since the conditions in the bin pose a high risk for insect infestation, and cause significant quality deterioration.

Now consider ambient aeration of the bin beginning on July 1, 1989, and continuing until the top layer of the pile has decreased below 15°C (see Figure 6.50). The aeration period lasts about three months. By late September the wheat bin is cooled. Significant cycling of the temperatures between a low of 17°C and a high of 30°C is observed during the three-month aeration period. The wheat moisture content is reduced gradually to 11.3% w.b., and interrupted by small reabsorption periods. The dry matter loss rapidly increases above 0.9% during the aeration period. After 12 months of storage the average dry matter loss in the bulk of the bin is 0.95%.

The same bin is aerated to a desired top layer temperature of 10°C beginning on July 1, 1989 (see Figure 6.51). The cooling time is even longer, i.e. about four and a half months. The additional aeration time is reflected in the moisture and dry matter loss in the bin. The average final bulk moisture content is 11.0% w.b. and the dry matter loss

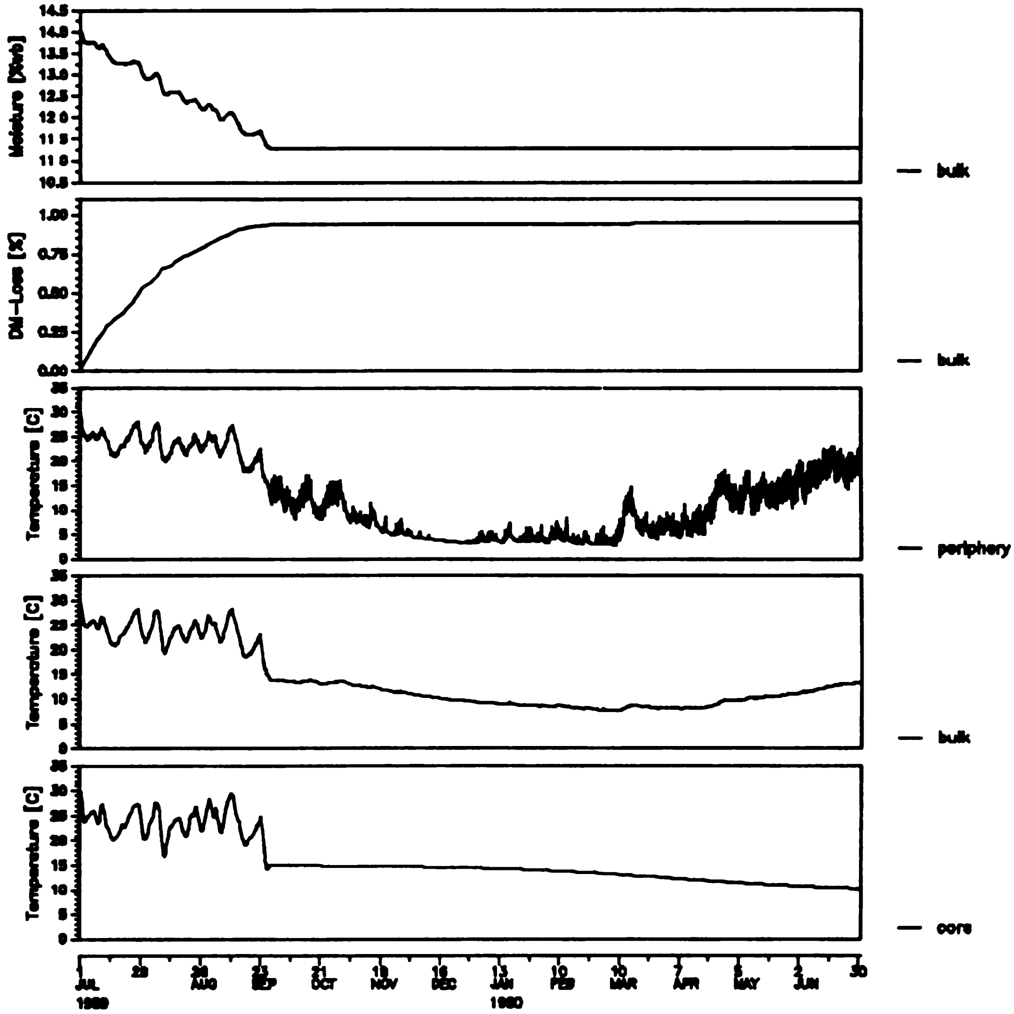

Figure 6.50 Simulated ambient aeration to 15°C and storage of a bin of wheat under Michigan conditions between July 1, 1989 and June 30, 1990.

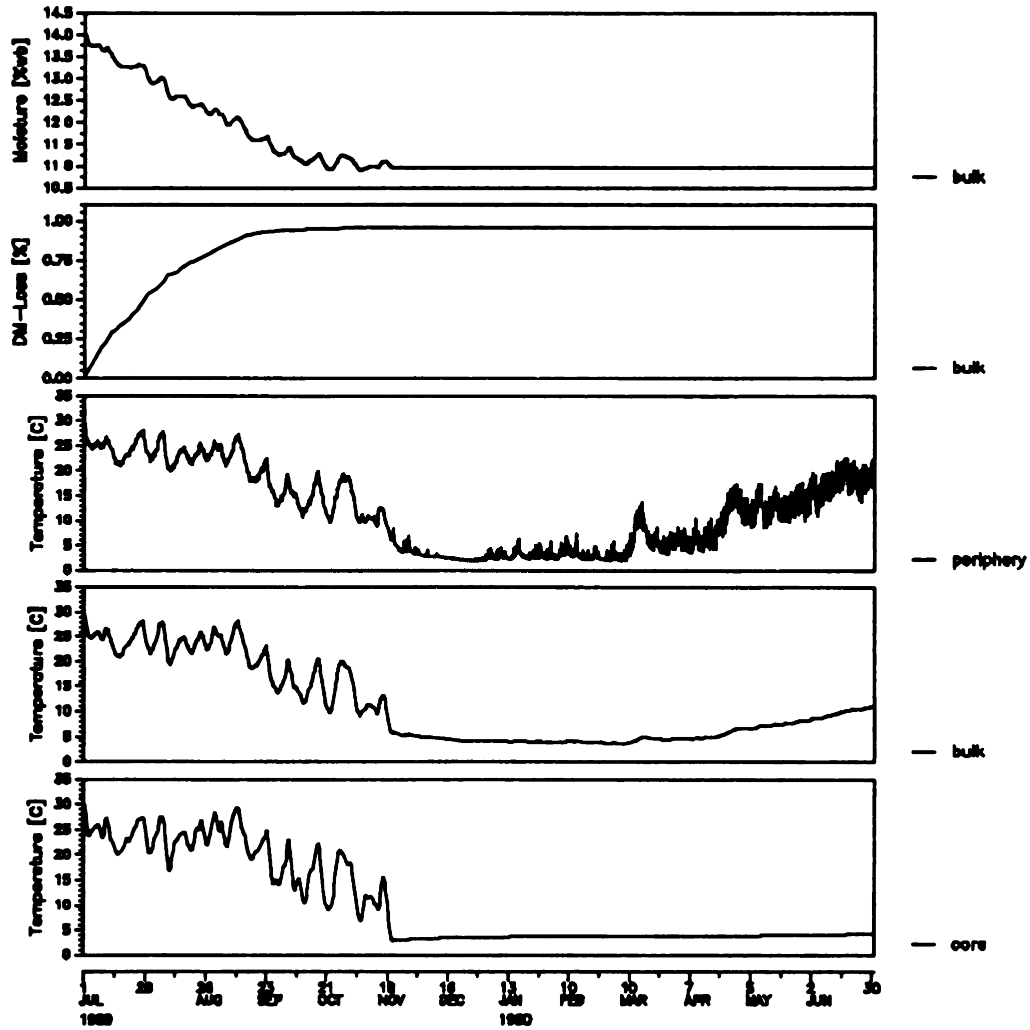

Figure 6.51 Simulated ambient aeration to 10°C and storage of a bin of wheat between July 1, 1989 and June 30, 1990.

is 0.96% for the 12-month storage period.

Using a grain chiller to cool the wheat bin only once in the first week of July to 15°C improves the quality preservation for the entire 12-month storage period significantly (see Figure 6.52). The final moisture content in the bin is 13.3% w.b. and the dry matter loss is 0.35%, a 63% improvement over the ambient aeration cases. The grain chiller is operated with a cold-air set-point of 8°C and a reheater set-point of 13°C plus 1°C of rewarming in the duct. A temperature rise to about 17°C by early September is observed in the bulk due to the high ambient summer conditions.

An additional reduction in the quality loss is achieved with one-time chilling to 10°C (see Figure 6.53). The final average bulk dry matter loss after the 12-month storage is 0.32%. The moisture content is slightly lower, i.e 13.2% w.b. The temperature profile in the periphery is similar as in the previous chilling case. The grain bulk temperature never rises above 15°C during the weeks following the initial chilling period, and remains below 15°C until the end of the period in June 1990.

Continuously aerating a wheat bin in an attempt to maintain quality is not uncommon (Doyle 1990). Although it may

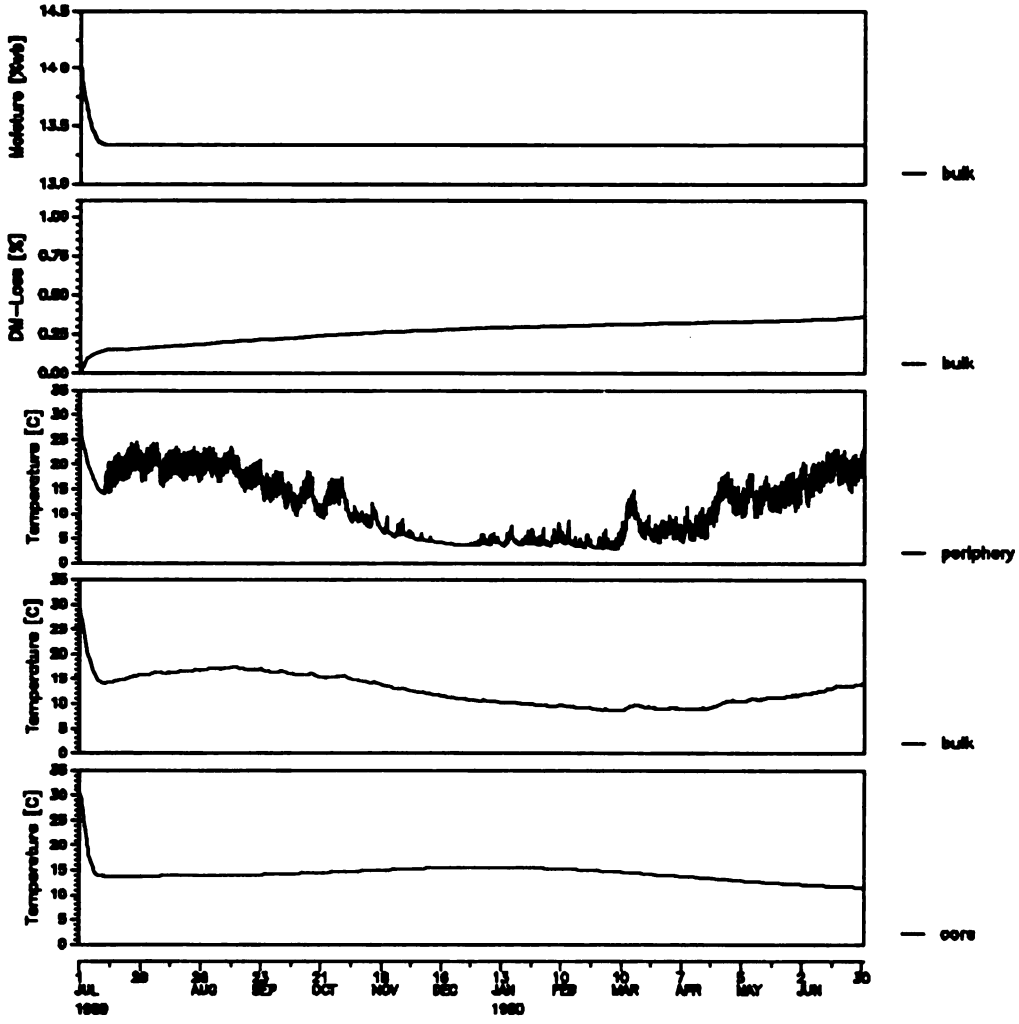

Figure 6.52 Simulated chilled aeration to 15°C and storage of a bin of wheat under Michigan conditions between July 1, 1989 and June 30, 1990.

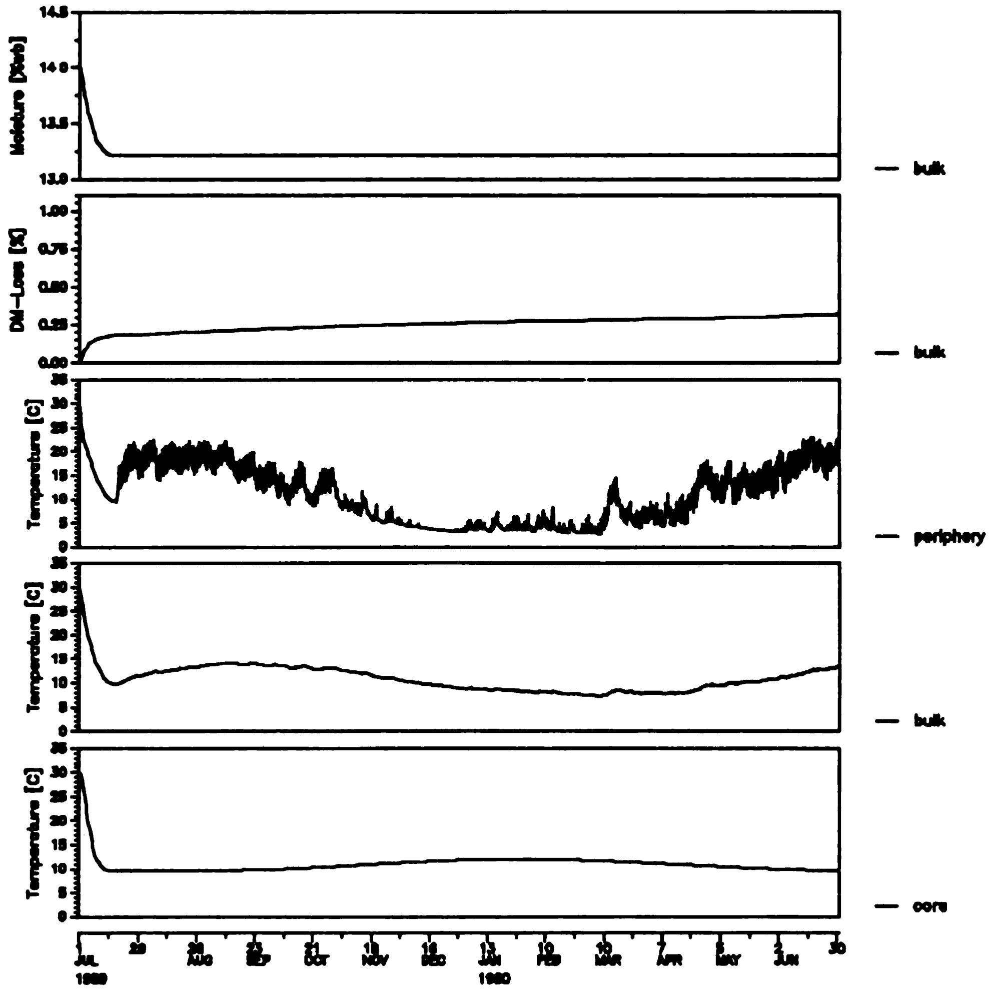

Figure 6.53 Simulated chilled aeration to 10°C and storage of a bin of wheat under Michigan conditions between July 1, 1989 and June 30, 1990.

reduce the danger of insect infestation, the deterioration index is essentially as high as not aerating the bin during the 12-month storage period. Also, operating an aeration fan continuously through the summer months is expensive. For example, operating a typical 11 kW fan beginning July 1 to cool a 579-tonne wheat bin under mid-Michigan conditions to 15°C and 10°C can cost 3.3 and 5.4 kWh/t per storage month, respectively. Excessive moisture loss in the wheat due to ambient aeration is also undesirable for the subsequent milling operation, which generally requires wheat at 15 - 16.5% moisture content (Hoseney 1986). Wheat temperatures above 15 - 17°C can lead to insect infestation, which requires fumigation treatments. One-time chilling immediately after the harvest to 10 - 15°C is sufficient to significantly improve the quality of a 579-tonne wheat bin stored under mid-Michigan conditions. The operating costs range from about 0.51 to 0.74 kWh per tonne per storage month for one-time chilling in July to 15°C and 10°C, respectively.

6.3.2 Controlling the Periphery Temperature

Now that a case has been made for the beneficial effect of chilled aeration of cereal grains the question arises whether to intermittently rechill a grain bin during the storage period, and if so how often. The difference between the periphery and core temperature profiles is a measure of the temperature gradient that exists in a grain bin. The core temperature hardly changes during the non-aerated storage period, while the periphery layers change continuously as they are exposed to the changes in the ambient conditions. Since the periphery volume (i.e. the top and bottom grain layers, and the wall surface layer) reaches temperatures above the desired 17°C insect-limit, particularly throughout the summer months, it is desirable to rechill the grain to prevent the temperature from rising above this limit. A temperature cable could be installed near the bin wall to monitor the periphery temperature and initiate rechilling.

Figure 6.54 illustrates the rechilling of the corn bin to 10°C whenever the periphery temperature rises above 16°C. The chiller settings are 5°C and 8°C for the cold-air and reheater set-points, respectively, plus 1°C duct warming. The same settings are used for the initial cool-down in the fall. During the 12-month storage period five rechilling cycles are needed. The first one occurs in late April of 1990, and the last one in late September. The cooling times depend on the ambient conditions. A continuous operating cycle is observed between late June and early September. During this period, the rechilling is interrupted 5 times

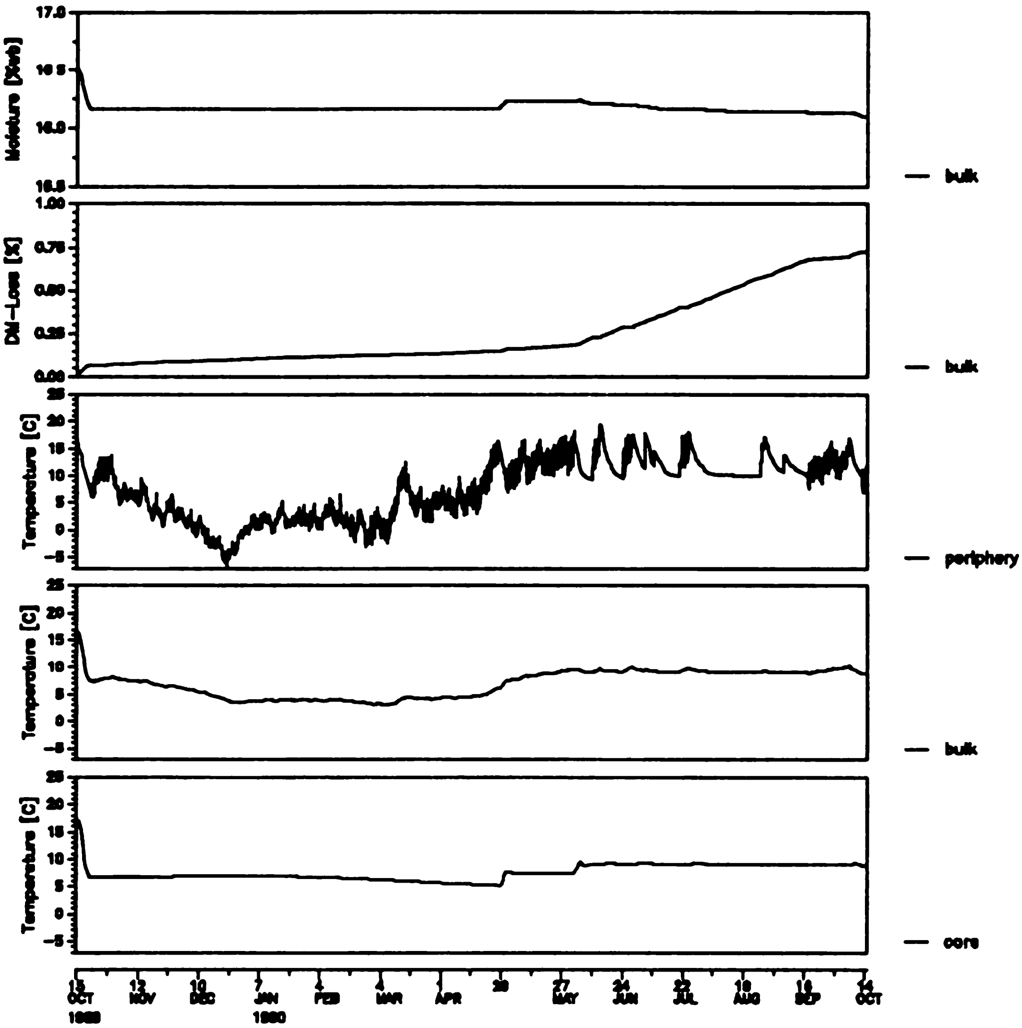

Figure 6.54 Simulated chilled aeration to 10°C and storage of corn with a periphery rechilling criterion of 16°C between October 15, 1989 and October 14, 1990.

due to insufficient refrigeration capacity of the KK140 chiller. The KK140 operates a total of 2,571 hours consuming 31,259 kWh, which results in 4.3 kWh/t per month of storage. The dry matter loss reaches 0.73% by October 14, 1990. This is 14% higher than in the non-aeration case, and 78% to 92% higher than the once-only chilling scenarios.

Table 6.4 summarizes four strategies evaluated using the periphery temperature as the rechilling criterion.

Table 6.4 Summary of four control strategies using the periphery temperature as an indicator for rechilling of the corn bin.

θ_{final} [°C]	θ_{limit} [°C]	Cooling Cycles	Power [kWh/t/month]	$M_{w\ final}$ [%wb]	DM-Loss [%]
10	13	11	5.7	16.1	0.86
10	16	6	4.4	16.1	0.73
7	13	5	6.1	16.3	0.70
7	16	3	5.7	16.3	0.67

The chilling unit is turned off when the periphery temperature drops below the desired final temperature, and is turned on when it rises above the grain temperature limit. The cold-air and reheater settings for the 7°C final temperature case are 3°C and 6°C, respectively, and no warming of the chilled air in the connecting duct is assumed. Rechilling to the lower temperature of 7°C causes a smaller moisture reduction in the grain, i.e. 0.2 percentage points compared to 0.4 points for cooling to 10°C.

The number of cooling cycles (including the initial cool-down) is as expected highest for the smallest allowable temperature rise, and lowest for the largest rise, i.e. 10°C to 13°C versus 7°C to 16°C. However, this observation is misleading, since in the case of chilling to 7°C the final temperature is never reached during the last rechilling cycle, and the chiller operates almost continuously from about June through October. A large number of rechilling cycles, and continuous summer operation are costly and undesirable from a management perspective, unless rechilling is controlled automatically.

Overall, rechilling of the periphery is significantly more expensive than one-time chilling in the fall, i.e. by a factor of 17 to 28 times. Additionally, in all four cases higher dry matter losses are observed after 12 months of storage compared to once-only chilling. Thus, rechilling of the grain bin based on periphery temperature control is undesirable. Even more so since the chilled aeration and storage model assumes that the effect of the ambient boundary conditions is negligible during the chilled aeration period. During the summer months the effect may be significant, which would increase the energy consumption even further. Thus, periphery temperature control of rechilling is not pursued further.

6.3.3 Controlling the Bulk Temperature

The bulk temperature represents the average temperature of 90% of the grain bulk. It changes more significantly than the core temperature, and yet does not show the large daily and seasonal variations as the periphery volume of the bin. Several strategies based on the bulk temperature are evaluated for the rechilling of corn and wheat under mid-Michigan conditions.

6.3.3.1 Corn

Figure 6.55 shows the need for two rechilling cycles when the bulk temperature is maintained between 10°C and 13°C, while Figure 6.56 shows the need for only one rechilling cycle if the temperature is maintained between 7°C and 13°C. The temperature profiles of the two cases are similar after the initial cool-down and before the first rechilling cycle. Rechilling is delayed in July by only about 4 days when the

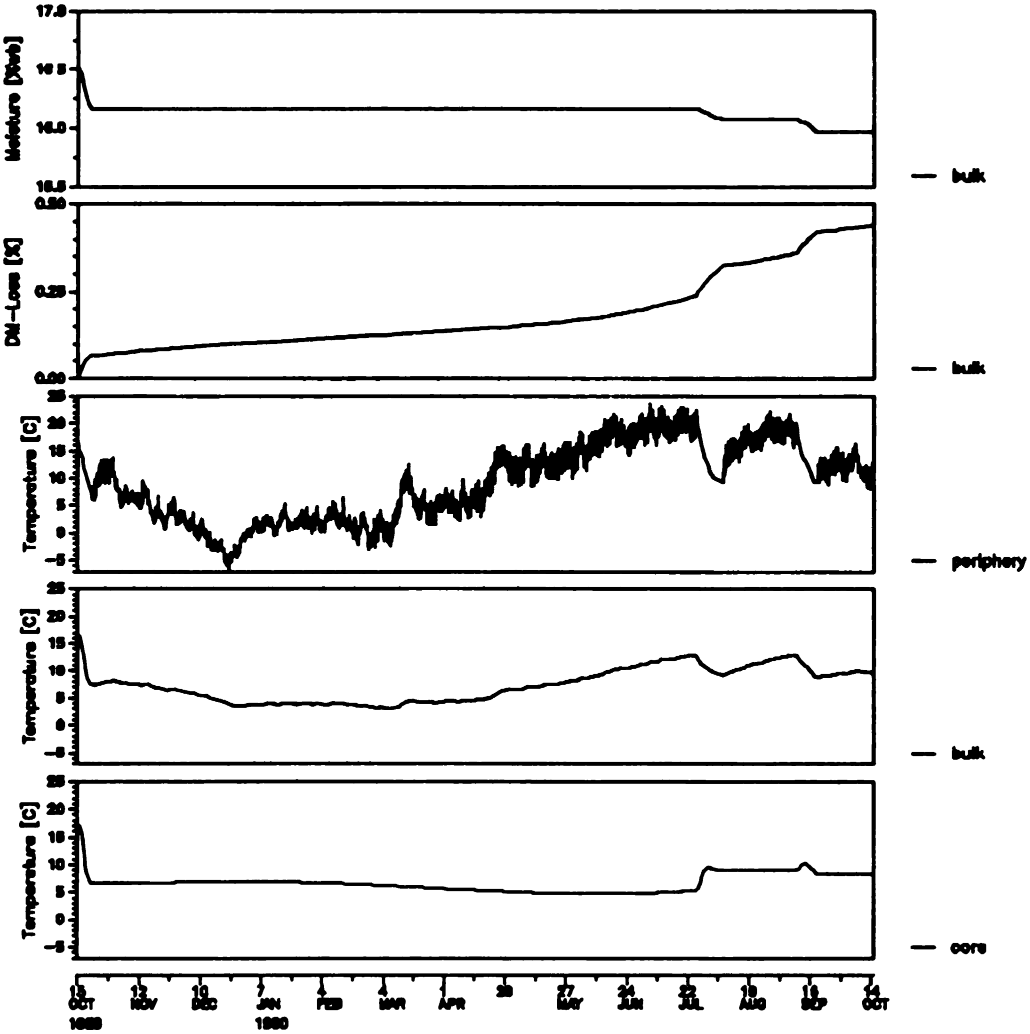

Figure 6.55 Simulated chilled aeration to 10°C and storage of corn with a bulk rechilling criterion of 13°C between October 15, 1989 and October 14, 1990.

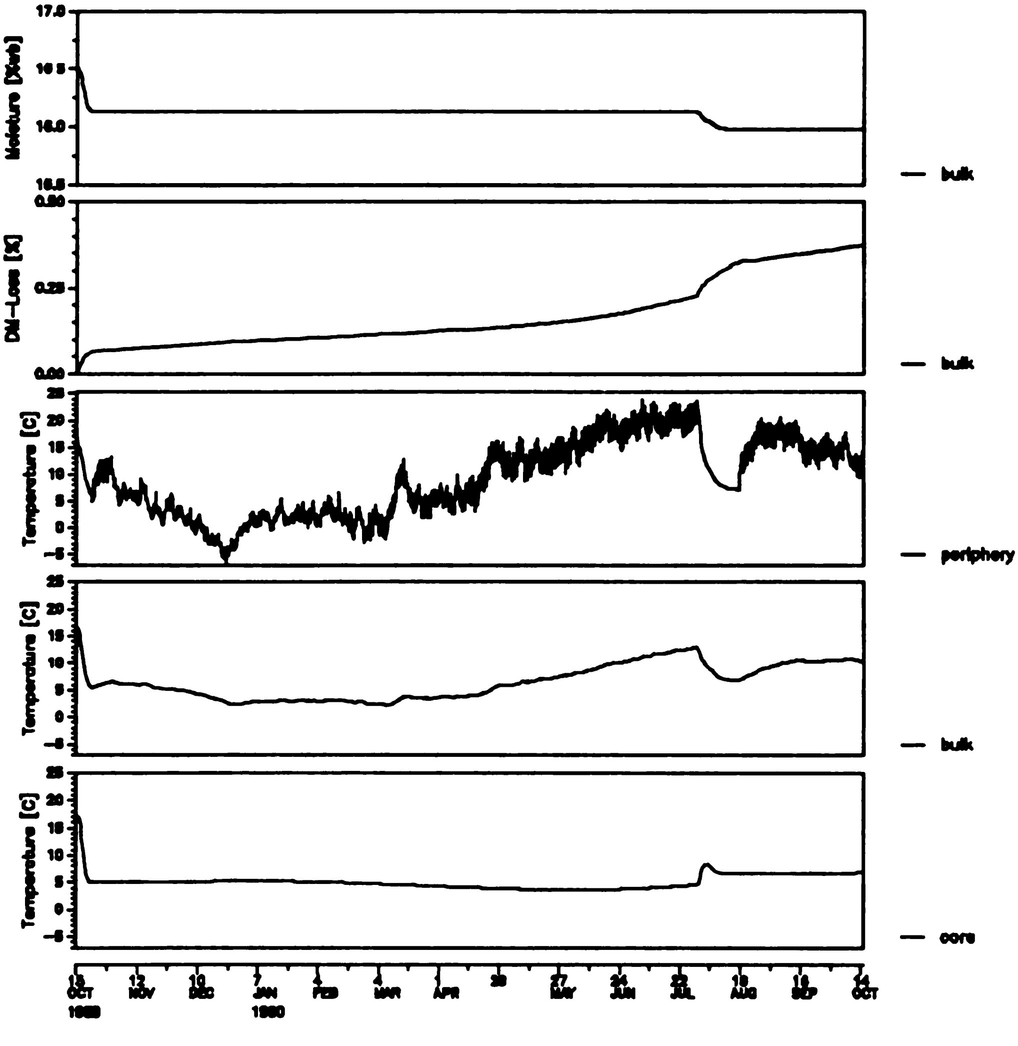

Figure 6.56 Simulated chilled aeration to 7°C and storage of corn with a bulk rechilling criterion of 13°C between October 15, 1989 and October 14, 1990.

bulk temperature in the pile is reduced to 7°C in the fall. It is slightly more energy efficient to chill to the lower limit in the fall, i.e. 1.08 kWh/t per month of storage versus 1.13 kWh/t per month at 10°C. There is no difference in the moisture content reduction. In both scenarios the final average bulk moisture after 12 months of storage is 16.0% w.b. However, the dry matter loss at the end of the storage period differs, i.e. 0.37% for rechilling to 7°C compared to 0.41% at 10°C.

Although rechilling to 7°C in the middle of August takes longer than chilling to 10°C, the bulk temperature does not increase above the 13°C limit again before the end of the season. It appears that the primary effect on the higher dry matter loss for the 10°C case is due to the second rechilling cycle. Whenever rechilling takes place, a cooling front is moved through the entire pile. Thus, the temperature in the core is raised during the first rechilling cycle. In the 10°C case the core temperature rises from 5°C to 9°C during the first rechilling cycle, while in the 7°C case the core temperature rises from 4°C to 7°C. Since the bottom grain layer warms due to the plenum boundary condition, the cooling front moves a warmer layer ahead of itself through the pile. This front is particularly visible in the 7°C case core profile (see Figure 6.56).

The effect of combining the two strategies to chilling initially to 7°C in the fall, and rechilling to 10°C after a maximum bulk temperature of 13°C is reached is shown in Figure 6.57. The onset of the first rechilling cycle at the end of July is delayed by only a few days. The combined effect on the dry matter loss falls between the two strategies, i.e. 0.40% at the end of the 12-month period. The moisture reduction is about the same. The power consumption is 1.05 kWh/t per storage month, which is better than either of the other two strategies.

Neither chilling/rechilling strategy improves on the quality preservation of the bulk of the corn over the 12-month storage period obtained by one-time chilling in the fall. Thus, the added costs of rechilling would have to be justified in terms of reducing the temperature gradient between the periphery and the core of the grain bin, and potentially reducing the risk of insect infestation in the outer grain layers. However, reducing the temperature gradient during the summer may worsen the average dry matter loss in the periphery. For fall-only chilling the average dry matter loss in the periphery at the end of 12 months is 0.72% compared to 0.72% for rechilling once to 7°C and 0.75% for rechilling twice to 10°C.

The attempt to maintain the bulk temperature below 10°C by

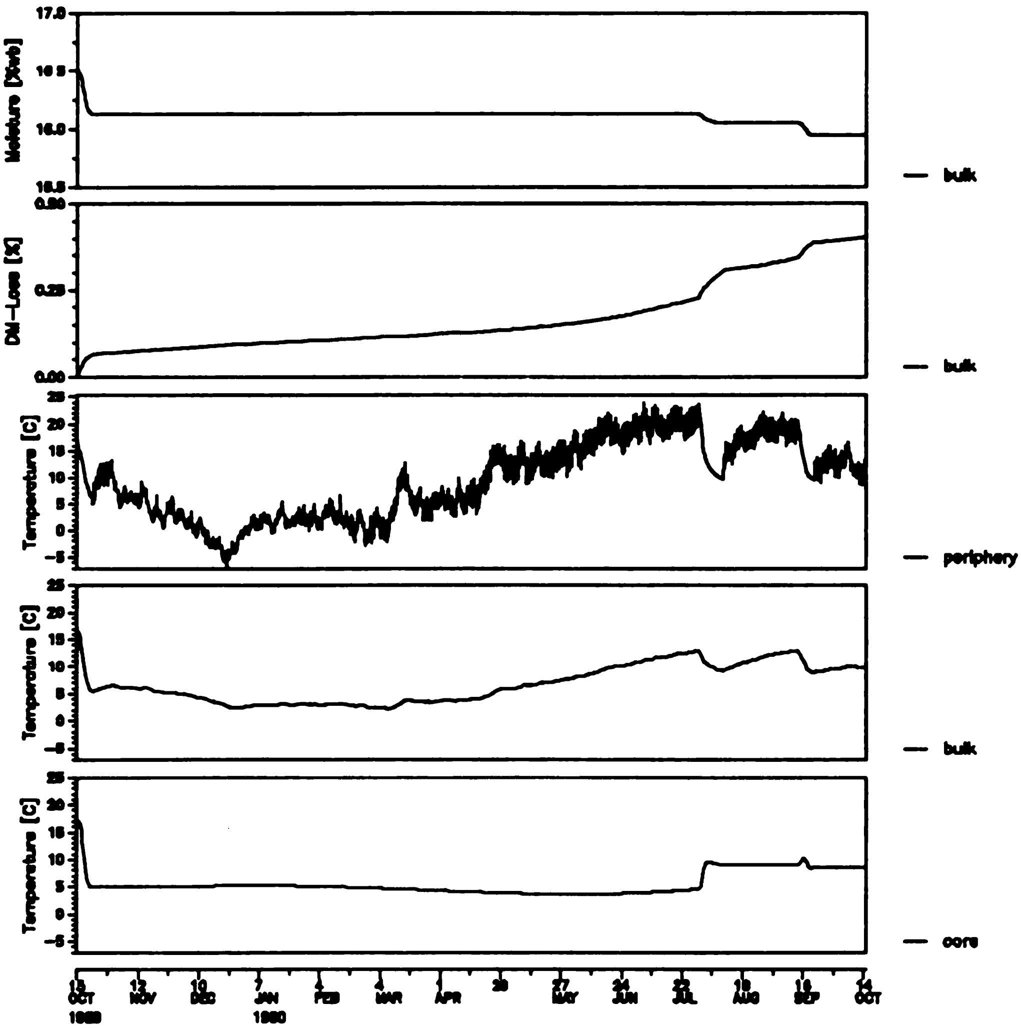

Figure 6.57 Simulated chilled aeration to 7°C, rechilling to 10°C and storage of corn with a bulk rechilling criterion of 13°C.

rechilling to 7°C is costly. In Figure 6.58 the corn is chilled to 7°C in the fall and rechilled to 7°C three times during the following summer. The energy costs are 3.3 kWh/t per month of storage. The final moisture content is 16% w.b. and the dry matter loss reaches 0.50% in the bulk. During June of 1990 the ambient cooling load is at times too high for the chilling unit to operate, and the unit is turned off twice before the cooling cycle is completed. The periphery temperature rises during the shut-down period, while the core and bulk temperatures remain unaffected. Maintaining the bulk temperature below 10°C by taking advantage of the evaporative cooling effect in the bin requires seven rechilling cycles (see Figure 6.59). The costs are similar to the 7°C-case, i.e. 3.3 kWh/t per storage month, while the dry matter loss is higher, i.e. 0.62%. In both cases the dry matter loss is at or above the maximum desired limit of 0.5%.

The number of rechilling cycles and the effect of the cooling front moving a warm front ahead of itself during the first rechilling cycle appear to deteriorate the grain quality during the 12-month storage period more than once-only chilling in the fall. The only positive benefit of rechilling the corn based on the bulk temperature limit may well be the fact that a smaller temperature gradient is maintained between the core and the periphery during summer

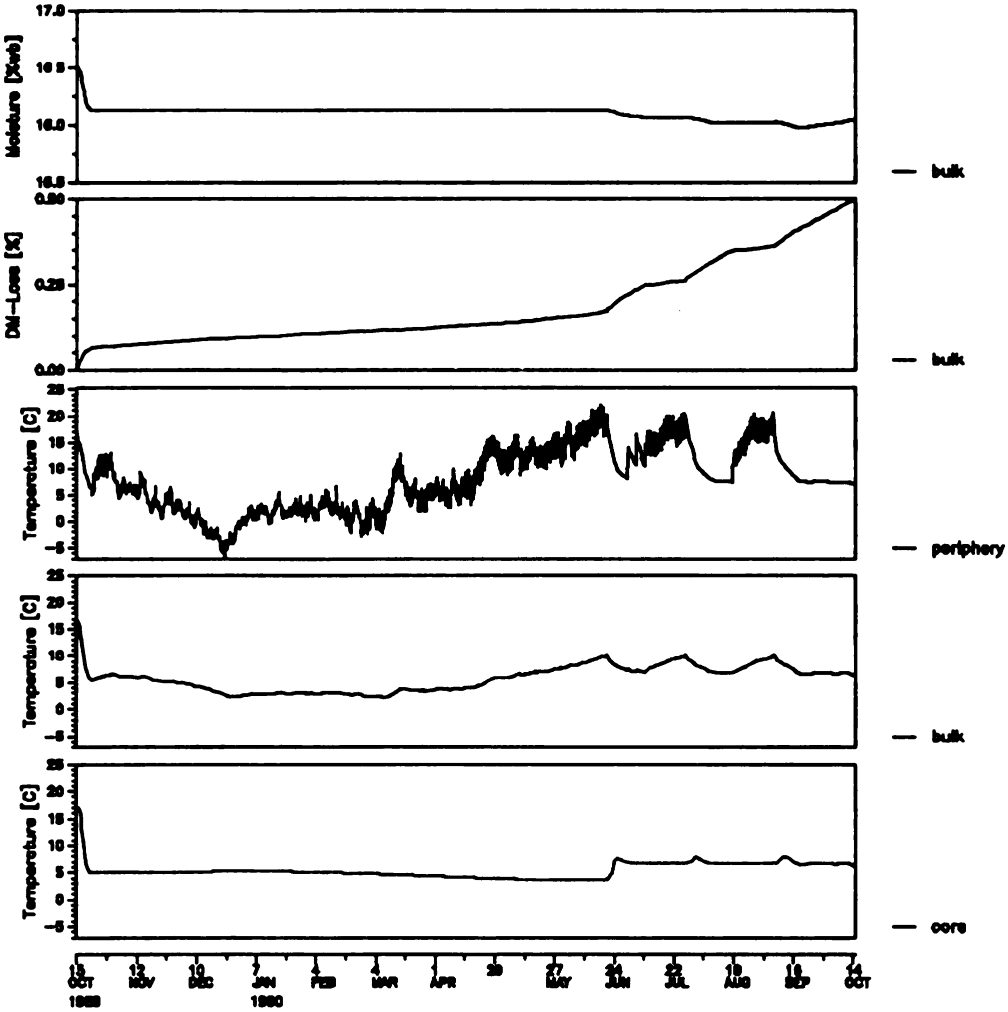

Figure 6.58 Simulated chilled aeration to 7°C, rechilling to 7°C and storage of corn with a bulk rechilling criterion of 13°C.

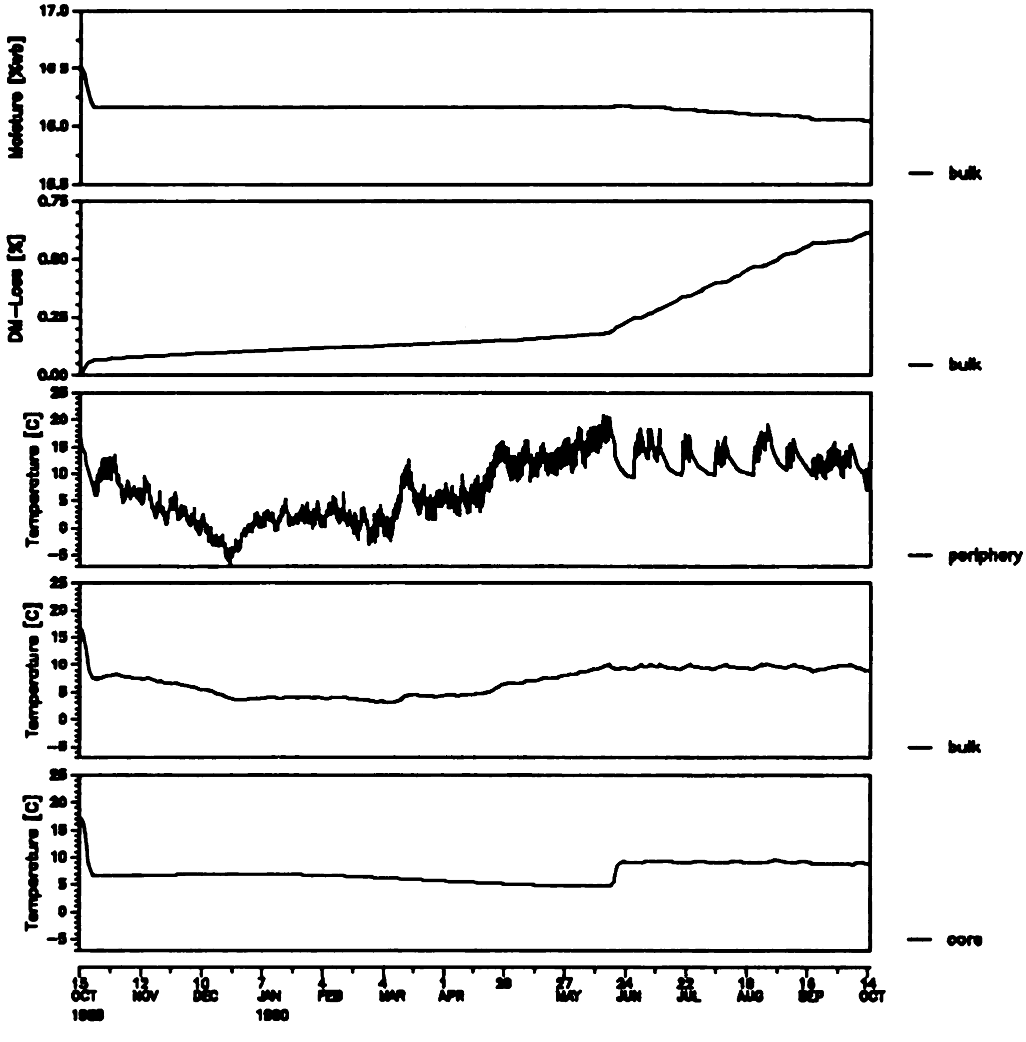

Figure 6.59 Simulated chilled aeration to 10°C and storage of corn with a bulk rechilling criterion of 10°C between October 15, 1989 and October 14, 1990.

storage, which in turn may reduce the risk of insect infestation in the outer volume. However, the costs in terms of power consumption and dry matter loss outweigh the advantage to justify this approach for 12-months of corn storage in mid-Michigan.

6.3.3.2 Wheat

The critical storage period for wheat is the summer time. Most wheat stored in mid-Michigan after the summer harvest is milled before the end of the 12-month period (Doyle 1990). Thus, in the following evaluation, a six month storage period between July 1 and December 31, 1989 is used to evaluate the bulk temperature rechilling criterion.

Figure 6.60 shows one rechilling cycle for wheat initially cooled to 15°C during the first 10 days of July. The maximum allowable bulk temperature rise of 2°C is reached about six weeks later in August. Rechilling of the wheat to 15°C bulk temperature takes about one week. There is only a negligible effect on the moisture reduction in the wheat compared to the once-only chilling case. However, after six months the dry matter loss in the once-only chilling case is 0.26%, while rechilling causes an additional 0.03% dry matter loss. Again, the apparent cause is the cooling

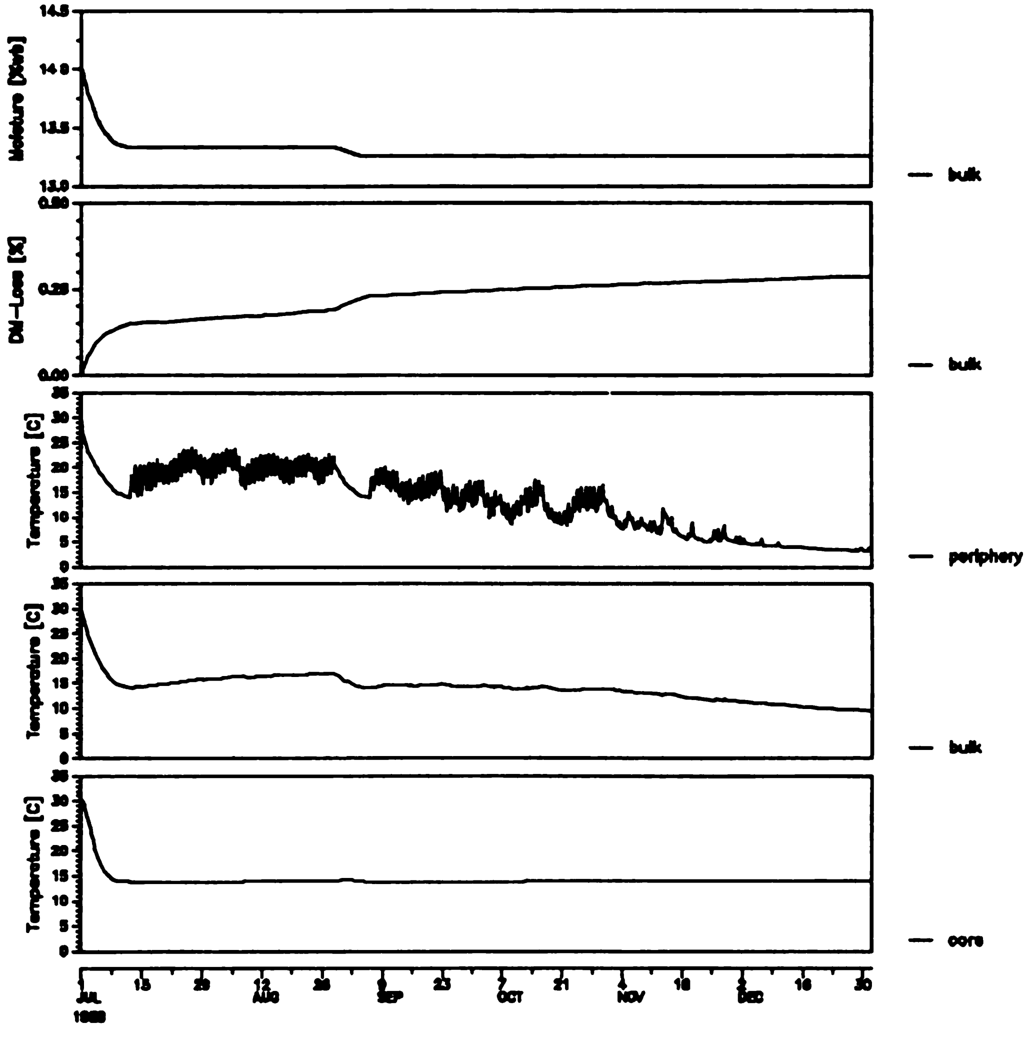

Figure 6.60 Simulated chilled aeration to 15°C and storage of wheat with a bulk rechilling criterion of 17°C between July 1, 1989 and June 30, 1990.

front, which moves warmer grain temperatures from the bottom to the top of the pile.

The additional cost of rechilling is 1.7 kWh/t per month of storage compared to 1.0 kWh/t per month for once-only chilling. Chilling the bin initially to 10°C, and allowing the bulk temperature to rise 7°C requires no additional rechilling during the six-month storage period, since the bulk never rises above 15°C again (see Figure 6.53). The dry matter loss by December 31, 1989 is 0.25%, and the cost for 6-month storage is 1.5 kWh/t per month.

These observations confirm that the chilled aeration and storage of wheat under Michigan conditions reduces the quality deterioration significantly. The costs of rechilling and the slightly higher dry matter loss may be avoided by chilling the wheat bin initially to at least 10°C. The temperatures in the bulk will then remain below the 17°C risk limit for insects for up to a year.

6.3.4 Controlling a Critical Pile Node

In the evaluation of the rechilling frequency of a corn and wheat bin, the idea of using the bulk temperature as a control criterion appears more satisfactory than the periphery temperature. However, it is obvious that significant temperature gradients develop in the bin due to the ambient boundary conditions. The bulk temperature may not account for this early enough during summer storage conditions. These temperature gradients may become significant enough to allow insect development and infestation in the periphery layers of the bin.

It has been proposed to place a single temperature sensor just below the top surface of the grain pile and near the south-side wall of the bin to monitor the rechilling needs of the grain (Burrell 1965, Brunner 1990). Although in practice this idea is easily accomplished, it is not extensively used in conjunction with grain chilling (Brunner 1990). Burrell (1965) proposed the placement of such a sensor 0.30 m (1 foot) below the surface and 0.15 m (6 inches) from the south-side wall. However, this places the sensor into the periphery volume of a 600-tonne grain bin, which was found undesirable in the above evaluation of corn and wheat rechilling.

In this investigation, a critical pile node is designated to be located at 0.74 m below the surface (i.e. 9.56 m from the perforated floor), and 0.72 m from the wall (i.e. 4.31 m from the center line). The node is outside the periphery volume of the grain pile, and near the top corner of the two-dimensional bulk profile. The best location of the critical node depends on the size and geographical location of the bin, and to some extent on the type of grain. No attempt is made here to define its location with more precision. However, the chilled aeration and storage model can be used to optimize the location of this node for a particular chiller-bin configuration.

6.3.4.1 Corn

Figure 6.61 shows the temperature in the core, bulk, periphery and at the critical node, and also the average dry matter loss in the bulk and the average moisture content for the case of chilling to 7°C in the fall, and rechilling to 10°C in the summer after the critical node reaches a temperature of 13°C in the spring and summer. Obviously, the rechilling criterion is too low, since an excessive number of rechilling cycles are required, i.e. seven. The power consumption is 3.1 kWh/t per storage month, which is about half of the value obtained by periphery control but about three times more than by the bulk control strategies. The average dry matter loss in the bulk reaches 0.58%, which is above the allowable 0.5% limit, and about 57% higher than the best bulk control strategy. On the other hand, the dry matter loss in the periphery volume is only 0.62%, which is

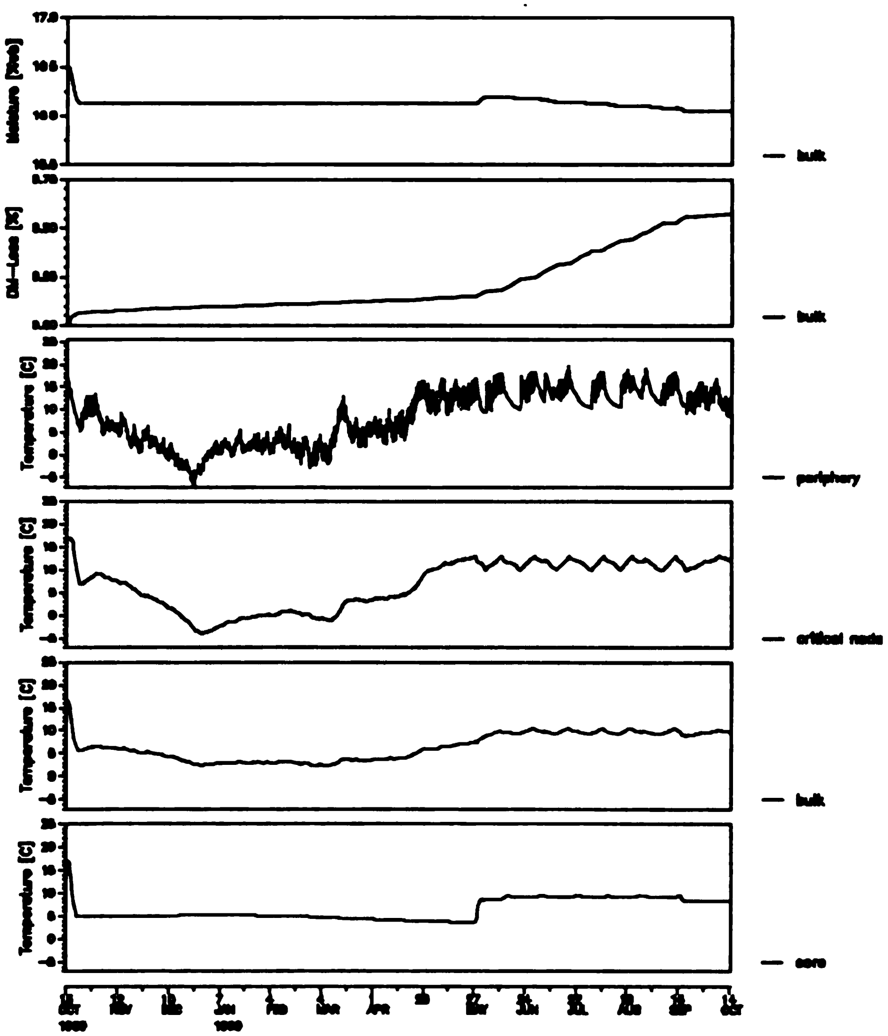

Figure 6.61 Simulated chilled aeration to 7°C and storage of corn with a critical node rechilling criterion of 13°C between October 15, 1989 and October 14, 1990.

about 14% better than in the best bulk strategy.

Increasing the rechilling criterion to 17°C, the maximum considered desirable for insect control reduces the number of rechilling cycles to four (see Figure 6.62). The first cycle takes place in early June, and the last one in the middle of September. They are spaced about three weeks apart. The dry matter loss is improved to 0.47%, but still lags the better bulk strategies. The periphery deterioration increases to 0.67% because the grain is allowed to warm up to a high level in the summer. Allowing a larger temperature increase at the critical node reduces the energy consumption to 2.0 kWh/t per storage month, which is about double than the bulk control strategies.

It appears that rechilling based on a critical pile node is more desirable to reduce temperature gradients in the grain bin than either bulk and periphery control. However, the costs in terms of power consumption and dry matter deterioration have to be weighed against the costs of applying a chemical insecticide to only the outer layers of the grain pile to reduce the risk of insect infestation.

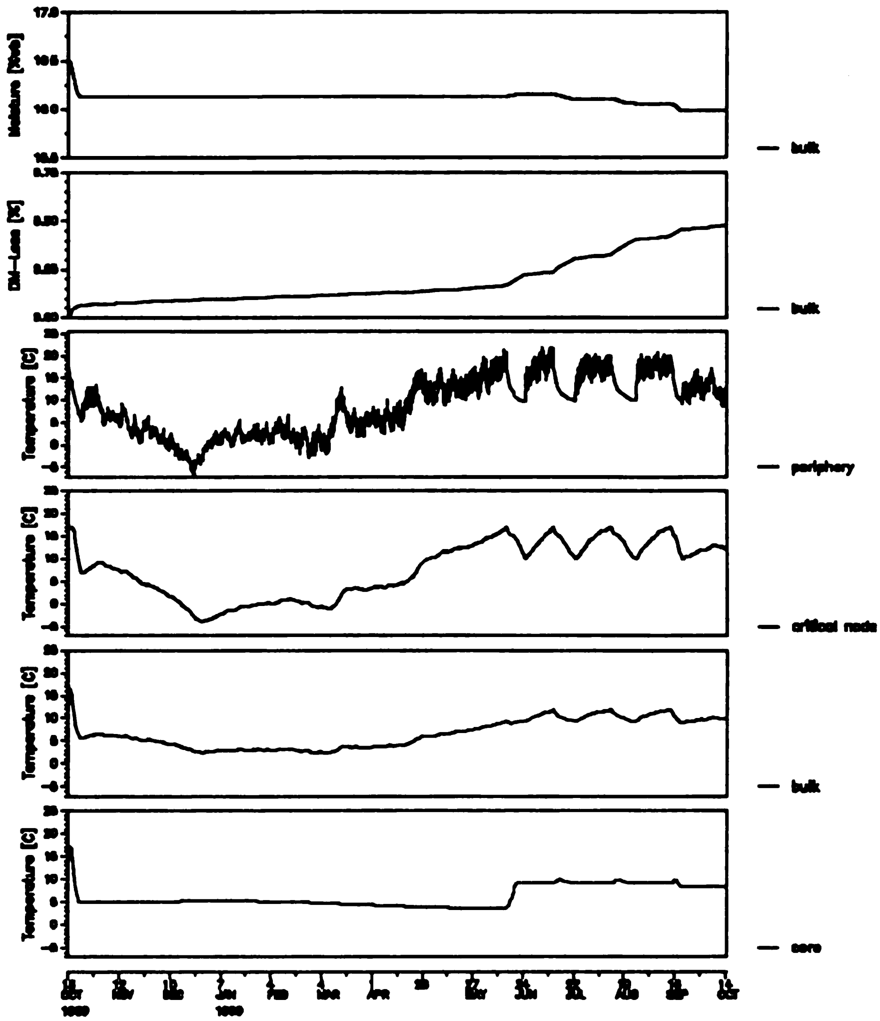

Figure 6.62 Simulated chilled aeration to 7°C and storage of corn with a critical node rechilling criterion of 17°C between October 15, 1989 and October 14, 1990.

6.3.4.2 Wheat

Figure 6.63 shows the temperature in the core, bulk, periphery and at the critical node, and also the average dry matter loss in the bulk and the average moisture content for the case of chilling wheat to 13°C in July, and rechilling after the critical node reaches a temperature of 17°C. The rechilling criterion causes an extensive rechilling cycle that lasts from the end of July through the end of September. The cost of this strategy is 6.4 kWh/t per storage month. It results in a dry matter loss of 0.38% by the end of December, which is 33% worse than chilling once only to 13°C. The long cooling time is caused partially by the low evaporative cooling effect of the dry wheat, and the high ambient cooling load on the chiller. Thus, the critical node concept may not be as desirable for the rechilling of wheat under Michigan conditions than chilling once-only.

6.3.5 Concept of Partial Bin Rechilling

The above observations have established the economic advantage of using a chilled aeration system for the long-term storage of corn and wheat under mid-Michigan conditions. However, the need to rechill and the rechilling

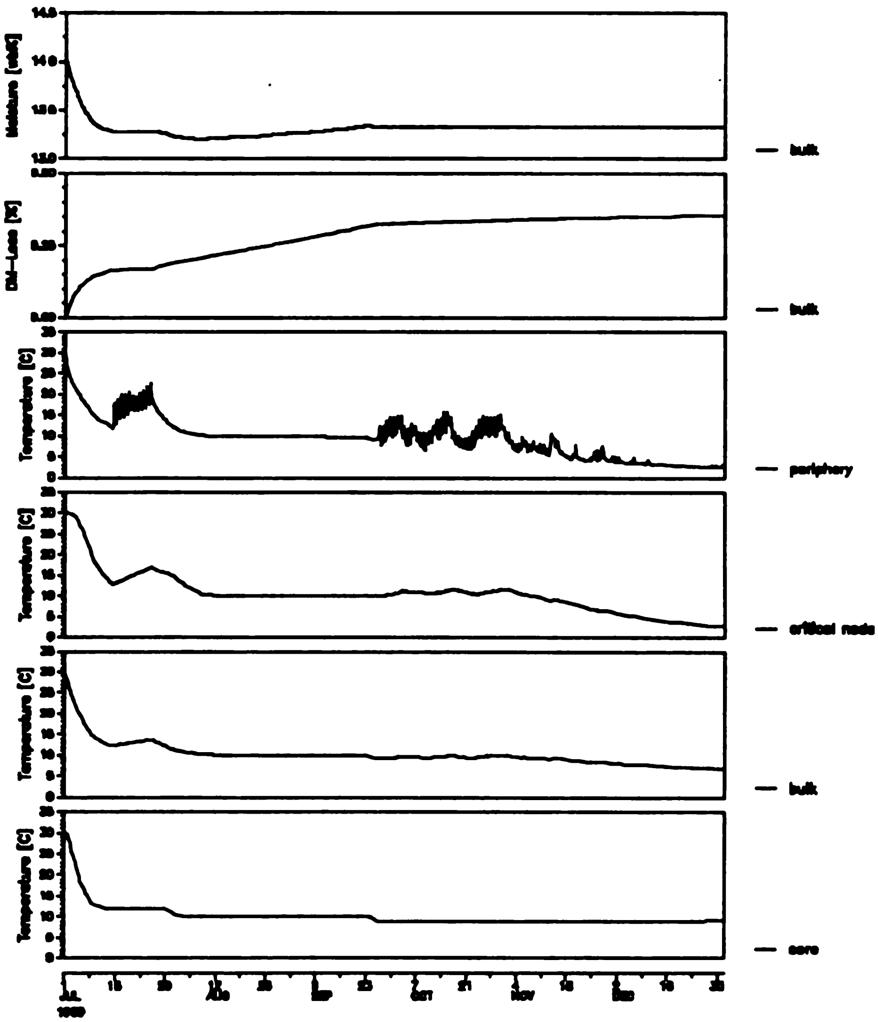

Figure 6.63 Simulated chilled aeration to 13°C and storage of wheat with a critical node rechilling criterion of 17°C between July 1, 1989 and June 30, 1990.

frequency have not been satisfactorily resolved. Once-only chilling at the beginning of the storage period maintains the quality of the grain better in terms of the dry matter loss than a variety of different rechilling strategies. However, the analysis of the periphery temperature and the critical node concept show that the grain temperatures rise above the allowable 17°C insect-limit in the outer layers of the bin in the summer due to the prevailing ambient conditions. The temperature rise can be prevented by rechilling the entire bin. But moving the cooling front through the entire pile during rechilling rewarms the grain in the core and in much of the bulk, thus increasing the grain deterioration rate.

This dilemma between minimizing the dry matter loss and the allowable temperature rise in the outer columns leads to the idea of only rechilling the grain that needs it most. Air can be moved through the outer columns of a circular steel grain bin by introducing the air along the circumference of the bin. This can be accomplished by adding a perforated duct around the circumference of the bin placed on top of the perforated bin floor at a certain distance from the bin wall. During the initial cool-down chilling is accomplished by moving the air through the perforated floor and the grain pile. During the rechilling periods the chiller is connected to the perforated duct, and air is moved upward through the outer columns of the grain bin. In an Australian experiment a single peripheral duct was used to cool-down and maintain wheat at temperatures low enough to give adequate insect control in an insulated bin (Sutherland 1986). The airflow from the duct was not uniformly upwards through the outer grain columns, but also cooled part of the bulk and peak of the pile.

Since the evaluation of non-uniform airflow through grain is beyond the scope of this dissertation, the concept of partial rechilling of the bin is evaluated in theory only by assuming that the air flows from the duct uniformly upward through the outer columns of the grain. In the chilled aeration and storage model this effect is simulated by applying the equilibrium heat and mass transfer equations only to the outer columns. This assumes that during the partial rechilling the temperatures and moisture contents do not change in the non-aerated volume of the bin. Additionally, a correction for the airflow is incorporated. Assuming the operating point of the chiller does not change significantly the same amount of airflow enters the bin. The outer grain mass that contains the critical node represents about 44% of the total grain volume in the 600-tonne bin. The floor area covered by this volume represents only about 26.5% of the total floor area. Thus, the effective airflow through the outer columns is increased by a factor of about 3.8 (i.e. 79.5 m^2 divided by 21.1 m^2). This reduces the cooling time needed to rechill the outer bin volume containing the critical node.

6.3.5.1 Partial Rechilling of Corn

In Figure 6.64 the corn bin is initially chilled to 7°C in the fall of 1989. The critical node initiates rechilling of the outer columns to 10°C when the grain temperature at this point rises above 17°C. Five rechilling cycles are needed with the first occurring in early June. Each cycle lasts three to four days. At the end of the storage period, the average dry matter loss in the bulk of the corn is 0.30%, the lowest of any previous chilling/rechilling strategy. In addition, the dry matter loss in the periphery volume is reduced to 0.50%, and the operating costs to 0.99 kWh/t per storage month, both of which are the lowest of any chilling/rechilling strategy considered so far. The final average moisture content is 16.0% w.b.

A distinct temperature profile change occurs in the core of the pile. No cooling front is moved through the core. The bulk temperature profile continues to rise slowly after each rechilling cycle, since only a part of the bulk is rechilled. The bulk is never reduced to 10°C as part of

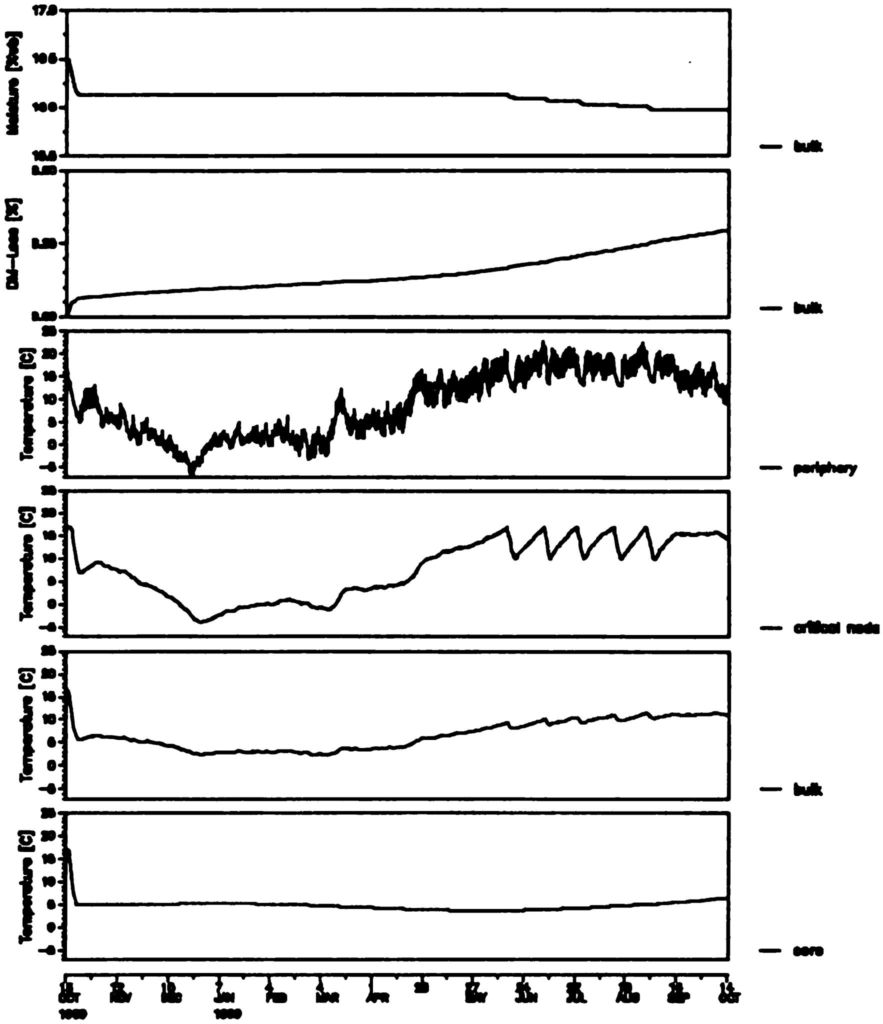

Figure 6.64 Simulated chilled aeration to 7°C and storage of corn with partial rechilling and a critical node rechilling criterion of 17°C in the 1989-90 season.

the rechilling cycle. The maximum bulk temperature of 12°C is reached before the final rechilling cycle. Thus, this strategy of rechilling the corn bin partially predicts the best quality preservation in the bin. Both the dry matter loss and the temperature gradients are minimized, although the rechilling frequency of five cycles is high from a management point of view. However, by establishing a regular rechilling schedule from bin to bin and allowing the temperature at the critical node to rise slightly higher than 17°C, the number of rechilling cycles can probably be reduced in mid-Michigan without compromising the quality preservation significantly.

To verify the above considerations, the chilled aeration and storage for the standard corn bin is evaluated for the 1988-90 season (see Figure 6.65). The same number of rechilling cycles as occurred during the summer of 1989 are predicted using the same rechilling limits. The first cycle occurs in late June (only a few days later than predicted in 1990), the last cycle in early September (again only a few days later than predicted in 1990). The final bulk dry matter loss after 12 months of storage is 0.32%, and the periphery deterioration is 0.53%. Both values are slightly higher than the 1989-90 season values. Such differences are to be expected since the ambient boundary conditions vary from year to year. The 1988-89 power consumption is 1.15 kWh/t

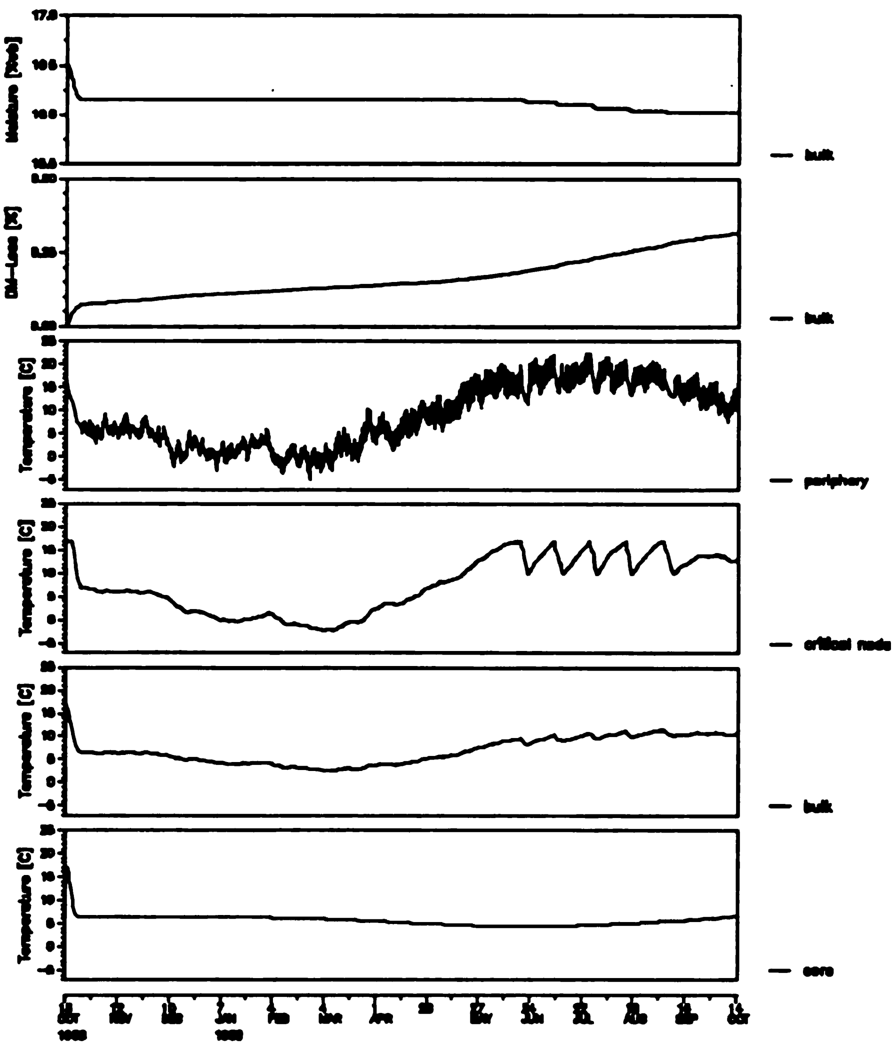

Figure 6.65 Simulated chilled aeration to 7°C and storage of corn with partial rechilling and a critical node rechilling criterion of 17°C in the 1988-89 season.

per storage month, which is about 16% higher than predicted for the 1989-90 season.

6.3.5.2 Partial Rechilling of Wheat

The same approach of partial rechilling as discussed for corn in Chapter 6.3.5.1 is evaluated for the 579-tonne wheat bin (see Figure 6.66). After initially chilling the pile to 13°C and allowing the critical node to rise to 17°C, four rechilling cycles are employed. The first is initiated 11 days after the first chilling cycle, the last one on September 7, 1989. Each cycle lasts two to three days. The final average bulk dry matter loss is 0.25%, and the loss in the outer columns is 0.26%. This is the best result for any of the wheat rechilling strategies considered. Although chilling once-only to 10°C also predicts a 0.25% bulk dry matter loss by December 31, it shows a higher periphery volume deterioration of 0.31%. The costs of rechilling are 2.1 kWh/t per storage month compared to 1.5 kWh/t per month in the once-only case. The added energy consumption has to be weighed against the lower dry matter loss in the periphery, and the reduced risk of insect infestation. The number of rechilling cycles can be reduced if the rechilling criterion is increased.

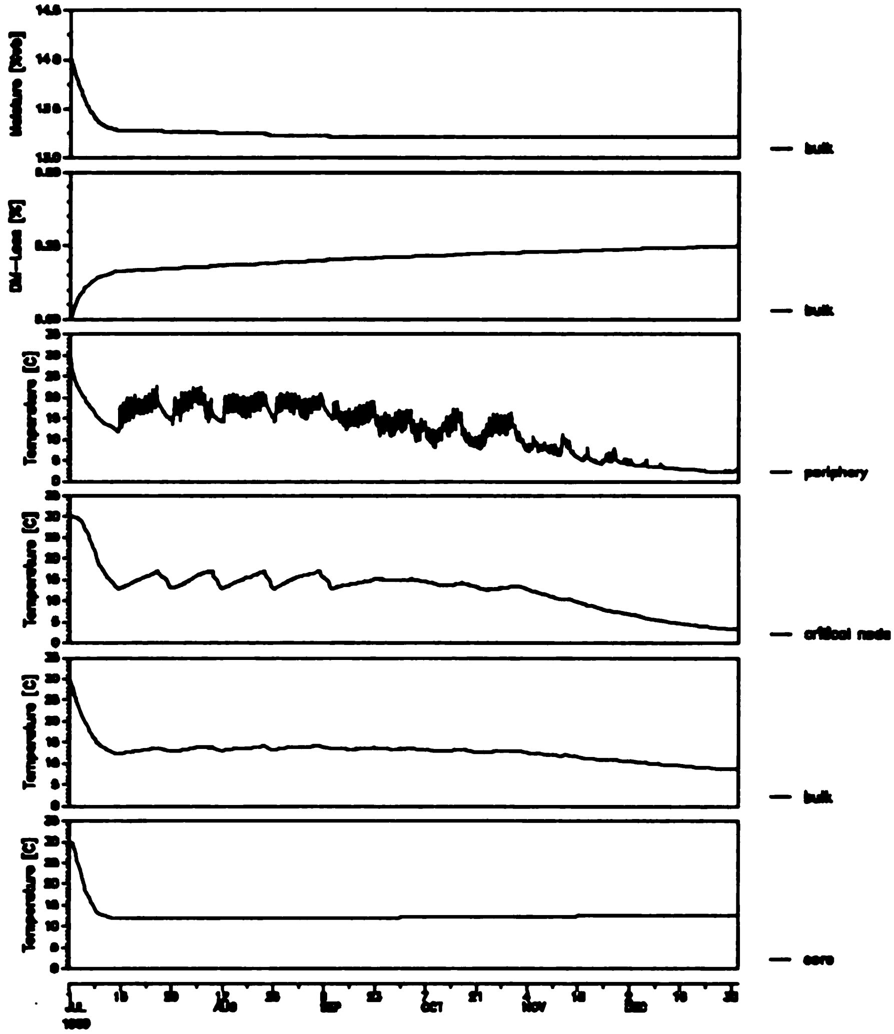

Figure 6.66 Simulated chilled aeration to 13°C and storage of wheat with partial rechilling and a critical node rechilling criterion of 17°C in the 1989 season.

The same bin of wheat is evaluated for the 6-month storage in 1990 (see Figure 6.67). One additional rechilling cycle is predicted. The first one occurs in the fourth week of July, and the last one in the second week of September. The cycles are spaced about 2.5 weeks apart. The predicted average dry matter loss by the end of December 1990 is 0.22%, and 0.23% in the periphery. This is slightly better than predicted for the previous year. In addition, the energy consumption is about 9% lower (i.e. 1.9 kWh/t per storage month) than in 1989. The average final moisture content is unchanged at 13.2% w.b.

The summer of 1990 was warmer and caused the bin temperatures to rise faster after a rechilling cycle than in 1989. However, the grain chiller operated fewer hours and used less energy to achieve a better grain quality than in the previous year. Such variations in bin warming and chiller operations are to be expected from year to year.

6.3.6 Controlling the Chiller

Some comments should also be made with respect to operating a grain chiller. The evaluation of the critical chilling parameters pointed to the importance of adjusting the cold-air and reheater set-points properly to match the grain

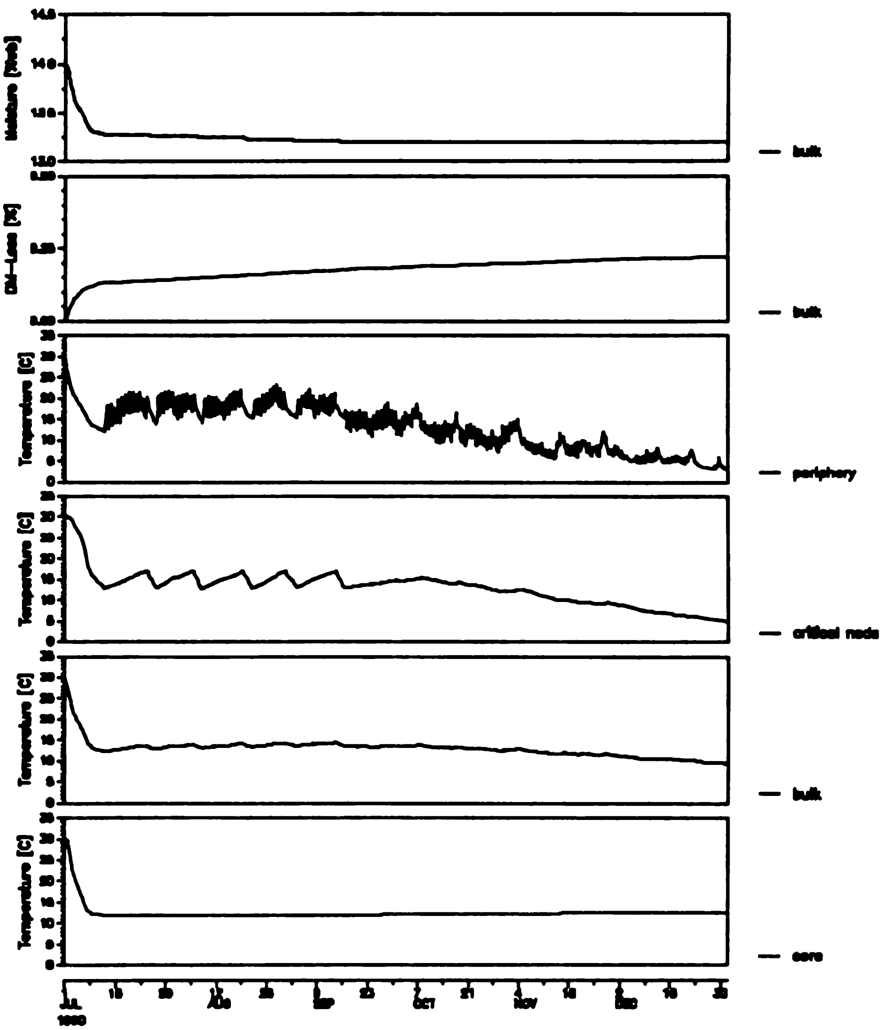

Figure 6.67 Simulated chilled aeration to 13°C and storage of wheat with partial rechilling and a critical node rechilling criterion of 17°C in the 1990 season.

conditions desired in the bin. Proper adjustment of the reheating of the air is critical when crops with different moisture contents are chilled and rechilled. If this is not done the cooling times can be extended significantly without the desired grain temperatures ever being reached. In addition, heat gain and loss occur in the duct connecting the chiller and the bin, and influence the air inlet conditions.

Thus, a controller for the grain chiller should be developed that incorporates (1) the automatic adjustment of the chiller set-points as a function of the grain and air conditions, (2) a sensor to indicate when partial rechilling of the bin is to occur, and (3) automatic shut-down of the chiller when the desired temperature is reached. The automatic adjustment of the cold-air and reheater set-points can be accomplished by specifying (a) the desired grain temperature, (b) the grain storage moisture content, and (c) the stored grain type. The controller sensors should be placed at the end of the connecting duct.

A control scheme along the following lines could be implemented. The reheater temperature is set equal to the desired grain temperature (i.e. the air temperature at the bin inlet). The cold-air temperature setting is determined by subtracting the amount of reheating needed from the reheater set-point. The amount of reheating depends on the temperature increase to lower the cold-air temperature after the evaporator to the equilibrium relative humidity (ERH) of the air at the bin inlet. The ERH can be calculated as a function of the selected grain temperature, moisture content, and the specified grain (see Chapter 4).

Many grain chilling applications require summer operation of the chiller. Thus, it may be assumed that the cold-air after the evaporator is saturated. Under those conditions only a temperature sensor at the bin inlet is needed to make the necessary psychrometric calculations to determine the needed cold-air temperature set-point. If the chiller is operated during low ambient temperature periods, or in very arid regions, the cold-air may not be saturated and a relative humidity sensor is needed after the evaporator to make the necessary psychrometric calculations. Today's technology has made electronic controllers readily available for applications in the agricultural field. Thus, it is believed that the development of an electronic controller for grain chillers is technically feasible. From a biological point of view it is definitely desirable. In addition, it appears more intuitive from an operator's point of view to specify the bin inlet conditions in terms of the grain temperature, moisture content, and crop than in terms of the cold-air and reheater set-points.

7. SUMMARY AND CONCLUSIONS

The following objectives have been achieved:

(1) A simulation model has been developed that accurately predicts the performance of a commercial grain chiller in terms of the flowrate, temperature, and relative humidity of the air into and out of the chiller, the evaporating and condensing refrigerant temperatures and capacities of the chiller refrigeration cycle, and the electrical power consumption under transient ambient conditions.

(2) The chiller model has been successfully integrated into a time-dependent grain aeration and storage model for upright silos that simulates the heat and mass transfer with two coupled differential equations in the grain bulk during the aerated period, and the heat transfer with a two-dimensional conduction equation during the non-aerated period.

(3) The critical operating and design parameters of a chilled grain aeration and storage system have been determined (see chilling and storage parameters summaries).

(4) A number of operational strategies for different physical and biological criteria of a chilled grain aeration and storage system have been analyzed (see chilling and rechilling strategies summary).

(5) The technical feasibility of chilled aeration and its superior grain quality preservation characteristics have been established in comparison to conventional aeration and storage of cereal grains.

Chilling Parameters Summary

The individual and combined effects of the critical chilling parameters have evaluated for corn and wheat under mid-Michigan conditions. The following observations are made:

(1) Variations in the weather conditions from one harvest year to the next affect the performance of a grain chiller. The cool-down time for corn varies by up to 1.5 days (for the fall of 1989, 1990 and 1991), and for wheat by up to 3 days (for the summer of 1988, 1990 and 1991). The fall chilling of corn is on average 34% faster than the summer chilling of wheat (i.e. 179 hours versus 240 hours, respectively), while the daily cooling rate for wheat is 12.5% higher than for corn (i.e. 1.5°C/day versus 1.3°C/day).

(2) The moisture reduction during grain chilling is significantly smaller compared to that of conventional drying processes. The moisture content of corn with an initial temperature from 12°C to 28°C is reduced on average between 0.2 and 0.8 percentage points; and of wheat at initially 30°C on average 0.7 percentage points. The moisture removal is highest at the higher initial grain temperature.

(3) Dry grain cools slower than higher moisture grain. The cooling time of corn increases by 5.3% when the initial moisture content is lowered from 18.5% w.b. to 16.5% w.b., and by 80% when the moisture content is lowered from 16.5% w.b. to 14.5% w.b. The chilling process is limited by the average grain equilibrium relative humidity of the bin inlet air, which is controlled by the reheater set-point temperature.

(4) The relative humidity of the chilled air into the bin has a significant influence on the cooling (and drying) of the grain. When the relative humidity of the cooling air is too high, the grain reabsorbs moisture in the bottom of the pile, which reduces the cooling effect. A decrease of the average relative humidity by 15 percentage points reduces the cooling time for corn by 45%, and a decrease by 30 points decreases it by

50%.

(5) The inlet air temperature has a similar effect on the cooling rate as the initial grain temperature; both are best evaluated in terms of the overall grain temperature reduction. Corn temperature reductions of 16 - 21°C yield cooling rates of 2.1 - 2.6°C per day, reductions of 10 - 13°C produce rates of 1.3 - 1.6°C per day, and reductions of 4 - 7°C result in rates of 0.7 - 1.0°C per day.

(6) The airflow rate into the bin is controlled by the chiller and varies as a function of the ambient cooling load on the refrigeration cycle. Increasing the airflow does not reduce the cooling time proportionally. Also, higher airflow rates are less economical in terms of power consumption and equipment cost. The chiller with a refrigeration capacity of 13 kW yields airflow rates of 2,000 - 4,200 m^3/h through 597 tonnes of corn (i.e. 0.06 - 0.12 $m^3/min/t$ or $ft^3/min/bu$), and 1,000 - 2,900 m^3/h through 579 tonnes of wheat (i.e. 0.03 - 0.08 $m^3/min/t$ or $ft^3/min/bu$).

(7) The combined effects of changing the bin inlet air temperature and relative humidity influence the cooling rate and time more significantly than the individual

effects. Increasing the reheater set-point raises the inlet air temperature and lowers the relative humidity of the chilled air. To assure the successful and timely cooling of corn and wheat, the chilled air should be reheated by at least 4 - 5°C before entering the bin; reheating more than 6 - 8°C may be needed if very dry grain is chilled (e.g. wheat below 11 - 12% w.b.).

(8) Changing the cold-air set-point by 3 to 5°C does not affect the cooling time of grain. Increasing the cold-air temperature increases the airflow through the grain, but the effect is off-set by higher relative humidity values of the air at the bin inlet.

(9) The combined effect of adjusting both the cold-air and reheater set-points can be evaluated in terms of a constant relative humidity differential. As the cold-air and reheater set-points are raised from 5°C and 10°C to 11°C and 16°C, respectively, the airflow rate increases sufficiently to shorten the cooling time and to increase the cooling rate while the equilibrium relative humidity of the bin inlet air remains constant.

Storage Parameters Summary

In the evaluation of the critical storage parameters the following observations are made:

(1) The periphery temperature, defined as 10% of the grain volume enveloping the grain bulk with a layer on the top and bottom of the pile plus a layer along the inside wall of the bin, closely follows the daily and seasonal variations due to the ambient boundary conditions. The bulk temperature, defined as the remaining 90% of the grain volume, shows a smoother pattern with smaller extremes.

(2) The bulk and periphery temperatures in a non-aerated grain bin oscillate in the long-term about a local mean, which depends on the crop type, bin dimensions, and ambient boundary conditions.

(3) The temperature pattern in a chilled grain storage bin is most sensitive to changes of the convective heat transfer between the bin wall surface and the ambient air (e.g. as influenced by the local wind velocity around the bin), the solar radiation flux (e.g. as influenced by the geographic location of the storage bin), and the bin surface-to-volume ratio (e.g. as influenced by the bin dimensions).

(4) The bin diameter and height are best evaluated in terms of the bin surface-to-volume ratio. A ratio of 1:3 dampens the bulk temperature profile in a corn bin over a three-year non-aerated storage period to a minimum-maximum difference of 11.5°C; a ratio of 1:1 shows significant oscillations, with a difference of 24.5°C between the extreme high and low.

(5) The thermal diffusivity value of a particular cereal grain determines the minimum and maximum temperatures, and the rate of cooling and warming given specific bin dimensions, initial grain conditions, and environmental boundary conditions. The heat propagation in corn is faster during the storage period than in wheat at equal moisture content.

(6) The effect of the initial grain temperature on the long-term temperature pattern in the bulk and periphery dissipates within the first few months of the storage period. The dissipation rate observed in the three-year storage of corn and wheat is about twice as fast in the periphery than in the bulk.

Chilling and Rechilling Strategies Summary

A number of chilling and rechilling strategies have been evaluated for corn and wheat under mid-Michigan conditions.

The following observations are made:

(1) A chilled aeration and storage system clearly preserves the quality of cereal grains, as defined by the risks of mold development and insect infestation, better than no aeration and continuous aeration. The average dry matter loss of corn after 12-month storage is 37% less for chilled aeration to 7°C than for ambient cooling (i.e. 0.38% versus 0.52%), and 68% better than for no aeration (i.e. 0.37% versus 0.64%); for wheat the dry matter loss is 200% better for chilled aeration to 10°C than ambient cooling (i.e. 0.32% versus 0.96%), and 244% better than no aeration (i.e. 0.32% versus 1.1%).

(2) The operating costs for once-only chilling of corn to 7°C in the fall under mid-Michigan conditions are about the same as for continuous ambient cooling (i.e. 0.26 kWh/t per month of storage), while chilling wheat once-only to 10°C in the summer is 630% less costly than continuous aeration (i.e. 0.74 kWh/t/month versus 5.4 kWh/t/month).

(3) Rechilling the entire grain bin based on the bulk or periphery temperature is not satisfactory. These strategies require either high operating costs (e.g. 4.4 - 6.1 kWh/t/month for periphery control), or cause

large temperature gradients (e.g. between the bulk and the outer layers for bulk control). Rechilling based on a critical node near the top and south-side of the grain pile reduces the temperature gradients and operating costs of the chilled aeration and storage system, but the dry matter loss of the grain is not minimized.

(4) The concept of partial-bin rechilling minimizes the dry matter loss and the temperature gradients in the bin most successfully. For the 12-month storage of corn the dry matter loss in the bulk is 23% smaller (i.e. 0.30% versus 0.37%), and in the periphery 24% smaller (i.e. 0.50% versus 0.62%) than for the optimum whole-bin rechilling strategy; in wheat the 6-month deterioration is 8% smaller in the bulk (i.e. 0.25% versus 0.27%), and 19% smaller in the periphery (i.e. 0.23% versus 0.31%). The operating costs for the chilled aeration and storage of corn range from 0.99 to 1.15 kWh/t/month, and of wheat from 1.9 to 2.1 kWh/t/month for mid-Michigan conditions using the partial-bin rechilling strategy.

Based on the evaluation of a series of chilling and rechilling strategies, the following two procedures for the successful quality preservation during the 12-month storage of corn and wheat under mid-Michigan conditions are proposed:

(i) <u>For corn:</u>

1) Cool the corn in the fall (preferably as the bin is filled) with a grain chiller until the top grain layer reaches 7°C.
2) Rechill the outer columns of the grain bin to 10°C once a month between mid-June and mid-September.
3) Initiate a rechilling cycle after a temperature probe placed on the south-side near the top grain surface reaches 17°C, but not later than 20°C.
4) Employ temperature cables in the bulk to monitor for hot spots, and treat them immediately by chilling the entire bulk if necessary.

(ii) <u>For wheat:</u>

1) Cool the wheat in the summer (preferably as the bin is filled) with a grain chiller until the top grain layer reaches 11 - 13°C.
2) Rechill the outer columns of the grain bin to 11 - 13°C every 3 - 4 weeks beginning 3 weeks after the initial cool-down, and continue through September.
3) Initiate a rechilling cycle after a temperature probe placed on the south-side near the top grain surface reaches 17°C, but not later than 20°C.

4) Employ temperature cables in the bulk to monitor for hot spots, and treat them immediately by chilling the entire bulk if necessary.

For chilled aeration and storage of cereal grains to be successful the same handling procedures are recommended for drying and cleaning the crop, and for filling and levelling as for conventional aeration systems (MWPS-13 1988). In addition to a grain chiller, a conventional aeration system needs to be modified by adding a duct around the circumference of the bin, and a valve to switch the air from whole-bin to partial-bin flow.

Since chilled aeration and storage appears desirable biologically for corn and especially for wheat in the climate of mid-Michigan, it seems at least as desirable in the warmer climates of the southern United States for corn, wheat and other crops. Economic and environmental considerations, including the public desire for the employment of fewer chemical preservatives in cereal grain products (Hendershot 1990, Heath 1990), must be taken into account in the total evaluation of the types of installations and the crops that would most benefit from the utilization of chilled aeration systems in the United States.

The general procedures developed for the chilled aeration and storage of corn and wheat in mid-Michigan can easily be modified to accommodate the use of chilling systems at other locations and for other crops throughout the world. The concept of initially chilling the entire grain bulk using a grain chiller, coupled with the partial rechilling of the grain columns is believed to be applicable to other crop types, bin sizes, and geographic locations.

8. SUGGESTIONS FOR FUTURE RESEARCH

The following recommendations for further study are made:

(1) The concept of partially rechilling the bin should be investigated in terms of the uniformity of airflow through grain, and the placement of the critical temperature sensor.

(2) The development of a controller strategy for a commercial grain chiller should be initiated to incorporate more operator-friendly input parameters, and the automatic adjustment of the cold-air and reheater temperature set-points.

(3) The chilled aeration and storage model could be expanded and employed for other crops and locations throughout the world. Of particular interest is the evaluation of the chilled aeration and storage of paddy and food corn in the southern United States, and of paddy in Southeast Asia.

(4) Optimization routines could be incorporated into the model to evaluate the most economic chilling and rechilling scenarios versus conventional aeration and storage systems.

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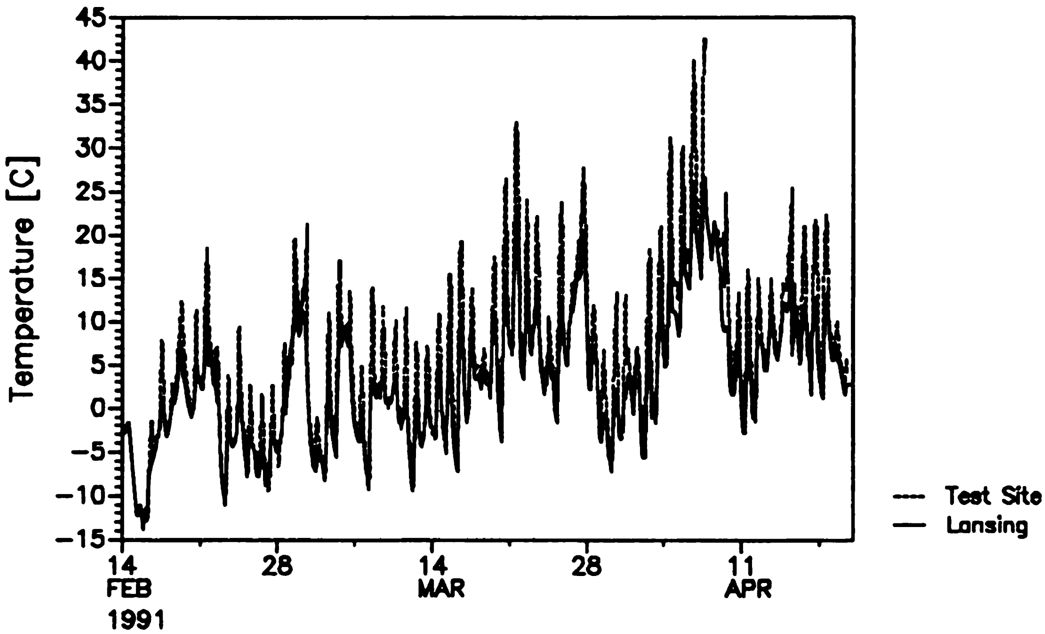
DISCLAIMER

Trade names are used in this study solely to provide specific information. Mention of a trade name does not constitute a warranty of the product by the author nor by Michigan State University nor an endorsement of the product to the exclusion of other products not mentioned.

APPENDIX



Appendix A.1 Ambient temperatures measured at the site of the field-test compared to the official Lansing weather record between February 14 and April 20, 1991.