This is to certify that the

thesis entitled

DRYER PERFORMANCE ENHANCEMENT THROUGH GRAIN

PRE-HEATING

presented by

Michael D. Montross

has been accepted towards fulfillment
of the requirements for

M.S. degree in Agricultural Engineering

F.W. Bakker-Arkema
Major professor

Date November 13, 1995

DRYER PERFORMANCE ENHANCEMENT THROUGH GRAIN PRE-HEATING

By

Michael David Montross

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

in

Agricultural Engineering

Department of Agricultural Engineering

1995

ABSTRACT

DRYER PERFORMANCE ENHANCEMENT THROUGH GRAIN PRE-HEATING

By

Michael David Montross

Increasing the capacity of continuous-flow corn dryers, without affecting corn quality, is physically and economically feasible by pre-heating the corn before it enters the dryer. This premise was tested successfully at a Midwestern commercial site. Corn was pre-heated in an intermittent-flow hopper-bottom wet-holding tank with 80-110°C air, resulting in a dryer capacity increase of up to 20%.

A steady-state two point boundary value simulation model was developed consisting of four differential equations. The model is solved using finite-differences, and has been verified with experimental data. The significant pre-heater design parameters were established, i.e. the air temperature, the grain and airflow rates, and the initial corn moisture content.

The pre-heater/dryer system results in positive cash flows if operated at least 147 hours per season at 5 percentage points of moisture removal, or 164 hours at 10 percentage points removal, under 1994-1995 economic conditions.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to the continued encouragement, guidance and support of Dr. Fred W. Bakker-Arkema. His trust over the years is greatly appreciated.

Appreciation is expressed to Dr. S. B. Harsh and Dr. L. J. Segerlind for serving on the guidance committee.

The partial financial support arranged through MFS/York Inc. was greatly appreciated. Special thanks goes to Mr. Robert Hines, General Manager of MFS/York for his advice and confidence.

Also acknowledged is the willingness of Elmo Meiner to provide the commercial facility and corn for the experimental testing of the corn pre-heater.

I would also like to thank the friends I have made in the Agricultural Engineering Department.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

A	constant in specific heat equation [kJ/kg·°C]
B	constant in specific heat equation [kJ/kg·°C]
D	diffusion coefficient [m^2/h]
G	flow rate [kg dry product/h·m^2]
L	depth of drying bed [m]
M	moisture content, dry basis [decimal]
$\overline{M}$	average moisture content, dry basis [decimal]
MR	dimensionless moisture ratio
Q	airflow rate [m^3/m^2/min]
RH	relative humidity [decimal]
T	air temperature [°C]
V	velocity [m^3/m^2/hr]
W	absolute humidity of air [kg/kg]
a	specific surface area [m^2/m^3]
c	constant in thinlayer drying equation
h	convective heat transfer coefficient [W/m^2·K]

h_{fg}	latent heat of vaporization [kJ/kg H_2O]
ind1	number of nodes in counterflow bed
k	constant in thinlayer drying equation
m	constant in convective heat transfer coefficient
n	constant in convective heat transfer coefficient
o	constant in convective heat transfer coefficient
p	constant in convective heat transfer coefficient
t	time [h or min or s]
x	bed depth coordinate [m]
c_a	specific heat of dry air [kJ/kg·°C]
c_v	specific heat of water vapor [kJ/kg·°C]
c_p	specific heat of corn kernels [kJ/kg·°C]
c_w	specific heat of liquid water [kJ/kg·°C]
r_o	corn kernel radius [m]
w.b.	moisture content, wet basis
Δx	finite difference stepsize [m]
$\Delta P'$	static pressure drop [Pa/m]
μ	viscosity [kg/hr·m]
Θ	corn temperature [°C]

subscripts

a	air
eq	equilibrium
exp	experimental
in	inlet or initial
p	corn
sim	simulated
w	water

coordinates

0	corn inlet to the counterflow bed
n	index for node numbers
L	air inlet to the counterflow bed

she

requ

tem

util

tem

U.S.

cour

conc

avai

selli

the d

New

CHAPTER 1

INTRODUCTION

During the 1992 corn harvest in the U.S. 241 MMT (9.48 billion bushels) of shelled corn was harvested (USDA, 1994). Much of the corn harvested in the U.S. requires drying, either as ear corn in a crib, or as shelled corn in a high-temperature dryer or a natural-air/low-temperature dryer. The drying equipment is utilized only for a 4-8 week period during the harvest season.

Figure 1.1 shows schematic views of the four major types of high-temperature dryers. The crossflow dryer is the most prevalent dryer type in the U.S., with a smaller number of concurrent-flow and mixed-flow dryers. The counterflow design is utilized in in-bin counterflow dryers and in the coolers of concurrent-flow dryers.

To increase the capacity of an existing dryer, a number of options are available. Dryer managers have the option of installing another drying stage, selling the old dryer and purchasing a new dryer, employ dryeration, or increase the drying air temperature.

For some dryers the option of adding another drying stage is not practical. New dryers are expensive and capital is not always available for the purchase of a

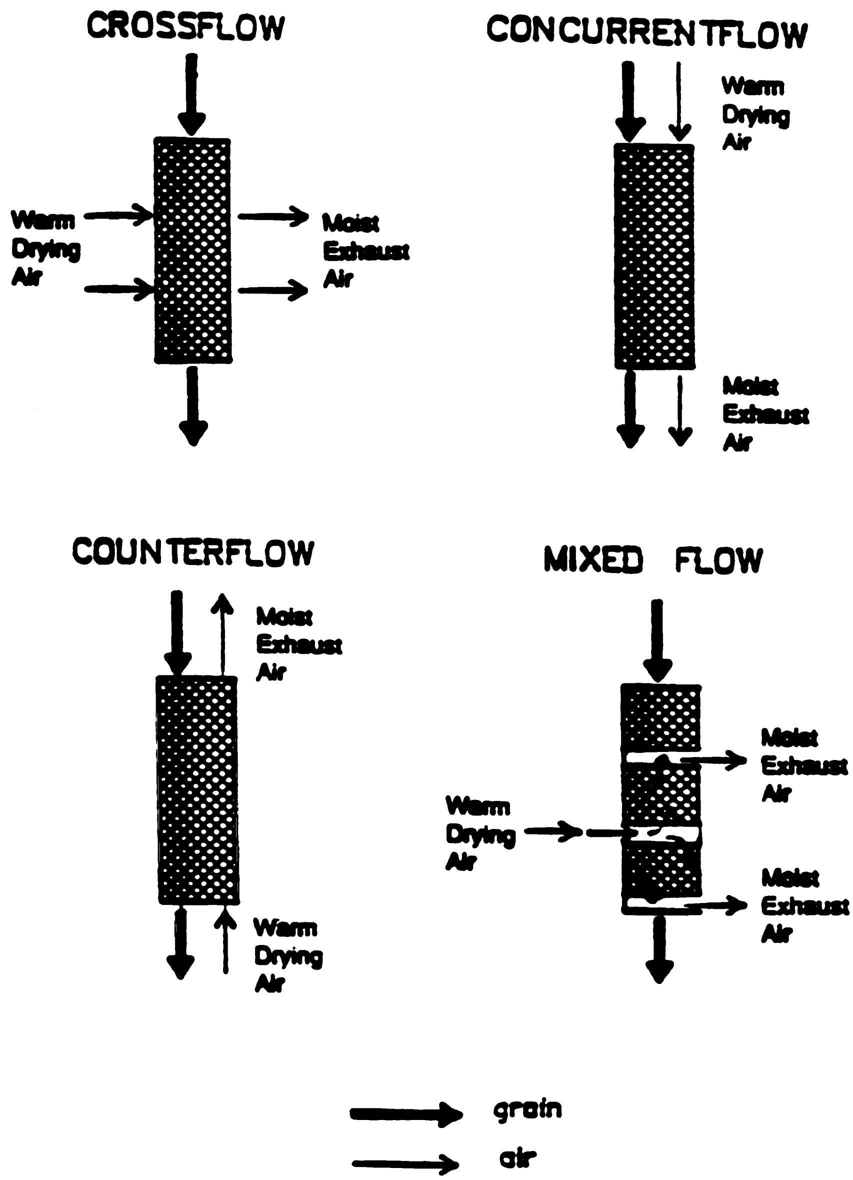

Figure 1.1 Schematics of the four major types of high-temperature grain dryers: crossflow, concurrent-flow, counterflow, and mixed-flow (Brooker et al., 1992).

nev

dry

but

also

fact

tem

loca

dev

para

app

con

new dryer. The disadvantage of dryeration is the requirement of an additional dryeration bin. Increasing the drying air temperature increases the dryer capacity, but the percentage of stress cracks and the breakage susceptibility of the dried corn also increase.

The capacity of a continuous-flow grain dryer depends on a number of factors, including the inlet grain temperature. In fact, increasing the initial corn temperature, increases the capacity of a dryer.

This study investigated the pre-heating of corn in a hopper-bottom bin located before the dryer at a commercial elevator. Experimental data was used to develop a simulation model of the pre-heating of corn. The effects of various parameters on the design of the in-bin counterflow pre-heater were determined by application of the model. The economic feasibility of employing a pre-heater in conjunction with a corn dryer was analyzed using a capital budgeting model.

CHAPTER 2

OBJECTIVES

The objectives of this study are:

(1) To obtain experimental data on the pre-heating of corn in a counterflow pre-heater.

(2) To develop a simulation model of the counterflow pre-heating of corn, and to validate the model.

(3) To determine the influence of various design parameters on the operation of a counterflow corn pre-heater.

(4) To determine the economic feasibility of an in-bin counterflow pre-heater for a corn drying system.

3.1

10°

repo

con

rang

flui

the

tem

incr

12°

appr

con

CHAPTER 3

LITERATURE REVIEW

3.1 Grain Pre-Heating

It has been claimed that pre-heating of grain can reduce the fuel costs by 10% and increase the dryer capacity by 33% (Behlen, 1968). Mühlbauer (1974) reported that pre-heating also improves the quality of the grain in comparison to conventionally dried grain.

Rezchikov et al. (1983) used a rotary pre-heater for wheat in the moisture range of 22-27% w.b. and an initial temperature of 10-15°C (50-59°F). A fluidized bed dryer was employed with the rotary pre-heater. During pre-heating of the wheat an airflow rate of 333 m^3/min (11,770 ft^3/min) and a drying air temperature of 150-200°C (302-392°F) were used. Pre-heating the wheat increased the dryer capacity by 34-40% and reduced the fuel consumption by 10-12%. During pre-heating the wheat decreased in moisture content by approximately 0.9%, and reached an average temperature of 40-50°C (104-122°F).

Bakker-Arkema et al. (1993) tested a pre-heater with a one-stage concurrent-flow dryer. An in-bin counterflow pre-heater was employed using both recy

dry

8.1

3.2

al.,

The

ker

pro

val

an

ma

sec

sus

recycled dryer air and non-recycled (i.e. ambient) air. With non-recycled air the dryer capacity increased by 15-20%. An airflow rate of 1.8-2.5 $m^3/m^2/min$ (6.0-8.1 $ft^3/ft^2/min$) and an air temperature of 71-93°C (160-200°F) were employed.

3.2 Stress Cracks

There are a number of properties that affect the quality of corn (Brooker et al., 1992). Included are:

(1) an appropriately low and uniform moisture content

(2) a high testweight

(3) a low percentage of broken corn and foreign material (BCFM)

(4) a low susceptibility to breakage.

The absence of stress cracks is an important quality attribute of corn. Stress-cracked kernels break more readily than sound kernels during handling, transport, and processing. This leads to lower yields in dry and wet milling, and to higher BCFM values in feed corn. Thus, the percentage of stress cracked kernels in a lot of corn is an important index of value to end-users.

Determination of the stress cracked kernels in a sample is usually made by manual inspection, i.e. by candling kernels against a bright-light background. Many sectors in the food industry use the number of stress cracks rather than the breakage susceptibility for establishing corn quality, mainly because the breakage susceptibility of a corn sample is moisture and temperature dependent (Kalchik, 1995).

Thompson and Foster (1963) were among the first to investigate the stress cracking of corn during drying; they reported total stress crack counts of 92-98% in corn dried in a crossflow dryer from 20-30% to 14% moisture content at air temperatures between 60 and 145°C (140-293°F). The authors distinguished between single/multiple/checked stress cracked kernels. Figure 3.1 illustrates the types of stress cracks in corn kernels.

Westerman et al. (1973) determined that the relative humidity of the drying air greatly affects the degree of stress cracking of corn dried in thin layers at high temperatures. At relative humidities below 50%, the percentage of stress cracked kernels at 45°C (113°F) was 80-95%. By maintaining a relative humidity above 60%, the percentage of stress cracked corn kernels was less than 20%, even at 70°C (158°F).

Sarwar (1988) conducted a fundamental study of the stress cracking of corn. At 20-25% initial moisture content, corn dried at 40-60°C (104-140°F) to 12-15% moisture did not stress crack during drying but developed 50% or more stress cracks within 48 hours after drying. The percentage of stress cracked kernels was reported to be related to: (1) the drying temperature, (2) the initial moisture content, (3) the final moisture content, and (4) the relative humidity of the storage environment.

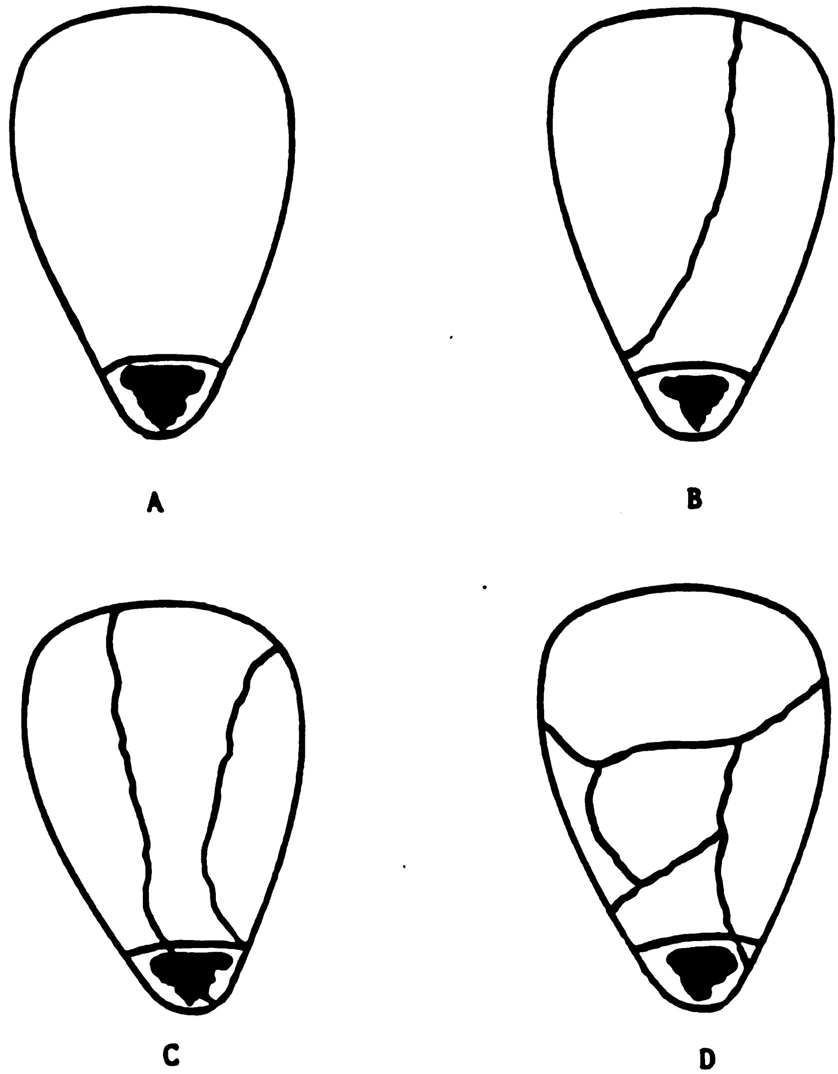

Figure 3.1 Types of stress cracks in dried corn kernels (Thompson and Foster, 1963).
A--Whole kernels
B--Single stress cracks
C--Multiple stress cracks
D--Checked kernels

No. 3 corn shipped from a U. S. port to Japan has in a typical year an average stress crack percentage of 60-65%, with a range from 28 to 90% (Paulsen et al., 1989). Export corn from Argentina has a similar percentage of stress cracked kernels (Hill and Paulsen, 1987).

Hill et al. (1991) evaluated the quality characteristics of corn used in a dry milling plant. Corn purchased by the plant was restricted to corn with a minimum test weight of 54 lbs per bushel (692 kg/m^3). The percentage of stress cracked kernels ranged from 30 to 60%.

Hill et al. (1993) compared the quality of U. S. natural-air dried, U. S. No. 3, and South African corn. The average percentage of stress cracked kernels of natural-air dried corn was 4.9%, and 50.9% for the U. S. No. 3 corn. South African corn arriving in Japan showed a percentage of stress cracked kernels of 11.0%.

It is clear from the above-quoted references that high-temperature dried corn may contain a percentage of stress cracked kernels varying from 50% to 98%.

Determination of stress cracked kernels in a sample is often considered to be a subjective test, and therefore the breakage susceptibility of a corn sample is in the opinion of some a better quality criterion than the stress crack percentage (Hill et al., 1991). However, there is an excellent correlation between stress cracked kernels and breakage susceptibility (Hill and Paulsen, 1987; Gunasekaran and Muthukumarappan, 1993).

The stress crack index (SCI) is a method of weighting stress cracked kernels according to the crack severity. The SCI is defined as (Gunasekaran and Muthukumarappan, 1993):

$$SCI = 1*(\%\ single) + 3*(\%\ multiple) + 5*(\%\ checked) \qquad (3.1)$$

The SCI correlates well with the breakage susceptibility of the sample.

3.3 Economic Analysis

A common economic analysis used in industry is the payback period. The payback period is defined as the initial cost divided by the net annual savings (Harsh, 1981). The payback period is often used in industry as a cutoff for investments. The payback period does not take into account the time value of money, the depreciation, the taxes, or the inflation.

A capital budgeting analysis uses the yearly cash flow of a project to determine the economic feasibility of an investment. The analysis allows the effect of the various economic variables to be assessed, including (Harsh et al., 1981; Riggs and West, 1986):

(1) the yearly operating costs and income

(2) alternative investments

(3) the inflationary effects

(4) the time value of money.

The cash flow for the project is calculated over the expected lifetime of the project, and are discounted and summed to determine the net present value (NPV) of the project. The discount rate is chosen as the average cost of capital and represents the rate at which alternative investments can be made. If the NPV of the cash flows is positive, a project is economically feasible.

The capital budgeting model can be generated using a spreadsheet program (e.g. Microsoft Excel) to calculate the cash flow over the life of the investment. Most spreadsheets have internal functions to discount cash flows from a future date to the present. [In this study Microsoft Excel 5.0 for Windows was used to calculate the NPV of the cash flow by employing the XNPV financial function; this function requires the discount rate, a series of cash flows, and the dates at which the cash flows occurred (Microsoft, 1993)].

CHAPTER 4

DEVELOPMENT OF THE COUNTERFLOW MODEL

4.1 Counterflow Deep-Bed Equations

In the counterflow heater/cooler the air and the grain flow in opposite directions. The differential equations are derived by formulating energy and mass balances on an elemental volume, with the grain flow in the positive direction. A schematic diagram of the counterflow model is shown in Figure 4.1.

The following assumptions are made in developing the counterflow heating or cooling model:

(1) the volume shrinkage is negligible during the drying process

(2) the temperature gradient within individual kernels is insignificant

(3) the kernel-to-kernel conduction is negligible

(4) the airflow and grainflow are plug type and constant

(5) the derivatives of the air temperature and humidity with respect to time are negligible compared to the derivatives with respect to position

(6) the bin walls are adiabatic and have an insignificant heat capacity

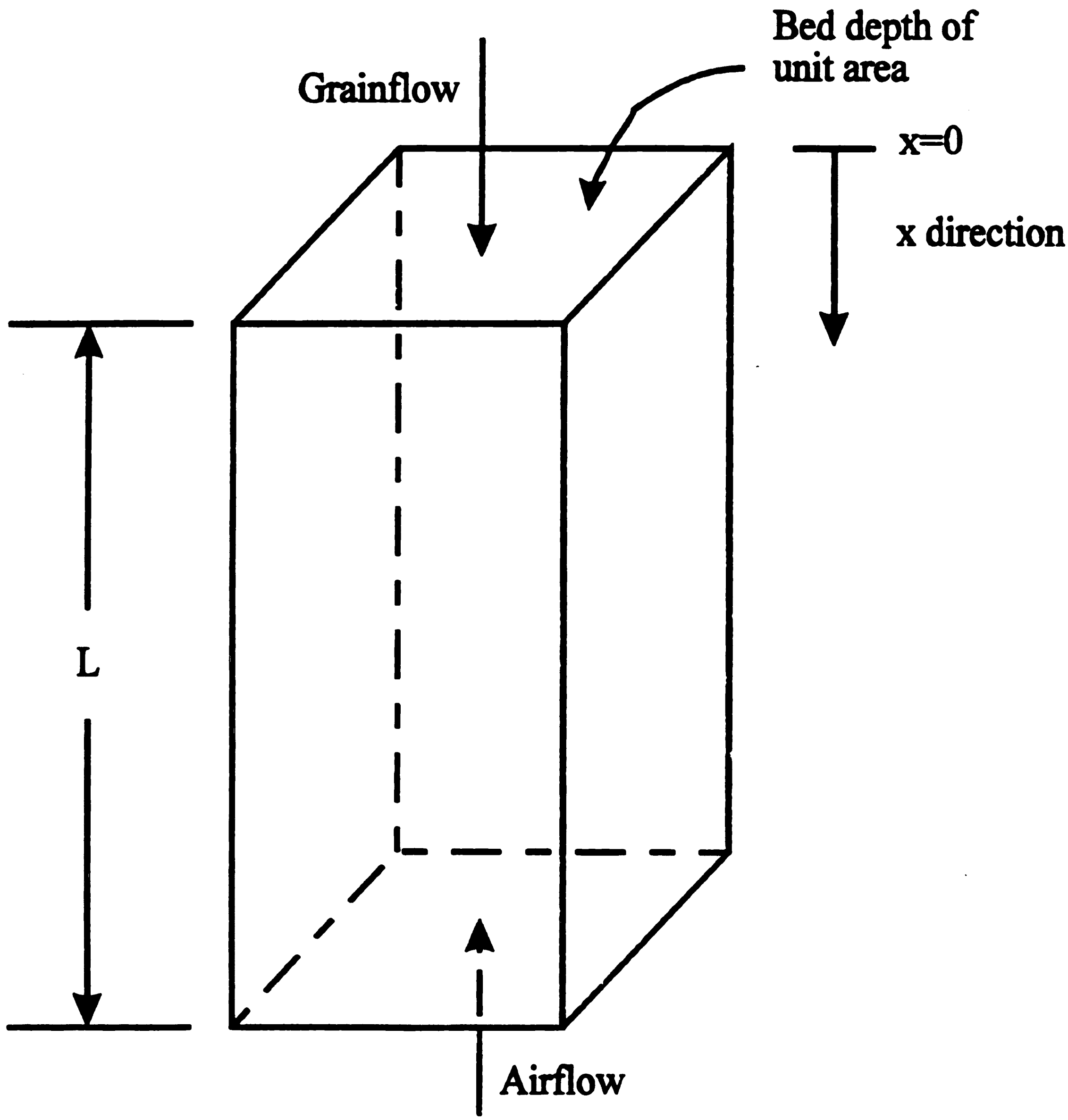

Figure 4.1 Block diagram of the counterflow model.

(7) the heat capacities of the air and the grain are constant during short time periods

(8) the single-kernel drying and the moisture equilibrium equations are sufficiently accurate.

The steady-state model of the counterflow heater/cooler can be described by the following system of ordinary differential equations (Brooker et al., 1992):

$$\frac{dT}{dx} = \frac{ha}{G_a c_a + G_a c_v W}(T - \Theta) \tag{4.1}$$

$$\frac{d\Theta}{dx} = \frac{ha}{G_p c_p + G_p c_w \overline{M}}(T - \Theta) + \frac{h_{fg} + c_v(T - \Theta)}{G_p c_p + G_p c_w \overline{M}} G_a \frac{dW}{dx} \tag{4.2}$$

$$\frac{dW}{dx} = \frac{G_p}{G_a}\frac{d\overline{M}}{dx} \tag{4.3}$$

$$\frac{d\overline{M}}{dx} = \text{a thin - layer drying equation} \tag{4.4}$$

The boundary conditions for the counterflow system are:

$$T(L)=T_{inlet} \tag{4.5}$$

$$\Theta(0)=\Theta_{initial} \tag{4.6}$$

$$W(L)=W_{inlet} \tag{4.7}$$

$$M(0)=M_{initial} \tag{4.8}$$

Solution of equations 4.1 through 4.4 using the boundary conditions given in equations 4.5 through 4.8 yield the air and grain temperatures, the air humidity, and the grain moisture content in the counterflow grain bed.

The equations describing the counterflow heater/cooler are ordinary first order differential equations. The solution is complex because it is a two-point boundary value problem.

4.2 Single-Layer Drying Equations

To solve the counterflow model an equation to describe the moisture loss of the grain during the heating/cooling process is needed. For grains there are two major types of thin-layer drying equations: (1) diffusion, and (2) empirical (or thin-layer). A diffusion equation usually assumes the grain kernel to be a brick, cylinder, or sphere. By solving the diffusion equation, the moisture gradient within a kernel during the drying process is modeled. Integration of the moisture gradient allows calculation of the average moisture content of the grain kernel. The general diffusion equation is written as (Brooker et al., 1992):

$$\frac{\partial M}{\partial t} = \nabla^2 (DM) \qquad (4.9)$$

where D is the diffusion coefficient in m^2/h (ft^2/hr).

A number of semi-empirical and empirical equations have been proposed to describe the drying behavior of a thin-layer of grain. An example is the Page equation (Page, 1949):

$$MR = \frac{\overline{M}(t) - M_{eq}}{M_{in} - M_{eq}} = \exp(-kt^{c}) \tag{4.10}$$

where c and k are empirical constants and MR is the so-called moisture ratio. Knowledge of the equilibrium moisture content, M_{eq}, is required to solve the Page equation. By rearranging equation 4.10, the average moisture content $\overline{M}(t)$ at time t can be determined.

Li and Morey (1984) fitted an empirical thin-layer model for corn to equation 4.10. The hybrid used in the study was Jacques JX-52 grown in 1981 and 1982 at the University of Minnesota Rosemount Agricultural Experiment Station. Coefficients for equation 4.10 were determined in the temperature range of 27 to 116°C (80 to 240°F) and the initial moisture content range of 18.7 to 26.5% w.b.:

$$k = 1.091 \cdot 10^{-2} + 2.767 \cdot 10^{-6} \cdot \Theta^{2} + 7.286 \cdot 10^{-6} \cdot \Theta \cdot M_{in} \tag{4.11}$$

$$c = 0.5375 + 1.141 \cdot 10^{-5} M_{in}^{2} + 5.183 \cdot 10^{-5} \cdot \Theta^{2} \tag{4.12}$$

where the moisture content in the thin-layer equation is expressed in percent d.b., the temperature in °C, and the time in minutes.

Solution of equation 4.10 gives the moisture content of a thin-layer of corn as a function of time. To use equation 4.10 in the counterflow model, the substitution $t=x/V_p$ is made, where V_p is the grain velocity. The substitution is valid if volume shrinkage of the grain is neglected. Solving equation 4.10 for $\overline{M}(t)$ and differentiating with respect to x yields:

$$\frac{d\overline{M}}{dx} = (M_{in} - M_{eq})c\left(-k\left(\frac{60}{V_p}\right)^c\right)(x^{c-1})\exp\left(-k\left(\frac{60}{V_p}\right)^c x^c\right) \tag{4.13}$$

Equation 4.13 is used for equation 4.4 as the thin-layer drying equation.

The diffusion equation was not used because it was not necessary to monitor the moisture gradient in the kernels during the counterflow heating process.

4.3 Equilibrium Moisture Content

The equilibrium moisture content (EMC) of grain is defined as the moisture content that the grain kernels reach after being exposed to an environment for an infinite period of time.

A number of models have been proposed to calculate the EMC of grains. The choice of the EMC equation to be used with a particular thin-layer equation is determined during the regression of the constants in the thin-layer equation. Li and Morey (1984) used the EMC equation developed for corn by Thompson et al. (1968) in thin-layer equation 4.10:

$$M_{eq} = \sqrt{\frac{-\ln(1-RH)}{0.00005904(\Theta+57.1)}} \tag{4.14}$$

where RH is the relative humidity (decimal) of the drying air, Θ is the corn temperature in °C, and M_{eq} is the equilibrium moisture content in percent d.b.

4.4 Specific Heat

The equation for the specific heat, c_p, of grains is written as:

$$c_p = A + B \cdot \overline{M} \tag{4.15}$$

where $\overline{M}$ is the average moisture content in % w.b. and the coefficients for shelled corn at 35.2°C (95.3°F) are (Brooker et al., 1992):

$$A=1.361 \text{ kJ/kg·°C } (0.325 \text{ Btu/lb·°F}) \tag{4.16}$$

$$B=0.0397 \text{ kJ/kg·°C } (0.00949 \text{ Btu/lb·°F}) \tag{4.17}$$

In the derivation of the differential equations the specific heat was written in the following form:

$$c_p = A + c_w \overline{M} \tag{4.18}$$

where A is defined by equation 4.16, and represents the specific heat of the dry corn. The quantity $c_w \overline{M}$ is the specific heat of liquid water times the average moisture content of the corn in decimal d.b. Table 4.1 shows the difference in the specific heat of corn as calculated using equations 4.15 and 4.18.

Table 4.1 Comparison of specific heat as calculated for corn using equation 4.15 and 4.18.

MC (% w.b.)	c_p using eqn 4.15 (kJ/kg·°C)	c_p using eqn 4.18 (kJ/kg·°C)
15.0	1.97	2.09
20.0	2.14	2.43
25.0	2.34	2.76
30.0	2.55	3.14

There is a difference in the specific heat calculated with equations 4.15 and 4.18. The counterflow model was programmed using equations 4.15 and 4.18 to compare the effect of the specific heat on the outlet corn temperature and moisture content. There was a minor difference in the corn temperature, between 0.0 and 0.4°C, and a negligible difference in the moisture content, between 0.0 and 0.03%. Therefore, equation 4.18 was employed in this research to allow for faster computation time.

The specific heat used for dry air is 1006.93 J/kg·K (0.2405 Btu/lb·°F), for liquid water 4187 J/kg·K (1000 Btu/lb·°F), and for water vapor 1875.69 J/kg·K (0.448 Btu/lb·°F) (Brooker et al., 1992).

4.5 Convective Heat Transfer Coefficient

The convective heat transfer coefficient is determined using an equation presented by Barker (1965):

$$h = mc_a G_a \left(\frac{2r_o G_a}{\mu_a} \right)^n \tag{4.19}$$

where h has units of W/m^2·K (Btu/hr·ft^2·°R) and r_o is the equivalent particle radius. Barker's equation requires knowledge of μ_a, the viscosity of the air which is estimated by:

$$\mu_a = o + pT \tag{4.20}$$

where the constants m, n, o, and p in equations 4.19 and 4.20 in SI units are:

$$m=0.2755 \tag{4.21}$$

$$n=-0.34 \tag{4.22}$$

$$o=0.06175 \tag{4.23}$$

$$p=0.000165 \tag{4.24}$$

The equivalent radius, r_0, of an average sized corn kernel is 0.98 cm (0.03217 ft) (Brooker et al., 1992).

4.6 Latent Heat of Vaporization

The equation for the latent heat of vaporization for corn in SI units is (Brooker et al., 1992):

$$h_{fg} = (2{,}502.2 - 2.39\Theta)\left[1 + 1.2925\exp(-16.961\overline{M})\right. \tag{4.25}$$

where the latent heat of vaporization, h_{fg}, has units of kJ/kg, Θ is in °C, and $\overline{M}$ is in decimal dry basis.

4.7 Other Properties

The bulk density of shelled corn is 660 kg/m^3 (41.2 lb/ft^3); and the specific surface area, a, of corn is 784 m^2/m^3 (239 ft^2/ft^3) and has a standard deviation of 217 m^2/m^3 (66 ft^2/ft^3) (Brooker et al., 1992).

4.8 Static Pressure

The static pressure drop for corn is given by (Brooker et al., 1992):

$$\Delta P' = \frac{20{,}700 Q_a^2}{\ln(1 + 30.4 Q_a)} \tag{4.26}$$

where the static pressure drop per unit foot, $\Delta P'$, has units of Pa/m with the airflow rate, Q_a, given in $m^3/m^2/min$.

4.9 Psychrometric Properties

The psychrometric properties of moist air are calculated using the English-form of the equations as programmed by Bakker-Arkema et al. (1974). The atmospheric pressure used in this study is 0.973 atm (14.3 psia).

4.10 Solution Procedure

A number of numerical methods have been used to solve the counterflow heating/cooling model. Evans (1970) used invariant programming and invariant imbedding. The solution requires extensive computer time and is complex. Bakker-Arkema and Schisler (1984) and Maier (1988) solved the counterflow cooler model using a two-step procedure:

(1) solve the absolute humidity and moisture contents using coefficients computed from stored values of the air and grain temperatures

(2) solve the air and grain temperatures directly using coefficients stored from the moisture content and humidities.

Bakker-Arkema et al. (1974) solved the counterflow cooler model using a shooting routine. The method employs an adaptive Runge-Kutta procedure and an optimization technique. To use the shooting method, a guess of the unknown boundary conditions is made and the equations are solved as an initial value problem; the air conditions at the outlet of the counterflow cooler, T_{out} and H_{out}, are guessed iteratively until the proper values of T_{inlet} and H_{inlet} are found. The solution of the counterflow cooler using the shooting method is somewhat unstable numerically, because the solution is very sensitive to the initial guess, and to the condensation process occurring in a counterflow pre-heater.

Marks et al. (1993) solved the counterflow heating model by assuming the grain bed to be a multiple system of thin layers of grain. In the simulation, a small layer is removed at the grain outlet, the other layers and shifted down, and a new layer is placed on top of the bed. This solution scheme allows the system to be treated as a fixbed model.

Since the counterflow heating/cooling model is non-linear, an iterative method using finite differences can be used to solve the equations (Segerlind, 1995). A discussion of solving boundary value problems for systems of ordinary differential equations, using either the shooting method or finite differences, can be found in texts on numerical analysis (Cheney and Kincaid, 1985; Press et al., 1986). The finite difference equations can be derived by using forward and backward differences. Finite difference approximations to equations 4.1 to 4.4 are:

$$\frac{T_{n+1} - T_n}{\Delta x} = \frac{ha}{G_a c_a + G_a c_v W_{n+1}} (T_{n+1} - \Theta_{n+1}) \tag{4.27}$$

$$\frac{\Theta_n - \Theta_{n-1}}{\Delta x} = \frac{ha(T_{n-1} - \Theta_{n-1})}{G_p c_p + G_p c_p M_{n-1}} + \frac{h_{fg} + c_v (T_{n-1} - \Theta_{n-1})}{G_p c_p + G_p c_p M_{n-1}} G_a \frac{W_n - W_{n-1}}{\Delta x} \tag{4.28}$$

$$\frac{W_{n+1} - W_n}{\Delta x} = \frac{G_p}{G_a} \frac{M_{n+1} - M_n}{\Delta x} \tag{4.29}$$

$$\frac{M_n - M_{n-1}}{\Delta x} = \text{a thin-layer drying equation} \tag{4.30}$$

Figure 4.2 shows the node indexing scheme. The solution assumes that the

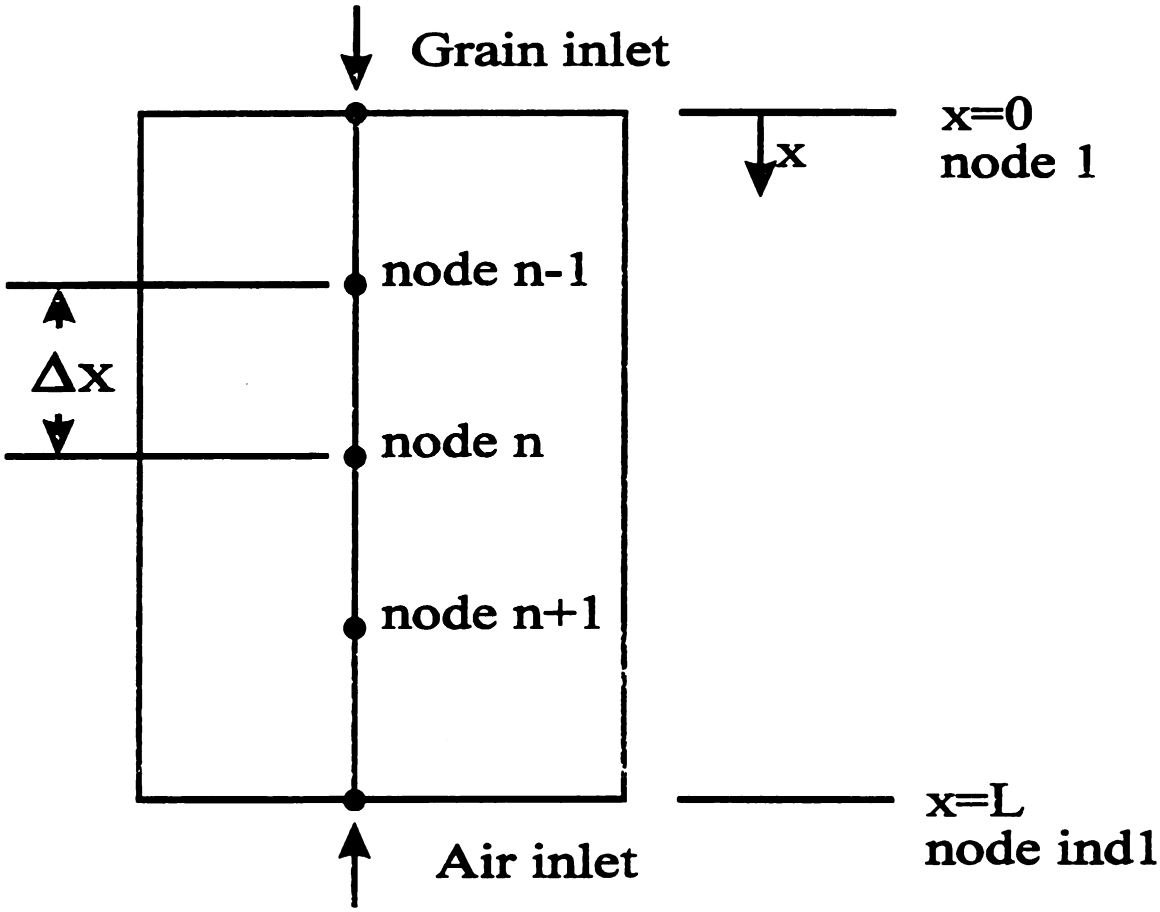

Figure 4.2 Indexing scheme for the counterflow model.

nodes are uniformly spaced (i.e. Δx is constant). The finite difference equations are solved as a "marching" problem, from the known boundary to the unknown boundary. The air temperature and humidity values are solved from the air inlet to the air exhaust, and the grain temperature and grain moisture content values from the grain inlet to the grain outlet. A flow chart showing the solution of the counterflow model is given in Figure 4.3. The finite difference equations 4.27 through 4.30 can be rearranged, and result in the following counterflow heating/cooling model:

$$T_n = T_{n+1} - \Delta x \frac{ha}{G_a c_a + G_a c_v W_{n+1}} (T_{n+1} - \Theta_{n+1}) \tag{4.31}$$

$$\Theta_n = \Theta_{n-1} + \Delta x \left(\frac{ha(T_{n-1} - \Theta_{n-1})}{G_p c_p + G_p c_p M_{n-1}} + \frac{h_{fg} + c_v (T_{n-1} - \Theta_{n-1})}{G_p c_p + G_p c_p M_{n-1}} G_a \frac{W_n - W_{n-1}}{\Delta x} \right) \tag{4.32}$$

$$W_n = W_{n+1} - \Delta x \left(\frac{G_p}{G_a} \frac{M_{n+1} - M_n}{\Delta x} \right) \tag{4.33}$$

$$M_n = M_{n-1} + \Delta x * \text{thin} - \text{layer equation} \tag{4.34}$$

4.10.1 Starting the Algorithm

The grain bed is divided into ind1 equally spaced nodes. The term ind1 is the integer portion of:

$$\text{ind1} = \frac{\text{L}}{\Delta x} + 1 \tag{4.35}$$

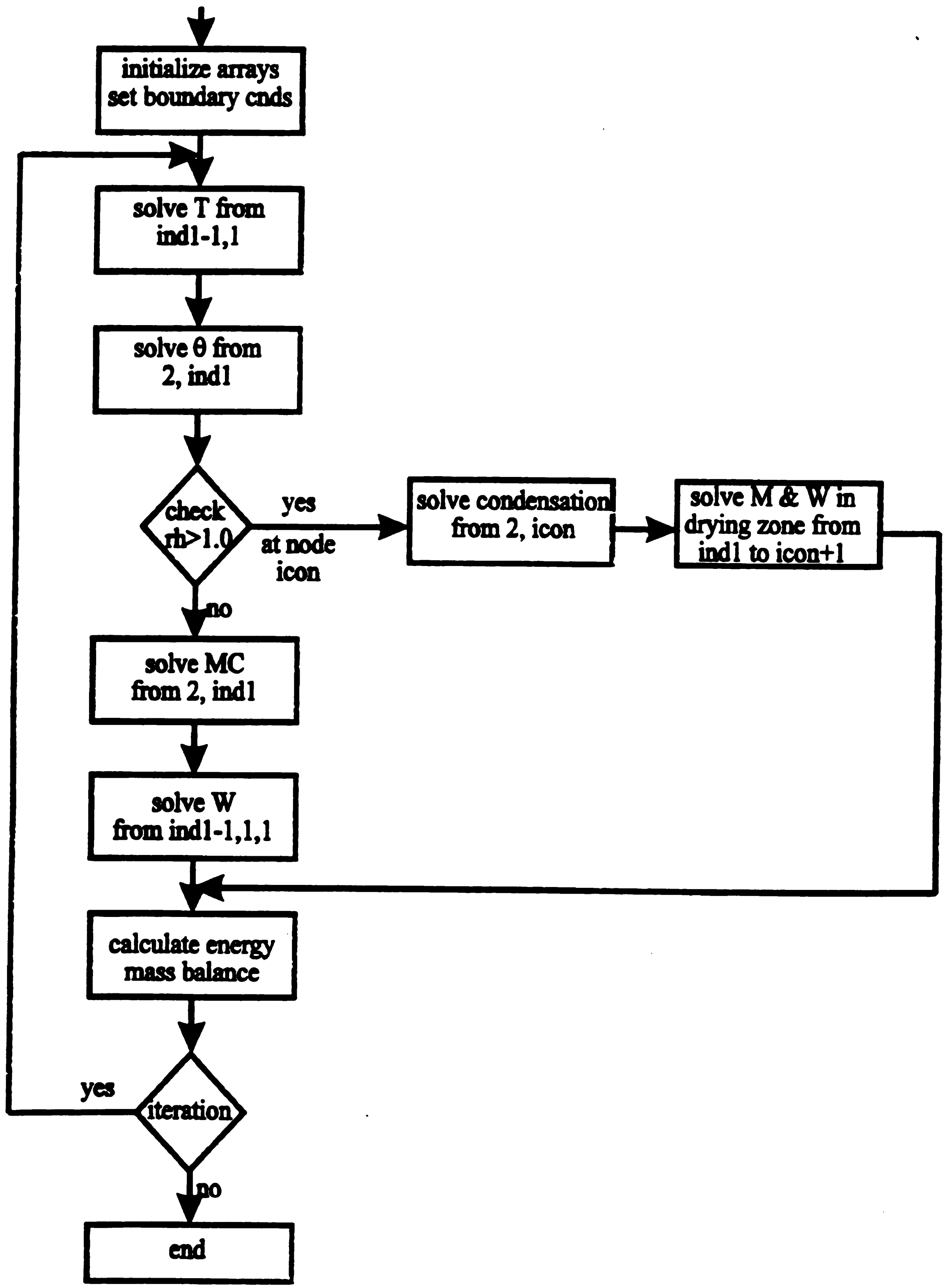

Figure 4.3 Flow chart for solution of the heating/cooling counterflow model.

where L is the length of the dryer and Δx is the stepsize in the finite difference approximation. Node number 1 corresponds to position x=0 (the grain inlet) and node ind1 is located at x=L (the air inlet) to the dryer.

In FORTRAN 77, the initial values of the arrays are automatically initialized to zero. In the simulation model, the array positions corresponding to the known boundary conditions are initialized first (T_{inlet}, H_{inlet}, $\Theta_{initial}$, $M_{initial}$). Next, the arrays for the humidity, the air and grain temperature, and the grain moisture content in the remainder of the grain bed are initialized, with an estimated outlet corn temperature and moisture content supplied by the user. Initializing of the arrays is performed by assuming a linear profile from x=0 to x=L. The outlet air temperature is assumed to be equal to the inlet grain temperature, and the estimated absolute humidity is found according to:

$$W_n = W_{n+1} - \frac{G_p}{G_a}(M_{n+1} - M_n) \tag{4.36}$$

It is possible to solve the equations without initialization of the arrays, but the procedure requires more computer time.

The Microsoft 32-bit FORTRAN 77 compiler was used because it allows the counterflow model to employ extended memory for array storage. The arrays in the counterflow model are too large for a 16-bit compiler. Since the counterflow model has to be solved for bed depths at least 6.1 m (20 ft), the use of extended memory is required.

4.10.2 Convergence and Stability of the Algorithm and Value of Stepsize

Termination of the solution process occurs when the energy and mass balances are within some preset accuracy. It is assumed that an acceptable solution has been found when the amounts of moisture calculated from the following three energy/mass balances are approximately equal:

1) the energy balance on the air and grain divided by the heat of vaporization
2) the difference in the inlet and outlet moisture contents of the grain
3) the difference in the inlet and outlet humidities of the drying air.

The energy in the counterflow system is either supplied by the drying air in a pre-heater, or by the cooling grain in a cooler. Thus:

$$Energy\_in_{preheat} = G_a(T_{in} - T_{amb})(c_a + c_v H_{in}) \tag{4.38}$$

or

$$Energy\_in_{cooler} = G_p(\Theta_{in} - \Theta_{out})(c_p + c_w \overline{M}) \tag{4.39}$$

The energy is absorbed by heating the grain in the pre-heater or heating the air in a cooler. Thus:

$$Energy\_used_{preheat} = G_p(\Theta_{out} - \Theta_{in})(c_p + c_w \overline{M}) \tag{4.40}$$

or

$$Energy\_used_{cooler} = G_a(T_{out} - T_{in})(c_a + c_v H_{in}) \tag{4.41}$$

It is assumed that the remainder of the energy is utilized for moisture removal. Therefore, the weight of water removed by the available energy in a pre-heater is approximately:

$$H_2O_{energy,preheat} = \frac{Energy\_in_{preheat} - Energy\_used_{preheat}}{h_{fg,avg}} \tag{4.42}$$

and the water removed by the available energy in a cooler is:

$$H_2O_{energy,cooler} = \frac{Energy\_in_{cooler} - Energy\_used_{cooler}}{h_{fg,avg}} \tag{4.43}$$

The amount of water removed by the difference in the air humidity is:

$$H_2O_{air} = G_a(H_{out} - H_{in}) \tag{4.44}$$

The weight of water removed by the difference in moisture content is found by:

$$H_2O_{mc} = G_p(M_{in} - M_{out}) \tag{4.45}$$

If the three balances H_2O_{energy}, H_2O_{air}, and H_2O_{mc} are within 10%, it is assumed that an acceptable solution has been found.

Frequently the program does not converge to an acceptable solution in 100 iterations. In fact, after approximately 100 iterations, errors associated with truncation appear to have a negative effect on the solution. A smaller stepsize, or a slightly different initial guess, is then used.

A common problem with finite difference approximations is the lack of stability of the solution as a result of a particular choice in stepsize, Δx (Hildebrand, 1968). If Δx is too large, the solution oscillates; if Δx is too small, the program requires excessive computer time. By trial and error, a stepsize of 0.003 m (0.01ft) was found to be optimum for use in the counterflow heating/cooling model of corn. If the accuracy criterion is not met, it is recommended to decrease the stepsize by increments of 0.00061 m (0.002ft) until an acceptable solution is found.

4.10.3 Solution of Algorithm - Counterflow Cooler

In a counterflow cooler, limited condensation occurs because of the relatively high grain temperature and small moisture removal in the cooling bed.

As shown in Figure 4.3, the air and grain temperatures are solved first. The air temperature (equation 4.31) is solved from node ind1-1 to node 1. Then the grain temperature (equation 4.32) is found from node 2 to node ind1, so that in the finite difference approximation the solution proceeds from a known boundary to an unknown boundary. Solving the equations requires the use of five arrays for: (1) the absolute humidity, (2) the relative humidity, (3) the grain temperature, (4) the air temperature, and (5) the grain moisture content.

A check is made of the relative humidity to determine if an infeasible humidity has been calculated. If no condensation has occurred, the moisture content is solved (equation 4.34) from node 2 to node ind1. Next, the corresponding increase in the absolute humidity of the air is calculated (equation 4.33) from node ind1-1 to node 1.

The program iterates until the energy/mass balance values (equations 4.39, 4.41, 4.42, 4.43, 4.44, and 4.45) are approximately the same, or after 100 iterations have been made. When a "good" solution has been found, the energy efficiency, static pressure, and capacity values are calculated. If an acceptable solution is not found, the user is alerted and a smaller stepsize and/or a different set of initial guesses is made,

Figure 4.4 shows the corn temperature and moisture content profile in a typical counterflow cooler. The conditions shown are for a counterflow cooler which is part of a concurrent-flow dryer. The variables in the simulation were: T_{in}=16°C (60°F), airflow=18.3 m^3/m^2/min (60 ft^3/ft^2/min), Θ_{in}=63°C (145 °F), M_{in}=15.8% w.b., L=1.5 m (5 ft), and G_p=5030 kg/hr/m^2 (1030 lb/hr/ft^2). It is obvious that the algorithm converges rapidly to an acceptable solution.

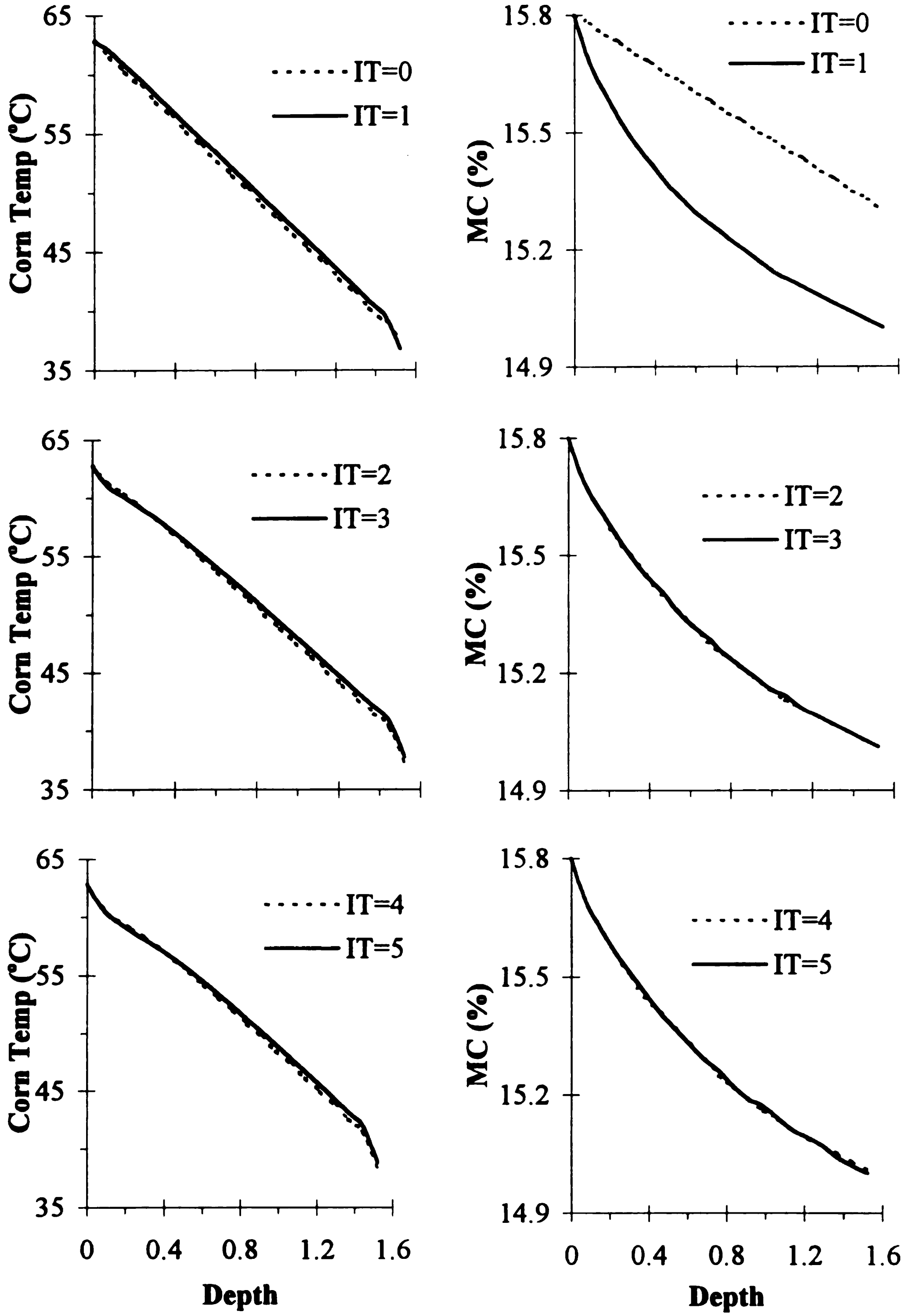

Figure 4.4 Change in corn temperature and MC after each iteration in a counterflow cooler of a concurrent-flow dryer; Tin=16°C, airflow=18.3 $m^3/m^2/min$, Θ_{in}=63°C, MC_{in}=15.8%, bed depth=1.5 m, grainflow=4850 $kg/m^2/hr$.

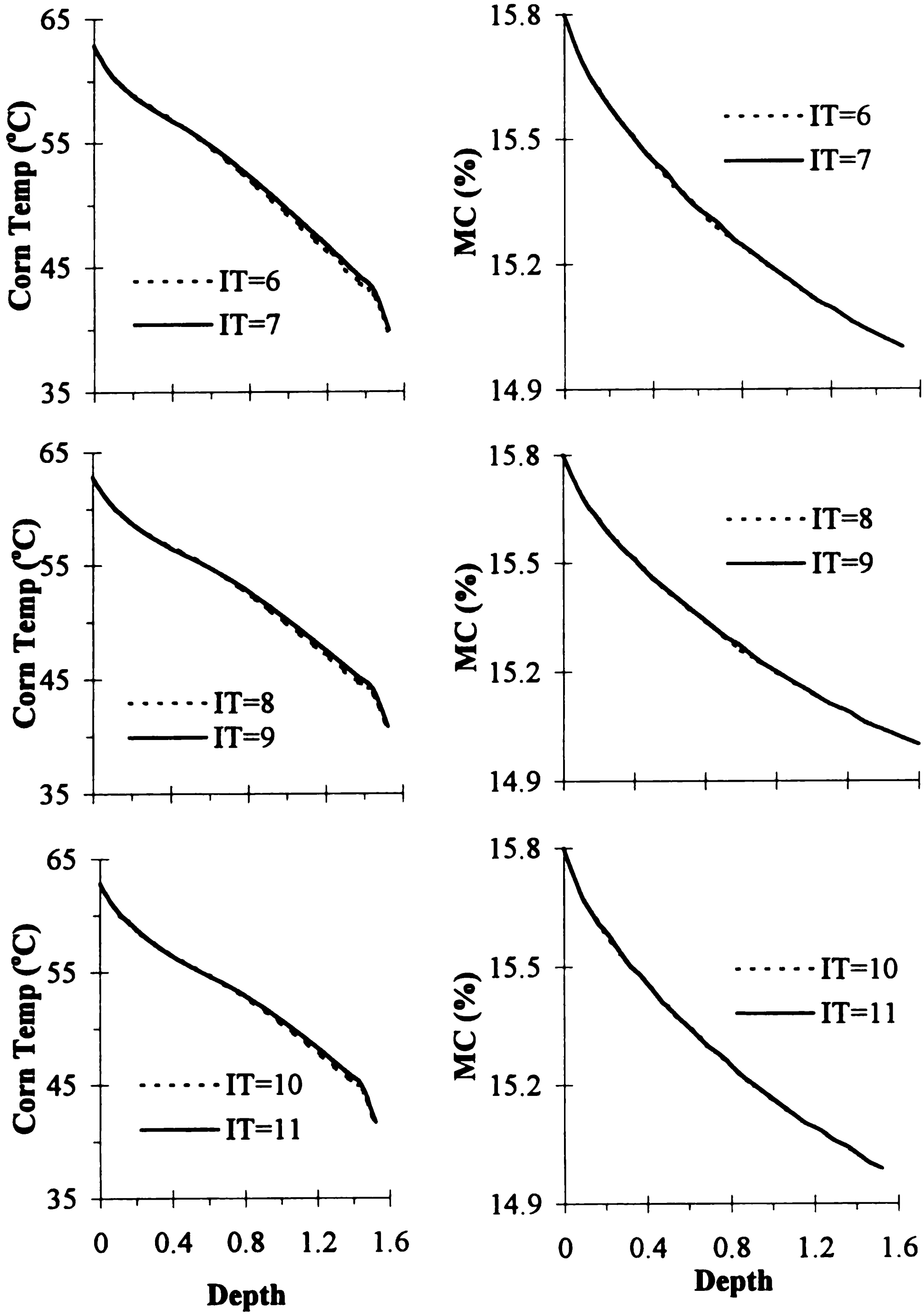

Figure 4.4 (cont'd).

4.10.4 Solution of Algorithm - Counterflow Pre-Heater

There are two distinct regions in a counterflow heater, namely the absorption region and the desorption region. Condensation, and thus moisture absorption, usually occurs near the grain-inlet/air-outlet. Once condensation has occurred at a node, it will also occur in subsequent nodes in the preheating bed. Desorption occurs at the air-inlet/grain-outlet.

The differential equations describing the air and grain temperatures are valid for absorption and desorption. As a result, when condensation occurs, the equations describing the air and grain temperatures do not need to be modified. There is a change in the air and grain temperatures as a result of condensation, but it is handled automatically by the equations in the next iteration.

A check of the relative humidity is made to determine if condensation has occurred. When condensation first occurs (at node icon see Figure 4.3), the algorithm divides the bed into two regions:

(1) the desorption (drying) region (from node ind1 to icon+1)

(2) the absorption (condensation) region of the bed (from node 1 to node icon).

The change in the humidity and moisture content is calculated using a modified set of equations from node 1 to node icon. The saturated absolute humidity (W_s) is calculated using the current air temperature and a relative humidity of

99.999999%. Therefore, the mass of water that condensates from the air is found from:

$$\Delta H_2O = G_a(W' - W_s) \tag{4.46}$$

where W′ is the current infeasible absolute humidity. The water that has condensed from the air changes the average moisture content of the grain according to:

$$\overline{M} = \overline{M'} + \frac{\Delta H_2O}{G_p} \tag{4.47}$$

where $\overline{M'}$ is the average moisture content of the grain before condensation.

After condensation has been simulated, drying is modeled from node icon+1 to node 1. The moisture content is found from Equation 4.34, and the absolute humidity changes according to Equation 4.33.

Finally, the energy and mass balances are calculated (equations 4.38, 4.40, 4.42, 4.44, and 4.45) to check if an acceptable solution has been found. If the balances are not within the desired accuracy, the program does another iteration.

A typical solution of the counterflow pre-heater is shown in Figure 4.5. The changes in the corn temperature and moisture content starting at initialization (IT=0) are shown. The algorithm converges to an acceptable solution in 14 iterations. The variables used were: T_{in}=104°C (220°F), airflow=6.2 m^3/m^2/min (20.1 ft^3/ft^2/min), Θ_{in}=15°C (60°F), M_{in}=25% w.b., L=1.5 m (5 ft), and G_p=1005 kg/hr/m^2 (206 lb/hr/ft^2).

The corn temperature in Figure 4.5 shows a slight increase occurring at approximately 0.8 m. Figure 4.6 indicates that a large amount of water condensed at about 0.8 m, releasing energy and causing an increase in corn temperature.

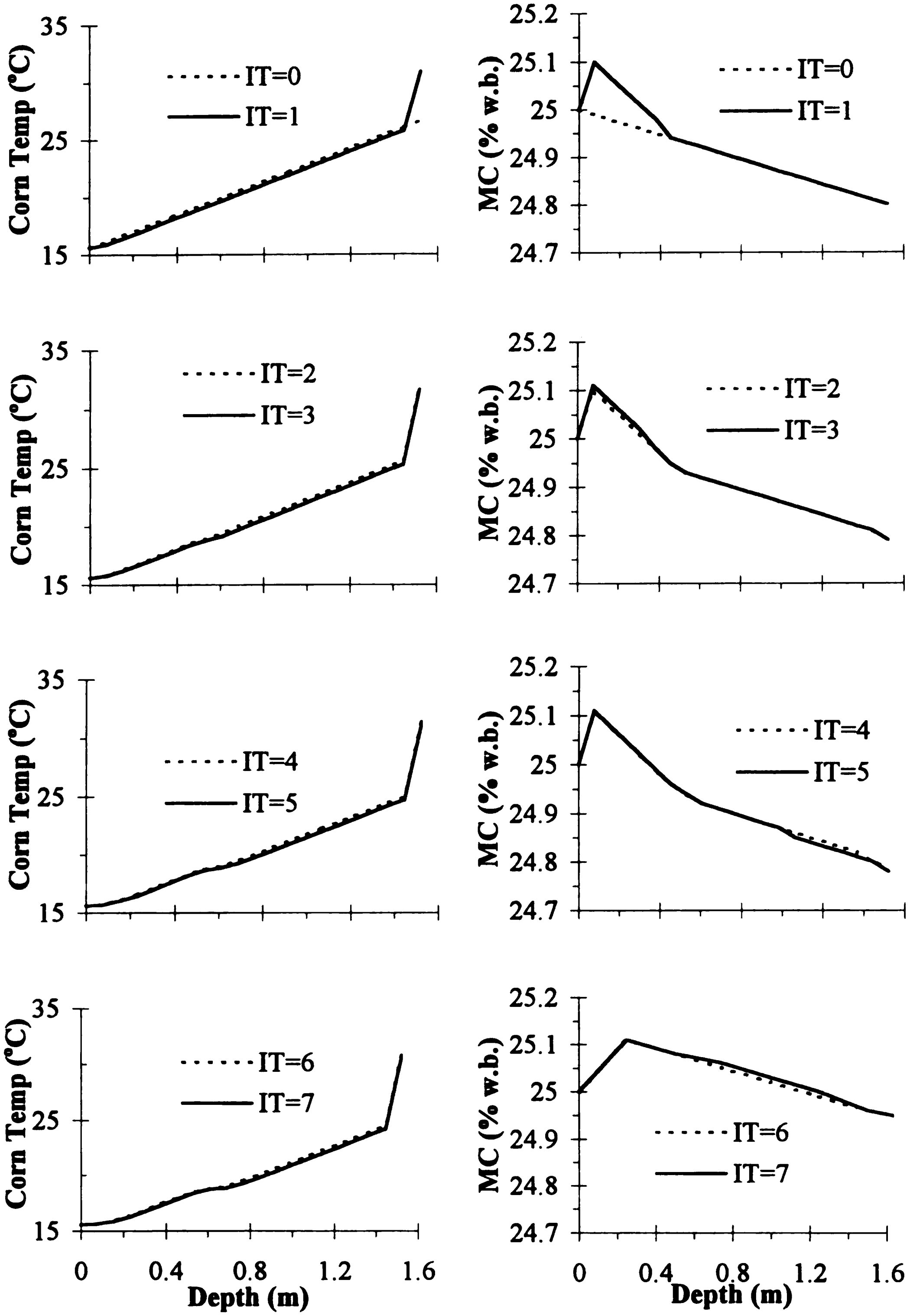

Figure 4.5 Change in corn temperature and MC after each iteration in a counterflow pre-heater; T_{in}=104°C, airflow=6.1 $m^3/m^2/min$, Θ_{in}=16°C, MC_{in}=25% bed depth=1.5 m, grainflow=970 $kg/m^2/hr$.

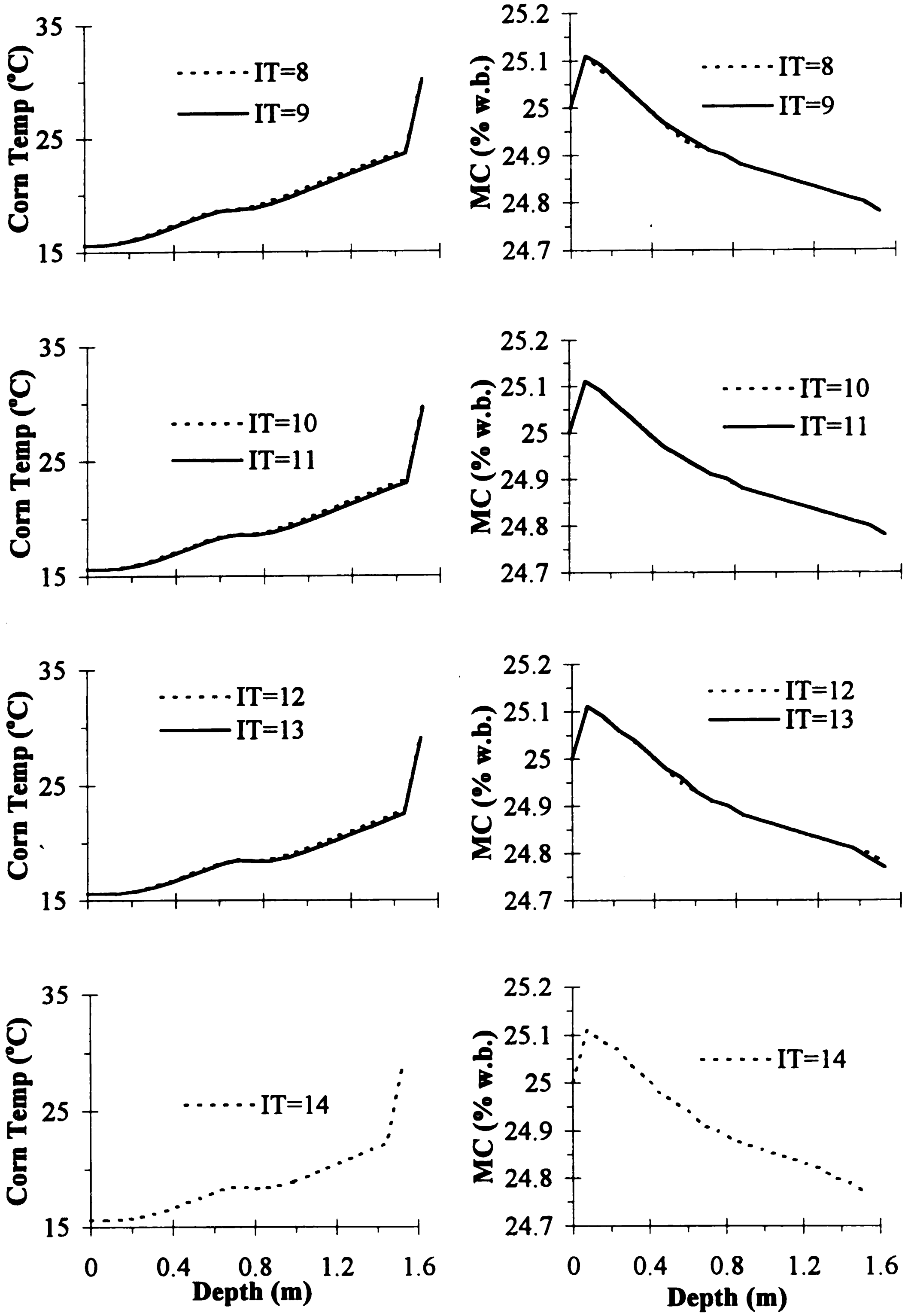

Figure 4.5 (con't).

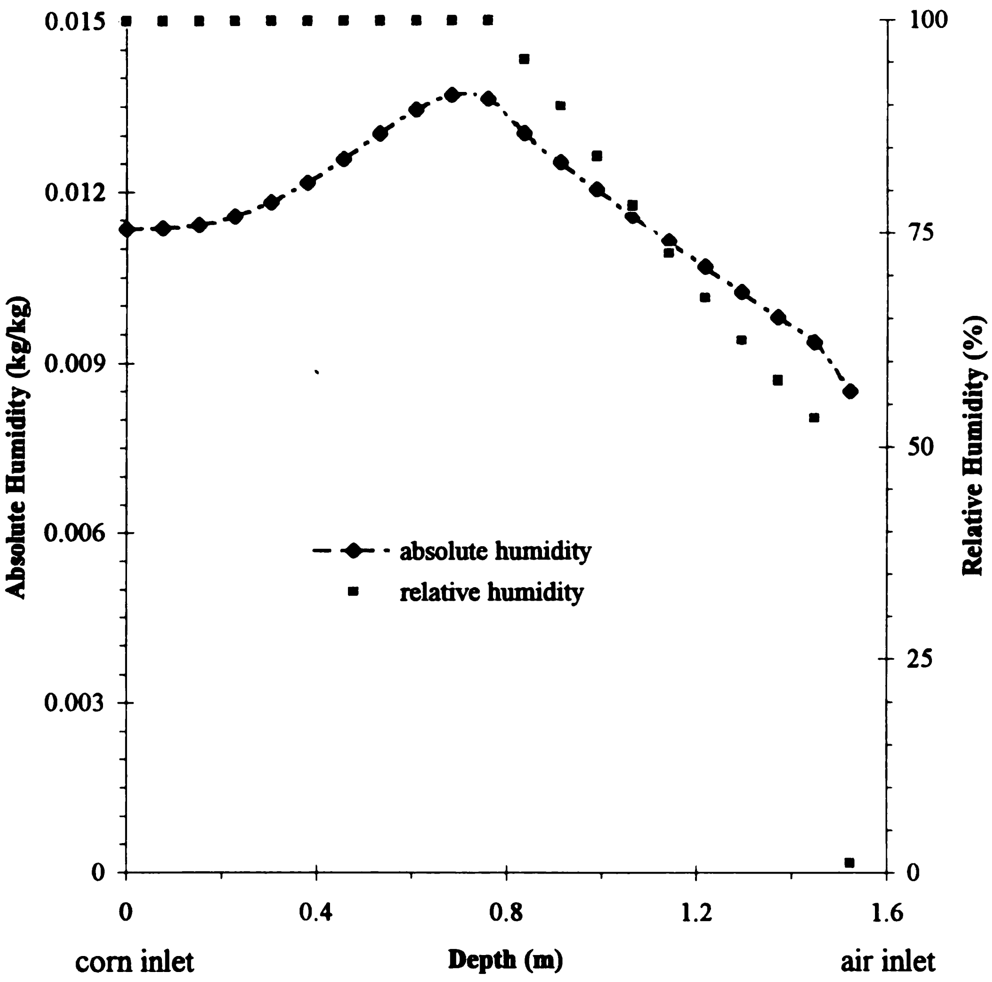

Figure 4.6 Humidity profiles of Figure 4.5 in the counterflow pre-heating bed.

CHAPTER 5

EXPERIMENTAL INVESTIGATION

5.1 Experimental Tests

Field tests were conducted to evaluate the pre-heating of corn dried in a one-stage CCF dryer during the Fall of 1994 at the Meiner Grain Company, Colfax, Illinois. The hybrids of the corn during the testing period are unknown.

The following parameters were measured or calculated in evaluating the performance of the pre-heating system:

(1) the corn moisture content out of the field, after pre-heating, and after drying

(2) the corn temperature out of the field, after pre-heating, and after drying

(3) the percentage of stress cracked kernels out of the field, after pre-heating, and after drying

(4) the drying capacity

(5) the ambient and drying-air temperatures and the ambient relative humidity

(6) the system energy efficiency

(7) the economic feasibility of the pre-heating system.

Experimental testing started when the dryer and the pre-heater had approached steady-state (or approximately at the time required for the corn to pass once through the pre-heater).

5.2 Pre-Heater Design

The pre-heating of corn was conducted in a commercial 5.5 m (18 ft) diameter hopper-bottom wet-holding tank with a 75-degree hopper angle. The height of the hopper is 2.1 m (7 ft) with a volume of 35.2 m^3 (1245 ft^3), holding about 25.3 MT (995 bu) of corn. The cylindrical portion of the bin has a height of 7.3 m (24 ft) and holds 124.3 MT (4885 bu) of corn.

The pre-heating bin is installed on an elevated platform positioned above the dump pits. A holding bin is positioned near the pre-heating bin to ensure a constant supply of wet corn. A small fan is located on the holding bin to provide enough airflow to prevent corn spoilage before drying. An overhead view of the pre-heating/CCF drying system is shown in Figure 5.1.

The airflow to the pre-heater is supplied by two 7.5 kW (10 HP) centrifugal fans. Each fan supplies air at an approximate rate of 102 m^3/min (7,500 ft^3/min) at a static pressure of 1915 Pa (7.7 in. H_2O). A partition divides the plenum in an attempt to limit the static pressure losses created by the two fans positioned in parallel.

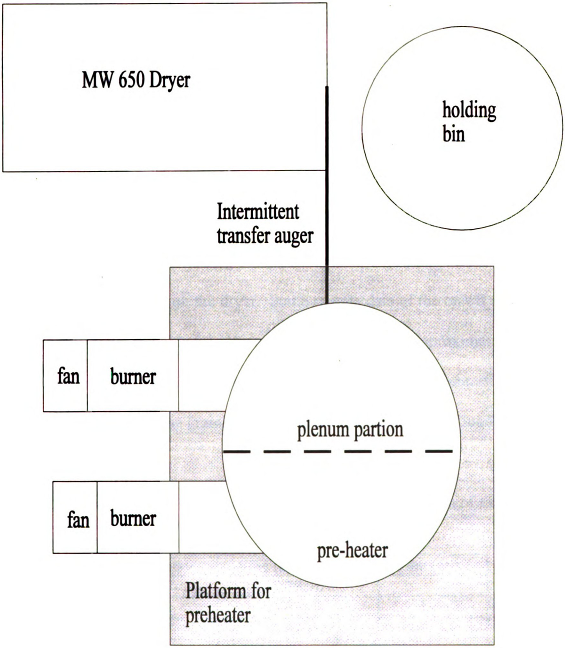

Figure 5.1 Overhead view of corn pre-heating/drying system.

The inlet-air temperature is controlled by two 633,000 kJ/hr (600,000 Btu/hr) natural gas burners. The depth of the counterflow pre-heating bed is 1.5 m (5 ft).

Airflow to the pre-heater is provided through a row of open-bottomed intake ducts located above the conical hopper of the bin. The air flows upward to a set of exhaust ducts located 1.5 m (5 ft) above the air inlet (Figure 5.2).

Corn is unloaded from the pre-heater by an intermittently-operating auger. The auger engages to fill the CCF dryer as needed. As a result, the movement of the grain through the pre-heating bin is intermittent, depending on the on/off action of the fill auger located on the dryer. Some sample data of the on/off action of the fill auger is given in Table 5.1; the auger remained on for approximately 46.1 minutes and was off for 22.2 minutes. It was assumed in the counterflow simulation model that the grainflow through the pre-heater is continuous.

Table 5.1 Timing of the fill auger of the pre-heater as a function of time (T_{in}=94°C, MC=19%, on 10/4/94).

auger state	time (hr:min:sec)	time (min)
off	5:38:30	
on	5:42:00	3.5 - off
off	5:49:00	7.0 - on
on	5:54:50	5.83 - off
off	6:07:30	12.4 - on
on	6:14:50	7.33 - off
off	6:28:00	13.17 - on
on	6:33:30	5.5 - off
off	6:47:00	13.5 - on

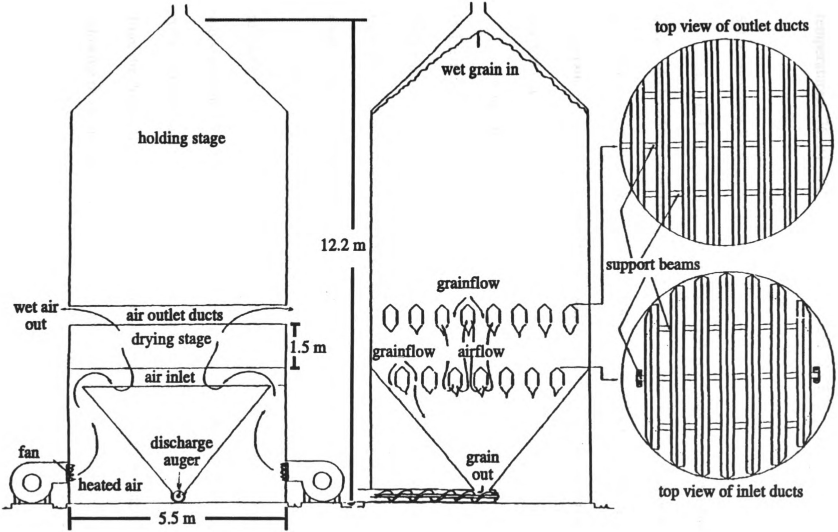

Figure 5.2 In-bin pre-heating system (Redrawn from M&W Gear Co.).

During the experimental tests the pre-heater was operated at three temperatures: 76, 94, and 106°C (168, 202, and 223°F).

5.3 Concurrent-Flow Dryer Design

The pre-heated corn was dried in a M&W one-stage concurrent-flow (CCF) dryer, Model 650 (M&W Gear Co., 1981). At 10-point moisture removal, the dryer is rated at 15.3 MT/hr (600 bu/hr) when operating with an inlet air temperature of 149°C (300°F). When drying corn at 5-point moisture removal, the dryer is rated at 22.4 MT/hr (880 bu/hr).

A schematic of the one-stage CCF dryer is shown in Figure 5.3. The corn is dried in a concurrent-flow drying section and is cooled in a counterflow cooler. Recycling of the cooling air improves the energy efficiency of the dryer. The recycled air is mixed with ambient air before being heated for use in the drying stage. All the air from the drying stage is exhausted.

The CCF dryer is a continuous-flow dryer, with the capacity controlled by manually changing the revolutions per minute of the metering rolls. The outlet moisture content is controlled by the operator by varying the speed of the metering rolls. Changes are made according to the reading of the exhaust air temperature from the dryer. By increasing the residence time of the corn within the CCF dryer (slowing of the metering rolls), the outlet moisture content decreases.

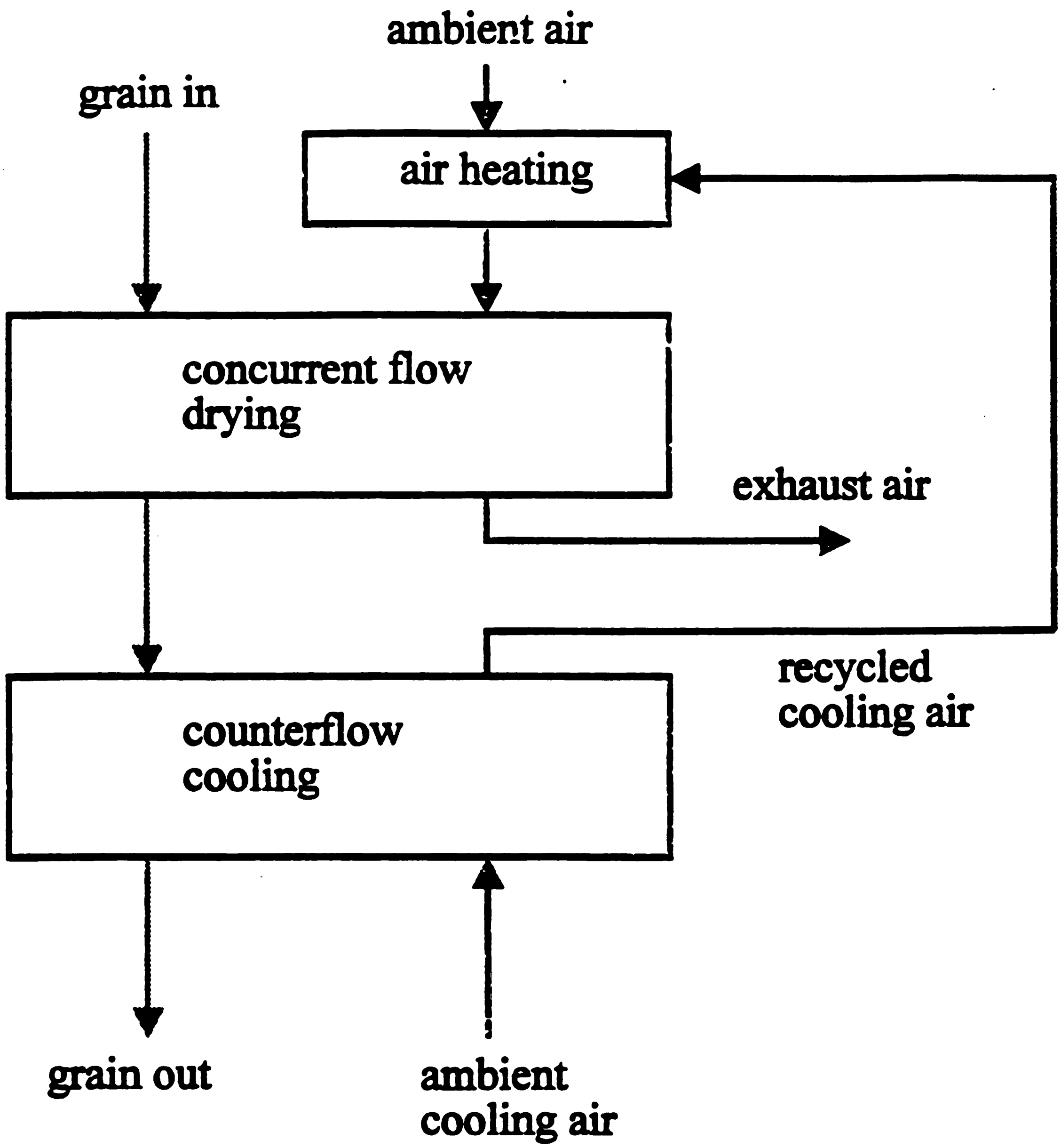

Figure 5.3 Schematic of one-stage concurrent-flow dryer with counterflow cooler.

The capacity of the dryer was determined by timing the metering rolls, and estimating the revolutions per minute. One revolution of the metering roll discharges 0.27 MT (10.5 bu) of corn (Meiner, 1994).

5.4 Instrumentation

5.4.1 Field Measurements

The temperature, relative humidity, and static pressure data were taken with a multi-functional handheld Solomat MPM 500e (Solomat Electronics, Norwalk, CT).

The temperature of the exhaust air from the pre-heater was measured at 30 minute intervals, and the relative humidity at one hour intervals. (The relative humidity probe is easily damaged by high temperatures and dusty conditions). The temperature of the air after the burner and in the plenum of the pre-heater was checked every 30 minutes. The humidity of the drying air was not measured but was obtained from a psychrometric chart reading.

Samples of corn were taken every 30 minutes the temperature and moisture content were determined. Samples were obtained at three locations: corn entering the pre-heater, exiting the pre-heater, and exiting the dryer.

The natural gas consumption was determined by reading a recently calibrated gas meter at 30 minute intervals.

5.4.2 Laboratory Measurements

After transport to MSU the samples were stored in a 4.4°C (40°F) cooler until the moisture content and percentage of stress cracks could be determined. The moisture content of the corn was measured using the ASAE oven method (1977), dried at 103°C (217°F) for 72 hours.

The number of stress cracked kernels was counted after allowing the samples to reach equilibrium. Fifty whole kernels were randomly chosen for each sample and the number of stress cracks determined using a candling method (Thompson and Foster, 1963). Kernels were divided into four stress-crack categories; none, single, multiple, and checked. Three individuals determined the stress cracks to test for subjectivity.

5.5 Experimental Results

5.5.1.1 Test Objectivity

Table 5.2 shows the percentage of stress-cracked kernels determined by three individuals. Sample A4 resulted in the largest variation in the percentage of stress-cracked kernels, 56 to 66%; sample A1 had the smallest variation, 64 to 66%.

Table 5.2 Variation in the percentage of stress-cracked corn kernels out of the CCF dryer without pre-heating as determined by three individuals.

Sample #	% SC1	% SC2	% SC3	average % SC
A1	64	66	66	65
A2	76	70	74	73
A3	64	56	58	59
A4	58	56	66	60

Table 5.3 shows the percentage of stress-cracked kernels exiting the CCF dryer at a pre-heating temperature of 76°C (168°F). Tables 5.4 and 5.5 present the percentage of stress-cracked kernels exiting the CCF dryer at pre-heating temperatures of 94°C (202°F) and 106°C (223°F). It is evident that the percentage of stress-cracked kernels is an objective test.

Table 5.3 Variation in the percentage of stress-cracked corn kernels out of the CCF dryer with pre-heating at 76°C (168°F) as determined by three individuals.

Sample #	% SC1	% SC2	% SC3	average % SC
B1	71	72	80	75
B2	66	62	66	65
B3	66	74	72	71
B4	74	74	76	75

Table 5.4 Variation in the percentage of stress-cracked corn kernels out of the CCF dryer with pre-heating at 94°C (202°F) as determined by three individuals.

Sample #	% SC1	% SC2	% SC3	average % SC
C1	64	66	72	67
C2	74	74	74	74
C3	67	72	71	70
C4	54	50	44	49

Table 5.5 Variation in the percentage of stress-cracked corn kernels out of the CCF dryer with pre-heating at 106°C (223°F) as determined by three individuals.

Sample #	% SC1	% SC2	% SC3	average % SC
D1	64	66	62	64
D2	68	64	62	65
D3	66	74	64	68
D4	64	62	62	63

Table 5.6 presents the SCI of the samples from Table 5.2. The SCI of sample #A1 has the largest range in values (i.e. from 194 to 254), and sample #A3 has the smallest range (i.e. from 214 to 236). There is an insignificant difference in the SCI values determined by three people. The data verifies that the percentage of stress cracked kernels is a non-subjective quality measure.

Table 5.6 Stress crack index (SCI) values of Table 5.2 (no pre-heating).

Sample #	SCI1	SCI2	SCI3	average SCI
A1	248	194	254	232
A2	252	254	286	264
A3	236	216	214	222
A4	214	168	218	200

Tables 5.7, 5.8, and 5.9 show the SCI of corn out of the CCF when pre-heated with temperatures of 76°C (168°F), 94°C (202°F), and 106°C (223°C).

Table 5.7 Stress crack index (SCI) values of Table 5.3 (pre-heating temperature of 76°C).

Sample #	SCI1	SCI2	SCI3	average SCI
B1	247	240	288	258
B2	238	198	266	234
B3	189	226	230	215
B4	246	238	256	247

Table 5.8 Stress crack index (SCI) values of Table 5.4 (pre-heating temperature of 94°C).

Sample #	SCI1	SCI2	SCI3	average SCI
C1	232	214	264	237
C2	230	206	254	230
C3	194	192	267	218
C4	150	146	132	143

Table 5.9 Stress crack index (SCI) values of Table 5.5 (pre-heating temperature of 106°C).

Sample #	SCI1	SCI2	SCI3	average SCI
D1	208	210	202	207
D2	204	164	218	195
D3	230	262	264	252
D4	228	230	230	229

5.5.1.2 Pre-Heating Effects

Table 5.10 shows the percentage of stress-cracked kernels at different pre-heating levels. The percentage of stress-cracked kernels increased slightly as the pre-heating temperature was increased. However, compared to the increase in the percentage of stress-cracked kernels exiting the CCF dryer, the increase is insignificant. Table 5.10 illustrates that the percentage of stress-cracked kernels out of the CCF was not effected by pre-heating. The maximum percentage of stress-cracked kernels after pre-heating was less than 13%, after drying the percentage was over 65%.

Table 5.10 Average percentage of stress-cracked corn kernels at different points in the pre-heating system.

Pre-Heater Temp (°C)	% SC in	% SC out pre-heater	% SC out CCF
-	5	-	65
76	5	4	71
94	5	9	65
106	5	13	65

Table 5.11 shows the SCI of the corn at different pre-heating temperatures. The SCI of corn out of the pre-heater increased slightly as the pre-heating temperature was increased. But, the SCI of the corn exiting the dryer shows an insignificant change.

Table 5.11 Average SCI of corn at different points in the pre-heating system.

Pre-Heater Temp (°C)	SCI in	SCI out pre-heater	SCI out CCF
-	10	-	230
76	10	8	239
94	10	17	207
106	10	32	221

5.5.2 System Capacity and Energy Efficiency

Table 5.12 presents the experimental effects of pre-heating on the CCF drying system. The drying capacity increased as a result of pre-heating, from 18.6 MT/hr (730 bu/hr) without pre-heating, to 29.5 MT/hr (1160 bu/hr) employing a pre-heating temperature of 106°C (223°F). A direct comparison of the capacity change can not be made because of the variation in the inlet moisture content and the ambient weather conditions during the testing period. A summary of the field data is given in Table 5.13.

Table 5.12 Experimental moisture removal, capacity, and system energy efficiency of the pre-heating/CCF drying system.

Pre-Heater Temp (°C)	Moisture Content (% w.b.)	Capacity (MT/hr)	System Eff (kJ/kg)	Ambient Temp (°C)	Ambient RH (%)
-	19.4 - 13.4	18.6	3710	16	40
76	19.6 - 14.1	22.7	4665	19	35
94	18.4 - 13.8	25.5	5990	18	45
106	18.3 - 13.9	29.5	6025	13	80

Table 5.12 shows a decrease in the overall system energy efficiency as a result of pre-heating. The energy consumption without pre-heating was 3710 kJ/kg H_2O (1595 Btu/lb H_2O); it increased to 6025 kJ/kg H_2O (2590 Btu/lb H_2O) when pre-heating at 106°C (223°F). The decrease in energy efficiency is a result of inefficiencies associated with the pre-heating bin, and changes in the inlet and outlet moisture content. Also, the corn was dried to a lower moisture content than

normally recommended, resulting in the relatively low energy efficiency for a one-stage CCF dryer.

There are a number of uncontrolled factors that effected the energy efficiency of the pre-heater. Leakage occurred along the bin walls, leading to inefficient use of the pre-heating air. The degree of leakage was determined by measuring the temperature of the air exhausting from the pre-heater. In a continuous-flow counterflow system, the air exhausts at saturation, at approximately the inlet grain temperature (Brooker et al., 1992). Table 5.14 shows that the measured exhaust air temperature and inlet corn temperature were not equal because of the leakage of approximately 13 to 15% of the energy supplied to the pre-heating bin.

Table 5.14 Experimental pre-heater inlet air temperature, exhaust temperature, and inlet corn temperature resulting from air leakage.

Inlet Pre-Heater Temp (°C)	Inlet Corn Temp (°C)	Pre-Heater Exhaust Temp (°C)	Leakage %
76	20.6	26.9	13
94	19.0	30.2	15
106	18.8	33.2	15

A second source of the loss inefficiency in the pre-heating system is the ducting between the burners and the plenum. Table 5.15 shows the burner and plenum temperatures. The thermal efficiency of the heating system is approximately 84-88%.

Table 5.13 Pre-heating test results obtained at Colfax, IL (Oct. 3-4, 1994).

Test Number	1	2	3	4
Ambient conditions				
temperature, °C	16.2	19.3	17.8	11.1
RH, %	40	37	45	82
Burner temp, °C	-	85.8	108.2	125.8
Plenum temp, °C	-	75.3	94.4	106.2
Static pressure, Pa	-	1915	1915	-
Exhaust from pre-heater, °C	-	26.9	30.2	33.2
range	-	18.2 - 28.4	29.3 - 30.7	31.6 - 34.7
RH, %		95 - 100	95 - 100	95 - 100
Inlet grain conditions				
temp, °C	22.8	20.6	19.0	18.8
temp range, °C	21.9 - 23.9	18.8 - 22.8	13.5 - 21.7	16.6 - 20.1
MC, % w.b.	19.4	19.6	18.4	18.3
MC range, % w.b.	17.7 - 20.9	16.4 - 21.3	15.0 - 19.5	16.8 - 20.9
% stress cracked[1]	-	4.5	4.5	4.5
SCI[1]	-	9.9	9.9	9.9
Out from pre-heater				
temp, °C	-	25.8	32.0	25.3
temp range, °C	-	22.6 - 29.7	26.3 - 40.2	21.3 - 29.1
MC, % w.b.	-	20.0	18.1	17.3
MC range, % w.b.	-	19.1 - 20.5	17.1 - 18.3	16.5 - 17.7
% stress cracked[1]	-	4.0	9.7	13.0
SCI[1]	-	8.0	17.0	31.7
Outlet from CCF				
temp, °C	22.1	26.2	29.8	29.2
temp range, °C	21.0 - 23.3	24.8 - 26.9	28.6 - 30.9	28.2 - 30.4
MC, % w.b.	13.4	14.1	13.8	13.9
MC range, % w.b.	12.7 - 14.2	13.3 - 14.7	13.0 - 14.1	13.4 - 14.7
% stress cracked[1]	64.7	71.3	65.0	65.3
SCI[1]	229.7	238.7	207.0	221.3
Grainflow rate, MT/hr	18.6	22.7	25.5	29.5
System energy eff, kJ/kg H_2O	3710	4665	5990	6025
Natural gas, m^3/hr	82.6	105.2	113.4	121.4

[1]averages as determined by 3 individuals

Table 5.15 Average burner and plenum air temperatures.

Burner Set Point (°C)	Plenum Temperature (°C)	Burner Efficiency (%)
86	75	88
108	94	87
126	106	84

Figure 5.4 shows the fan and system curves for the grain bed. There is approximately 425 m^3/min (15,000 ft^3/min) supplied to the pre-heater, according to the fan curve. The energy consumption of the system, of the CCF dryer and of the pre-heater, are shown in Table 5.16, along with the pre-heater airflow rate. An average airflow rate of 215 m^3/min (7640 ft^3/min) was obtained from Table 5.16. The average leakage efficiency and burner efficiency from Tables 5.14 and 5.15 were found to be: burner efficiency 88%, and leakage efficiency 86%. After burner and leakage losses an airflow rate of 164 m^3/min (5780 ft^3/min) was assumed to be available for pre-heating.

Table 5.16 Performance characteristics of the pre-heater/dryer system.

Pre-Heater Temp (°C)	Energy Supplied (MJ/hr)	Energy CCF (MJ/hr)	Energy Pre-Heater (MJ/hr)	Airflow Pre-Heater (m^3/min)
-	3,070	3,070	-	-
76	3,915	2,960	955	237
94	4,230	3,010	1,220	223
106	4,525	3,210	1,315	189

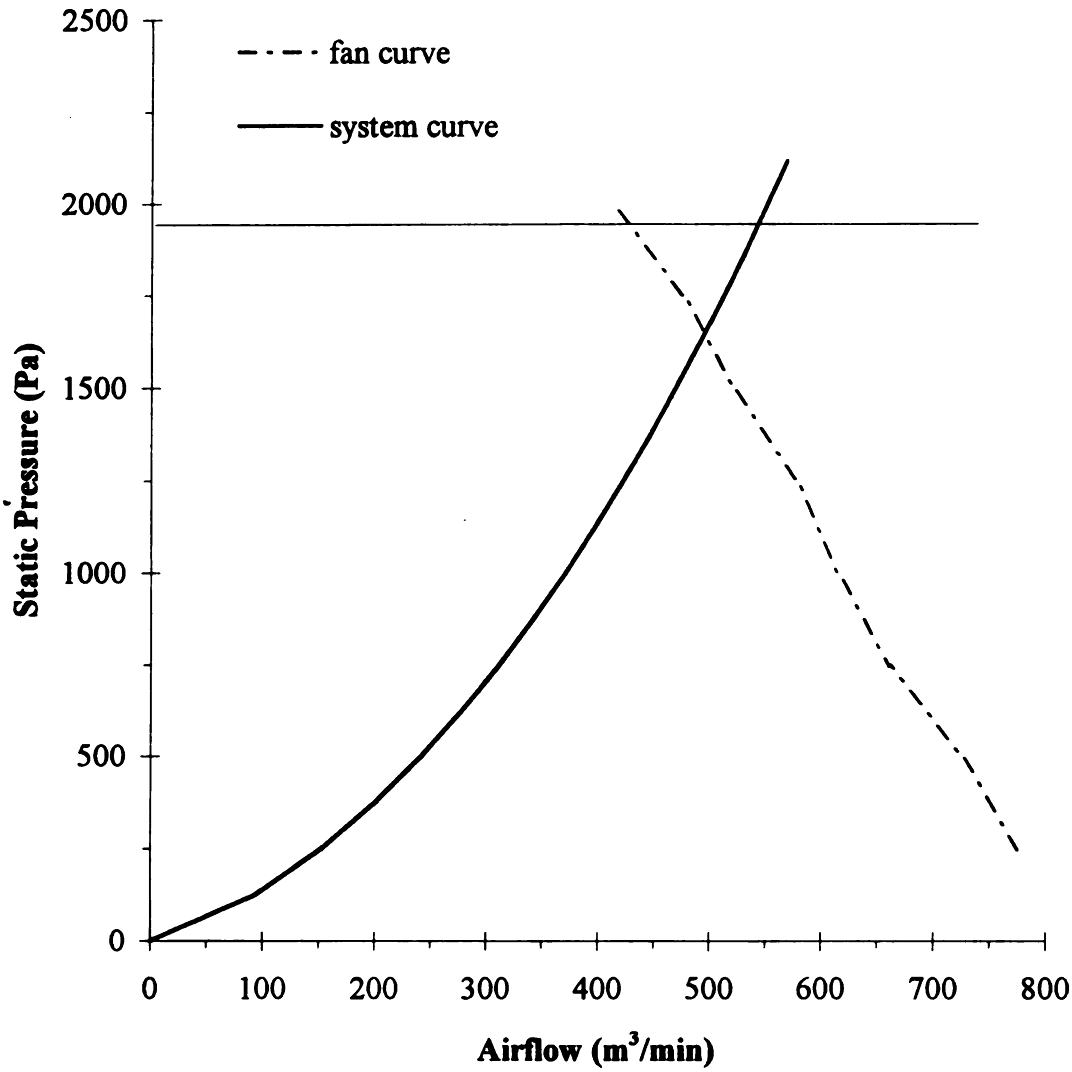

Figure 5.4 Fan and system curves for the pre-heating bin.

CHAPTER 6

SIMULATED RESULTS

6.1 Verification of the Simulation Model

Table 6.1 compares the experimental and simulated pre-heating results. The data is presented graphically in Figure 6.1. At an airflow rate of 6.9 $m^3/m^2/min$ (22.8 $ft^3/ft^2/min$) the expected decrease in moisture content in the pre-heater is 0.2 - 0.3%, which appears to contradict the experimental results. The difference is a result of fluctuations in the experimental inlet moisture content. The simulated outlet corn temperature does not compare well with the experimental data also because of the variation in the inlet moisture content.

Table 6.1 Experimental and simulated temperatures and moisture contents of corn pre-heated at an airflow rate of 6.9 $m^3/m^2/min$ (22.8 cfm/ft^2) at a bed depth of 1.5 m (5 ft).

	Inlet		Outlet Exp		Outlet Sim	
Pre-Heater Temp (°C)	Θ_{in} (°C)	MC_{in} (% w.b.)	Θ_{exp} (°C)	MC_{exp} (% w.b.)	Θ_{sim} (°C)	MC_{sim} (% w.b.)
76	20.6	19.6	25.8	20.0	30.5	19.3
94	19.0	18.1	32.0	17.8	33.4	17.8
106	18.8	18.3	25.3	17.3	32.8	18.1

The experimental and simulated corn temperatures at the pre-heating temperature of 94°C (202°F) compare well [the experimental conditions fluctuated

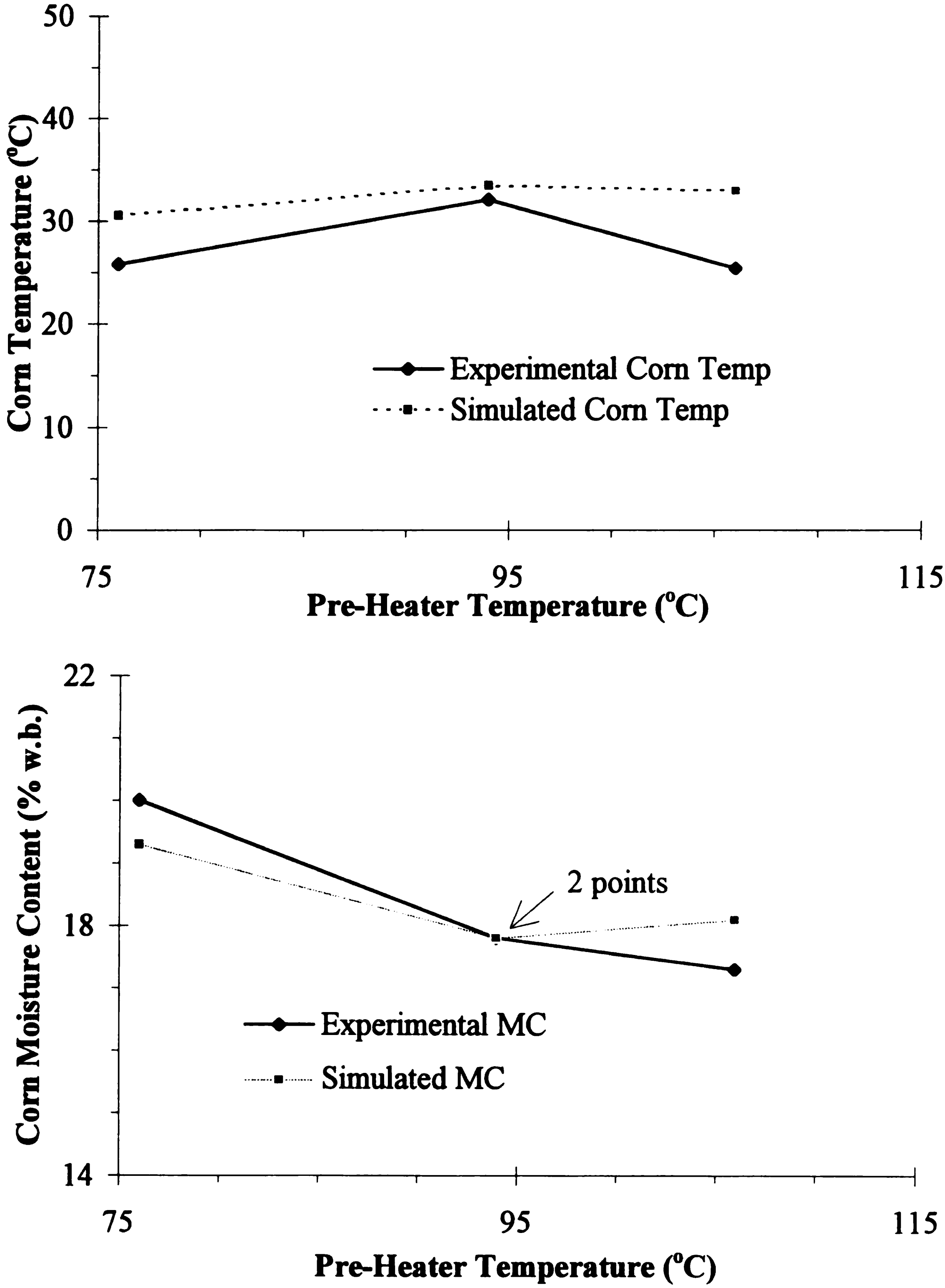

Figure 6.1 Comparison of experimental and simulated temperatures and moisture contents of corn exiting a pre-heater.

little]. The experimental corn temperature and moisture content were 32.0°C (89.6°F) and 17.8%, respectively; the simulated values are 33.4°C (92.2°F) and 17.8%. Thus, the difference in the experimental and simulated corn temperatures is only 1.4°C (2.6°F); the difference in the moisture content is zero. At 106°C (223°F) the simulated and experimental compared fairly well. The simulated corn temperature is 32.8°C (91.0°F) with a moisture content of 18.1%, while the experimental values were 25.3°C (77.5°C) and 17.3% respectively.

Several reasons appear to exist for the relatively poor comparison of the experimental and simulated results. The ambient conditions varied throughout the testing period which influenced moisture removal in the pre-heater. It should be remembered that the variation in the inlet moisture content, and therefore in the amount of moisture removed, has a significant effect on the performance of the pre-heater.

Also, the temperature of the corn exiting the pre-heater fluctuated due to the on/off action of the fill auger, and possibly the non-uniform emptying of the hopper-bottom pre-heating bin. The simulated results do not reflect these effects. Table 6.2 shows the variation in corn temperature during an on cycle of the fill auger.

Table 6.2 Corn temperature variation out of the pre-heater when the fill auger was on (pre-heater at 94°C (202°F), Oct. 4, 1994). The average corn temperature was 32.6°C (90.7°F).

time (min)	Corn Temp (°C)
0	31.4
2.3	31.7
4.7	33.8
8.8	35.0
12.8	31.2

6.2 Influence of Design Parameters

In this section, the simulated effects of grainspeed, air temperature, airflow rate, ambient conditions, bed depth, and inlet moisture content on the operation of the pre-heater are analyzed.

The standard conditions for the simulated pre-heating results are taken as:

(1) an ambient temperature of 15.6°C (60°F) and relative humidity of 60%

(2) an airflow rate of 7.3 $m^3/m^2/min$ (24.1 $ft^3/ft^2/min$) at a static pressure of 300 Pa (1.2 in H_2O)

(3) a bed depth of 1.5m (5.0 ft)

(4) a grainflow rate of 1.34 $m^3/m^2/hr$ (22.8 MT/hr) (4.4 $ft^3/ft^2/hr$ - 900 bu/hr)

(5) a pre-heating temperature of 93.3°C (200°F)

(6) an initial corn moisture content of 20% w.b.

(7) an initial corn temperature of 15.6°C (60°F).

6.2.1 Effect of Air Temperature

The temperature of the pre-heater significantly effects the outlet corn temperature. Table 6.3 shows the exit corn temperature and moisture content as a function of the inlet pre-heating temperature. At an airflow rate of 7.3 $m^3/m^2/min$ (24.1 cfm/ft^2) and a grainflow rate of 1.34 $m^3/m^2/hr$, the decrease in moisture content is approximately 0.2%, regardless of the pre-heating temperature. Increasing the air temperature results in a higher outlet corn temperature. At 65.6°C (150°F) the corn temperature increases by 11.1°C (20°F), at a pre-heating temperatures of 93.3°C (200°F) the corn temperature increases by 18.4°C (33°F), and at an air temperature of 121.1°C (250°F) the corn temperature increases by 24.5°C (44°F).

Table 6.3 Simulated effect of air temperature on the temperature and moisture content of corn exiting a pre-heater[1].

T_{in} (°C)	Θ_{out} (°C)	MC_{out} (% w.b.)
65.6	26.7	19.8
93.3	34.0	19.8
121.1	40.1	19.8

[1]airflow=7.3 $m^3/m^2/min$, grainflow=1.34 $m^3/m^2/hr$, MC_{in}=20%, θ_{in}=15.6°C

6.2.2 Effect of Airflow Rate

Table 6.4 shows the effect of the airflow rate on the pre-heating of corn. As the airflow rate increases, the amount of moisture removal increases, and the corn temperature increases. The increase in the corn temperature associated with higher airflow rates is the result of the increased energy supplied to the pre-heater. As the airflow rate doubles, the energy supplied to the pre-heater doubles.

The exit corn temperature is 23.7°C (74.7°F) at an airflow rate of 3.7 $m^3/m^2/min$ (3.0 cfm/bu), and 51.4°C (125.6°F) at an airflow rate of 14.7 $m^3/m^2/min$ (12.0 cfm/bu). At the lower airflow rate the moisture content decreases by 0.1%, at the higher airflow rate the moisture decrease is 0.4%. Also, increasing the airflow rate from 3.7 to 14.7 $m^3/m^2/min$ (12.0 to 48.2 $ft^3/ft^2/min$) increases the horsepower requirement from 0.14 to 3.95 W/m^2 (0.002 to 0.057 hp/ft^2), and the static pressure increases from 110 to 885 Pa (0.4 to 3.6 in H_2O).

Table 6.4 Simulated effect of airflow rate on the temperature and moisture content of corn exiting a pre-heater[1].

Airflow Rate ($m^3/m^2/min$)	Static Pressure (Pa)	W/m^2	Θ_{out} (°C)	MC_{out} (%)
3.7	110	0.14	23.7	19.9
7.3	305	0.69	34.0	19.8
11.0	565	1.87	43.3	19.7
14.7	885	3.95	51.4	19.6

[1]grainflow=1.34 $m^3/m^2/hr$, T_{in}=93.3°C, MC_{in}=20%, θ_{in}=15.6°C

6.2.3 Effect of Grainflow Rate

The grainflow rate through the pre-heater effects the level of pre-heating. This effect is illustrated in Table 6.5. At a grainflow rate of 1.18 $m^3/m^2/hr$ (3.9 $ft^3/ft^2/hr$) the outlet corn temperature is 34.7°C (94.5°F), while at a grainflow rate of 1.49 $m^3/m^2/hr$ (4.9 $ft^3/ft^2/hr$) the exit corn temperature is 32.1°C (89.8°F). At low grainflow rates the corn remains in the pre-heater for a longer period of time, and thus reaches a higher temperature. However, the grainflow rate does not have a significant effect on the outlet moisture content within the grainflow range investigated.

Table 6.5 Simulated effect of grainflow rate on the temperature and moisture content of corn exiting a pre-heater[1].

Grainflow Rate ($m^3/m^2/hr$)	Θ_{out} (°C)	MC_{out} (%)
1.18	34.7	19.8
1.34	34.0	19.8
1.49	32.1	19.8

[1] T_{in}=93.3°C, airflow rate=7.3 $m^3/m^2/min$, θ_{in}=15.6°C, MC_{in}=20%

6.2.4 Effect of Inlet Moisture Content

Table 6.6 shows the effect of the inlet moisture content when pre-heating corn. At an inlet moisture content of 20% w.b., the exit corn temperature is 34.0°C (93.2°F); it decreases to 28.1°C (82.6°F) when the inlet moisture content is 30% w.b. The decrease in moisture content is approximately 0.2% regardless of the moisture content of the corn entering the pre-heater.

The smaller increase in the outlet corn temperature at higher moisture contents appears to be a result of the effect of moisture content on the specific heat. The value of the specific heat of 20% moisture content corn is 2.16 kJ/kg·°C (0.52 Btu/lb·°F), and 2.55 kJ/kg·°C (0.61 Btu/lb·°F) at 30% moisture content. The increase in the specific heat offsets the decrease in the latent heat of vaporization in higher moisture content corn. [Note: the heat of vaporization of water in 20% moisture content corn is 2322 kJ/kg H_2O (998 Btu/lb H_2O), and at 30% moisture content 2281 kJ/kg H_2O (981 Btu/lb H_2O)].

Table 6.6 Simulated effect of <u>initial moisture content</u> on the temperature and moisture content of corn exiting a pre-heater[1].

Initial MC (%)	Θ_{out} (°C)	MC_{out} (%)
20	34.0	19.8
25	31.1	24.8
30	28.1	29.8

[1] T_{in}=93.3°C, airflow rate=7.3 m^3/m^2/min, θ_{in}=15.6°C, grainflow=1.34 m^3/m^2/hr

6.2.5 Effect of Ambient Relative Humidity

Table 6.7 shows the effect of the ambient relative humidity on the operation of the pre-heater. At an ambient relative humidity of 40% the corn moisture content decreases by 0.3%, at an exit corn temperature of 31.5°C (88.7°F). When the ambient relative humidity is 95%, very little moisture is removed, and the exit corn temperature is 35.9°C (96.6°F).

The relative humidity of the inlet drying air at 93°C (200°F) is 0.9% when the ambient conditions are 15.6°C (60°F) and 40% relative humidity, and 2.1% when the ambient humidity increases to 95%. At low relative humidities it is expected that the corn will dry considerably. The steady-state moisture content distribution in the bed for different ambient relative humidity values is shown in Figure 6.2; moisture is condensed in the top 0.5 - 0.6 m of the bed, especially when the ambient relative humidity is 95%.

At high ambient relative humidities only a very small amount of water is evaporated in the pre-heater. Thus, the energy supplied to the pre-heater is mostly available for increasing the corn temperature at such ambient air conditions since little is required for evaporation.

Table 6.7 Simulated effect of ambient relative humidity on the temperature and moisture content of corn exiting a pre-heater[1].

Ambient RH (%)	Θ_{out} (°C)	MC (% w.b.)
40	31.5	19.7
60	34.0	19.8
80	34.8	19.9
95	35.9	20.0

[1] T_{in}=93.3°C, airflow rate=7.3 $m^3/m^2/min$, $\theta_{in}=T_{amb}$=15.6°C, grainflow=1.34 $m^3/m^2/hr$

6.2.6 Effect of Initial Corn Temperature

Table 6.8 shows the effect of the initial corn temperature on the operation of the pre-heater. It was assumed that the initial corn temperature and ambient

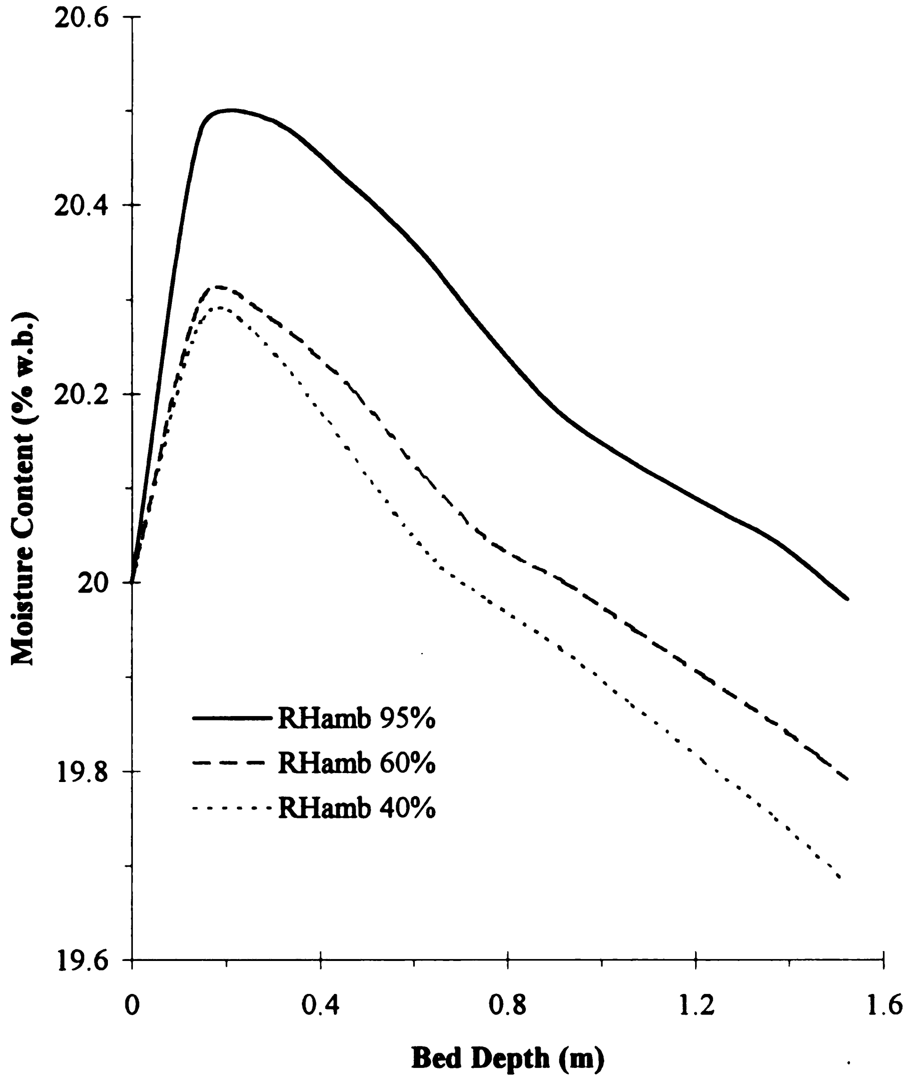

Figure 6.2 Effect of the ambient relative humidity on the moisture content profile of the counterflow bed; initial corn moisture content = 20%.

temperature are the same, and the ambient relative humidity is 60%. At an initial corn temperature of 4.4°C (40.0°F) the corn temperature increases to 27.6°C (81.7°F), and the moisture content decreases by 0.1%. When the initial corn temperature is 26.7°C (80.0°F) the corn temperature increases to 41.2°C (106.2°F), and the average moisture content decreases by 0.4%. The larger increase in the outlet corn temperature at the lower initial corn temperature is mainly the result of less moisture removed at the lower grain bed temperatures.

Table 6.8 Simulated effect of initial corn temperature on the temperature and moisture content of corn exiting a pre-heater[1].

Θ_{in} (°C)	Θ_{out} (°C)	$\Delta\Theta$	MC_{out} (%)
4.4	27.6	23.2	19.9
15.6	34.0	18.4	19.8
26.7	41.2	14.5	19.6

[1] Θ_{in}=T_{in}, RH_{amb}=60%, T_{in}=93.3°C, airflow rate=7.3 m^3/m^2/min, grainflow=1.34 m^3/m^2/hr

6.2.7 Effect of Bed Depth

Table 6.9 shows the effect of bed depth on the performance of the pre-heater. The data is for a constant airflow rate of 7.3 m^3/m^2/min (24.1 ft^3/ft^2/min). There is only a small change in the corn temperature when the bed depth is increased from 0.76 m to 3.05 m (2.5 to 10 ft). The air exhausts at saturation at a bed depth of 3.05 m as well as at 0.76 m, implying that all of the energy in the pre-heating air has been utilized in both cases. The horsepower requirements for the fans, assuming a 50% efficiency, increase from 0.34 W/m^2 (0.005 hp/ft^2) at a bed depth of 0.76 m (2.5 ft) to 1.37 W/m^2 (0.020 hp/ft^2) at a bed depth of 3.05 m (10.0 ft) without a positive result. Thus, at an airflow rate of 7.3 m^3/m^2/min (24.1 ft^3/ft^2/min) an increase in the bed depth beyond 0.76 m is not recommended.

Table 6.9 Simulated effect of bed depth on the temperature and moisture content of corn exiting a pre-heater at a constant airflow rate of 7.3 m^3/m^2/min (24.1 ft^3/ft^2/min).

Bed Depth (m)	Θ_{out} (°C)	MC_{out} (%)	Static Pressure (Pa)	Power Requirement (W/m^2)
0.76	33.7	19.8	150	0.37
1.52	34.0	19.8	305	0.68
3.05	34.1	19.8	610	1.37

[1]T_{in}=93.3°C, airflow rate=7.3 m^3/m^2/min, θ_{in}=15.6°C, grainflow=1.34 m^3/m^2/hr, MC_{in}=20%

Table 6.10 shows the effect of bed depth at a constant static pressure of 300 Pa (1.2 in H_2O). The exit corn temperature at 0.76 m (2.5 ft) is 41.4°C (106.6°F), and at a bed depth of 3.05 m (10.0 ft) the exit corn temperature is 22.8°C (73.0°F). The corn moisture content decrease is 0.3% at a bed depth of 0.76 m (2.5 ft), and 0.1% at a bed depth of 3.05 m (10.0 ft). The horsepower requirements of the fans decreases as the bed depth is increased. Assuming a 50% fan efficiency, the power requirements for a bed depth of 0.76 m (2.5 ft) is 0.94 W/m^2 (0.014 hp/ft^2), while at a bed depth of 3.05 m (10.0 ft) the power requirement decreases to 0.37 W/m^2 (0.005 hp/ft^2).

The results of both Table 6.9 and Table 6.10 show that a shallow bed is advantageous in an in-bin counterflow grain pre-heater.

Table 6.10 Simulated effect of bed depth on the temperature and moisture content of corn exiting a pre-heater at a constant static pressure of 300 Pa (1.2 in H_2O).

Bed Depth (m)	Θ_{out} (°C)	MC_{out} (%)	Airflow ($m^3/m^2/min$)	Power Requirement (W/m^2)
0.76	41.4	19.7	10.3	0.94
1.52	34.0	19.8	7.3	0.67
3.05	22.8	19.9	4.1	0.37

[1]T_{in}=93.3°C, θ_{in}=15.6°C, grainflow=1.34 $m^3/m^2/hr$, MC_{in}=20%, static pressure=300 Pa

6.2.8 Effect of Constant Horsepower

Table 6.11 shows the effect of a constant horsepower of 1.7 W/m^2 (0.025 hp/ft^2) at different bed depths. The airflow rate increases from 7.6 $m^3/m^2/min$ to 13.7 $m^3/m^2/min$ (25 to 45 $ft^3/ft^2/min$) as the bed depth is decreased from 3.05 m to 0.76 m (10 to 2.5 ft). The exit corn temperature at 0.76 m (2.5 ft) is 48.3°C (119°F), and at a bed depth of 3.05 m (10 ft) the exit corn temperature is 32.8°C (91°F). The corn moisture decrease is 0.4% at a bed depth of 0.76 m (2.5 ft), and 0.2% at a bed depth of 3.05 m (10 ft).

Again, a shallow bed is preferred for an in-bin counterflow pre-heater.

Table 6.11 Simulated effect of bed depth on the temperature and moisture content of corn exiting a pre-heater at a constant horsepower of 1.7 W/m^2 (0.025 hp/ft^2).

Bed Depth (m)	Θ_{out} (°C)	MC_{out} (%)	Airflow ($m^3/m^2/min$)	Static Pressure (Pa)
0.76	48.3	19.6	13.7	420
1.52	41.7	19.7	10.4	545
3.05	32.8	19.8	7.6	620

6.3 Effect of Pre-Heating on System Performance

The MSU counterflow and concurrent-flow models were used to simulate the performance of the pre-heating/CCF drying system under standard operating conditions. The pre-heater was assumed to operate ideally without air leakage. Also, the calculations of the energy efficiency assume that the burners operate ideally. The standard conditions for the pre-heater are given in section 6.2.

The one-stage CCF dryer is simulated as a 0.6 m (2.0 ft) drying bed with an airflow rate of 30.5 $m^3/m^2/min$ (100 cfm/ft^2). The cooling in the dryer is by counterflow with a bed depth of 0.6 m (2.0 ft) and an airflow rate of 15.2 $m^3/m^2/min$ (50 cfm/ft^2). The bed area of the pre-heater is 23.6 m^2 (254 ft^2), and the CCF dryer has a bed area of 23.6 m^2 (254 ft^2).

The effect of pre-heating on the drying of 20% corn to 15% is given in Table 6.12. The capacity of the CCF dryer without corn pre-heating is approximately 976 $kg/hr/m^2$ (200 $lb/hr/ft^2$), with an energy efficiency of 5164 kJ/kg H_2O (2220 Btu/lb H_2O). When using 93°C (200°F) air in the pre-heater, the capacity increases by 241 kg/hr/m^2 (49 lb/hr/ft^2), a 25% change. At a pre-heating temperature of 110°C (230°F), the capacity of the system increases by 263 kg/hr/m^2 (54 lb/hr/ft^2), an increase of 27%. With pre-heating, the system energy efficiency improves by approximately 8%. A slight decrease in the energy efficiency occurs when the pre-heating temperature is increased from 93 to 110°C; the decrease is 40 kJ/kg H_2O (17 Btu/lb H_2O), a change of less than 1%. This change in energy efficiency is insignificant.

Table 6.12 Simulated effect of pre-heating 20% corn and drying to 15% MC in a one-stage CCF dryer[1].

Pre-Heater Temp (°C)	Out Pre-Heater Θ(°C)/MC	Out CCF Θ(°C)/MC	Out Cooler Θ(°C)/MC	Energy Efficiency (kJ/kg H_2O)	Capacity (kg/hr/m^2)
-	-	59/15.8	19/15.0	5165	976
93	31/19.8	60/16.1	19/15.0	4720	1217
110	32/19.8	60/16.1	18/15.0	4760	1239

[1]corn temp into pre-heater is 15.6°C (60°F)

Table 6.13 shows the effect of pre-heating when drying 25% corn. The capacity of the CCF dryer without pre-heating is approximately 496 kg/hr/m^2 (108 lb/hr/ft^2), with an energy efficiency of 4762 kJ/kg H_2O (2047 Btu/lb H_2O). Using a pre-heating temperature of 93°C (200°F), the capacity of the system increases by 86 kg/hr/m^2 (19 lb/hr/ft^2), an increase of 17%. When at 110°C (230°F), the capacity increases by 99 kg/hr/m^2 (21 lb/hr/ft^2), an increase of 20%. Again, the system energy efficiency shows an insignificant increase of 2% when the pre-heating temperature is increased from 93 to 110°C (200 to 230°F).

Table 6.13 Simulated effect of pre-heating 25% corn and drying to 15% MC in a one-stage CCF dryer[1].

Pre-Heater Temp (°C)	Out Pre-Heater Θ(°C)/MC	Out CCF Θ(°C)/MC	Out Cooler Θ(°C)/MC	Energy Efficiency (kJ/kg H_2O)	Capacity (kg/hr/m^2)
-	-	64/15.6	16/15.0	4760	496
93	44/24.7	66/15.8	16/15.0	4625	582
110	49/24.7	67/15.8	16/15.0	4650	595

[1]corn temp into pre-heater is 15.6°C (60°F)

Table 6.14 shows the estimated capacity of the drying system at different pre-heating temperatures. Without pre-heating the capacity is 23.0 MT/hr (905 bu/hr) when drying corn from 20 to 15% moisture content; the capacity increases to 29.2 MT/hr (1150 bu/hr) at a pre-heating temperature of 110°C (230°F).

When drying corn from 25 to 15% moisture content the CCF dryer, without pre-heating, has a capacity of 11.7 MT/hr (460 bu/hr). By pre-heating the corn with 110°C (230°F) air the capacity is increased to 14.0 MT/hr (550 bu/hr).

Table 6.14 Simulated capacity of pre-heater/CCF drying system with different pre-heating temperatures.

Pre-Heater Temp (°C)	Capacity - 20 to 15% (MT/hr)	Capacity - 25 to 15% (MT/hr)
-	23.0	11.7
93	28.7	13.7
110	29.2	14.0

CHAPTER 7

ECONOMIC ANALYSIS

7.1 Payback Period

The payback period of the pre-heating system will depend on the average annual system use and the average amount of moisture removed. Table 7.1 shows the effect of the yearly operating time on the payback period when drying corn from 20 to 15% moisture content. The initial cost of the pre-heater is $18,118 (Hines, 1995). With an average yearly drying season of 100 hours the payback period is 7.4 years; at an average yearly drying season of 400 hours the payback period is reduced to 1.9 years.

Table 7.1 Payback period of the pre-heater when drying corn from 20 to 15% moisture content with a capacity increase of 6.2 MT/hr (245 bu/hr) and a drying charge of $3.93/MT ($0.10/bu).

System Use (hr/yr)	Dryer Increase (MT/yr)	Yearly Savings ($/yr)	Payback Period (yr)
100	620	2,437	7.4
200	1,240	4,873	3.7
300	1,860	7,310	2.5
400	2,480	9,746	1.9

Table 7.2 shows the payback period when corn is dried from 25 to 15% moisture content. When the average yearly system use is 100 hours the payback

period is 8.0 years; at an average yearly system use of 400 hours the payback period is reduced to 2.0 years.

Table 7.2 Payback period of the pre-heater when drying corn from 25 to 15% moisture content with a capacity increase of 2.3 MT/hr (90 bu/hr) and a drying charge of \$9.82/MT (\$0.25/bu).

System Use (hr/yr)	Dryer Increase (MT/yr)	Yearly Savings (\$/yr)	Payback Period (yr)
100	230	2,259	8.0
200	460	4,517	4.0
300	690	6,776	2.7
400	920	9,034	2.0

7.2 Parameter Values

The simulation model of the pre-heater/dryer system is used in the economic analysis. It is assumed that the pre-heater is operated at 110°C (230°F), resulting in an increase in energy consumption of 1.4 million kJ/hr (1.3 million Btu/hr) compared to drying without the pre-heater. This value takes into account the leakage and inefficiencies associated with the burners. [An additional electric load of 14.9 kW for the fans in the pre-heater is included in the analysis]. The hourly operating cost of the pre-heater is \$6.72/hr, which is based on a gas consumption of 39.6 m^3/hr (1400 ft^3/hr) and an electric load of 14.9 kWh.

The increase in capacity when drying corn from 20 to 15% moisture content is approximately 6.2 MT/hr (245 bu/hr) (see section 6.3). When drying corn from 25 to 15% moisture content the increase in capacity is 2.3 MT/hr (90 bu/hr).

The parameter values in the capital budgeting analysis are listed in Table 7.3. Varying income tax rates of 0, 17, and 34% were used. It is assumed that the extra insurance associated with the employment of the pre-heater is negligible.

Table 7.3 Parameters used in the economic analysis.

Input Parameters	
discount rate	12% and 17%
life of pre-heater (yr)	10
federal income tax rate	0, 17, 34%
depreciation method	straight-line
Capital Costs	
pre-heater cost (fans/burners)	\$10,590
dealer profit and miscellaneous costs	\$2,650
installation labor (\$23/hr)	\$3,680
crane time (\$75/hr)	\$1,200
salvage value	\$2,000
Operating Costs	
natural gas	\$2.83/m^3 (\$0.40/100 ft^3)
electricity (kWh)	\$0.075
Drying Costs	
5 percentage points of moisture removed	\$3.93/MT (\$0.10/bu)
capacity increase at 5 points	6.2 MT/hr (245 bu/hr)
10 percentage points of moisture removed	\$9.82/MT (\$0.25/bu)
capacity increase at 10 points	2.3 MT/hr (90 bu/hr)

The total cost of purchasing and installing the pre-heater is \$18,118. The breakdown in cost is: (1) materials costs (fans and burners) \$10,590, (2) dealer profit \$2,650 (25% of the materials cost), and (3) installation cost \$4,880 (Hines, 1995). Straight-line depreciation is used, and a salvage value of \$2,000 after 10 years is assumed. A total of 200 hours is required to install the pre-heater, 184 hours of general labor at \$20/hr and 16 hours of crane time at \$50/hr.

Discount rates were chosen as 12 and 17%, included is a 2% premium for risk (Harsh 1995). The natural gas and electricity costs were obtained from a local utility. The 1995 farm rates in Michigan for natural gas are \$2.83/m^3 (\$0.40/100ft^3), and for electricity \$0.075/kWh (Consumers Power Co., 1995). The income generated from the increased drying capacity is equated to the drying charge at a local elevator (Turner, 1995). The 1994 drying charge in mid-Michigan for 20% moisture content corn is \$3.93/MT (\$0.10/bu), and for 25% moisture content corn \$9.82/MT (\$0.25/bu). The drying charge is on the basis of net bushels, and no discounts are charged for low testweight and excessive BCFM.

7.3 Capital Budgeting Analysis

A capital budgeting analysis was performed to determine the economic feasibility of the pre-heater (Harsh et al., 1981; Riggs and West, 1986). A spreadsheet was used to generate the costs and benefits of the pre-heater over a 10 year planning horizon. The cash flows are discounted to the present and summed. The sum of the cash flows is the net present value (NPV) of the investment.

Table 7.4 is a typical spreadsheet used in a capital budgeting analysis. At the top of the spreadsheet the various input parameters are entered.

Input Parameters		
discount rate	0.12	dec
income tax rate	0.34	dec
AT discount rate	0.0792	dec
# of years	10	

Financing		
amount financied	1	dec
length of loan	5	yrs
interest rate	0.1	dec/yr

Income		
savings @ 5pt removal	4.35	$/MT
total operating time	400	hr/yr
savings inflation	0.025	dec/year
capacity increase	6.2	MT/hr
extra corn dried	2,480	MT/yr
drying charge savings	10,788	$/yr

Operating Costs		
natural gas used	14	$100ft^3$/hr
natural gas cost	0.4	$/$100ft^3$
gas cost	2,240	$/yr
gas inflation	0.025	dec/yr
electricity cost	0.075	$/kWh
electric cost	447	$/yr
electric inflation	0.003	dec/yr
operating cost	2,687	$/yr

Capital Costs		
material	10,590	$
dealer profit	2,648	25% of material
labor costs	3680	@ $20/hr
crane	1,200	@ $50/hr
total cost	18,118	$
salvage value	2,000	$

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
end of year	date	gas inflation	electricity inflation	operating cost	income inflation	income	before tax cash flow	depreciation charges	interest on loan	taxable income	taxes paid	loan cash flow	after-tax cash flow	NPV
0	12/31/94	1.000	1.000		1.000		-18,118					18,118	0	28,078
1	12/31/95	1.025	1.003	2,744	1.025	11,058	8,313	1,612	1,812	4,890	1,663	-4,779	1,871	
2	12/31/96	1.051	1.006	2,803	1.051	11,334	8,531	1,612	1,515	5,404	1,837	-4,779	1,914	
3	12/31/97	1.077	1.009	2,863	1.077	11,617	8,754	1,612	1,189	5,954	2,024	-4,779	1,950	
4	12/31/98	1.104	1.012	2,925	1.104	11,908	8,983	1,612	829	6,542	2,224	-4,779	1,979	
5	12/31/99	1.131	1.015	2,988	1.131	12,206	9,218	1,612	434	7,171	2,438	-4,779	2,000	
6	12/31/00	1.160	1.018	3,053	1.160	12,511	9,458	1,612	0	7,846	2,668	0	6,790	
7	12/31/01	1.189	1.021	3,119	1.189	12,824	9,704	1,612	0	8,093	2,751	0	6,953	
8	12/31/02	1.218	1.024	3,187	1.218	13,144	9,957	1,612	0	8,345	2,837	0	7,120	
9	12/31/03	1.249	1.027	3,257	1.249	13,473	10,216	1,612	0	8,604	2,925	0	7,291	
10	12/31/04	1.280	1.030	3,328	1.280	13,810	10,482	1,612	0	8,870	3,016	0	7,466	
10	12/31/04					2,000	2,000			0	0		2,000	

Table 7.4 Sample capital budgeting analysis of a pre-heater for a 23.0 MT/hr (900 bu/hr) corn dryer.

The discount rate represents the average cost of capital for a company. The federal income tax rate is variable, depending on the accounting practices and the tax bracket of a business. The after tax discount rate is calculated according to:

$$\text{after tax discount rate} = (1 - \text{income tax rate}) * \text{discount rate} \qquad (7.1)$$

when the income tax rate is a decimal.

The capital cost of the pre-heater is an input, and includes the labor required for installation, the dealer profit, and the material costs (fans and burners). Also, the percentage of the pre-heater financed, the interest rate, and the length of the loan are inputs. It is assumed that the pre-heater is installed in year 0 and its useful life is ten years.

The cash flows, i.e. operating costs, drying charge savings, and loan payments are generated over the 10 year period. It is assumed that without the pre-heater the extra corn dried would have been dried at a commercial facility. The drying charge at a local commercial elevator is used to determine the costs that would have been incurred if the pre-heater had not been installed.

The operating costs associated with the pre-heater include the natural gas and electric power consumption. The consumption of natural gas and electric consumption are inputs in the analysis, along with the costs of the natural gas and the electricity.

The income generated (or the savings in drying charge) is a function of the length of the drying season and the average moisture removal. The average length of the drying season and the moisture removal vary according to the location and the seasonal weather. The decrease in moisture and the duration of the drying season are assumed to be constant over the ten year planning horizon.

Column-item A in Table 7.4 contains the dates at which the costs and income occur. The inflation factors for the cost of natural gas and electricity are listed in column-items B and C, receptively. The inflation rate is assumed not to vary from year to year, and is calculated by compounding the inflation rate according to the following expression:

$$\text{inflation factor} = (1+\text{inflation rate})^N \tag{7.2}$$

where N is the number of years.

The annual operating cost is calculated in column-item D.

The income inflation factor for the savings in the drying charge (column-item E) is found using equation 7.1, allowing for the calculation of the annual income (column-item F). The before-tax cash flow is calculated in column-item G. The before-tax cash flow is found by subtracting the operating costs from the income. The allowable tax deductions for the depreciation and for the interest on the loan determine the taxable income (column-item J). [Straight-line depreciation for the pre-heater is used]. The income tax and the loan cash flow are calculated in column-items K and L, respectively.

The after-tax cash flow (column-item M) is found by subtracting the taxes paid (column-item K) and the loan cash flow (column-item L) from the before-tax cash flow (column-item G). Finally, the NPV of the pre-heater is calculated in column-item N of Table 7.4 using the after tax discount rate.

7.4 Results of Capital Budgeting Analysis

7.4.1 Effect of Discount Rate

Table 7.5 shows the NPV of the pre-heater as a function of the discount rate (i.e. 12 and 17%). It is assumed that (1) no inflation occurs, (2) no loan is required to purchase the pre-heater, (3) the federal income tax rate is 34%, and (4) the corn is dried from 20 to 15% moisture content. As expected, the NPV of the pre-heater is lower for a discount rate of 17% rather than 12%. At a yearly drying season of 400 hours the NPV at a discount rate of 12% is $17,872; at a discount rate of 17% the NPV decreases to $12,946.

Table 7.5 Net present value of the pre-heater with a federal income tax of 34%, drying cost of $3.93/MT ($0.10/bu), and 6.2 MT/hr (245 bu/hr) increase in capacity when drying corn from 20% moisture content to 15%.

System Use (hr/yr)	Dryer Increase (MT/yr)	Discount Rate 12%	Discount Rate 17%	Difference $NPV_{12\%}$-$NPV_{17\%}$
100	620	-5,654	-7,437	1,783
200	1,240	2,188	-643	2,831
300	1,860	10,030	6,152	3,878
400	2,480	17,872	12,946	4,926

Table 7.6 illustrates the effect of the discount rate on the NPV of the pre-heater when corn is dried from 25 to 15% moisture content for the case that (1) no

inflation occurs, (2) no loan is required to purchase the pre-heater, and (3) the federal income tax rate is 34%. For a discount rate of 17%, the NPV of the pre-heater decreases. At a discount rate of 12% and a yearly drying season of 300 hours, the NPV is \$7,657. At a discount rate of 17% and a drying season of 300 hours, the NPV is \$4,096 a decrease of \$3,561.

Table 7.6 Net present value of the pre-heater with a federal income tax of 34%, drying cost of \$9.82/MT (\$0.25/bu), and 2.3 MT/hr (90 bu/hr) increase in capacity when drying corn from 25% moisture content to 15%.

System Use (hr/yr)	Dryer Increase (MT/yr)	Discount Rate 12%	Discount Rate 17%	Difference $NPV_{12\%}$-$NPV_{17\%}$
100	230	-6,445	-8,122	1,677
200	460	606	-2,013	2,619
300	690	7,657	4,096	3,561
400	920	14,708	10,205	4,503

7.4.2 Effect of Length of Drying Season

Table 7.7 shows the average yearly increase in capacity required for the NPV of the pre-heater to be zero at 12% discount rate. Thus, for a facility drying corn from 20 to 15% moisture content, the length of the drying season has to be 172-175 hours, depending on the tax rate. If a facility dries corn from 25 to 15% moisture content, the pre-heater needs to operate between 191-195 hours annually.

Table 7.7 Corn to be dried (MT/yr) and annual operating time (hr) required for the NPV of the pre-heater to be zero at a discount rate of 12% and variable tax rate.

Tax Rate and Time Required	Drying 20 to 15%	Drying 25 to 15%
corn dried at 0% tax, MT/yr	1,087	448
time required, hr	175	195
corn dried at 17% tax, MT/yr	1,077	444
time required, hr	174	193
corn dried at 34% tax, MT/yr	1,067	440
time required, hr	172	191

Table 7.8 illustrates the effect of a 17% discount rate on the minimum operating time per year for the NPV to be zero. The minimum length of the drying season increases when the discount rate is increased from 12% to 17%. When the federal income tax rate is 0%, the pre-heater has to be operated 40 additional hours per season when the discount rate is raised from 12 to 17%. In drying corn from 20 to 15% moisture content, the pre-heater has to operate 209-215 hours per season to show a NPV of zero. If the usual moisture removal is 25 to 15%, the dryer and pre-heater need to operate a minimum of 233-240 hours annually, depending on the tax rate.

Table 7.8 Corn to be dried (MT/yr) and annual operating time (hr) required for the NPV of the pre-heater to be zero at a discount rate of 17% and variable tax rate.

Tax Rate and Time Required	Drying 20 to 15%	Drying 25 to 15%
corn dried at 0% tax, MT/yr	1,336	551
time required, hr	215	240
corn dried at 17% tax, MT/yr	1,318	544
time required, hr	213	236
corn dried at 34% tax, MT/yr	1,299	536
time required, hr	209	233

7.4.3 Effect of Federal Income Tax Rate

Table 7.9 shows the effect of the federal income tax rate on the NPV of the pre-heater for the case that no loan is required, the discount rate is 12%, and no inflation occurs in the operating income or operating costs. The NPV is significantly effected by the federal income tax rate and the length of the drying season. The NPV of the pre-heater when operated 300 hr/yr increases from $10,030 at a tax rate of 34% to $12,429 when the tax rate is 0%, a difference of $2,399.

Table 7.9 Effect of federal income tax rate on the NPV of the pre-heater when drying corn from 20 to 15% and a discount rate 12% (no inflation or loan required).

System Use (hr/yr)	Dryer Increase (MT/yr)	NPV taxed @ 34%	NPV taxed @ 17%	NPV taxed @ 0%
100	620	-5,654	-6,646	-7,507
200	1,240	2,188	2,368	2,461
300	1,860	10,030	11,381	12,429
400	2,480	17,872	20,394	22,397

7.4.4 Effect of Drying Charge

The drying charge varies between elevator facilities. Table 7.10 shows the NPV of the pre-heater when the drying charge is $4.35/MT ($0.11/bu) [rather than $3.93/MT ($0.10/bu)] in drying corn from 20 to 15% moisture content. The NPV increases as a result of the larger drying charge. For an annual operating time of 300 hours, and drying charge of $4.35/MT, the NPV of the pre-heater is $14,142 at zero tax rate. This is an increase of $4,112 compared to when the drying charge is $3.93/MT ($0.10/bu) [see Tables 7.9 and 7.10].

Table 7.10 Effect of drying charge ($4.35/MT ($0.11/bu)) on the NPV of pre-heater when the drying corn from 20 to 15% and a discount rate of 12% (no inflation or loan required).

System Use (hr/yr)	Dryer Increase (MT/yr)	NPV taxed @ 34%	NPV taxed @ 17%	NPV taxed @ 0%
100	620	-3,856	-4,543	-5,143
200	1,240	5,143	5,800	6,296
300	1,860	14,142	16,143	17,734
400	2,480	23,141	26,486	29,173

7.4.5 Effect of Inflation

The price for natural gas and electricity usually inflates over time. The price of natural gas is expected to increase 45% between 1993 and 2010, at a yearly inflation rate of approximately 2.5% per year (Energy Information Administration, 1995). The electricity costs are expected to increase by

$0.004/kWh (0.3% per year) during this period (Energy Information Administration, 1995).

Inflation of the drying charge increases the NPV of the pre-heating system because of the higher yearly savings in drying charges. Inflation of the fuel costs decreases the NPV of the pre-heating system. The drying charge at a commercial facility is a combination of the amortization of the dryer, the labor costs, the energy costs, and other miscellaneous expenses. The increase in drying charge is assumed to be approximately the same as the average national inflation rate. Therefore, a projected national inflation rate of 2.5 to 3.0% is used in this study (Ferris, 1995).

Table 7.11 shows the effect of inflation on the NPV of the pre-heating system. The NPV increases as a result of 0.3% inflation in electricity prices, 2.5% in natural gas prices, and 2.5% in the drying charge. With this inflation, a tax rate of 34%, and an annual operating time of 300 hours, the NPV of the pre-heater is $13,279, and without inflation $3,249 (Table 7.7).

Table 7.11 Effect of inflation on the NPV of the pre-heater when drying corn from 20 to 15% and a discount rate 12% (drying charge inflation = 2.5%, electrical inflation = 0.3%, natural gas inflation = 2.5%, and no loan required).

System Use (hr/yr)	Dryer Increase (MT/yr)	NPV taxed @ 34%	NPV taxed @ 17%	NPV taxed @ 0%
100	620	-4,571	-5,441	-6,217
200	1,240	4,354	4,777	5,041
300	1,860	13,279	14,995	16,298
400	2,480	22,204	25,213	27,556

Table 7.12 illustrates the effect of inflation when drying corn from 20 to 15% moisture content, and an inflation rate of 3.0% in the drying charge. The NPV increases to $14,201 is a drying season of 300 hours, and a tax rate of 34%. This is an increase of $922 (Table 7.11) due to the change in the drying charge inflation rate from 2.5% to 3.0%.

Table 7.12 Effect of inflation on the NPV of the pre-heater when drying corn from 20 to 15% and a discount rate 12% (drying charge inflation = 3.0%, electrical inflation = 0.3%, natural gas inflation = 2.5%, and no loan required).

System Use (hr/yr)	Dryer Increase (MT/yr)	NPV taxed @ 34%	NPV taxed @ 17%	NPV taxed @ 0%
100	620	-4,264	-5,099	-5,852
200	1,240	4,969	5,460	5,770
300	1,860	14,201	16,019	17,393
400	2,480	23,433	26,578	29,015

7.4.6 Effect of Loan Policy

The effect of taking a loan on the NPV of the pre-heater is shown in Table 7.13. It is assumed that no inflation occurs during the 10 year planning horizon. A loan of $18,118 is taken out. The loan is repaid in 5 years at an interest rate of 12%. The NPV increases when a loan is needed to finance the project, because the interest paid on a loan is deducted from the company's net income.

Table 7.13. Effect of a loan required to purchase the pre-heater when drying corn from 20 to 15% moisture content and a discount rate of 12% (100% financed, 5 year loan, and 10% interest rate).

System Use (hr/yr)	Dryer Increase (MT/yr)	NPV taxed @ 34%	NPV taxed @ 17%	NPV taxed @ 0%
100	620	-5,013	-5,873	-6,614
200	1,240	2,829	3,140	3354
300	1,860	10,671	12,153	13,322
400	2,480	18,513	21,166	23,290

Table 7.14 shows the effect of taking out a 3 year loan instead of a five year loan to finance the pre-heater. The NPV increases slightly compared to the case that no loan is required, and decreases from the case of a five year loan. At a tax rate of 34% and an annual operating time of 300 hours, the NPV is \$10,467 which is an increase of \$437 (Table 7.9) for the case of no loan.

Table 7.14 Effect of a loan required to purchase the pre-heater when drying corn from 20 to 15% moisture content and a discount rate of 12% (100% financed, 3 year loan, and 10% interest rate).

System Use hr/yr	Dryer Increase MT/yr	NPV taxed @ 34%	NPV taxed @ 17%	NPV taxed @ 0%
100	620	-5,217	-6,113	-6,884
200	1,240	2,625	2,900	3084
300	1,860	10,467	11,913	13,052
400	2,480	18,309	20,927	23,020

7.4.7 Effect of Loan Value and Inflation

Table 7.15 shows the effect of taking out a 5 year loan at an interest rate of 10%. The inflation rate assumed for the price of natural gas is 2.5%, for electricity 0.3%, and for the drying charge 2.5%. The corn is dried from 20 to 15% moisture content.

Table 7.15 Effect of a loan required to purchase the pre-heater when drying corn from 20 to 15% moisture content and a discount rate of 12% (100% financed, 5 year loan, 10% interest rate, gas inflation=2.5%, electricity inflation=0.3%, drying charge inflation=2.5%).

System Use (hr/yr)	Dryer Increase (MT/yr)	NPV taxed @ 34%	NPV taxed @ 17%	NPV taxed @ 0%
100	620	-3,930	-4,668	-5,324
200	1,240	4,995	5,549	5934
300	1,860	13,920	15,767	17,191
400	2,480	22,845	25,985	28,449

Table 7.16 illustrates the minimum time required for the NPV of the pre-heater to become zero. The loan and inflationary effects reduce the required operating time. When drying corn from 20 to 15% moisture content, the pre-heater has to be operated between 172-175 hours annually (Table 7.7). When a loan is needed and inflation is considered the minimum annual operating time is 144-147 hours. Drying corn from 25 to 15% moisture content requires 191-195 hours per season (Table 7.7) for the NPV to become zero. However, with a loan and inflation the minimum operating time is only 160-164 hours per season.

Table 7.16 Corn dried to be dried (MT/yr) and annual operating time (hr) required for the NPV of the pre-heater to be zero (discount rate of 12%, variable tax rate, 100% financed, 5 year loan, 10% interest rate, gas inflation=2.5%, electricity inflation=0.3%, drying charge inflation=2.5%).

Tax Rate and Time Required	Drying 20 to 15%	Drying 25 to 15%
corn dried at 0% tax, MT/yr	913	377
time required, hr	147	164
corn dried at 17% tax, MT/yr	903	372
time required, hr	146	162
corn dried at 34% tax, MT/yr	893	368
time required, hr	144	160

CHAPTER 8

SUMMARY AND CONCLUSIONS

In this study the following objectives have been achieved:

(1) Experimental data on the counterflow pre-heating of corn was collected.

(2) A computer simulation model was developed and validated with experimental data.

(3) The simulation model was used to determine the influence of various design parameters on the pre-heating and moisture loss of corn in a counterflow pre-heater.

(4) The economic feasibility of the pre-heater was assessed using a capital budgeting analysis.

The following conclusions can be drawn from this study:

(1) The airflow rate, the air temperature, and the inlet moisture content of the corn have a significant effect on the level of pre-heating.

(2) The increase in capacity by pre-heating corn with 106°C air is approximately 20% when drying in a one-stage CCF dryer from 20 to 15% moisture content.

(3) Determination of stress cracked kernels is an objective measure of corn quality.

(4) The corn quality, as measured by the percentage of stress-cracked kernels, is not influenced by pre-heating.

(5) The addition of a pre-heater is economically feasible under 1994-1995 conditions if the pre-heater is operated between 144-147 hours per year when drying corn from 20 to 15% moisture content, and between 160-164 hours per year when drying corn from 25 to 15% moisture content.

(6) The economic feasibility of the pre-heater is strongly influenced by (a) the discount rate, (b) the length of the drying season, and (c) the drying charge at a local elevator.

CHAPTER 9

RECOMMENDATIONS FOR FURTHER STUDY

The following recommendations for further study are proposed:

(1) Determine the influence of pre-heating on other dryer types, i.e. crossflow and mixed-flow.

(2) Determine the advantages of pre-heating for other grain crops requiring drying, i.e. rice and wheat.

(3) Determine the stepsize by deriving the eigenvalues of the differential equations.

CHAPTER 10

LIST OF REFERENCES

ASAE. 1977. Agricultural Engineers Yearbook. American Society of Agricultural Engineers, St. Joseph, MI.

Bakker-Arkema, F. W., L. E. Lerew, S. F. DeBoer, and M. G. Roth. 1974. Grain Dryer Simulation. Mich. State Univ. Agr. Exp. Sta., Res. Rep. 224.

Bakker-Arkema, F. W. and I. P. Schisler. 1984. Counterflow cooling of grain. Paper No. 84-3523. Am. Soc. Agric. Eng., St. Joseph, MI.

Bakker-Arkema, F. W., H. Widayat, D. E. Maier, and E. Meiners. Dryer-capacity increase through grain pre-heating. Paper No. 93-6016. Am. Soc. Agric. Eng., St. Joseph, MI.

Barker, J. J. 1965. Heat transfer in packed beds. Ind. Eng. Chem. 57: 43-51.

Behlen. 1968. Behlen pre-heat model. Brochure AD-12602MA. Behlen Manufacturing Company, Columbus, NE.

Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1992. Drying and Storage of Grains and Oilseeds. Van Nostrand Reinhold, New York, NY.

Cheney, W., and D. Kincaid. 1985. Numerical Mathematics and Computing. Brooks/Cole Publishing Co., Pacific Grove, Calif.

Consumers Power Company. 1995. Personal Communication. Lansing, MI.

Energy Information Administration. 1995. Annual Energy Outlook. Department of Energy. Washington, D.C.

Evans, T. W. 1970. Simulation of Counter-Flow Drying. Unpublished M.S. Thesis, Michigan State University. East Lansing, MI.

Ferris, J. 1995. Personal Communication. Department of Agricultural Economics. East Lansing, MI.

Gunasekaran S., S. Deshpande, M. R. Paulsen and G. C. Shove. 1985. Size characterization of stress cracks in corn kernels. Trans. ASAE 28(5): 1668-1672.

Gunasekaran, S. and K. Muthukumarappan. 1993. Breakage susceptibility of corn of different stress-crack categories. Trans. ASAE 36(5): 1445-1446.

Harsh, S. B. 1995. Personal Communication. Department of Agricultural Engineering. Michigan State University. East Lansing, MI.

Harsh, S. B., L. J. Connor, and G. D. Schwab. 1981. Managing the Farm Business. Prentice-Hall. Englewood Cliffs, New Jersey.

Hildebrand, F. B. 1968. Finite-Difference Equations and Simulations. Prentice-Hall, Inc., Englewood Cliffs, N.J.

Hill, L. D. et al. 1991. Economic evaluation of quality characteristics in the dry milling of corn. Bulletin 804. Agric. Exp. Station, Univ. of Illinois, Urbana, IL.

Hill, L. D. and M.R. Paulsen. 1987. Maize production and marketing in Agrentina. Bulletin 785. Agric. Exp. Station, Univ. of Illinois, Urbana, IL.

Hines, R.E. 1995. Personal Communication. MFS/York, Inc. Grand Island, NE.

Kalchik, S. 1995. Personal Communication. Kellogg Co. Battle Creek, MI.

Li, H., and R. V. Morey. 1984. Thin-layer drying of yellow dent corn. Trans. ASAE 27(2): 581-585.

M&W Gear Co. 1981. Instruction manual for model 650R continuous-flow air recirculating grain dryer. Gibson City, IL.

Maier, D. E. 1988. The counterflow cooling of feed pellets. Unpublished M.S. Thesis, Michigan State University. East Lansing, MI.

Marks, B. P., D. E. Maier, and F. W. Bakker-Arkema. 1993. Optimization of a new in-bin counterflow corn drying system. Trans ASAE 36(2): 529-534.

Meiner, E. R. Personal Communication. M&W Gear Co. Gibson City, IL.

Microsoft Corporation. 1993. Microsoft Excel 5.0 Online Help. Microsoft Co., U.S.

Mühlbauer, W. 1974. Research about the drying of mais under concurrent-flow conditions. Ph.D. thesis, University of Hohenheim. Stutgart, Germany. In German.

Page, C. 1949. Factors influencing the maximum rates of drying shelled corn in layers. Unpublished M.S. Thesis, Purdue University. West Lafayette, IN.

Paulsen, M. R., L. L. Darrah, R. L. Stroshine. 1989. Genotype differences in breakage susceptibility of corn and soybeans. Paper presented at the NC-151 Fine Materials Symposium, St. Louis, MO, Feb. 15, 1989.

Press, W. H., B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling. 1986. Numerical Recipes - The Art of Scientific Computing. Cambridge University Press, Cambridge, United Kingdom.

Rezchikov, V. A., V. F. Sorochinsky, and R. P. Dubinicheva. Preheating as a method for grain drying intensification. In: Developments in Food Science, vol. 5A. Elsevier Scientific Publishing Co., Amsterdam, the Netherlands.

Riggs, J.L. and T.M. West. 1986. Essentials of Engineering Economics. McGraw-Hill, New York.

Sarwar, G. 1988. Environmental factors and physical properties that produce stress cracks in corn. PhD Thesis. Dept. of Agr. Eng., Univ. of Texas, College Station, TX.

Segerlind, L. J. 1995. Personal Communication. Department of Agricultural Engineering. Michigan State University. East Lansing, MI.

Tabil, L.G., A. Noomhorm, and L.R. Verma. 1991. Breakage susceptibility of shelled corn due to rehydration and redrying. Journal of Food Process Engineering 14: 69-82.

Thompson, R. A. and G. H. Foster. 1963. Stress cracks and breakage in artificially dried corn. Market Research Report 631. USDA: Washington, D.C.

Thompson, T. L. 1967. Predicted performances and optimal designs of convection grain dryers. Unpublished Ph.D. Thesis. Purdue University, West Lafayette, IN.

Thompson, T. L., R. M. Peart, and G. H. Foster. 1968. Mathematical simulation of corn drying-a new model. Trans. ASAE 11:582-586.

Turner, M. 1995. Personal Communication. Jorgensen Farm Elevator. Williamston, MI.

USDA. 1994. National Agricultural Statistics Service Statistical Bulletin No. 896. Washington, D.C.

Westerman, P.W., G.M. White, and I.J. Ross. 1973. Relative humidity effect on the high temperature drying of shelled corn. Trans ASAE 16: 1136-1139.

APPENDICES

APPENDIX A Experimental Pre-Heating Results

APPENDIX B Stress Crack Results

APPENDIX A

From Elmo Meiner's, Colfax, ILL Oct. 3, 1994

English units were used during the testing period (°F and in H_2O)
Four moisture meters were used a handheld Farmex and Dickey John, a single-kernel and the ASAE oven method. The single-kernel meter returns the average moisture content, standard deviation, and histograms of the kernel moisture contents.

no pre-heating

in pre-heater / from field

time	corn temp	MC Farmex	MC DJ	MC Oven	MC kernel	variance	std. dev.	MC range	
5:30 PM	73.4	22.7	20.7	20.9	19.6	15.47	3.93	8.5 - 37.0	
5:45 PM	72.4	21.8	22.0	-	-	-	-	-	
6:45 PM	-	19.6	20.6	19.9	18.3	12.40	3.52	9.0 - 8.0	
7:05 PM	75.1	22.4	20.4	19.5	19.2	15.14	3.89	8.5 - 36.5	
7:50 PM	71.9	23.0	20.4	19.1	18.5	8.11	2.84	9.5 - 28.5	
8:05 PM	71.8	21.2	19.7	19.4	19.2	11.91	3.45	8.0 - 29.0	
9:15am 10/4	71.4	-	13.9	-	13.2	7.84	2.80	8.5 - 26.5	
9:45am 10/4	74.0	-	15.3	-	13.7	6.50	2.55	8.0 - 29.0	
10:15am 10/4	73.8	-	13.9	17.7	13.7	10.44	3.23	8.0 - 29.5	
	73.0	21.8	18.5	19.4	16.9	10.98	3.28		averages
	71.4	19.6	13.9	17.7	13.2	6.50	2.55		min
	75.1	23.0	22.0	20.9	19.6	15.47	3.93		max

Outlet CCF

time	corn temp	MC Farmex	MC DJ	MC Oven	MC kernel	variance	std. dev.	MC range	
6:45 PM	-	15.0	15.5	12.7	14.1	13.62	3.69	7.5 - 30	
7:05 PM	-	15.0	15.9	13.8	13.9	13.06	3.61	8.5 - 32.5	
7:50 PM	70.6	15.5	15.2	14.2	14.2	17.25	4.15	8.5 - 33.5	
8:05 PM	71.7	16.2	14.6	12.9	14.7	14.34	3.78	8.0 - 33.0	
8:30 PM	70.4	15.0	15.0	14.0	13.8	8.32	2.88	7.5 - 23.5	
8:45 PM	69.8	16.0	15.2	-	14.0	10.95	3.31	7.5 - 25.5	
9:00 PM	-	15.5	14.7	12.8	14.3	17.74	4.21	8.0 - 26.0	
9:15am 10/4	71.4	14.2	13.9	-	13.2	7.84	2.80	8.5 - 26.5	
9:45am 10/4	74.0	15.4	15.3	-	13.7	6.50	2.55	8.0 - 29.0	
10:15am 10/4	73.8	15.3	13.9	-	13.7	10.44	3.23	8.0 - 29.5	
	71.7	15.3	14.9	13.4	14.0	12.01	3.42		averages
	69.8	14.2	13.9	12.7	13.2	6.50	2.55		min
	74.0	16.2	15.9	14.2	14.7	17.74	4.21		max

CCF dryer and fuel consumption

time	sec/rev	bu/hr	Tamb	RH amb	gas	
5:30 PM	55	687				
5:57 PM	53	713	64.9	31	18842	120sec for 100ft3
6:05 PM	50	756				
7:25 PM					18885	
7:27 PM					18886	
7:29 PM					18887	
7:31 PM	50	756	57.3	47.3	18888	
8:22 PM					18913	
8:25 PM					18914	

preheater 76C (168F)

in pre-heater / from field

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
9:30 AM	68.6	-	-	16.4	16.7	2.52	1.58	8.5 - 21.0	
10:20 AM	67.7	20.2	17.7	20	18.8	7.23	2.69	8.5 - 27.5	
10:45 AM	65.9	22.4	-	18.8	18.7	5.14	2.26	8.0 - 27.5	
11:15 AM	67.1	-	23.3	21.3	21.3	23.46	4.84	8.5 - 34.0	
12:05 PM	67.6	21.1	20.6	19.4	21.3	20.60	4.53	12.0 - 37.0	
12:45 PM	68.4	21.1	19.6	20.3	19.4	15.22	3.90	10.5 - 34.0	
1:00 PM	70.9	21.3	19.9	18.9	19.8	15.03	3.87	11.0 - 36.5	
1:30 PM	72.3	21.7	20.2	20.6	20.2	18.55	4.30	14.0 - 36.0	
2:00 PM	73.0	20.5	20.9	20.6	20.3	23.79	4.07	8.0 - 37.5	
	69.1	21.2	20.3	19.6	19.6	14.62	3.56		averages
	65.9	20.2	17.7	16.4	16.7	2.52	1.58		min
	73.0	22.4	23.3	21.3	21.3	23.79	4.84		max

outlet pre-heater

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
11:05 AM	72.7			20.5	19.0	5.73	2.39	10.5 - 27.5	
11:35 AM	74.9	20.7	20.2	20.2	19.2	6.06	2.46	12.5 - 28.0	
12:15 PM	77.3	21.6	21.2	20.4	20.8	14.78	3.84	10.5 - 32.5	
1:15 PM	76.4	21.5	20.1	19.7	20.0	16.83	4.10	12.0 - 33.0	
2:00 PM	85.4	21.1	19.5	19.8	20.3	17.70	4.20	12.0 - 31.5	
2:50 PM	82.5	20.2	20.3	19.1	19.2	14.22	3.77	8.5 - 35.5	
3:30 PM	79.7	20.4	20.1		19.4	12.32	3.50	7.5 - 35.5	
	78.4	20.9	20.2	20.0	19.7	12.52	3.47		averages
	72.7	20.2	19.5	19.1	19.0	5.7	2.4		min
	85.4	21.6	21.2	20.5	20.8	17.7	4.2		max

outlet CCF

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
11:25 AM	79.8	14.4		14	14.2	8.47	2.91	8.0 - 23.0	
12:20 PM	76.6	15.3	12.4	14.7	14.8	10.47	3.23	8.5 - 25.0	
1:20 PM	80.0	14.4	14.8	14.3	15.1	16.35	4.04	9.0 - 30.0	
2:15 PM	79.2	14.0	15.5	13.3	14.3	15.58	3.94	8.0 - 30.0	
3:00 PM	80.5	13.8	15.0	14.4	14.0	15.52	3.94	8.5 - 35.5	
	79.2	14.4	14.4	14.1	14.5	13.28	3.61		averages
	76.6	13.8	12.4	13.3	14.0	8.5	2.9		min
	80.5	15.3	15.5	14.7	15.1	16.4	4.0		max

3:30 PM temperature in plenum is changed to 190F
dryer down at 4:00pm takes to 5:00pm to fix

Testweights for corn 10/3/94

MC	TW		MC	TW
15.2	55.6		21.2	56.5
14.9	57.5			
16.4	58			
15.3	57			
15.4	56			
15.44	56.82	averages		

burner settings

time	location	gauge T
11:40 AM	N	178
	S	190
12:50 PM	N	180
	S	188
1:40 PM	N	186
	S	190
2:30 PM	N	189
	S	188
3:10 PM	N	186
	S	189
		186.4

Condtitions of pre-heater

plenum temperature

time	location		gauge T	solomat	SP
9:50 AM	plenum	E	161	162.7	7.9
9:50 AM	plenum	SE		158.1	7.6
10:30 AM	plenum	E	164	167.5	7.7
10:30 AM	plenum	SE		161.7	7.7
11:40 AM	plenum	E	167	168.5	
	plenum	SE		165.9	
12:50 PM	plenum	E	170	170.9	7.7
		SE	166	167.8	
1:40 PM	plenum	E	172	172.9	
		SE	168	168.1	
2:30 PM	plenum	E	171	172.6	7.5
		SE	168	168.2	7.5
3:10 PM	plenum	E	171	173.1	
		SE		168.6	
			167.8	167.6	7.7

exhaust temperature

time	location	temp
9:50 AM	middle	64.8
10:30 AM	middle	74.4
	E	77.2
11:40 AM	middle	81.9
	E	81
12:50 PM	middle	82.8
	E	82.4
1:40 PM	W	82.8
	middle	83.2
	E	82.4
2:30 PM	W	82.9
	midd	82.9
	E	81.9
3:10 PM	W	82.5
	middle	82.2
	E	82.2
		80.5

exhaust CCF

	gauge	solomat
1:40 PM	140	
2:30 PM		142.2

time	sec/rev	bu/hr	Texh CCF gauge	Tamb	RHamb	gas
11:00 AM				64	44	
11:25 AM	43	879				
11:35 AM	42	900	148			
2:30 PM		910		69.5	29	
2:37 PM						18746 92 sec for 100ft3
2:59 PM		880				18760 96 sec for 100ft3
3:40 PM						18785 89 sec for 100ft3

preheater at 94C (202F)

Inlet

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
9:45	56.3	21.5	18.5	19.2	17.7	14.99	3.87	7.0 - 30.5	
10:15	59.4	20.8	17.9	19.3	17.1	12.02	3.46	12.0 - 35.0	
10:45	60.4	21.8	19.5	19.1	17.4	13.34	3.65	12.5 - 31.0	
11:10	63.5	21.4	19.3	18.5	17.3	13.25	3.64	11.5 - 35.5	
11:35	64.3	20.9	17.7	18.3	16.8	12.97	3.6	10.0 - 30.5	
12:10	65.2	21.6	18.0	17.1	17.5	14.65	3.82	11.5 - 34.0	
12:35	71.1	20.8	17.9	18.1	17.0	14.68	3.83	10.5 - 33.5	
12:45	69.2	20.7		17.9	19.2	23.46	4.84	11.0 - 36.5	
1:45	71.1	21.7	18.9	16.4	17.4	12.65	3.55	11.0 - 32.0	
2:00		21.9	18.4	19.1	17.9	14.22	3.77	12.5 - 33.5	
2:30	71.1	20.2	18.6	18.8	17.9	13.28	3.64	13.5 - 34.5	
3:40	70.6	21.0	17.7	18.8	14.5	26.32	5.13	6.5 - 29.5	
5:15	66.5	20.7	18.0	18.4	16.4	7.36	2.71	11.0 - 33.0	
5:45	69.1	20.7	17.1	17.7	16.1	6.66	2.58	11.0 - 29.5	
6:05	68.1	20.6	17.9	18.1	16.1	6.39	2.52	10.5 - 27.5	
6:30	67.1	20.6	17.5	17.8	16.3	6.93	2.63	11.5 - 26.5	
6:50	66.4	20.3	16.7	18.1	16.2	7.71	2.77	11.5 - 29.5	
7:10		21.1	18.0	18.5	16.3	6.42	2.53	10.5 - 29.5	
	66.2	21.0	18.1	18.3	17.0	12.63	3.47		averages
	56.3	20.2	16.7	16.4	14.5	6.4	2.5		min
	71.1	21.9	19.5	19.3	19.2	26.3	5.1		max

farmers switched fields at approx 3:30 -- note the difference in the standard deviation

Outlet preheater

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
1:30	104.3	20.5	18.3	17.6	17.5	10.48	3.23	12.0 - 37.5	
2:00	94.1	20.0	17.7	17.1	17.2	9.3	3.05	9.0 - 31.0	
3:15	86.3	21.3	18.6	18.0	17.5	8.18	2.86	9.0 - 30.0	
3:30				18.1					
3:50	86.8	21.7	18.4		17.7	9.43	3.07	9.5 - 32.5	
	84.7								
4:30	91.3	22.0	18.8	18.0	17.9	10.12	3.18	8.0 - 30.0	
5:00	79.4	21.1	18.6	17.7	16.7	6.86	2.61	10.0 - 27.0	
	89.6	21.1	18.4	17.8	17.4	9.06	3.00		averages
	79.4	20.0	17.7	17.1	16.7	6.9	2.6		min
	104.3	22.0	18.8	18.1	17.9	10.5	3.2		max

Outlet CCF

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
2:00		16.2	14.3	12.9	14.1	9.15	3.02	7.5 - 26.0	
3:15	85.4	15.5	15.4	13.9	13.8	7.67	2.77	8.5 - 25.0	
3:50	87.7	15.9	15.1	14.0	14.5	13.74	3.7	8.5 - 34.0	
4:30	83.4			14.1	14.5	12.71	3.56	7.5 - 34.5	
5:00	85.7	16.6	15.2	13.6	14.5	17.24	4.15	7.5 - 30.0	
	85.6	16.1	15.0	13.7	14.3	12.10	3.44		averages
	83.4	15.5	14.3	12.9	13.8	7.7	2.8		min
	87.7	16.6	15.4	14.1	14.5	17.2	4.2		max

miscellaneous

10:30 temperature in burners turned up to 190F

5:00pm preheater turned up to 230F

Condtitions of pre-heater

auger timing

		delt
3:37:20 off	5:38:30 off	
3:42:25 on	5:42:00 on	0:03:30
3:53:00 off	5:49:00 off	0:07:00
	5:54:50 on	0:05:50
	6:07:30 off	0:12:40
	6:14:50 on	0:07:20
	6:28:00 off	0:13:10
	6:33:30 on	0:05:30
	6:47:00 off	0:13:30
	6:49:45 on	0:02:45

exhaust from pre-heater

time	location	temp
12:50	m	84.7
13:10	e	86.5
	m	85.9
15:30	w	86.8
	m	86.5
16:30	e	86.1
	w	87.3
	m	87.3
average		86.4

time	location		gauge T	solomat	SP
1:10	plenum	east	202	204.2	7.7
	plenum	se	200	198.3	7.7
2:45	plenum	east	204	204.2	
	plenum	se	201	199.9	
4:10	plenum	east	202	206.4	7.6
		se	200	199.1	7.6
			201.5	202.0	7.7

	exhaust from ccf	solomat	burner		
2:45	exhaust ccf	140.1	1:10	n	224
				s	228
			2:45	north	225
				south	228
			4:10	n	225
				s	230
					226.7

timing of auger in preheater		variation in corn temp out of pre-heater at 3:00	grain temp out of pre-heater at 2:30
off	2:50	88.1	88.5
on	2:56	94.2	89.1
off	3:10	89.1	92.8
		86.3	95
			88.1

CCF and fuel consumption

time	sec/rev	bu/hr	Texh CCF gauge	Tamb	RHamb	gas	
10:20	49	771				19337	
11:00	48	788	154			19363	
11:07	48	788					
11:10	45	840					
11:30	45	840					
12:00	40	945	156	64	45	19403	83sec for 100ft3
12:30	40	945	152			19424	
1:00	40	945	151			19444	
1:30			152			19464	
2:30	36	1050	154			19504	
3:30	36	1050	152			19544	
4:00			151			19564	
4:30	36	1050	152			19584	
5:00	36	1050	153			19604	

pre-heater at 106C (223F)

Inlet

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
6:05 PM	68.1	20.6	17.9	18.1	16.1	6.39	2.52	10.5 - 27.5	
6:30 PM	67.1	20.6	17.5	18.3	16.3	6.93	2.63	11.5 - 26.5	
6:50 PM	66.4	20.3	16.7	17.5	16.2	7.71	2.77	11.5 - 29.5	
7:10 PM		21.1	18	17.8	16.3	6.42	2.53	10.5 - 29.5	
8:15 PM	61.9	20	19.6	20.9	19.5	19.58	4.42	8.0 - 34.5	
8:30 PM				20.3	19.5	23.01	4.79	10.5 - 32.5	
	65.9	20.5	17.9	18.8	17.3	11.67	3.28		averages
	61.9	20.0	16.7	17.5	16.1	6.4	2.5		min
	68.1	21.1	19.6	20.9	19.5	23.01	4.79		max

Outlet pre-heater

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
8:00 PM	74.4	20.4	17.8	17.3	16.6	5.64	2.37	12.5 - 29.0	
8:25 PM	74.6	20.2	18.3	16.5	16	3.05	1.74	12.0 - 23.0	
9:00 PM	84.3	19.4	17.1	17.7	16.9	9.28	3.04	7.5 - 30.0	
9:15 PM	84.4	18.9	18.2	17.5	17.3	15.71	3.96	7.0 - 34.5	
9:45 PM	70.4	20.3	18.2	17.7	17.1	8.93	2.98	10.0 - 30.5	
	77.6	19.8	17.9	17.3	16.8	8.52	2.82		averages
	70.4	18.9	17.1	16.5	16.0	3.1	1.7		min
	84.4	20.4	18.3	17.7	17.3	15.7	4.0		max

Outlet CCF

time	corn temp	MC Farmex	MC DJ	MC oven	MC kernel	variance	std. dev.	MC range	
8:00 PM	86.8	16.2	15	13.4	13.9	6.88	2.62	8.5 - 25.0	
8:25 PM	85.9	16.4	15.2	13.4	14	7.09	2.66	9.0 - 24.5	
9:00 PM	82.7	16.7	15.9	14.7	13.9	6.35	2.52	7.0 - 21.5	
9:15 PM		15.9	14.3	14.3	13.9	9.85	3.13	8.0 - 31.5	
9:45 PM	82.7	15.9	14.7	13.7	13.7	9.46	3.07	8.0 - 28.5	
	84.5	16.2	15.0	13.9	13.9	7.93	2.80		averages
	82.7	15.9	14.3	13.4	13.7	6.35	2.52		min
	86.8	16.7	15.9	14.7	14	9.85	3.13		max

Condtitions of pre-heater

5:00 PM burners turned up to 260F

time	location	gauge T	solomat	SP
7:50 PM	e	226	228.5	
	se	220	220.1	
8:45 PM	e	222	224.7	
	se	217	219.4	
		221.25	223.18	

exhaust from pre-heater

time	location	temp
7:50 PM	e	91.9
	m	91.7
8:45 PM	e	88.8
	m	94.5
		91.7

			solomat
8:45 PM	exhaust	ccf	141.3

burners

7:50 PM	n	260
	s	256
8:45 PM	n	256
	s	262
		258.5

CCF and fuel consumption

time	sec/rev	bu/hr	Texh CCF gauge	Tamb	RHamb	gas
9:00 PM				52.2	82.4	
5:30 PM	36	1050	151			19626
6:00 PM			154			19648
6:30 PM	34	1112				19669
7:00 PM	30	1260	160			19690
7:30 PM			153			19711
8:00 PM	31	1219	151			19732
8:30 PM	31	1219	150			19753
9:00 PM	34	1112	151			19776

APPENDIX B

Elmo Meiner stress crack data
individual #1

time	date	type	none	single	multiple	crazed	% SC	# kernel	SCI
9:30 AM	10/3/94	in #1	46	2	1	1	8	50	20
9:30 AM	10/3/94	in #2	46	1	2	1	8	50	24
10:45 AM	10/3/94	in	49	1	0	0	2	50	2
11:15 AM	10/3/94	in	50	0	0	0	0	50	0
12:05 PM	10/3/94	in	49	1	0	0	2	50	2
1:30 PM	10/3/94	in	47	2	1	0	6	50	10
9:45 AM	10/4/94	in	49	0	1	0	2	50	6
10:15 AM	10/4/94	in	48	2	0	0	4	50	4
10:45 AM	10/4/94	in	48	2	0	0	4	50	4
12:50 PM	10/4/94	in	48	1	0	1	4	50	12
7:10 PM	10/4/94	in	46	4	0	0	8	50	8
11:05 AM	10/3/94	out - pre	46	3	1	0	8	50	12
11:35 AM	10/3/94	out - pre	46	2	1	1	8	50	20
12:15 PM	10/3/94	out - pre	47	3	0	0	6	50	6
2:00 PM	10/3/94	out - pre	47	2	1	0	6	50	10
2:50 PM	10/3/94	out - pre	48	2	0	0	4	50	4
1:30 PM	10/4/94	out - pre	47	1	2	0	6	50	14
2:00 PM	10/4/94	out - pre	47	2	1	0	6	50	10
3:15 PM	10/4/94	out - pre	46	4	0	0	8	50	8
5:00 PM	10/4/94	out - pre	47	2	1	0	6	50	10
8:20 PM	10/4/94	out - pre	46	4	0	0	8	50	8
9:00 PM	10/4/94	out - pre	39	5	5	1	22	50	50
9:15 PM	10/4/94	out - pre	42	4	3	1	16	50	36
11:25 AM	10/3/94	out - ccf	14	6	15	14	71	49	247
12:20 PM	10/3/94	out - ccf	17	6	11	16	66	50	238
1:20 PM	10/3/94	out - ccf	16	10	13	8	66	47	189
2:15 PM	10/3/94	out - ccf	13	8	15	14	74	50	246
7:05 PM	10/3/94	out - ccf	18	5	8	19	64	50	248
8:05 PM	10/3/94	out - ccf	12	6	20	12	76	50	252
8:05 PM	10/3/94	out - ccf 2	18	5	11	16	64	50	236
9:00 PM	10/3/94	out - ccf	21	5	9	15	58	50	214

11:25 AM	10/3/94	out - ccf	14	10	10	16	72	50	240
12:20 PM	10/3/94	out - ccf	19	10	8	13	62	50	198
1:20 PM	10/3/94	out - ccf	13	12	12	13	74	50	226
2:15 PM	10/3/94	out - ccf	13	7	19	11	74	50	238
7:05 PM	10/3/94	out - ccf	17	14	6	13	66	50	194
8:05 PM	10/3/94	out - ccf	15	4	16	15	70	50	254
8:05 PM	10/3/94	out - ccf 2	22	1	14	13	56	50	216
9:00 PM	10/3/94	out - ccf	22	9	10	9	56	50	168
2:00 PM	10/4/94	out - ccf	17	9	11	13	66	50	214
3:15 PM	10/4/94	out - ccf	13	16	9	12	74	50	206
3:50 PM	10/4/94	out - ccf	14	14	14	8	72	50	192
4:30 PM	10/4/94	out - ccf	25	10	6	9	50	50	146
8:00 PM	10/4/94	out - ccf	17	7	16	10	66	50	210
8:25 PM	10/4/94	out - ccf	18	14	11	7	64	50	164
9:00 PM	10/4/94	out - ccf	22	9	10	9	56	50	168
9:15 PM	10/4/94	out - ccf	13	8	11	18	74	50	262
9:45 PM	10/4/94	out - ccf	19	4	12	15	62	50	230

individual #3

time	date	type	none	single	multiple	crazed	% SC	# kernel	SCI
9:30 AM	10/3/94	in #1	46	1	1	2	8	50	28
9:30 AM	10/3/94	in #2	47	2	0	0	4	49	4
10:45 AM	10/3/94	in	50	0	0	0	0	50	0
11:15 AM	10/3/94	in	49	0	1	0	2	50	6
12:05 PM	10/3/94	in	49	1	0	0	2	50	2
1:30 PM	10/3/94	in	48	1	1	0	4	50	8
9:45 AM	10/4/94	in	49	0	1	0	2	50	6
10:15 AM	10/4/94	in	47	2	1	0	6	50	10
10:45 AM	10/4/94	in	48	1	0	1	4	50	12
12:50 PM	10/4/94	in	47	1	1	1	6	50	18
7:10 PM	10/4/94	in	47	1	2	0	6	50	14
11:05 AM	10/3/94	out - pre	48	0	2	0	4	50	12
11:35 AM	10/3/94	out - pre	48	1	1	0	4	50	8
12:15 PM	10/3/94	out - pre	49	0	0	1	2	50	10
2:00 PM	10/3/94	out - pre	48	1	1	0	4	50	8
2:50 PM	10/3/94	out - pre	50	0	0	0	0	50	0

1:30 PM	10/4/94	out - pre	44	3	3	0	12	50	24
2:00 PM	10/4/94	out - pre	46	1	3	0	8	50	20
3:15 PM	10/4/94	out - pre	42	3	5	0	16	50	36
5:00 PM	10/4/94	out - pre	47	1	2	0	6	50	14
8:20 PM	10/4/94	out - pre	47	3	0	0	6	50	6
9:00 PM	10/4/94	out - pre	41	2	5	2	18	50	54
9:15 PM	10/4/94	out - pre	41	2	4	3	18	50	58
11:25 AM	10/3/94	out - ccf	10	3	21	15	80	49	288
12:20 PM	10/3/94	out - ccf	17	2	12	19	66	50	266
1:20 PM	10/3/94	out - ccf	13	5	21	8	72	47	230
2:15 PM	10/3/94	out - ccf	12	4	23	11	76	50	256
8:05 PM	10/3/94	out - ccf	13	1	19	17	74	50	286
8:05 PM	10/3/94	out - ccf2	21	2	15	12	58	50	214
9:00 PM	10/3/94	out - ccf	17	5	18	10	66	50	218
2:00 PM	10/4/94	out - ccf	14	4	16	16	72	50	264
3:15 PM	10/4/94	out - ccf	13	6	17	14	74	50	254
3:50 PM	10/4/94	out - ccf	14	4	14	17	71	49	267
4:30 PM	10/4/94	out - ccf	28	5	12	5	44	50	132
7:05 PM	10/4/94	out - ccf	17	1	17	15	66	50	254
8:00 PM	10/4/94	out - ccf	19	5	17	9	62	50	202
8:25 PM	10/4/94	out - ccf	19	3	17	11	62	50	218
9:15 PM	10/4/94	out - ccf	18	1	12	19	64	50	264
9:45 PM	10/4/94	out - ccf	19	3	14	14	62	50	230