This is to certify that the

thesis entitled

COUNTERFLOW COOLING OF CORN

presented by

OSNY WALTRICK DE SOUZA

has been accepted towards fulfillment
of the requirements for

M. S. degree in Ag. Eng.

F. W. Bakker-Arkema
Major professor

Date 11/6/84

COUNTERFLOW COOLING OF CORN

By

Osny Waltrick de Souza

A THESIS

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

MASTER OF SCIENCE

Department of Agricultural Engineering

1984

ABSTRACT

COUNTERFLOW COOLING OF CORN

By

Osny Waltrick de Souza

Cooling of grain after drying is a necessary practice in the United States as well as in Brazil. Inadequate and non-uniform cooling is a frequent problem. By optimizing the cooling of grain, the overall energy efficiency of the dryer and the quality of the end-product are improved.

A laboratory-scale counterflow cooling unit was employed to cool corn at different conditions of grain temperature, grain and air flow rate, grain moisture content, and bed depth.

The outlet grain temperature from the cooler was decreased by: (1) decreasing the inlet grain temperature, (2) increasing the air flow rate, (3) increasing the inlet grain moisture content, (4) decreasing the air flow rate, (5) increasing the bed depth.

The lack of adequate information about the cooling of grain requires further studies under typical United States and Brazilian conditions.

Major Professor
11/6/84

Department Chairman
11/8/84

ACKNOWLEDGMENTS

The author wishes to acknowledge the encouragement and guidance of Dr. Fred W. Bakker-Arkema, his support and understanding throughout the development of this study.

Appreciation is expressed to Dr. Roger G. Brook and Dr. Robert F. Ruppel for serving on the guidance committee.

The financial support by Companhia Paranaense de Silos e Armazens--Copasa, Curiba, Parana, Brazil, was greatly appreciated.

Special thanks goes to my family and friends, for their support. Special gratitude is expressed to my wife, Nilceia T. C. Souza, for her love, support and understanding.

TABLE OF CONTENTS

		Page
LIST OF TABLES		vi
LIST OF FIGURES		x
LIST OF SYMBOLS		xii
I.	INTRODUCTION	1
II.	OBJECTIVES	5
III.	LITERATURE REVIEW	6
	3.1 Grain Production	6
	3.2 Grain Quality	7
	3.3 Equilibrium Moisture Content	8
	3.4 Moisture Adsorption and Desorption of grain	10
	3.4.1 Hysteresis Effect	11
	3.5 Cooling Theory	17
	3.5.1 Types of Coolers	17
	3.6 Grain Moisture Content Before Harvesting	18
	3.7 Cooling Immediately Before Drying	21
	3.8 Cooling Immediately After Drying	24
	3.8.1 Tempering Between Drying and Cooling	26
	3.8.2 Dryeration	29
	3.9 Cooling in Storage	31

Page

IV. EXPERIMENTAL 33

4.1 Cooling After Drying 33

4.1.1 Cooler 34
4.1.2 Grain 34
4.1.3 Grain Flow Rate 34
4.1.4 Temperatures 36
4.1.5 Air Flow Rate 37
4.1.6 Moisture Content 37

4.2 Procedure 39
4.3 Auxiliary Equations 40

4.3.1 Heat and Mass Transfer Equations . . 40

4.3.1.1 Latent heat of vaporization . 40
4.3.1.2 Specific heat
- For the specific heat of the air 41
- For the specific heat of the corn 41

4.3.2 Airflow Rate Calculation 41
4.3.3 Moisture Removed 42
4.3.4 Heat Balance 43
4.3.5 Latent/Total Heat Ratio 44

V. RESULTS AND DISCUSSION 46

5.1 Experiment 1 48

5.1.1 Comments on Experiment 1 48

5.2 Experiment 2 57

5.2.1 Comments on Experiment 2 58

5.3 Experiment 3 66

5.3.1 Comments on Experiment 3 74

5.4 Experiment 4 75

5.4.1 Comments on Experiment 4 83

5.5 Experiment 5 84

5.5.1 Comments on Experiment 5 92

Page

5.6 Experiment 6 94

5.6.1 Comments on Experiment 6 94

5.7 Comments on Experiments 1-6 106

VI. CONCLUSIONS 110

VII. SUGGESTIONS FOR FURTHER STUDIES 112

REFERENCES 113

LIST OF TABLES

Table		Page
1	Average monthly dry bulb temperature (^{o}C) and relative humidity (%) in four states of Southern Brazil during 1979	3
2	Production of cereal grain in the world, United States, and Brazil during the period of 1973 to 1982	7
3	Comparison of rate of moisture adsorption by grains initially at different moisture contents before being subjected to approximately the same pressure increases	13
4	Drying and rewetting of soft red winter wheat .	15
5	Desorption and adsorption EMC (% w.b.) of shelled corn at $72^{o}F$	16
6	Safe corn storage period (days)	25
7	Effect of tempering rice followed by cooling by aeration upon the amount of moisture removed during the cooling and upon the milling yield	28
7A	Corn and air temperatures for drying at 100 cfm/bu, followed by 4 hours tempering, and cooling at 20 cfm/bu	30
8	Table of experiments with experimental conditions	47
9	Inlet and outlet air conditions in experiment 1 in which the Ga/Gp ratio values are 0.18 , 0.19 , and 0.19 w.b., respectively, during the first, second and third pass of the corn through the dryer/cooler system	49
10	Experimental bed temperature in the cooling bed and calculated outlet grain temperature in experiment 1	50
11	Air and grain inlet and outlet temperatures in experiment 1	52

Table | Page

12 Experimental grain moisture content and moisture removed (MR) per hour in experiment 1 . . . 53

13 Heat balance in experiment 1 with Ga/Gp ratios of 0.18 , 0.19 , and 0.19 respectively during the 1,2, and 3 hours of operation 54

14 Inlet and outlet air conditions in experiment 2 in which the Ga/Gp ratio values are 0.29, 0.19, and 0.18 w.b., respectively, during the three hours of operation 59

15 Experimental bed temperatures in the cooling bed and calculated outlet grain temperature in experiment 2 60

16 Experimental air and grain inlet and outlet temperatures in experiment 2 62

17 Experimental grain moisture content and moisture removed (MR) per hour in experiment 2 . . . 63

18 Heat balance in experiment 2 with GA/Gp ratios of 0.29, 0.19, and 0.18, respectively during the 1, 2, and 3 hours of operation 64

19 Inlet and outlet air conditions in experiment 3 in which the Ga/Gp ratio values are 0.67, 0.45, and 0.41 w.b., respectively, during the three hours of operation 67

20 Experimental bed temperature in the cooling bed and calculated outlet grain temperature in experiment 3 68

21 Experimental air and grain inlet and outlet temperatures in experiment 3 70

22 Experimental grain moisture content and moisture removed (MR) per hour in experiment 3 . . . 71

23 Heat balance in experiment 3 with Ga/Gp ratios of 0.67, 0.45, and 0.41, respectively during the 1, 2, and 3 hours of operation 72

24 Inlet and outlet air conditions in experiment 4 in which the Ga/Gp ratio value is 0.25 w.b. 76

25 Experimental bed temperature in the cooling bed and calculated outlet grain temperature in experiment 4 77

Table Page

26 Experimental air and grain inlet and outlet temperatures in experiment 4 79

27 Temperature at the same level (4.7 inches (12.0 cm)) from top of the cooler in experiment 4 80

28 Experimental grain moisture content and moisture removed (MR) per hour in experiment 4 . 81

29 Heat balance in experiment 4 with a (Ga/Gp) wet ratio of 0.25, during the 2-hour cooling operation 82

30 Inlet and outlet air conditions in experiment 5 in which the Ga/Gp ratio value is 0.43 w.b. 85

31 Experimental bed temperature in the cooling bed and calculated outlet grain temperature in experiment 5 86

32 Experimental air and grain inlet and outlet temperature in experiment 5 88

33 Temperature at the same level (4.7 inches (12.0 cm)) from top of the cooler in experiment 5 89

34 Experimental grain moisture content and moisture removed per hour in experiment 5 . . . 90

35 Heat balance in experiment 5 with a Ga/Gp ratio value of 0.43 w.b., during the 2-hour cooling operation 91

36 Inlet and outlet air conditions in experiment 6 in which the Ga/Gp ratio value is 0.34 w.b. 95

37 Experimental bed temperature in the cooling bed and calculated outlet grain temperature in experiment 6 96

38 Experimental air and grain inlet and outlet temperatures in experiment 6 99

39 Moisture content changes during the cooling process in experiment 6 with a Ga/Gp ratio of 0.34 w.b. 100

Table		Page

Table		Page
40	Experimental grain moisture content and moisture removed (M.R.) per hour in experiment 6	102
41	Heat balance in experiment 6 with a Ga/Gp ratio value of 0.34 w.b.	103
42	Major results of tests 1-6	107

LIST OF FIGURES

Figure		Page
1	Concurrent flow grain cooling system	19
2	Counter flow grain cooling system	19
3	Cross flow grain cooling system	19
4	Mixing flow grain cooling system	19
5	Block diagram of concurrent flow dryer with counter flow cooler	35
6	Schematic of the pilot-scale concurrent flow dryer and counter flow cooler showing the thermocouple locations (dots).	38
6A	Thermocouple positions at the 4.7 inch (12.0 cm) level from the inlet of the cooler . .	38
7	Temperature profile in the cooling bed during cooling in experiment 1	51
8	Latent/total heat ratio vs time during cooling in experiment 1	55
9	Temperature profile in the cooling bed during cooling in experiment 2	61
10	Latent/total heat ratio vs time during cooling in experiment 2	65
11	Temperature profile in the cooling bed during cooling in experiment 3	69
12	Latent/total heat ratio vs time during cooling in experiment 3	73
13	Temperature profile in the cooling bed during cooling in experiment 4	78
14	Temperature profile in the cooling bed during cooling in experiment 5	87
15	Temperature profile in the cooling bed during cooling in experiment 6	98

Figure		Page

16 Grain moisture content and temperature profiles during a specific cooling period in experiment 6 101

17 Latent/total heat ratio vs time during cooling in experiment 6 104

LIST OF SYMBOLS

BD	Bed depth, ft.
Ca	Specific heat of the air, BTU/lb°F.
Cp	Specific heat of the product, BTU/lb°F.
Ga	Air flow rate, lb/h ft^2.
Gp	Grain flow rate, lb/h ft^2.
hfg	Latent heat of vaporization, BTU/lb.
M	Average moisture content, decimal dry basis.
MC	Moisture content, percent dry basis or otherwise specified.
MF	Final moisture content, percent dry basis or otherwise specified.
MO	Initial moisture content, percent dry basis or otherwise specified.
MR	Moisture removed, lb/h.
MRa	Moisture removed from or to the air, lb/h.
MRp	Moisture removed from or to the product, lb/h.
RH	Relative humidity, percent.
SP	Static pressure due to airflow inches of water.
T	Cooling air temperature, °F or otherwise specified.
W	Humidity ratio, lb water/lb dry air.
θ	Grain temperature, °F or otherwise specified.
ρ	Density of the air, lb/ft^3.

CHAPTER 1

INTRODUCTION

Providing an adequate food reserve is possible in two ways. The first one is through production, in which a lot of effort is made in a short period of time (3-5 months in the case of grain). The second is through conservation, which can take a few days or years. Each time the grain storage period increases, the more complex it becomes to manage a storage facility and maintain quantity and quality of the stored-grain.

There are major problems when dealing with grain storage: moisture content, insects and mold. In order to solve moisture content problems, the cheapest way is drying. When drying, the grain is usually heated to increase the water vapor pressure in the grain to facilitate moisture removal. Cooling is required after drying, because high temperatures can cause deterioration during the storage period.

When cooling takes place in a drying process, many factors are important. This process can cause serious damage to the grain kernels. Fissuring and breakage can occur as well as rewetting of the kernels.

The main purpose is to take the water out of the grain during the drying and cooling stages. Depending on the climatic and grain conditions, the grain can lose or gain water during the cooling period.

To improve the overall energy efficiency of the drying process, it is recommended that some drying be carried out during the cooling process. Many efforts have been conducted to overcome unfavorable climatic conditions; additional studies are necessary to supply necessary information.

Cooling is an operation necessary to maintain grain quality, and to improve drying efficiency. It is not only used after drying, but also during the storage period in order to protect grain against insects, mold, and deterioration.

Another use for cooling is before the grain is dried. Grain can be kept at a high moisture content for a short period of time when properly ventilated, even when the climatic conditions are unfavorable. To deal with high moisture content grain, insects, and molds is not an easy task, especially not in Southern Brazil where the climatic conditions are unfavorable for grain storage. As shown in Table 1, grain in Brazil is harvested during hot and humid seasons. This requires special care in the control of the grain moisture content, the insects, and the mold growth. Cooling plays a very important role also in Brazil, because cooling helps to improve the quality of the harvested crop.

Countries, like Brazil, which are increasing agricultural production very fast, need not only to develop their

Table 1. Average monthly dry bulb temperature (^{o}C) and relative humidity (%) in four states of Southern Brazil during 1979.

States / Months	Sao Paulo		Parana		S. Catarina		R.G. Sul.	
	T (^{o}C)	RH(%)	T (^{o}C)	RH(%)	T (^{o}C)	RH(%)	T (^{o}C)	RH(%)
January	12.4	80	17.8	81	22.9	75	23.2	63
February*	24.0	80	20.3	79	24.7	79	24.4	73
March*	20.4	77	18.1	82	22.4	81	21.6	75
April*	18.7	79	16.2	82	20.6	81	18.6	81
May*	17.9	76	14.1	80	17.2	80	14.9	79
June	15.6	75	12.0	80	14.4	83	12.4	80
July	15.0	73	11.7	78	15.0	82	13.5	78
August	18.0	79	15.1	80	17.8	84	16.2	83
September*	17.2	81	14.2	84	17.3	81	15.8	74
October*	20.4	79	17.5	82	20.6	84	19.1	82
November*	19.9	81	17.1	81	21.0	80	20.4	71
December	21.7	83	19.6	82	23.7	79	22.9	75
Averages	18.4	79	16.1	81	19.8	81	18.6	76

* Harvest season in Southern Brazil.

Note: Meteorological observations were taken at the capital city of each state.

production technology, but also to improve their conservation techniques. This involves training of personnel and development of appropriate physical facilities.

To be successful in a modern grain storage operation, it is important to employ up-to-date technology over the total storage period.

CHAPTER 2

OBJECTIVES

The main purpose of this research is to analyze the counterflow cooling of shelled corn after the drying process. The specific objectives are:

(1) To collect data on the cooling rate of shelled corn in a pilot-scale counterflow cooler.

(2) To measure the effects of inlet air temperature and the inlet grain temperature on the cooling rate of the grain.

(3) To measure the moisture content change (adsorption or desorption) of the grain during the cooling process.

(4) To measure the effects of grain flow rate and air flow rate on grain cooling.

(5) To measure the effects of bed depth changes on the grain cooling process.

CHAPTER 3

LITERATURE REVIEW

3.1 GRAIN PRODUCTION

Wheat is the most produced grain crop in the world, followed by rice. Corn is the leading grain crop in the United States; Brazil is the largest producer of coffee in the world (FAO, 1978-1982). Grains are the major source of food for humans and for animals. The above cited grains are important as well as barley, oats, rye, sorghum and soybeans.

Grain production has increased rapidly, largely as a result of new varieties, fertilizers, and weed and insect control measures. The increase in production, as shown in Table 2, necessitates continued emphasis on postharvest operations in order to economically preserve the crop produced.

Grain production is periodic, while the need for food occurs throughout the year. So storage is a necessity to ensure proper distribution and a stable price to the consumer. This can be accomplished by establishing a network of storage facilities, adequately distributed over the production and consumption areas. Such facilities should be equipped with drying, cleaning, handling, and cooling

Table 2. Production of cereal grain* in the World, United States, and Brazil during the period of 1973 to 1982.

Year	PRODUCTION (1,000,000 MT)		
	World	United States	Brazil
1973	1,377.1	237.6	23.6
1974	1,334.9	204.4	27.3
1975	1,359.2	249.1	26.2
1976	1,479.9	258.1	31.2
1977	1,471.0	265.8	30.9
1978	1,601.9	276.5	24.0
1979	1,553.9	302.9	27.2
1980	1,565.0	269.6	33.2
1981	1,653.4	333.5	32.1
1982	1,695.1	338.9	34.0

Sources: -United States Department of Agriculture (1983)
-Food and Agriculture Organization (1978-1982)
-Anuario Estatistico do Brasil (1980)

MT = metric ton.

* Includes corn, rice, oats, barley, rye, and sorghum.

equipment to ensure the quality of grain during the storage period.

3.2 GRAIN QUALITY

Grains are classified in different grades according to visual and physiological criteria. Grain moisture content and percentage of foreign materials are among the criteria largely used in U.S. grain standards. Germination capability is used in the seed market. In Brazil, test weight is one of the major criteria in the wheat market.

The visual condition refers to the external appearance of a kernel such as a crack in the seed coat, a broken kernel, or separated cotyledones.

Many factors can affect the quality of grains such as: climatic conditions in the field, harvesting, handling, drying, cooling, storage and milling. In a processing plant, all previous operations are important because the damage will appear at the end of the process as a summation of the damage that occurred in each step.

Drying is one of the most important steps in a processing plant, not only because it can cause serious damage to the grains, but also because it is one of the most expensive operations in the grain processing system. Since heated air drying is the usual procedure, cooling will be necessary. Damage occurs when the hot grain kernels are suddenly cooled. Fissuring during cooling is directly related to the moisture and temperature gradients between the grain and the air.

Henderson (1954) studied short grain rice and concluded that fissuring during fast drying was due to an increase in temperature rather than a decrease in moisture in portions near the surface of the kernel. It was found that fissuring was also caused by a rapid increase in moisture which occurs in the field if dew accumulates on the kernels.

Kunze (1965) reported that cracking occurred when brown rice, equilibrated at a particular humidity, was subjected to a high moisture environment. The degree of cracking is dependent on the magnitude of the change in relative humidity. Kunze hypothesized that adsorptive fissures are caused when external cells expand by adsorbing moisture, producing compressive stress in the surface layers.

Wasserman (1972) concluded that when high moisture content air is used in a fixed bed dryer, rewetting of some of the grain occurs causing serious quality deterioration. Wasserman made the following recommendations to overcome the problem of rewetting: (1) use supplemental heat when the relative humidity is above 75% for a prolonged period, and (2) provide enough energy to raise the air temperature about 12.0°F (6.7°C).

Normally, damage caused to grain kernels during drying and cooling is not measured separately. Therefore, it is hard to distinguish which damage to attribute to drying and which to cooling. Further studies are necessary in the cooling stage, in order to determine the cause of the damage to the grain kernels.

In Brazil, broken kernels and separated cotyledones are considered damaged kernels and cannot be more than 1.0 percent when summed with foreign materials. Fissuring is not considered damage in the Brazilian grain market, except in the case of rice. Germination capability is also used in the seed market only.

3.3 EQUILIBRIUM MOISTURE CONTENT

The equilibrium moisture content (EMC) refers to the quantity of moisture in the product when it is in equilibrium with the surrounding environment, usually air. The EMC of grain depends on the air temperature and humidity, the grain variety, the maturity and the previous history. In addition, the EMC will depend on whether or not the grain adsorbed or desorbed moisture to achieve equilibrium. The EMC achieved by desorption is higher than that achieved by adsorption. This phenomenon is referred to as the "hysteresis effect." The relative humidity of the air surrounding the grain in equilibrium with its environment is called the equilibrium relative humidity.

Several EMC equations are available for grains. Some are specific for grains while others can predict the EMC for different agricultural products, by varying one or more coefficients in the equations. Variations in the EMC values reported for one product at the same relative humidity and temperature are common. Some of the causes responsible for the variation are:

(1) a difference in moisture equilibrium determination;

(2) an experimental error in the EMC determination, resulting from difficulties in maintaining and measuring the relative humidity and temperature while a sample equilibrates;

(3) inaccurate measurement of the moisture content and relative humidity; and

(4) the grains are of different varieties and have different histories.

One of the best known relationships for predicting the EMC of grains is the semi-empirical model proposed by Henderson (1952):

$$1 - (P_v/P_{vs}) = \mathrm{Exp}\,(-hT_{abs}M^i) \quad (1)$$

where M is the moisture equilibrium content (%d.b.) and h and i are product constants; P_v and P_{vs} are vapor pressure of the surrounding air and vapor pressure at the saturation point, respectively; T_{abs} is the absolute temperature. Other EMC equations can be found in the literature (Brooker et al., 1974).

3.4 MOISTURE ADSORPTION AND DESORPTION OF GRAIN

Grain is a living organism. It is hygroscopic and adsorbs or desorbs moisture as the temperature and humidity conditions change. Many studies have been conducted on the drying (desorption of moisture) of grain, but only a secondary interest has been shown in the wetting process (adsorption of moisture).

Moisture adsorption and desorption by grain kernels has been reported to cause cracking and fissuring damage to the grains (Kunze and Hall, 1967); no quantitative data was reported by these authors on the amount and rate of adsorption or desorption, which is necessary to produce damaged grains. However, it is known that the damage starts at the surface and can reach the center if the variations in temperature and moisture are great and take enough time.

Kunze and Hall (1967) studied moisture adsorption characteristics of brown rice. The highest adsorption rate occurred immediately after the grains were exposed to the more humid atmosphere. Fissuring did not start until after the period of peak adsorption, thus indicating that there was a lag between the highest rate of moisture adsorption and grain damage. It was also observed by the authors that the grains with the higher moisture content adsorbed moisture much faster than those with the low moisture content. The results are shown in Table 3.

Literature on grain drying has long indicated that moisture removal from low moisture grain is more difficult than from a high moisture grain (Kunze and Hall, 1967). Free water vapor in the atmosphere experiences a similar difficulty in being absorbed by dry grain. Thus, higher moisture-content grain will adsorb moisture more readily than will dry grain subjected to the same vapor pressure change at the same temperature (Kunze and Hall; 1967).

Table 3. Comparison of rate of moisture adsorption by brown rice initially at different moisture contents before being subjected to approximately the same vapor pressure increases.

Variety	Initial RH Percent	Initial EMC (db)	Final RH Percent	VP (PSI)	H_2O adsorbed in 23 h. grams	Ratio*
TEMPERATURE, 38°F						
Fortuna	59.6	15.2	86.7	0.030	0.0388	10.5 to 1
Fortuna	11.2	9.4	34.8	0.027	0.0037	
Century	59.6	15.2	86.7	0.030	0.0324	11.6 to 1
Century	11.2	9.4	34.8	0.027	0.0028	
Fortuna	59.6	15.2	100.0	0.045	0.0552	3.7 to 1
Fortuna	11.2	9.4	59.6	0.055	0.0149	
Century	59.6	15.2	100.0	0.045	0.0506	4.3 to 1
Century	11.2	9.4	59.6	0.055	0.0118	
TEMPERATURE, 68°F						
Fortuna	54.9	13.9	86.6	0.107	0.0682	9.2 to 1
Fortuna	11.2	7.8	33.6	0.077	0.0074	
Century	54.9	13.9	86.6	0.107	0.0522	9.3 to 1
Century	11.2	7.8	33.6	0.077	0.0056	
Fortuna	54.9	13.9	100.0	0.151	0.1230	4.3 to 1
Fortuna	11.2	7.8	54.9	0.150	0.0286	
Century	54.9	13.9	100.0	0.151	0.0971	4.9 to 1
Century	11.2	7.8	54.9	0.150	0.0198	

Source: Kunze and Hall (1967).

$$* \text{ Ratio} = \frac{\text{Grain moisture (db)} \times 10^{-3}}{\text{Grain moisture (db)} - \text{humidity ratio}}$$

Fortes et al. (1981) studied drying and rewetting (desorption and adsorption) of soft red winter wheat. The wheat was hand harvested from the very early stages of maturity (84 percent moisture content, d.b.) until the wheat moisture content had decreased to about 30 percent. Drying tests were performed on the day of harvesting. The conditions in which this experiment was conducted are shown in Table 4. Drying refers to desorption conditions and rewetting refers to adsorption conditions. Table 5 shows the difference between the desorption and adsorption isotherms for corn at 72.0^{o}F (22.2^{o}C). A number of theories have been advanced to explain the hysteresis effect in grains. The "ink bottle" theory is probably the best-known (Brooker et al., 1981).

3.4.1 Hysteresis Effect

Chung and Pfost (1967) conducted a series of tests of adsorption and desorption of water vapor at 122.0^{o}F (50.0^{o}C) using freshly harvested wheat. After three cycles of adsorption and desorption, the hysteresis loop disappeared. This phenomenon was explained by the concepts of shrinkage and crack formation. Cracks might be increased only during the first three adsorption-desorption cycles. Consequently, the availability of sorptive sites inside the grain kernels is changed only during these cycles and not subsequently.

Table 4. Drying and rewetting conditions of soft red winter wheat.

Harvest Date	Dry Bulb Temp. (^{o}C)	Relative Humidity (%)	M.C. at Harvest (decimal, db)	Air Velocity (m/s)
DRYING EXPERIMENTS				
29 June	47.0	33.8	0.864	1.50
1 July	47.0	33.8	0.667	1.50
5 July	47.0	33.8	0.341	1.50
6 July	47.0	33.8	0.292	1.50
7 July	67.5	13.3	0.256	1.61
7 July	47.0	33.8	0.211	1.50
7 July	47.0	33.8	0.200	1.50
7 July	26.7	41.2	0.211	1.40
7 July	87.0	5.6	0.211	1.71
REWETTING EXPERIMENTS				
---	26.1	96.2	0.120	1.40
---	26.1	91.3	0.123	1.40
---	37.8	84.8	0.125	1.50

Source: Fortes et al. (1981).

Table 5. Desorption and adsorption EMC (% w.b.) of shelled corn at 72.0°F (22.2°C).

RH (%)	Desorption	Adsorption
88.5	24.2	23.4
67.6	16.5	15.2
46.5	12.9	11.5
25.8	9.8	8.0
9.4	7.0	5.6

Source: Chung and Pfost (1967).

3.5 COOLING THEORY

The cooling of a moist material involves the simultaneous processes of heat and mass transfer. During the cooling of grain, air is used to carry heat from the grains and sometimes moisture. Heat, which comes with grain, is used to evaporate moisture from the kernels; moisture transfer of water occurs within the kernels and on the grain surfaces.

Grain and air conditions are the driving forces of the cooling process; relative temperatures and moisture contents determine the direction of the heat and moisture flow.

3.5.1 Type of Coolers

Basically, grains are cooled inside closed compartments. Sometimes open space, as on a floor, can be safely used when the amount of grain to be cooled is small. In most cases, a cooler can be defined as an extension of the dryer.

A cooler can be a silo, a bin, a portion of the dryer, or another compartment adapted for this function. A grain mass can be cooled in three ways:

(1) moving the grains through the air;

(2) moving the air through the grains; and

(3) moving both the air and the grains.

Based on the relative direction of the air and the grain, coolers can be classified in four categories:

(1) concurrent flow;

(2) counterflow;

(3) crossflow; and

(4) mixed flow.

These types of coolers are called continuous flow and are commonly used after drying, because they are attached to the dryer, forming a single processing unit.

The four types of coolers are illustrated in Figures 1, 2, 3, and 4.

The air flow/grain flow (Ga/Gp) ratio is one way to evaluate cooler efficiency. For example, a commercial crossflow dryer has a Ga/Gp ratio in the cooler of about 2.5 in order in removing 5.0 percentage points of moisture from corn (e.g., from 20-15 percent) (Bakker-Arkema et al., 1979). However, a commercial concurrent flow dryer, has a Ga/Gp ratio of about 0.4 for the same grain conditions (Bakker-Arkema, 1984).

In Brazil, cascade dryers are the most widely used with two-thirds of a typical unit used for the drying section and one-third for cooling section. The Ga/Gp ratio in the the cooler of such dryers is about 0.6 for the same conditions above cited.

3.6 GRAIN MOISTURE CONTENT BEFORE HARVESTING

Even in the field, where weather is the primary influence on the plants, grain kernels are subjected to stresses, which may cause formation of small fissures.

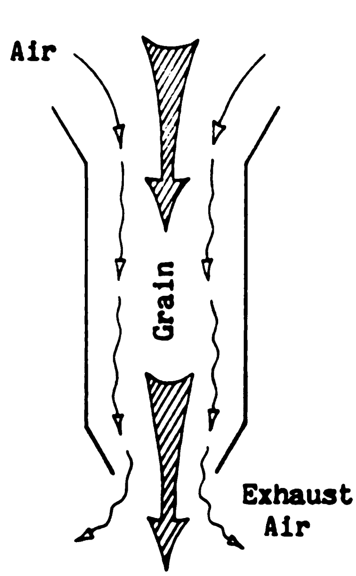


Figure 1. Concurrent flow grain cooling system.

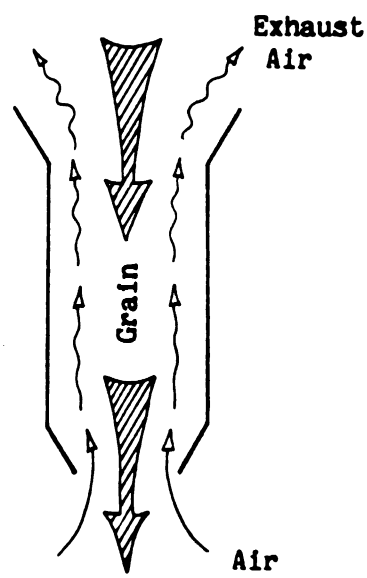


Figure 2. Counter flow grain cooling system.

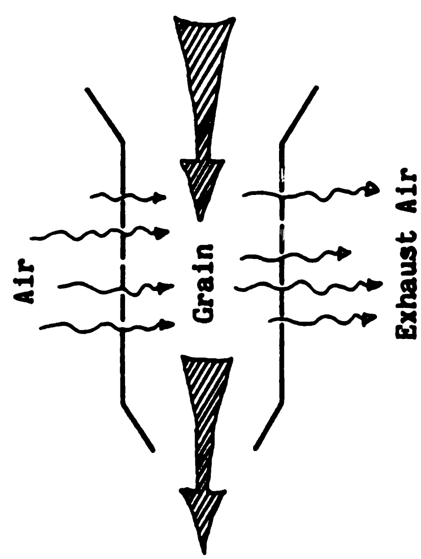


Figure 3. Cross flow grain cooling system.

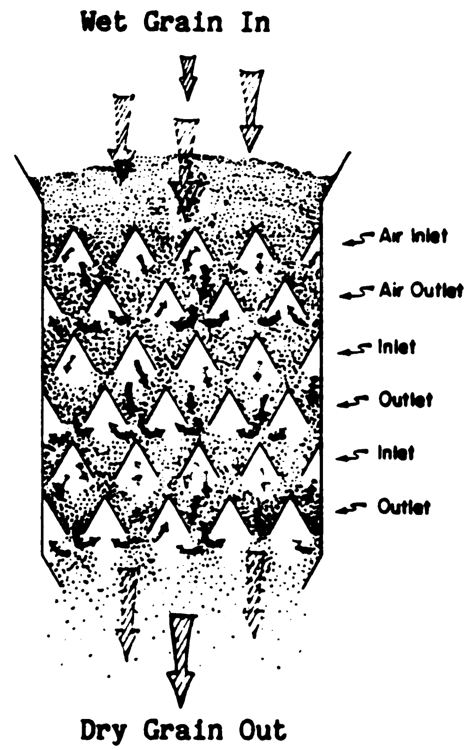


Figure 4. Mixing flow grain cooling system.

Climatic conditions cannot be managed. However, there are some growth factors which can be managed such as: seed-time, length of growing period, and harvest time.

From the drying and storage point of view, all the above cited factors are important, because in one way or another they will affect the subsequent operations. For example, harvest time is closely related to moisture content of grains, which may vary greatly from plant to plant, and sometimes on one plant.

Chau and Kunze (1982) studied medium grain rice in the field and concluded that the range in moisture content of grains in mature panicles was less than 10 percent (w.b.) when the average field moisture control of the rice was 22 percent. A variation up to 46 percent moisture content was observed among grains in immature panicles.

Variation among grain kernels has several reasons. The top of a plant matures faster than the bottom. Also, draught conditions after seeding causes some seeds to remain dormant until it rains. And thus, plants will germinate at different times, resulting in different maturation time and different moisture contents during the harvesting period. There are other sources of non-uniform maturation such as: fertilizer distribution, weeds, topography, soil, quality of seed, etc. (Brooker et al., 1974).

When the harvesting operation is delayed and the moisture in the air increases to a level whereby the grain is rewetted, serious damage may result to the grain.

3.7 COOLING IMMEDIATELY BEFORE DRYING

Between harvesting and storage drying is required to prepare the crop for safe storage. Frequently the drying capacity is lower than the harvesting capacity. Drying of grain can be done 24 hours a day. However, harvesting of the same crop is possible in 12 hours or less per day. On some days, it is impossible to harvest because of the weather and other factors that affect the operation. So, it is a common procedure to have a certain amount of wet grain waiting to be dried. If the waiting exceeds 24 hours, cooling should take place in order to maintain the grain free of insects and molds, and to maintain the temperature at an acceptable level to prevent deterioration due to the respiration process. This cooling/drying process is often called aeration.

Cooling of wet grain does not only keep the grain temperature at an acceptable level and prevent insect and mold development, but also helps the subsequent operations. During the cooling period, the moisture from one grain kernel will migrate to another through the air, which will result in equalization of the moisture content among the kernels. At the same time, the average grain moisture content decreases or increases slightly, depending upon the air and grain conditions.

Grain with a moisture content above an average of 18 percent usually loses moisture during cooling. Converse et al. (1973) studied cooling of high moisture corn in Kansas and concluded that storage conditions for the first few days are critical with regard to mold invasion. Delays in cooling increased mold invasion and the amount of deterioration in quality. Cooling as an adjunct to drying, to maintain quality during short-term storage, had to be started immediately after harvest.

Thompson (1972) studied the drying/cooling of high moisture shelled corn using ambient air. He concluded that under certain conditions the amount of grain deterioration is:

(1) doubled each time the airflow rate is halved, in the range of 0.5 to 2.0 cfm per bu (0.5 to 1.9 mcm/ton);
(2) halved for each 15 days delay in date of harvest;
(3) doubled for each 2 percent increase in moisture content, in the range of 20 to 25 percent;
(4) dependent upon the grain temperature and date of harvest.

Hodges et al. (1971) stored moist shelled corn in a bin at 35.0-40.0^{o}F (1.6-4.4^{o}C) for periods of 2, 4, and 8 days. To prevent mold growth, corn with 26 to 28 percent moisture content and an initial temperature of 70.0-90.0^{o}F (21.0-32.0^{o}C) should be cooled within 2 days. Biological activity was low for corn at 20 percent moisture content. High temperatures permitted rapid growth of <u>aspergillus flavus</u> whereas extensive growth of <u>Penicillium sp</u> occurred in corn held at 25-28 percent moisture content.

Calderwood (1966) conducted research using aeration to aid heated-air drying of rice. A series of aeration tests using small-sized bins showed a wide variation in the time rice could be maintained at its initial grade. The moisture content, ambient temperature, and airflow rate each affected the safe storage time. The use of aeration for additional drying, by cooling rice after one pass through the drier, reduced the dryer operating time. The heat absorbed by the rice was utilized more efficiently for drying when it was dissipated by aeration than when it was retained for preheating of rice for the next dryer pass.

Souza (1978) conducted research in cooling of wheat while holding the crop in a silo before drying. He concluded that wheat initially at 14-22 percent moisture content, reached an overall average moisture content about 17.0 $\pm$ 1.0 percent after 22 hours of aeration using natural air (58.0 percent average relative humidity and 71.6^{o}F (22.0^{o}C) average temperature), 1.0 percent less than initially. The grain temperature sometimes fell as low as 10.0^{o}F (5.5^{o}C) below ambient, maintaining the grain cool enough to protect it from spoilage during aeration period.

Cooling with natural air before drying can remove some water from the grain, equalize moisture content and reduce the temperature to levels below the ambient, because heat of vaporization takes place. So, it is a recommended procedure since it will aid the subsequent operations and will improve the final quality of the grain. Table 6 shows the safe corn storage period, relating moisture content and temperature.

3.8 COOLING IMMEDIATELY AFTER DRYING

Storage of grain is possible for short or long periods, given certain conditions. One of the main factors affecting the grain during storage is the moisture content, which can be reduced to acceptable levels by drying the product. This can be accomplished with unheated air or with heated air.

When natural unheated air is used, it is ready for safe storage as soon as the grain reaches the desirable level of moisture content. When heat is used to raise the temperature of the inlet air, subsequent cooling must take place, because the grain cannot be safely stored at high temperature levels. High temperatures can cause deterioration of the agricultural crop in a short period of time by respiration, insects, molds, etc. Thus, cooling plays a crucial role in many grain production systems.

Cooling after drying is usually assumed to remove some water from the grain, helping the drying process. Common values in the literature are between 0.5 to 1.0 percent of moisture (Brooker et al., 1974). In order to have any removal of water from the grain, the inlet air conditions should be favorable. The opposite will happen and the grain will absorb water, if the air conditions are not favorable. Absorption followed by desorption during cooling may cause fissuring and cracking of the grain kernels.

Table 6. Safe corn storage periods (days).

Storage air temperature, °C	Percent corn moisture content (w.b.)			
	15	20	25	30
23.9	116.0	12.1	4.3	2.6
21.1	155.0	16.1	5.8	3.5
18.3	207.0	21.5	7.8	4.6
15.6	259.0	27.0	9.6	5.8
12.8	337.0	35.0	12.5	7.5
10.0	466.0	48.0	17.0	10.0
7.2	725.0	75.0	27.0	16.0
4.4	906.0	94.0	34.0	20.0
1.7	1,140.0	118.0	42.0	25.0

Source: U.S.D.A. (1968).

Sabbah et al. (1972) studied cooling of shelled corn after drying. As the cooling air passed through the hot grain, heat was transferred from the grain to the air in two forms, as sensible heat and as latent heat. As the air flow rate increased, cooling attributed to moisture removal decreased. The air flow rate reached a level where the additional amount of moisture removed became insignificant; beyond that level, cooling occurred as a result of sensible heat transfer only.

3.8.1 Tempering Between Drying and Cooling

Tempering of grain is a practice used between drying and cooling and between passes during drying. Tempering is practiced to improve the energy efficiency of the grain drying process and to obtain a dried product of better quality. Gustafson et al. (1983) studied the effect of tempering of corn before cooling on the breakage susceptibility and moisture removal rate during cooling, and concluded that short-term tempering reduces the breakage susceptibility of grain. In addition, tempering causes more water to be removed during cooling, thereby improving the efficiency of the drying process. In a thin layer of corn, the breakage susceptibility decreased by 67 percent after 15 minutes of tempering and by 96 percent after 30 minutes. Approximately 50 percent of the improvement in moisture content removal occurred in the first 15 minutes of tempering and 70 percent during the first 30 minutes.

Steffe et al. (1979) studied the effects of tempering between dryer passes in rice, and concluded that tempering between dryer passes aids in removing moisture and maintaining head yield. In drying high-moisture rice (31.1 percent d.b.) at 100.0°F (38.0°C) by 3.0 to 4.5 percent per pass during a 20-minute drying period, a 35-minute tempering time is sufficient. For a 35-minute drying period at 122.0°F (50.0°C), a 20-minute tempering time is satisfactory and shorter times may be adequate. The prevailing environmental conditions were 79.0°F (26.0°C) and 31 percent relative humidity.

Calderwood and Webb (1971) studied the effects of tempering on rice. They concluded that tempering rice for periods up to 12 hours at a high temperature (Table 7) following drying did not significantly change the amount of moisture removed during a subsequent cooling cycle. The duration of the tempering period appeared to have no effect on the milling yield. Drying treatments, during which rice attained a maximum temperature of 122.0°F (50.0°C), appeared to have no adverse effects on the cooking quality. Table 7 shows the results of this research.

Sabbah (1971) studied the drying of corn at 100 cfm/bu followed by 4 hours of tempering, and cooling at 20 cfm/bu. He concluded that tempering increases the moisture removed during the cooling process. As the inlet cooler grain temperature increased, the grain was cooled faster due to

Table 7. Effect of tempering rice followed by cooling by aeration upon the amount of moisture removed during the cooling and upon the milling yield.

Variety	Tempering time h	Rice temperature leaving dryer (°C)		Moisture removed during cooling % w.b.	Milling yield		
		Ave.	Max.		control %	treated %	change %
Belle	0	43.9	44.4	1.0	52.6	48.7	-3.9
Patna	0	45.6	48.3	1.2	50.6	48.9	-1.7
	6	43.9	44.4	1.1	51.5	47.3	-4.2
	6	46.1	47.2	0.5	49.4	49.2	-0.2
	12	43.9	44.4	1.3	48.5	48.2	-0.3
	12	45.6	47.2	0.8	49.7	46.0	-3.7
Nato	0	45.0	45.6	1.0	66.4	67.1	+0.7
	0	43.9	45.0	1.4	66.4	65.5	-0.9
	6	43.9	46.1	1.2	65.4	64.0	-1.4
	6	43.9	45.0	0.8	67.2	64.6	-2.6
	12	43.9	44.4	1.4	65.3	64.0	-1.3
TP49	0	45.0	45.0	1.0	65.0	61.9	-3.1
	0	41.1	43.9	1.4	62.4	62.1	-0.3
	6	44.4	46.1	1.3	64.3	62.0	-2.3
	6	41.1	43.3	1.2	62.5	64.5	+2.0
	12	44.4	45.6	1.0	64.1	60.2	-3.9
	12	42.2	43.9	1.1	63.0	63.2	+0.2

Source: Calderwood and Webb (1971).

the increased mass transfer during the cooling process after tempering. The results are shown in Table 7A.

3.8.1.1 Dryeration

Foster (1964) developed a new method of grain drying known as dryeration, which consists of three stages. Dryeration was developed to improve the quality of dried grain. The three stages are:

(a) rapid drying with heated air to a moisture level two to three percentage points higher than the desired final moisture level;

(b) tempering without air flow for a prescribed length of time, and;

(c) cooling the grain slowly at a low air flow rate to remove the final two to three percentage points of moisture utilizing the heat in the grain.

A field study by Thompson and Foster (1967) on dryeration of shelled corn showed that the amount of moisture removed during cooling increased as the tempering time increased. Under one set of drying conditions using heated air [187.0°F (86.0°C)], they found that the amount of moisture removed during the cooling process was higher after an 8-hour tempering period than after either a 2-4 hour or a 12-hour tempering period. Thus, there appears to be an optimal length of time for tempering.

Table 7A. Corn and air temperatures for drying at 100 cfm/bu, followed by 4 hours tempering, and cooling at 20 cfm/bu.

TIME	A_1*	G_1**	A_2	G_2	A_4	G_4	A_7	G_7	A_8	G_8
START DRYING										
0	47	47	47	47	47	47	47	47	47	47
10	151	151	136	134	118	113	67	67	67	67
77	168	168	165	165	162	161	140	139	135	133
STOP DRYING AND START TEMPERING										
0	168	168	165	165	162	161	140	139	135	133
120	158	158	158	158	158	158	144	143	138	138
240	148	148	148	148	148	148	143	142	140	140
STOP TEMPERING AND START COOLING										
0	148	148	148	148	148	148	143	142	140	140
5	113	115	121	121	122	122	121	121	120	120
10	90	91.5	105	108	113	114	114	114	113	113
20	71	71	78	80	92	93	98	99	100	100
30	64	64	66	66	71	73	94	94	94	94
40	63	63	63	63	64	65	87	88	88	88
60	63	63	63	63	63	63	63	70	73	74
80	63	63	63	63	63	63	63	63	64	65
STOP COOLING										

Source: Sabbah (1971)

* Air temperature, ^oF
** Grain temperature, ^oF

3.9 COOLING IN STORAGE

In stored grain, insect infestation is a cyclic problem. The repeated use of insecticides has caused residue problems. The trend in government regulations has been to reduce chemical-residue tolerance in stored food and feed grains.

A storage method which provides a low-temperature environment offers an alternative solution to insect and mold control and to decrease respiration rate. Aeration in which the dried grain is treated periodically with ambient air at a low flow rate, guarantees the low temperature environment. The air flow rate is between 0.1 and 0.01 cfm/bu depending on the size of the storage.

Moisture losses during aeration are usually between 0.3 and 0.6 percent. The effect of aerating with air at relative humidity not in equilibrium with the grain has been considered by Foster (1967). Grain at 12.0 percent moisture content and 80.0°F (16.7°C) was cooled with air at 50.0°F (10.0°C) and 100 percent relative humidity. Upon entering the grain, the saturated air gave up moisture to the grain until equilibrium was reached. If the process proceeded adiabatically, heat released from the condensation of the moisture added to the grain would warm the air to 57.0°F (13.9°C). The grain between the cooling zone and the slower moving wetting zone cannot be cooled to below 57.0°F (13.9°C). Only the grain in contact with the entering air would be cooled to the entering temperature of 50.0°F

(10.0°C), since it would reach a moisture content in equilibrium with the saturated air. Thus, the amount of temperature reduction possible in saturated air cooling is less than with air in moisture equilibrium with the grain due to condensation.

The cooling times ranged from 17.5 hours at an airflow rate of 0.8 cfm/bu (0.9 MCM/ton) to 48 hours at an airflow rate of 0.2 cfm/bu (0.2 MCM/ton). The cooling time at 0.5 cfm/bu (0.5 MCM/ton) airflow rate averaged 23 hours. The cooling due to evaporation of moisture from the wheat was 54 percent of the total. The cooling air conditions were: air temperature 50.0°F (10.0°C) and relative humidity in moisture equilibrium. The initial grain temperature was 80.0°F (26.7°C).

CHAPTER 4

EXPERIMENTAL

4.1 COOLING AFTER DRYING

During the fall of 1983 and summer of 1984, corn was dried and cooled in a pilot-scale concurrent flow dryer located in the processing laboratory in the Agricultural Engineering Department at Michigan State University. The concurrent flow dryer consists of a single drying stage and a counterflow cooling stage.

The overall dimensions are: a cross-sectional area of 1.0 ft^2 (0.0929 m^2) and a length of 1.0 ft (0.3048 m).

A bucket elevator carries the grain into the dryer and an auger, driven by a variable speed motor, transports the grain from the dryer. The variable speed auger controls the grain flow rate through the dryer.

Liquid propane provides the fuel for the burner. The drying air temperature is measured by an iron-constantan thermocouple (type J) with an accuracy of $\pm$ 4.0^{o}F ($\pm$ 2.2^{o}C).

The drying air is supplied by an 8.0 in. (20.3 cm) diameter fan driven by a 3/4 horsepower (0.56 kw) electrical motor.

The moisture content was obtained by sampling the corn at 10-minute intervals as the dryer was being filled.

4.1.1 Cooler

The counterflow cooler has a cross-sectional area of 1.0 ft^2 (0.0929 m^2); the length is 3.0 ft (0.91 m). The cooler is not insulated. The connection between the dryer and the cooler consists of a 4.0 in. (10.2 cm) diameter auger. The grain is moved from the cooler by a 4.0 in. (10.2 cm) diameter auger. The natural air used to cool the grain was forced through the grain by a 2.0 Hp (1.49 kw) centrifugal fan. A schematic of the cooler/dryer system is shown in Figure 5.

4.1.2 Grain

Corn of an unknown variety harvested in the fall of 1983 was used in the drying/cooling experiments.

Two sources of corn were used. The first one was from the Michigan State University farm; it was used in experiments 1, 4, 5, and 6. The second was from the Magg Farm--Clinton County, Michigan; it was used in experiments 2 and 3.

4.1.3 Grain Flow Rate

A variable speed DC motor powers the auger from the outlet of the concurrent section of the dryer to the upper part of the cooler. It controls the grain flow rate in the system. Determination of the grain flow rate was accomplished by recording the weight of the grain over a measured time period.

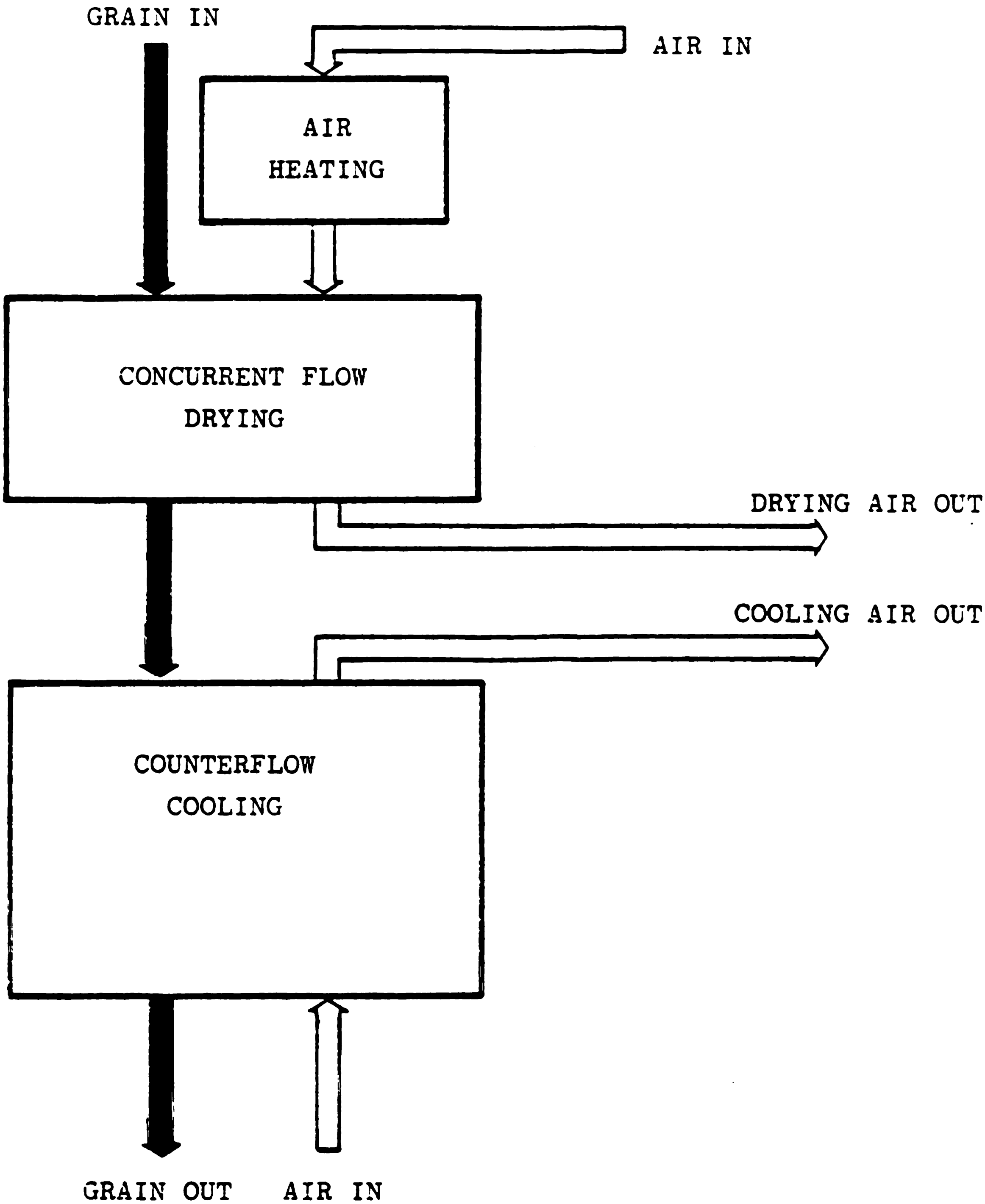


Figure 5: Block diagram of concurrent flow dryer with counter flow cooler.

The cooler holds 2.9 ft^3 (0.083 m^3) of grain. In order to fill the dryer and the transfer auger, an additional volume of 7.3 ft^3 (0.207 m^3) of grain is required.

4.1.4 Temperatures

The cooling air temperatures were measured by copper-constantan thermocouples (type T) with an accuracy of $\pm$0.5 percent; the temperatures were recorded by means of a 10 channel digital recording unit (Omega Engineering Model 199) in experiments 1, 2, and 3, and by means of a 16 channel recording unit (Digistrip II) in experiments 4, 5, and 6.

Three thermocouples were used as wet bulb thermometers. The inlet dry and wet bulb air temperatures were measured in two different positions. The first thermocouple measured the environmental temperature in the laboratory; it was placed close to the entrance of the air before the fan in such a way that no turbulence was present. The second point was located after the fan at the inlet air stream of the fan. The two thermocouples thus detected the rise in temperature in the fan. This rise was found to be, on the average, 1.0°F (0.5°C).

The dry and wet bulb temperatures were also measured at the cooler outlet. By measuring these temperatures, it is possible to calculate the exit air relative humidity and, consequently, the amount of water removed from or added to the grain in the cooler. The dry bulb temperatures were also measured along the length of the cooling section. In experiments 1, 2, and 3 the final temperature was evaluated by inserting a mercury-in-glass thermometer into the grain mass as it left the cooler. In experiments 4, 5, and 6, a thermocouple was used. Figure 6 shows the dryer, the cooler, and the thermocouple positions in the cooler.

4.1.5 Airflow Rate

In order to achieve two airflow rates, separate fans were placed at the inlet of the cooler. A 15.0 in. (38.1 cm) diameter fan attached to a 2.0 horsepower (1.49 kw) electrical motor produced an airflow rate of 206.8 lb/h ft^2 (47.0 cfm/ft^2) (8.7 kg/h m^2) at 1.4 in. static pressure, an additional 18.0 in (45.7 cm) diameter fan attached to a 5.0 horsepower (3.7 kw) electrical motor produced a combined airflow rate of 484.0 lb/h ft^2 (110.0 cfm/ft^2) (20.4 kg/h m^2) at 9.4 in. static pressure.

The connection between the fan and the cooler consists of a flexible plastic hose. A manometer was connected to the hose to read the static pressure required to calculate the airflow rate.

4.1.6 Moisture Content

The initial moisture content was obtained by sampling the grain as the dryer was being filled. Subsequent samples were taken during the tests by collecting cooled grain at regular time intervals. From those samples a small amount ($\pm$ 20 g) was taken to determine the moisture content. The difference between the inlet and outlet cooler grain moisture content was the value used to evaluate the efficiency

Figure 6. Schematic of the pilot-scale concurrent flow dryer and counter flow cooler, showing the thermocouple locations (dots).

Legend:

1 - Bucket elevator
2 - Grain storage hopper
3 - Natural grain airlock
4 - Heating air and grain boundary area
5 - Concurrent drying section
6 - Dryer exhaust
7 - Burner
8 - Grain flow rate metering auger
9 - DC motor
10 - Cooler exhaust
11 - Cooling section
12 - Cooling air entrance
13 - Cooling section discharge auger
14 - Cooler base.

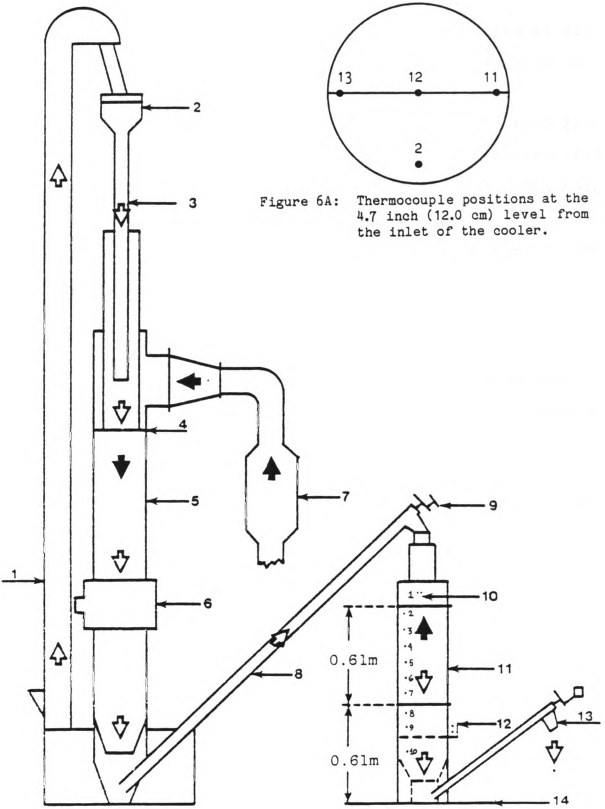


Figure 6A: Thermocouple positions at the 4.7 inch (12.0 cm) level from the inlet of the cooler.

Figure 6: Schematic of the pilot-scale concurrent flow dryer used in the laboratory, showing the thermocouple locations (dots).

of the cooler from the moisture removal point of view.

The moisture content was determined with an air oven heated to 217.0°F (102.7°C). Samples were kept in the oven for 72 hours.

All samples were collected in plastic bags and were stored until the grain temperature equilibrated with the surrounding environment at 68.0°F (20.0°C). The moisture content was determined, using whole grain.

A high accuracy scale was used to weigh the samples before and after placement in the oven.

4.2 PROCEDURE

The grain from the field was stored in burlap bags at room temperature about 68.0°F (20.0°C) for five days before the tests were performed.

The corn was heated (and partially dried) in the concurrent flow drying section described in Chapter 4. A short period of time for tempering (±10 min.) was allowed before cooling. The grain was fed by gravity through the cooler.

The corn samples and temperatures were taken at 10-minute intervals.

Several operating parameters were varied to study their effects on the cooling process: (1) grain flow rate--444, 480, 720, 840, 1065, 1100, and 1170 lb/h ft^2 (18.7, 20.3, 30.7, 35.5, 45.0, 46.5, and 49.4 kg/h m^2), (2) the airflow rate--206.8 and 484.0 lb/h ft^2 (8.7 and 20.4 kg/h m^2), and (3) the bed depth--2.0 and 3.0 ft (0.61 and 0.91 m).

The inlet grain temperature varied from approximately 90.0°F (32.2°C) to 150.0°F (65.5°C), and the inlet grain moisture content from about 8.0 to 20.0 percent.

The laboratory ambient temperature was approximately 70.0°F (21.1°C) for all tests; the relative humidity varied from about 15 percent to 80 percent.

4.3 AUXILIARY EQUATIONS

4.3.1 Heat and Mass Transfer Equations

The heat and mass transfer equations required for the cooling calculations were originally developed for the drying of grain, but are equally acceptable for cooling calculations.

4.3.1.1 Latent Heat of Vaporization

The energy required to evaporate or condensate moisture in a product is called the latent heat of vaporization (or condensation). Rodrigues-Arias (1956) proposed the following equation for the latent heat of vaporization for corn in the temperature range of 40.0 to 140.0°F (4.4 to 60.0°C).

$$hfg = (1{,}094.0 - 0.57\theta)\ [1 + 4.35\ \mathrm{Exp}\ (-2{,}825.0\ M)] \quad (2)$$

θ = grain temperature (°F)

M = average moisture content (decimal d.b.)

Lerew (1972) proposed a simplified equation for the latent heat of vaporization of corn:

$$hfg = 1{,}075.8965 - 0.56983\ (T - 459.69) \quad (3)$$

$491.69 \leq T \leq 609.69$

Note: The temperature (T) is in degrees Rankine.

4.3.1.2 Specific Heat

The specific can be treated as constant during the cooling process, since there are no great changes in the temperature during the cooling process.

For the specific heat of air (Holman, 1981):

$$Ca = 1.0057 \text{ KJ/Kg}^{\circ}\text{C} \tag{4}$$

The specific heat of corn, is dependent on the temperature and moisture content of the product. At 14.7 percent moisture content wet basis and a temperature of 54.0-83.8°F (12.2-28.8°C), the specific heat of corn is (Brooker et al., 1974):

$$Cp = 0.484 \text{ BTU/lb}^{\circ}\text{F } (4.187 \text{ KJ/}^{K}\text{g}^{\circ}\text{C}) \tag{5}$$

4.3.2 Airflow Rate Calculation

Calculation of the airflow rate is based on of the static pressure which was measured during the cooling operation (Brooker et al., 1981):

$$SP/BD = \text{pressure drop per foot of grain (inch } H_2O) \tag{6}$$

where: SP = static pressure (inch H_2O)

BD = bed depth (ft)

Packing factor = 1.0

The pressure drop per foot of grain and the grain species are the parameters needed. Then:

$$(\text{CFM/ft}^2) \times 60 \times \sigma = \text{Airflow (lb/h ft}^2) \qquad (7)$$

Where σ is measured at the ambient temperature.

The packing factor is related to the presence of foreign materials (FM) mixed with the grain. The FM tends, in general, to increase the resistance to air flow rate since the foreign material is usually of smaller equivalent diameter than that of the grain (Patterson, 1969). In this study, the packing factor is considered to be 1.0. If it had been 1.5, the air flow rate value of 206.8 lb/h ft^2 would have been 162.8 lb/h ft^2, and 484.0 lb/h ft^2 would have been 440.1 lb/h ft^2.

The fans used for the experimental cooler were over-dimensioned for the hose connecting the fan and the cooler; this made it impossible to use the characteristic fan curves to calculate the airflows.

4.3.3 Moisture Removed

During cooling, the grain kernel can absorb or lose water, depending upon the grain and air conditions. If evaporation takes place, the grain loses energy and the grain temperature decreases; if condensation takes place, the grain receives energy and the temperature increases. Sensible heat is the other form of energy removal from the grain.

The amount of water removed is expressed by the following equation:

$$MRp = Gp\ (Mo - Mf) \tag{8}$$

where

Mo and Mf = the initial and final moisture content, decimal d.b.

Gp = grain flow rate, lb per hour per square foot

MRp = moisture removed from the product, lb per hour per square foot.

The moisture removed can also be calculated from the air inlet and outlet cooler conditions. The amount of water received or lost by the grain is the same as that lost or received by the air:

$$MRa = Ga \times \Delta W \tag{9}$$

where

MRa = moisture removed from the air, lb per hour per square foot.

Ga = dry airflow rate, lb per hour per square foot.

ΔW = humidity ratio difference, lb of water per lb dry air.

4.3.4 Heat Balance

During the cooling process, the amount of energy extracted from the grain is equal to that received by the air. It is equal to the sum of the latent and sensible heat.

Thus,

$$Gp\ Cp\ \theta\Delta = Gp\ hfg\ \Delta Mp + Ga\ Ca\ \Delta T \qquad (10)$$

In equation (10) the losses of energy by convection and conduction through the walls of the cooler to the surrounding environment are assumed to be zero. Since the cooler is not insulated, a slight loss of sensible heat can take place. This is only significant when the air flow is very low.

4.3.5 Latent/Total Heat Ratio

The latent/total heat ratio is a measure of the cooling efficiency. The ratio varies from -1.0 to +1.0. A positive ratio, form 0.0 to +1.0, means that evaporation takes place and water is removed from the grain to the air, drying the grain during the cooling process. A negative ratio, from -1.0 to 0.0, means that condensation takes place, and water is added to the grain during the cooling process.

As cooling air passes through hot grain, heat is transferred from the grain to air in the form of sensible and latent heat. The ratio of sensible and latent heat flow is governed by both internal and external resistances. The equation for the latent/total heat ratio is:

$$\text{Ratio} = \frac{\text{latent heat}}{\text{total heat}} \quad \frac{Gp\ hfg\ \Delta Mp}{Ga\ Cp\ \Delta\theta} \qquad (11)$$

where both the latent and sensible heat are calculated from the air conditions.

The amount of heat that can be removed during cooling is limited. As the air flow rate increases, cooling attributed to sensible heat transfer increases, and cooling attributed to moisture removal decreases. The air flow rate can reach a level where the amount of moisture removed becomes insignificant, and therefore, all cooling is due to sensible heat transfer.

From the latent/total heat ratio, it is possible to evaluate whether or not the cooling process results in drying or rewetting of the grain. The ratio is also useful in analyzing the drying efficiency in the cooler and the final quality of the grain.

A small absolute value of the latent heat/total heat ratio of close to zero means that no or little mass transfer occurred in the cooler. A large ratio close to +1 or -1 indicates that considerable mass transfer occurred during the cooling process.

CHAPTER 5

RESULTS AND DISCUSSION

The analysis of the cooling immediately after drying is based on the data acquired during the test runs in the laboratory in a counter flow cooler with a concurrent flow grain dryer. Six experiments (1, 2, 3, 4, 5, and 6) have been conducted; the results are discussed in the following sections. A summary of the experimental conditions is shown in Table 8.

Table 8 shows the air flow rate (lb/h ft^2), the grain flow rate (lb/h ft^2), the bed depth (ft), the inlet grain temperature (^oF), and the inlet air temperature (^oF) during cooling in the six experiments.

Experiment 1 was conducted to investigate the moisture removal and temperature behavior during cooling of high moisture content grain after successive passes through the dryer without tempering between passes.

Grain was cooled only once in experiments 2 through 6. The effect of a variation in air flow rate was investigated in experiments 2 and 3.

Experiments 4 and 5 were conducted to investigate the effect of grain flow rate.

The effect of bed depth was studied in experiment 6.

Table 8. Table of experiments with experimental conditions.

Experiment number	Airflow* (wet lb/h ft^2)	Grainflow (wet lb/h ft^2)	$\frac{Ga}{Gp}$	Bed Depth (ft)	Inlet grain temperature (^oF)	Inlet air temperature (^oF)	Inlet cooler grain (% d.b.)
1	206.8	1100	0.18	2.0	101.2	70.0	19.85
1	206.8	1065	0.19	2.0	105.3	64.9	16.63
1	206.8	1065	0.19	2.0	113.5	64.5	13.98
2	206.8	720	0.29	2.0	106.8	70.1	14.94
2	206.8	1065	0.19	2.0	104.0	71.0	15.19
2	206.8	1170	0.18	2.0	101.1	69.5	15.32
3	484.0	720	0.67	2.0	97.0	72.5	14.12
3	484.0	1065	0.45	2.0	95.2	71.7	14.50
3	484.0	1170	0.41	2.0	95.2	71.1	14.37
4	206.8	840	0.25	2.0	128.2	85.6	12.96
5	206.8	480	0.43	2.0	144.8	88.6	10.20
6	149.6	444	0.34	3.0	131.3	67.8	8.97

1 lb/h ft^2 = 4.902 Kg/hm^2 = 0.227 cfm/ft^2 (at ambient conditions).
1 ft = 0.3048 m
F = (9/5)C + 32
* assuming a packing factor of 1.0

5.1 EXPERIMENT 1

Experiment 1 was conducted on October 31, 1983. Corn, originally at about 30 percent moisture content, was dried to approximately 20 percent and stored at 70°F (21.1°C) in burlap bags for two days. Subsequently, it was further dried and cooled in each pass through the concurrent flow dryer until the moisture content had reached about 13 percent. Ambient laboratory air was used to cool the grain mass after each drying pass.

The results are shown in Tables 9, 10, 11, 12, and 13 and in Figures 7 and 8.

5.1.1 Comments on Experiment 1

The inlet and outlet air conditions are shown in Table 9. During the three hours of the test, the air absorbed water from the grain. The desorption of water can be seen in the humidity ratio difference (ΔW) of about 0.028 lb H_2O/lb d.a. (28.0 g H_2O/Kg d.a.). The inlet relative humidity was about 40 percent; the outlet relative humidity varied from 45-80 percent. Between 5.5 and 6.1 lbs. of H_2O was removed from the corn per hour per ft^2.

The humidity ratio (W) and relative humidity (RH) were calculated from psychrometric data (ASHRAE, 1981). The outlet humidity ratio increased in value during the three-hour cooling period. Since the outlet wet-bulb temperature was not measured, the values used in the calculations of this experiment are the calculated values.

Table 9. Inlet and outlet air conditions in experiment 1 in which the Ga/Gp ratio values are 0.18 , 0.19 , and 0.19 w.b., respectively, during the first, second and third pass of the corn through the dryer/cooler system.

Pass	Ga*	INLET				OUTLET					ΔW	MR
	lb/h ft^2	Temperature (^{o}F)		R.H.	W	Temperature (^{o}F)			R.H.**	W**		
		Dry bulb	Wet bulb	%	$\frac{lb\ H_2O}{lb\ d.a.}$	Dry bulb	Wet bulb	Wet** bulb	%	$\frac{lb\ H_2O}{lb\ d.a.}$	$\frac{lb\ H_2O}{lb\ d.a.}$	$\frac{lb}{h\ ft^2}$
1	206.8	70.0	56.0	41.0	0.0064	101.2	96.0	95.5	79.0	0.0360	0.0296	6.13
2	206.8	64.9	52.6	44.0	0.0056	105.3	95.4	95.4	64.0	0.0340	0.0284	5.87
3	206.8	64.5	52.7	45.0	0.0058	113.5	96.7	96.0	46.0	0.0332	0.0274	5.56

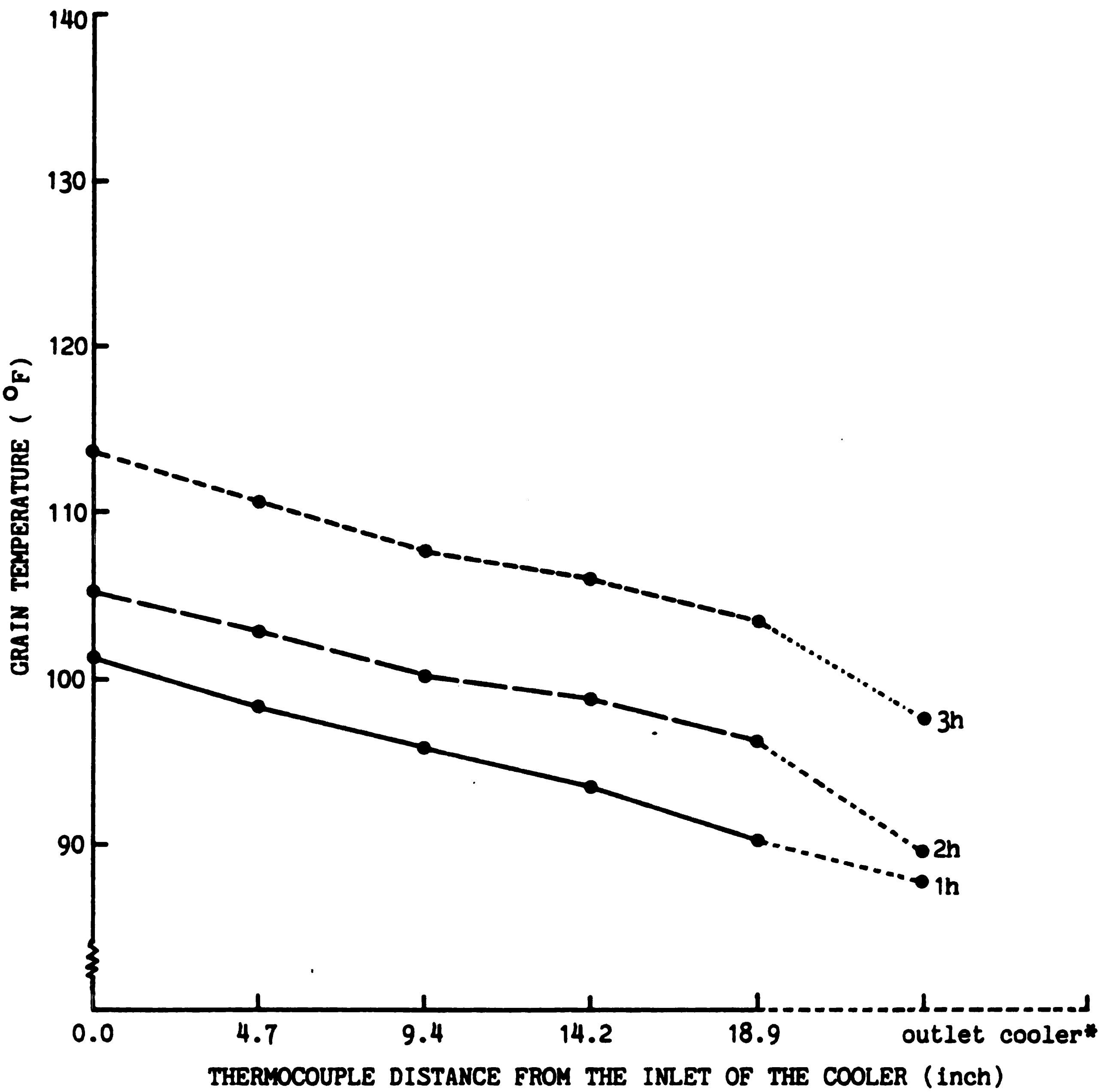
* Air flow rate (Ga)
** Calculated value.
Note: Each temperature is an average of six (6) measurements over the 3.5-hour period.
MR = moisture removed, lb per hour per square foot.
RH = relative humidity, percent.
W = humidity ratio, lb of water per lb of dry air.
1 lb/h ft^2 = 4.902 Kg/h m^2 = 0.227 cfm/ft^2 (at ambient conditions).
1 lb H_2O/lb d.a. = 1,000.0 g H_2O/Kg d.a.
F = (9/5)C + 32.

Table 10. Experimental bed temperatures in the cooling bed and calculated outlet grain temperature in experiment 1.

Time hour	TEMPERATURE (°F) THERMOCOUPLES 1	2	3	4	5	Out*	Δ T1 1-5	Δ T2 1-out*
0:10	98.8	96.1	94.6	91.8	89.8			
0.20	100.8	97.2	95.4	92.5	88.9			
0.30	101.2	97.9	95.4	92.5	88.9			
0.40	101.7	99.0	96.4	94.3	90.7			
0.50	101.8	99.3	96.8	94.3	91.8			
1.00	101.9	98.6	95.7	93.6	88.9			
1:10	102.4	100.0	97.5	95.4	92.5			
Average	101.2	98.3	96.0	93.5	90.2	87.9	11.0	13.3
1:20	103.8	101.5	99.0	97.5	95.0			
1:30	103.6	101.5	99.3	97.2	95.4			
1:40	103.4	101.1	97.9	96.4	94.3			
1:50	107.0	104.7	102.2	100.4	98.2			
2:00	108.9	106.2	104.0	102.6	99.3			
2:10	---	---	---	---	---			
2:20*	---	---	---	---	---			
Average	105.3	103.0	100.5	98.8	96.4	89.8	8.9	15.5
2:30	102.0	97.9	93.6	92.5	92.1			
2:40	110.5	108.0	105.1	102.9	100.0			
2:50	116.5	112.6	108.7	106.2	100.0			
3:00	113.0	110.1	106.9	105.4	103.3			
3:10	115.4	113.4	111.9	109.8	108.0			
3:20	117.5	115.2	113.4	112.3	109.4			
3:30	119.4	117.7	115.9	114.8	112.6			
Average	113.5	110.7	107.9	106.3	103.6	97.7	9.9	15.8

* Calculated values.

$F = \frac{9}{5} C + 32.$



* Calculated value .

Figure 7. Temperature profile in the cooling bed during cooling in experiment 1.

Table 11. Air and grain inlet and outlet temperatures in experiment 1.

Time hour	TEMPERATURE (^oF)					
	Grain out*	Air in	ΔT1	Grain in	Air out	ΔT2
0:10	---	77.0		98.8	98.8	
0:20	---	77.0		100.8	100.8	
0:30	---	70.2		101.2	101.2	
0:40	---	67.6		101.7	101.7	
0:50	---	66.9		101.8	101.8	
1:00	---	65.8		101.9	101.9	
1:10	---	65.8		102.4	102.4	
Average	87.9	70.0	17.9	101.2	101.2	
1:20	---	65.1		103.8	103.8	
1:30	---	65.5		103.6	103.6	
1:40	---	65.1		103.4	103.4	
1:50	---	64.4		107.0	107.0	
2:00	---	64.4		108.9	108.9	
2:10	---	---		---	---	
2:20	---	---		---	---	
Average	89.8	64.9	24.9	105.3	105.3	
2:30	---	64.4		102.0	102.0	
2:40	---	64.8		110.5	110.5	
2:50	---	64.8		116.5	116.5	
3:00	---	64.0		113.0	113.0	
3:10	---	64.4		115.4	115.4	
3:20	---	64.8		117.5	117.5	
3:30	---	64.4		119.4	119.4	
Average	97.7	64.5	33.2	113.5	113.5	

ΔT1 means the difference between the laboratory ambient temperature and the outlet grain temperature (outlet grain - inlet air).

Assumption: The outlet air temperature was assumed to be equal to the inlet grain temperature (ΔT2 = 0).

$F = \frac{9}{5} C + 32.$

Table 12. Experimental grain moisture content and moisture removed (MR) per hour in experiment 1.

Pass	Time hour	Gp lb/h ft^2	MOISTURE CONTENT (% d.b.) inlet dryer	inlet cooler	outlet cooler	ΔMC	MR lb/h ft^2
First	0:10	1100	23.30	20.16	19.40	0.76	
	0:20	1100	---	20.90	20.68	0.22	
	0:30	1100	22.41	20.29	19.35	0.94	
	0:40	1100	---	20.42	18.80	1.62	
	0:50	1100	22.41	19.62	19.47	0.15	
	1:00	1100	---	19.03	19.03	0.00	
	1:10	1100	22.68	18.54	17.70	0.84	
	Average	1100	22.70	19.85	19.20	0.65	6.13
Second	1:20	1065	19.54	18.20	17.70*	0.50	
	1:30	1065	---	17.87	17.75*	0.12	
	1:40	1065	18.92	17.30	16.71*	0.59	
	1:50	1065	---	16.74	16.41*	0.33	
	2:00	1065	18.41	16.06	16.09*	-0.03	
	2:10	1065	---	15.54	14.49*	1.05	
	2:20	1065	17.30	14.68	15.20*	-0.52	
	Average	1065	18.54	16.63	16.34*	0.29*	2.65*
Third	2:30	1065	15.85	15.53	14.90	0.63	
	2:40	1065	---	14.90	14.10	0.80	
	2:50	1065	15.85	14.23	12.90	1.33	
	3:00	1065	---	13.88	14.45	-0.57	
	3:10	1065	15.66	13.00	12.78	0.22	
	3:20	1065	---	13.13	12.68	0.45	
	3:30	1065	14.14	13.22	11.76	1.46	
	Average	1065	15.38	13.98	13.37	0.61	5.56

* Discharged values.
ΔMC means inlet-outlet cooler grain moisture content (% d.b.).
MR = moisture removed, lb per hour per square foot.
1 lb/h ft^2 = 4.902 Kg/h m^2.

Table 13. Heat balance in experiment 1 with Ga/Gp ratios of 0.18 , 0.19 , and 0.19 respectively during the 1, 2, and 3 hours of operation.

Time (hour)	HEAT (BTU/h)			Latent/Total Heat Ratio*
	Corn	Air		
	Sensible*	Sensible*	Latent*	
1	7787.21	1548.52	6238.69	0.801
2	7966.50	2005.13	5961.39	0.748
3	8150.57	2431.97	5718.60	0.702

* Values derived from equation 10.

1 BTU/h = 0.293 W.

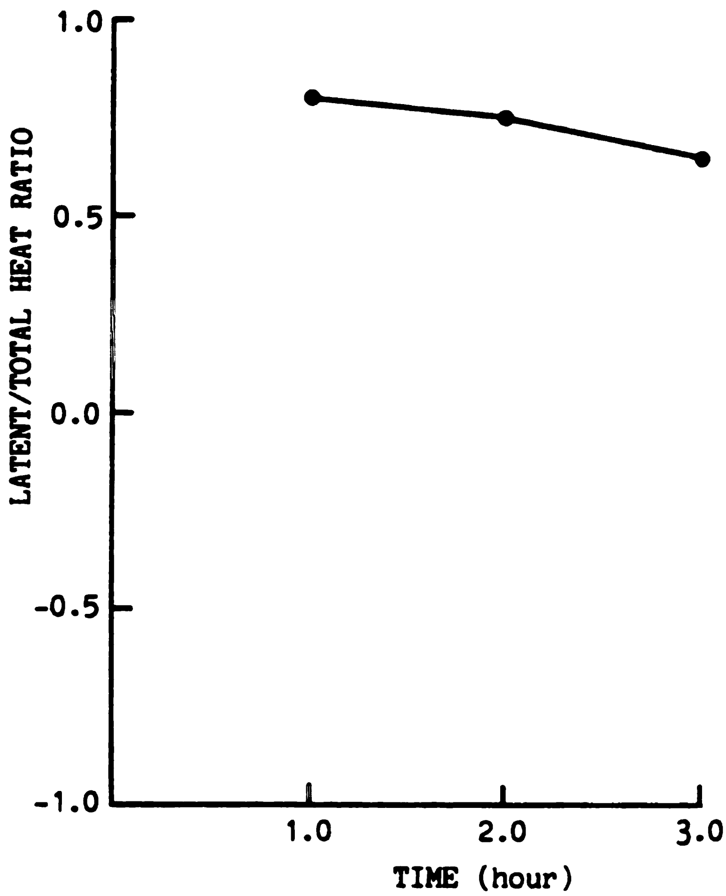


Figure 8. Latent/total heat ratio vs. time during cooling in experiment 1.

Table 10 and Figure 7 show the decrease in temperature as the grain flows through the cooler. Thermocouple 1 measured the inlet grain temperature, while thermocouple 5 measured the temperature at the position 18.9 inches (48.0 cm) from the inlet to the cooler. The outlet cooler grain temperature is a calculated value, based on equation 8. As the inlet grain temperature increased, the outlet grain temperature increased also. The difference between the inlet and calculated outlet grain temperature remained approximately constant during the second and third hour of the three-hour cooling period. The difference is due to the different inlet grain temperature.

Table 11 shows the air and grain inlet and outlet temperatures during the course of the experiment. The desired outlet grain temperature was about 10°F (5.5°C) above the ambient temperature. Table 11 shows that the outlet grain temperature was well above the recommended value during this experiment. As the inlet grain temperature increased, the outlet grain temperature increased also.

In Table 11 the inlet grain and the outlet air temperatures are assumed to be the same. The actual inlet grain temperature was not measured in this test.

Table 12 shows the moisture content change of the corn in the cooler. The data shows that the grain lost water during the three-hour cooling period. As the inlet moisture content decreased, the moisture removed during the cooling process decreased also. The fact that no tempering occurred between two passes, influenced this phenomenon. Since the measured moisture content values were erratic during the second hour of cooling, they were replaced with the calculated values.

Table 13 and Figure 8 show the heat balance and the latent/total heat ratio during the three hours of operation. The latent/total heat ratio was positive, which implies that evaporation took place during the whole period of cooling. Note that 70-80 percent of the cooling is due to evaporation during the cooling process, which implies an efficient cooling process.

In conclusion, the ambient air and grain conditions are the main factors that affect the cooling process. As the inlet grain temperature increased, the outlet grain temperature increased also. When the grain moisture content decreased, the amount of water removed during cooling decreased also. The moisture content decrease from about 20-13 percent caused a decrease in the value of the latent/total heat ratio from about 0.8 to about 0.7. The value of experiment 1 is limited because of the changing inlet grain condition.

5.2 EXPERIMENT 2

On December 12, 1983, corn, previously dried on the farm, was dried and cooled in a single pass of the pilot-scale concurrent flow drier located in the laboratory.

The corn initial moisture content was about 14.0 percent and among the grains were around 15 percent of broken kernels plus foreign material.

Three grain flow rates were studied (720, 1065, and 1170 lb/h ft^2 (3,529.4, 5,520.6, and 5,735.3 Kg/h m^2)) to observe their effects on the cooling rate and moisture removed. Each grain flow rate took an hour of operation.

The results are shown in Tables 14, 15, 16, 17, and 18 and in Figures 9 and 10.

5.2.1 Comments on Experiment 2

Table 14 shows the cooling air conditions. The air received water from the grain at 720, 1065 and 1170 lb/h ft^2 (3,529.4, 5,520.6, and 5,735.0 Kg/h m^2) of grain flow rate. In other words, the grain was dried in the cooler during the three-hour operation. The amount of water removed at 1065 lb/h ft^2 (5,520.6 Kg/hm^2) was the lowest in this experiment (Table 17); this may have been due to uncontrollable factors.

The relative humidity (RH) and the humidity ratio (W) shown in Table 14 were calculated from psychrometric data (ASHRAE, 1981).

Table 15 and Figure 9 show the temperature behavior during the cooling process. The inlet grain temperature remained almost constant. The slight variations noticed in the inlet temperature was also noticed in the outlet grain temperature.

Table 14. Inlet and outlet air conditions in experiment 2 in which the Ga/Gp ratio values are 0.29, 0.19, and 0.18 w.b., respectively, during the three hours of operation.

		INLET				OUTLET					ΔW	MR
Time	Ga*	Temperature (°F)		R.H.	W	Temperature (°F)			R.H.**	W**		
Hour	lb/h ft²	Dry bulb	Wet bulb	%	$\frac{lb\ H_2O}{lb\ d.a.}$	Dry bulb	Wet bulb	Wet** bulb	%	$\frac{lb\ H_2O}{lb\ d.a.}$	$\frac{lb\ H_2O}{lb\ d.a.}$	$\frac{lb}{h\ ft^2}$
1	206.8	70.1	53.7	30.0	0.0036	106.8	93.1	88.2	49.0	0.0248	0.0212	4.39
2	206.8	71.0	54.0	31.0	0.0050	104.0	93.8	86.0	50.0	0.0230	0.0180	3.73
3	206.8	69.5	53.1	30.0	0.0046	101.1	91.3	92.0	68.0	0.0323	0.0277	5.73

* Air flow rate (Ga)
** Calculated value.

Note: The experimental temperatures are averages of six (6) measurements over the 3-hour period.

MR = moisture removed, lb per hour per square foot.
RH = relative humidity, percent.
W = humidity ratio, lb of water per lb of dry air.
1 lb/h ft^2 = 4.902 Kg/h m^2 = 0.227 cfm/ft^2 (at ambient conditions).
1 lb H_2O/lb d.a. = 1,000.0 g H_2O/Kg d.a.
F = (9/5)C + 32.

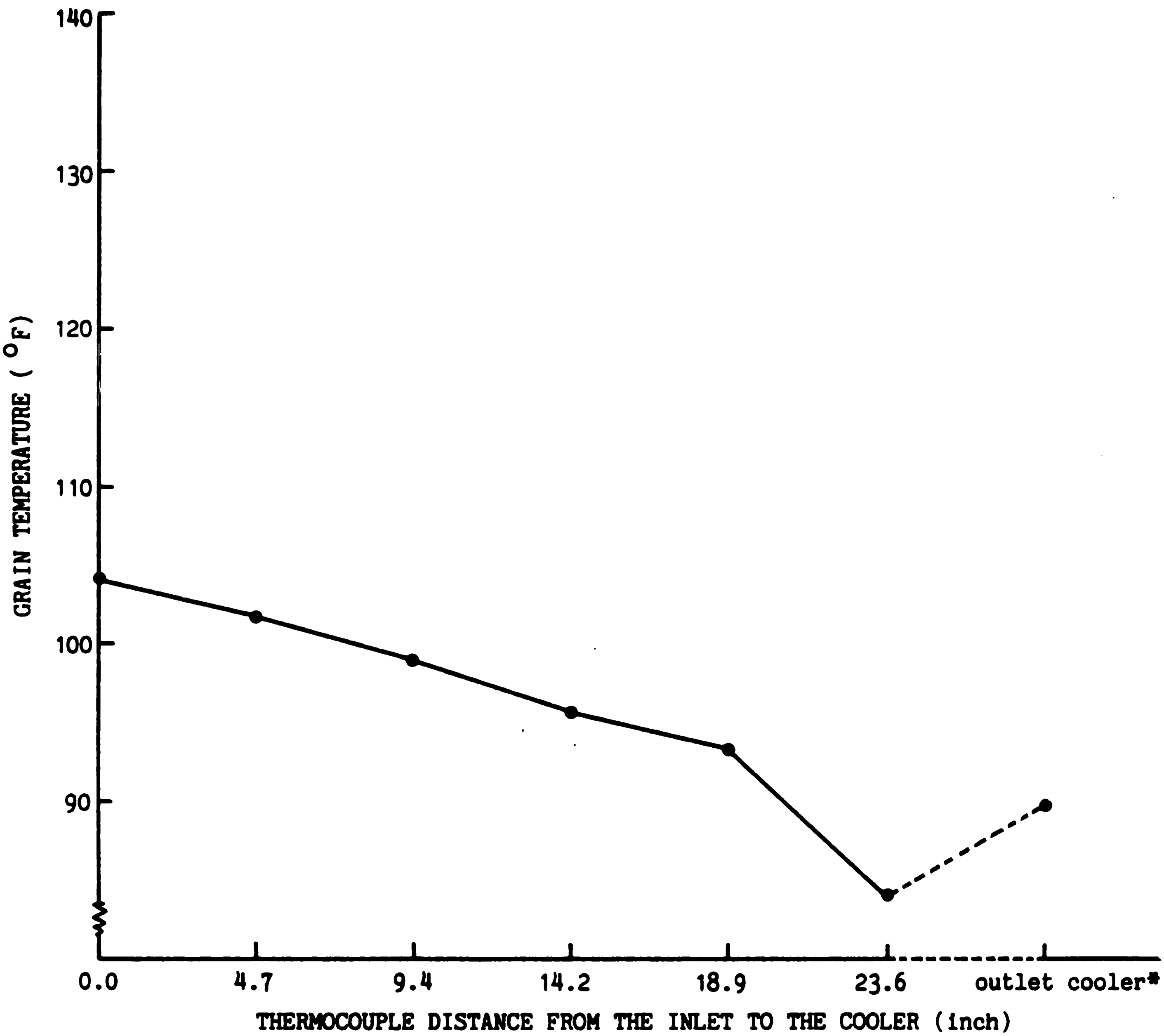
Table 15. Experimental bed temperatures in the cooling bed and calculated outlet grain temperature in experiment 2.

Time (hour)	TEMPERATURE (°F) THERMOCOUPLES 1	2	3	4	5	6	Out*	ΔT1 1-6	ΔT2 1-out*
0:10	103.0	100.0	96.0	94.0	91.0	85.0			
0:20	103.0	100.0	97.0	95.0	92.0	84.0			
0:30	109.0	107.0	101.0	98.0	94.0	84.0			
0:40	108.0	106.0	102.0	99.0	97.0	83.5			
0:50	107.0	101.0	98.0	94.0	92.0	84.0			
1.00	111.0	105.0	101.0	99.0	95.0	84.0			
Average	106.8	103.2	99.2	96.5	93.5	84.1	88.6	22.7	18.2
1:10	101.0	99.0	97.0	93.0	90.0	83.3			
1:20	103.0	102.0	99.0	96.0	92.0	86.0			
1:30	104.0	102.0	100.0	97.0	95.0	86.0			
1:40	104.0	102.0	100.0	98.0	95.0	86.9			
1:50	106.0	102.0	100.0	98.0	97.0	86.9			
2:00	106.0	105.0	101.0	98.0	95.0	86.0			
Average	104.0	102.0	99.5	96.7	94.0	85.8	93.1	18.2	10.9
2:10	97.0	95.0	92.0	89.0	85.0	77.0			
2:20	100.0	99.0	97.0	95.0	92.0	82.8			
2:30	102.0	101.0	99.0	97.0	94.0	82.4			
2:40	103.0	103.0	100.0	98.0	95.0	82.4			
2:50	102.0	101.0	100.0	97.0	96.0	84.2			
3:00	103.0	103.0	101.0	98.0	96.0	84.2			
Average	101.2	100.3	98.2	95.7	93.0	82.2	88.0	19.0	13.2

* Calculated values of outlet grain temperature (°F).

Note: Thermocouples 1-5 were placed 12.0 cm equidistant starting from top (grain entrance, TC1) to the outlet of the cooler (grain outlet, TC5). TC6 was located out of the cooler in a bucket. The temperature was measured with a glass-tube thermometer.

F = (9/5)C + 32.



* Calculated value of outlet corn temperature.

Figure 9. Temperature profile in the cooling bed during cooling in experiment 2.

Table 16. Experimental air and grain inlet and outlet temperatures in experiment 2.

Time (hour)	Gp lb/h	TEMPERATURE (°F) Inlet air	Outlet grain	ΔT1	Outlet air	Inlet grain	ΔT2
0:10	720	71.0	85.0	14.0	103.0	103.0	
0:20	720	71.0	84.0	13.0	103.0	103.0	
0:30	720	71.0	84.0	13.0	109.0	109.0	
0:40	720	70.0	83.5	13.5	108.0	108.0	
0:50	720	70.0	84.0	14.0	107.0	107.0	
1:00	720	68.0	84.0	16.0	111.0	111.0	
Average	720	70.2	84.1	13.9	106.8	106.8	
1:10	1065	71.0	83.3	12.3	101.0	101.0	
1:20	1065	71.0	86.0	15.0	103.0	103.0	
1:30	1065	71.0	86.0	15.0	104.0	104.0	
1:40	1065	71.0	86.9	15.9	104.0	104.0	
1:50	1065	71.0	86.9	15.9	106.0	106.0	
2:00	1065	71.0	86.0	15.0	106.0	106.0	
Average	1065	71.0	85.8	14.8	104.0	104.0	
2:10	1170	69.0	77.0	8.0	97.0	97.0	
2:20	1070	69.0	82.8	13.2	100.0	100.0	
2:30	1170	69.0	82.4	13.4	102.0	102.0	
2:40	1170	70.0	82.4	12.4	103.0	103.0	
2:50	1170	70.0	84.2	14.2	102.0	102.0	
3:00	1170	70.0	84.2	14.2	103.0	103.0	
Average	1170	69.5	82.2	12.7	101.2	101.2	

ΔT1 = the difference between the laboratory ambient temperature and the outlet grain temperature (outlet grain minus inlet air).

Assumption: The outlet air temperature was assumed to be equal to the inlet grain temperature (ΔT2 = 0).

$$F = \frac{9}{5} C + 32.$$

Table 17. Experimental grain moisture content and moisture removed (MR) per hour in experiment 2.

Time (hour)	Gp lb/h ft^2	MOISTURE CONTENT (% d.b.)				MR lb/h ft^2
		inlet dryer	inlet cooler	outlet cooler	ΔMC	
0:10	720	16.47	15.09	14.82	0.27	
0:20	720	16.40	15.50	14.59	0.91	
0:30	720	16.14	14.34	13.61	0.73	
0:40	720	16.14	14.93	14.14	0.79	
0:50	720	16.54	14.82	14.47	0.35	
Average	720	16.34	14.94	14.33	0.61	4.39
1:00	1065	16.48	15.47	15.13	0.34	
1:10	1065	16.35	14.97	14.90	0.07	
1:20	1065	16.37	15.33	14.81	0.52	
1:30	1065	16.47	15.38	15.05	0.33	
1:40	1065	16.12	15.03	14.69	0.34	
1:50	1065	15.14	14.98	14.46	0.52	
Average	1065	16.15	15.19	14.84	0.35	3.73
2:00	1170	16.00	15.38	15.18	0.20	
2:10	1170	16.08	15.15	14.74	0.41	
2:20	1170	15.43	15.09	14.45	0.64	
2:30	1170	14.89	15.29	14.70	0.59	
2:40	1170	15.47	15.33	14.65	0.68	
2:50	1170	16.02	15.66	15.23	0.43	
Average	1170	15.65	15.32	14.83	0.49	5.73

ΔMC means inlet-outlet cooler grain moisture content (% d.b.).
MR = moisture removed, lb per hour per square foot.
1 lb/h ft^2 = 4.902 Kg/h m^2.

Table 18. Heat balance in experiment 2 with Ga/Gp ratios of 0.29, 0.19, and 0.18, respectively during the 1, 2, and 3 hours of operation.

Time (hour)	HEAT (BTU/h)			Latent/Total Heat Ratio*
	Corn	Air		
	Sensible*	Sensible*	Latent*	
1	6510.30	1972.88	4537.42	0.717
2	5582.96	1637.50	3945.46	0.667
3	7453.21	1571.50	5880.71	0.789

* Values derived from equation 10.

1 BTU/h = 0.293 W.

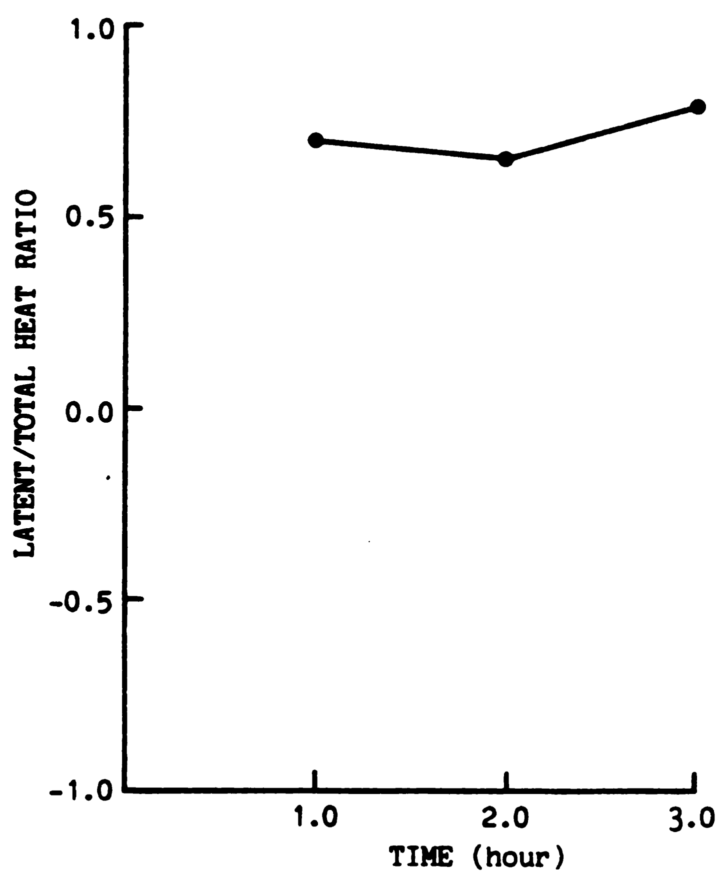


Figure 10. Latent/total heat ratio vs. time during cooling in experiment 2.

Table 16 shows the difference between inlet air and outlet grain temperatures ($\Delta T1$), the grain flow rate of 1065 lb/h ft^2 (5,520.6 Kg/h m^2). Outlet air and inlet grain temperatures (T2) were assumed to be equal.

Table 17 shows the moisture content of the grain and its variation during the three-hour cooling period. The moisture removed during cooling increased when the grain flow rate increased.

Table 18 and Figure 10 show the latent/total heat ratio. All values shown are above positive 0.6, which means that evaporation of water from the grain took place during the three-hour operation. One of the most important factors in this particular test was the humidity of the air, which remained at low levels (Table 14) during the whole operation, making the drying process during the cooling more efficient.

5.3 EXPERIMENT 3

On December 20, 1983, an experiment similar to experiment 2, was conducted. The air flow rate was increased in order to study its effects on cooling rate of grain.

The procedure of experiment 3 was exactly the same as for experiment 2. The air and corn conditions and the results are shown in Tables 19, 20, 21, 22, and 23 and in Figures 11 and 12.

Table 19. Inlet and outlet air conditions in experiment 3 in which the Ga/Gp ratio values are 0.67, 0.45, and 0.41 w.b., respectively, during the three hours of operation.

		INLET				OUTLET					ΔW	MR
Time	Ga*	Temperature (^oF)		R.H.	W	Temperature (^oF)			R.H.	W		
(Hour)	lb/h ft^2	Dry bulb	Wet bulb	%	lb H_2O / lb d.a.	Dry bulb	Wet bulb	Wet** bulb	%	lb H_2O / lb d.a.	lb H_2O / lb d.a.	lb / h ft^2
1	484.0	72.5	49.5	12.0	0.0020	97.0	70.7	69.0	24.0	0.0087	0.0067	3.24
2	484.0	71.7	49.0	14.0	0.0022	95.2	71.0	72.9	35.0	0.0123	0.0101	4.90
3	484.0	71.1	49.0	15.0	0.0024	95.2	70.7	74.6	38.5	0.0138	0.0114	5.50

* Air flow rate (Ga).
** Calculated value.
Note: The experimental temperatures are averages of six (6) measurements over the 3-hour period.
MR = moisture removed, lb per hour per square foot.
RH = relative humidity, percent.
W = humidity ratio, lb of water per lb of dry air.
1 lb/h ft^2 = 4.902 Kg/h m^2 = 0.227 cfm/ft^2 (at ambient conditions).
1 lb H_2O/lb d.a. = 1,000.0 g H_2O/Kg d.a.
F = (9/5)C + 32.

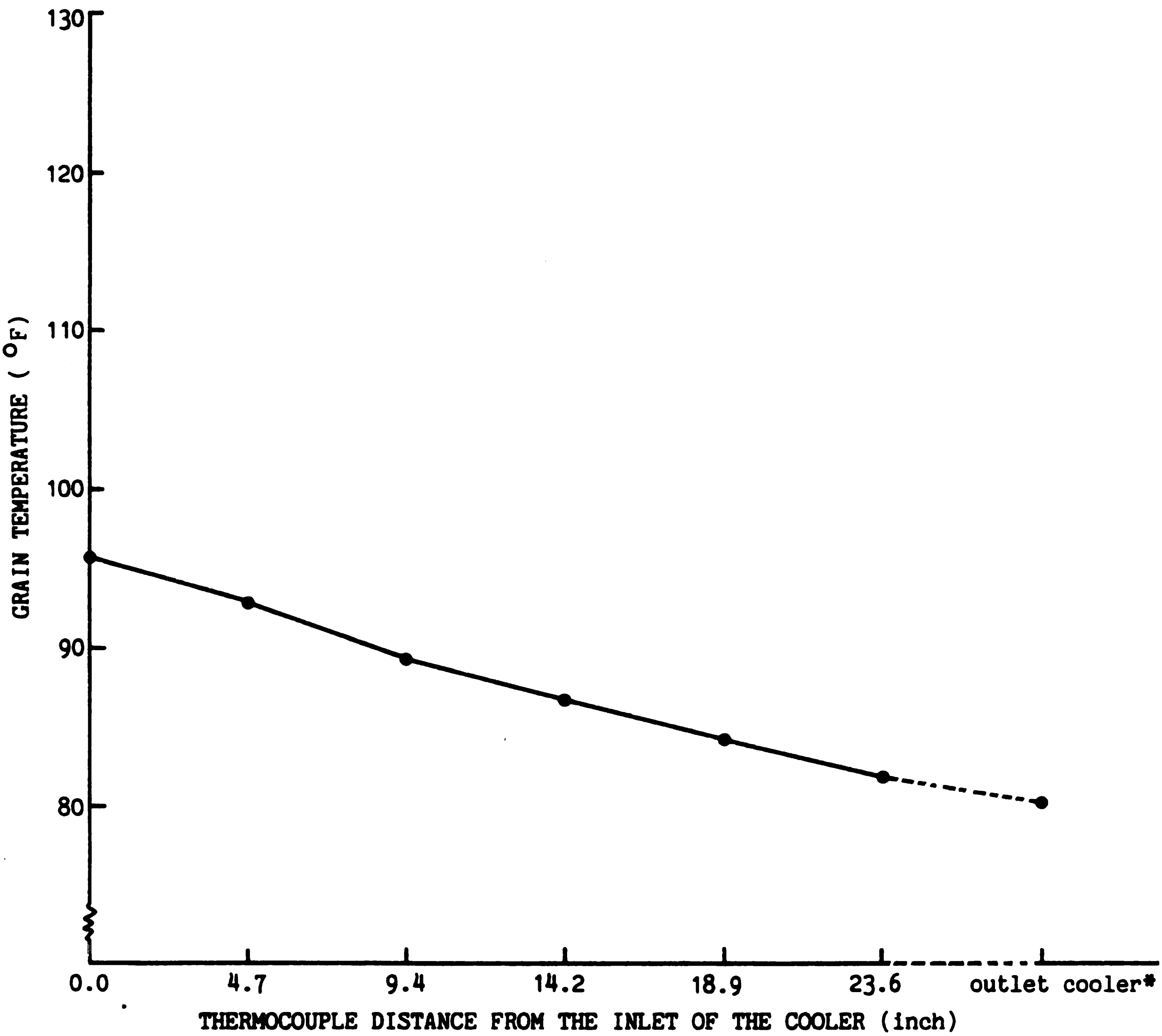
Table 20. Experimental bed temperatures in the cooling bed and calculated outlet grain temperature in experiment 3.

Time (hour)	TEMPERATURE (^{o}F)							ΔT1	ΔT2
	THERMOCOUPLES								
	1	2	3	4	5	6	Out*	1-6	1-out*
0:05	98.0	97.0	92.0	89.0	86.0	81.5			
0:10	96.0	93.0	91.0	88.0	86.0	81.5			
0:15	96.0	93.0	89.0	87.0	85.0	81.5			
0:20	95.0	93.0	87.0	85.0	84.0	81.5			
0:25	98.0	93.0	88.0	85.0	83.0	81.5			
0:30	99.0	96.0	91.0	86.0	83.0	81.5			
Average	97.0	94.2	89.7	86.7	84.5	81.5	79.6	15.5	17.4
0:35	96.0	94.0	90.0	89.0	86.0	82.5			
0:40	107.0	92.0	90.0	88.0	86.0	82.5			
0:45	79.0	85.0	90.0	94.0	86.0	82.5			
0:50	93.0	88.0	79.0	77.0	81.0	81.0			
0:55	98.0	94.0	88.0	85.0	81.0	81.0			
1:00	98.0	96.0	92.0	88.0	86.0	81.0			
Average	95.2	91.5	88.2	86.8	84.3	81.7	77.5	13.5	15.0
1:05	90.0	89.0	84.0	80.0	76.0	82.0			
1:10	96.0	94.0	89.0	85.0	82.0	82.0			
1:15	96.0	94.0	90.0	87.0	86.0	82.0			
1:20	96.0	93.0	91.0	89.0	86.0	82.5			
1:25	96.0	94.0	92.0	90.0	87.0	82.5			
1:30	97.0	96.0	94.0	91.0	86.0	82.5			
Average	95.2	93.3	90.0	87.0	83.8	82.2	80.3	13.0	14.9

* Calculated values of outlet grain temperature (^{o}F).

Note: Thermocopules 1-5 were placed 12.0 cm equidistant, starting from top of the cooler (grain entrance, TC1) to the outlet of the cooler (grain outlet, TC5). TC6 was located out of the cooler in a bucket. The temperature was measured with a glass-tube thermometer.

$$F = \frac{9}{5}C + 32.$$



* Calculated value of outlet corn temperature.

Figure 11. Temperature profile in the cooling bed during cooling in experiment 3.

Table 21. Experimental air and grain inlet and outlet temperatures in experiment 3.

Time (hour)	TEMPERATURE (°F)					
	Inlet air	Outlet grain	ΔT1	Outlet air	Inlet grain	ΔT2
0:05	71.0	81.5	10.5	98.0	98.0	
0:10	70.0	81.5	11.5	96.0	96.0	
0:15	70.0	81.5	11.5	96.0	96.0	
0:20	74.0	81.5	7.5	95.0	95.0	
0:25	75.0	81.5	6.5	98.0	98.0	
0:30	75.0	81.5	6.5	99.0	99.0	
Average	72.5	81.5	9.0	97.0	97.0	
0:35	72.0	82.5	10.5	96.0	96.0	
0:40	72.0	82.5	10.5	107.0	107.0	
0:45	71.0	82.5	11.5	79.0	79.0	
0:50	73.0	81.0	8.0	93.0	93.0	
0:55	71.0	81.0	10.0	98.0	98.0	
1:00	71.0	81.0	10.0	98.0	98.0	
Average	71.7	81.7	10.0	95.2	95.2	
1:05	73.0	82.0	9.0	90.0	90.0	
1:10	71.0	82.0	11.0	96.0	96.0	
1:15	71.0	82.0	11.0	96.0	96.0	
1:20	71.0	82.5	11.5	96.0	96.0	
1:25	71.0	82.5	11.5	96.0	96.0	
1:30	71.0	82.5	11.5	97.0	97.0	
Average	71.3	82.2	10.9	95.2	95.2	

ΔT1 = the difference between the laboratory ambient temperature and the outlet grain temperature (outlet grain minus inlet air).

Assumption: The outlet air temperature was assumed to be equal to the inlet grain temperature (ΔT2 = 0).

$F = \frac{9}{5} C + 32.$

Table 22. Experimental grain moisture content and moisture removed (MR) per hour in experiment 3.

Time hour	Gp wet lb/ h ft^2	MOISTURE CONTENT (% d.b.) inlet dryer	inlet cooler	outlet cooler	ΔMC	MR lb/h ft^2
0:05	720	14.42	14.30	13.95	0.35	
0:10	720	---	14.16	13.58	0.58	
0:15	720	15.49	14.09	13.71	0.38	
0:20	720	---	14.36	13.62	0.74	
0:25	720	16.54	14.26	13.82	0.44	
0:30	720	---	13.57	13.35	0.22	
Average		15.48	14.12	13.67	0.45	3.24
0:35	1065	15.77	14.26	13.56	0.70	
0:40	1065	---	13.95	13.89	0.06	
0:45	1065	15.61	13.01*	14.42*	-1.41*	
0:50	1065	---	15.50	13.80	1.70	
0:55	1065	13.95	14.38	14.84	-0.46	
1:00	1065	---	14.42	14.09	0.33	
Average		15.11	14.50	14.04	0.46	4.90
1:05	1170	14.19	14.35	13.92	0.43	
1:10	1170	---	14.09	13.86	0.23	
1:15	1170	15.29	14.84	13.97	0.87	
1:20	1170	---	14.10	13.78	0.32	
1:25	1170	14.93	14.34	13.80	0.54	
1:30	1170	---	14.53	14.10	0.43	
Average		14.80	14.37	13.90	0.47	5.50

* = Discharage value.
ΔMC = Inlet-outlet cooler grain moisture content (% d.b.).
MR = Moisture removed, lb per hour per square foot.
Gp = Grain flow rate, lb per hour per square foot.
1 lb/h ft^2 = 4.902 Kg/h m^2.

Table 23. Heat balance in experiment 3 with Ga/Gp ratios of 0.67, 0.45, and 0.41, respectively during the 1, 2, and 3 hours of operation.

Time (hour)	HEAT (BTU/h)			Latent/Total Heat Ratio*
	Corn	Air		
	Sensible*	Sensible*	Latent*	
1	6233.50	2869.15	3364.35	0.540
2	7734.82	2729.76	5005.06	0.641
3	8417.51	2799.46	5618.05	0.667

* Values derived from equation 10.

1 BTU/h = 0.293 W.

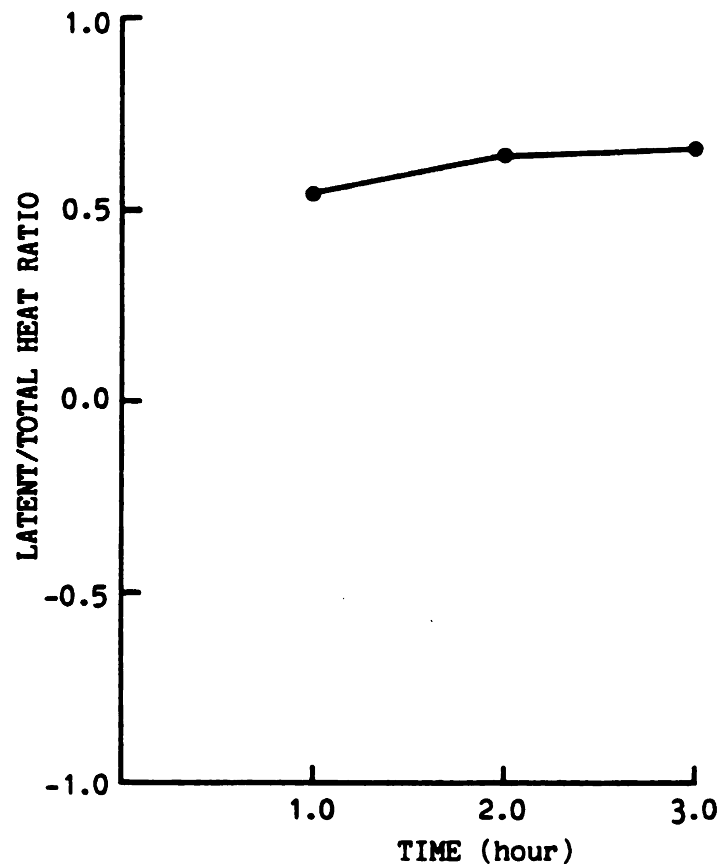


Figure 12. Latent/total heat ratio vs. time during cooling in experiment 3.

5.3.1 Comments on Experiment 3

Experiment 3 was a repetition of experiment 2 except for changing the air flow rate from 206.8 lb/h ft^2 to 484.0 lb/h ft^2 (1,013.7 Kg/h m^2 to 2,372.5 Kg/h m^2). The materials and method employed were the same.

Table 19 shows the laboratory ambient air conditions. The relative humidity (RH) and humidity ratio (W) were very low, which helped the cooling process to be efficient, removing water from the grain during the whole period of operation.

Table 20 and Figure 11 show the temperature decrease during the cooling period. There is no significant difference among the three grain flow rates studied (720, 1065, and 1170 lb/h ft^2 (3529.4, 5520.6, and 5735.3 Kg/h m^2)).

Table 21 shows the difference between inlet air and outlet grain temperature. A low ΔT1 value means a good efficiency of the cooling process. The outlet grain temperature is lower than inlet air temperature, which means that evaporation took place. The difference between inlet air and outlet grain temperatures (ΔT1) is around 10^{o}F (5.5^{o}C), which means that the grain is cool enough to be safely stored.

Table 22 shows the moisture content of the grain and its variation during the three-hour cooling period. The moisture removed during cooling increased when the grain flow rate increased.

Table 23 and Figure 12 show the heat balance. The latent/total heat ratio increased as the grain flow rate increased.

Comparing experiment 3 (Ga = 484.0 lb/h ft^2 (2372.5 Kg/h m^2)) and experiment 2 (Ga = 206.8 lb/h ft^2 (1013.7 Kg/h m^2)), the amount of water removed in experiment 2 is greater than that for experiment 3. However, the inlet grain temperature in experiment 2 was greater than in experiment 3 (Tables 15 and 20). The inlet grain temperature and moisture content and the laboratory ambient air were similar in both experiments.

In conclusion, increasing the air flow rate does increase the amount of moisture removed from the grain. Under the specific conditions during which the experiments were conducted, the increase in air flow rate decreased the amount of water removed from the grain. Consequently, it decreased the drying efficiency during the cooling process and decreased the cooling rate.

5.4 EXPERIMENT 4

Experiment 4 was conducted on July 24, 1984. Corn, originally approximately 14 percent moisture content, was dried to around 12 percent and cooled in a single pass. The number of thermocouples were increased to reach the bottom of the cooler. The air and corn conditions are shown in Tables 24, 25, 26, 27, 28, and 29 and in Figure 13.

Table 24. Inlet and outlet air conditions in experiment 4 in which the Ga/Gp ratio value is 0.25 w.b.,

		INLET				OUTLET					ΔW	MR
Time	Ga*	Temperature (°F)		R.H.	W	Temperature (°F)			R.H.**	W**		
(Hour)	lb/h ft^2	Dry bulb	Wet bulb	%	$\frac{lb\ H_2O}{lb\ d.a.}$	Dry bulb	Wet bulb	Wet** bulb	%	$\frac{lb\ H_2O}{lb\ d.a.}$	$\frac{lb\ H_2O}{lb\ d.a.}$	$\frac{lb}{h\ ft^2}$
1	206.8	84.6	71.2	53.0	0.0132	123.1	97.5	96.8	40.0	0.0327	0.0195	4.03
2	206.8	86.6	72.7	64.0	0.0148	130.2	100.5	96.5	30.0	0.0306	0.0158	3.28

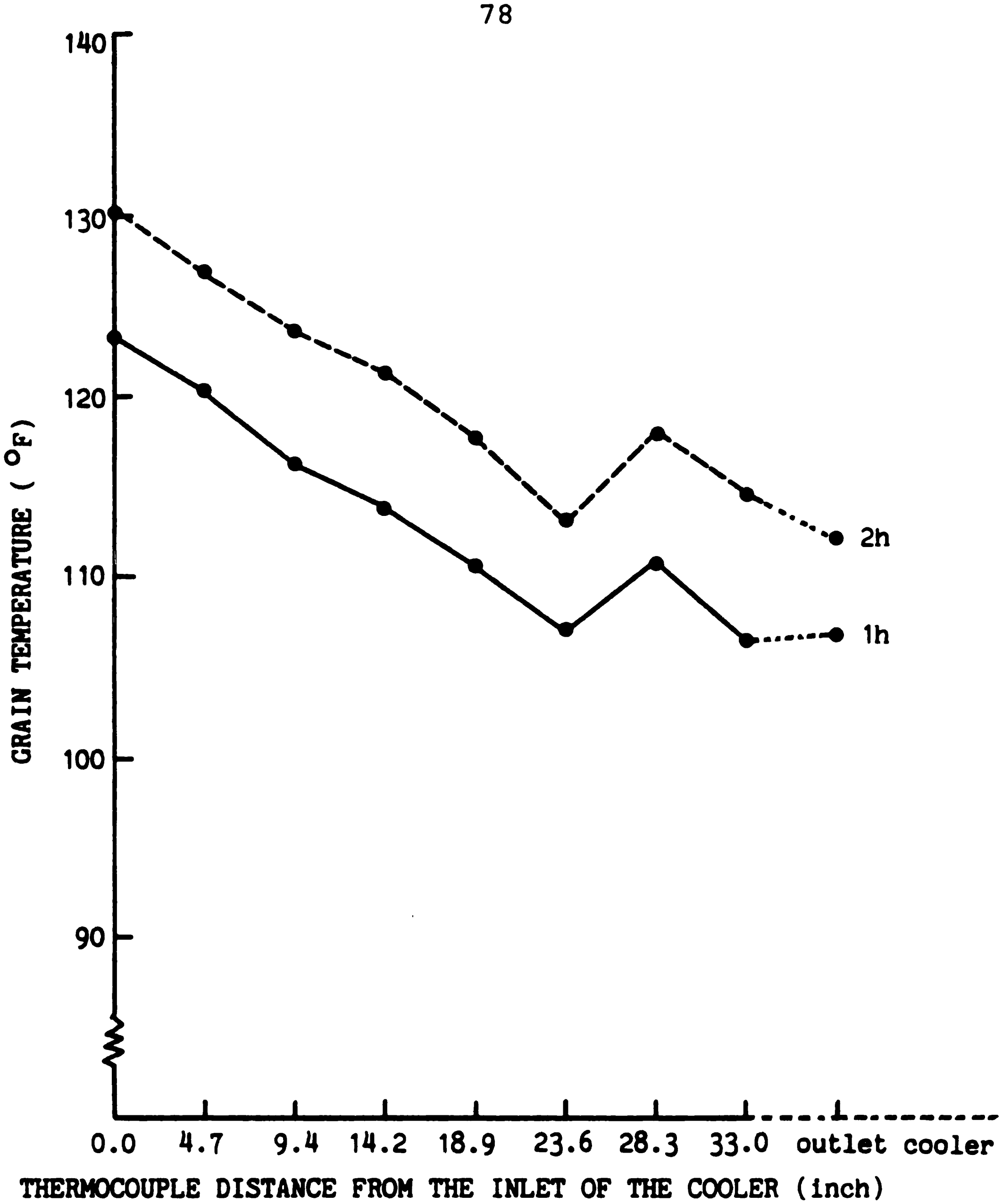
* Air flow rate (Ga)
** Calculated value.
Note: The experimental temperatures are averages of sixty (60) measurements over the 2-hour period.
MR = moisture removed, lb per hour per square foot.
RH = relative humidity, percent.
W = humidity ratio, lb of water per lb of dry air.
1 lb/h ft^2 = 4.902 Kg/h m^2 = 0.227 cfm/ft^2 (at ambient conditions).
1 lb H_2O/lb d.a. = 1,000.0 g H_2O/Kg d.a.
F = (9/5)C + 32.

Table 25. Experimental bed temperatures in the cooling bed and calculated outlet grain temperature in experiment 4.

Time (hour)	TEMPERATURE (^oF) THERMOCOUPLES 1	2	3	4	5	6	7	8	Out	Out*	ΔT1 1-out	ΔT2 1-out*
0:10	130.8	124.7	117.0	114.4	110.6	106.7	110.8	100.1	105.4			
0:20	113.1	119.4	120.3	120.0	117.2	112.7	117.7	111.8	107.3			
0:30	112.5	106.4	102.6	101.1	101.1	103.6	103.4	107.3	116.4			
0:40	124.5	120.2	115.5	111.0	105.5	99.8	104.4	100.3	98.8			
0:50	128.9	125.2	121.2	118.0	113.7	108.1	113.1	108.1	104.3			
1:00	128.8	125.7	121.9	119.4	115.7	111.0	115.8	111.6	108.6			
Average	123.1	120.3	116.4	114.0	110.6	107.0	110.9	106.5	106.8	108.4	16.3	14.7
1:10	129.2	126.0	122.3	119.8	116.0	110.3	116.6	113.0	110.2			
1:20	130.4	127.1	123.6	121.2	117.4	112.9	117.4	113.6	110.0			
1:30	130.9	127.7	124.6	122.3	118.5	113.5	118.6	114.9	115.1			
1:40	130.3	127.3	124.1	121.8	118.8	115.0	119.0	115.8	112.9			
1:50	130.1	127.0	123.7	121.5	117.9	113.8	117.9	115.2	112.5			
2:00	130.1	127.2	123.4	121.0	117.7	113.3	118.3	115.1	111.8			
Average	130.2	127.0	123.6	121.3	117.7	113.1	118.0	114.6	112.1	116.8	18.1	13.4

* Calculated values of outlet grain temperature (^oF).
Note: Each temperature value is an average of ten measurements.
Out means out of the cooler.
ΔT1 means the difference between inlet and outlet experimental grain temperatures.
ΔT2 means the difference between the experimental inlet and calculated outlet grain temperature.

$$F = \frac{9}{5} C + 32.$$



1h = the first hour.
2h = the second hour.

Figure 13. Temperature profile in the cooling bed during cooling in experiment 4.

Table 26. Experimental air and grain inlet and outlet temperatures in experiment 4.

Time (hour)	TEMPERATURE (°F)					
	Grain out	Air in	ΔT1	Grain in	Air out	ΔT2
0:10	105.4	84.5	20.9	123.9	130.8	-6.9
0:20	107.3	84.5	22.8	124.5	113.1	11.4
0:30	116.4	84.7	31.7	113.9	112.5	1.4
0:40	98.8	84.5	14.3	121.3	124.5	-3.2
0:50	104.3	84.3	20.0	131.1	128.9	2.2
1:00	108.6	85.0	23.6	130.2	128.8	1.4
Average	106.8	84.6	22.2	124.2	123.1	1.0
1:10	110.2	85.5	24.7	130.7	129.2	1.5
1:20	110.0	86.3	23.7	132.1	130.4	1.7
1:30	115.1	86.1	29.0	134.1	130.9	3.2
1:40	112.9	87.2	25.7	133.8	130.3	3.5
1:50	112.5	87.2	25.3	130.7	130.1	0.6
2:00	111.8	87.0	24.8	131.1	130.1	1.0
Average	112.1	86.6	25.5	132.1	130.2	1.9

ΔT1 = the difference between the laboratory ambient temperature and the outlet grain temperatures (grain out minus air in).

ΔT2 = the difference between the inlet grain and outlet air temperatures (grain in minus air out).

$$F = \frac{9}{5} C + 32.$$

Table 27. Temperature at the same level (4.7 inches (12.0 cm)) from the inlet of the cooler in experiment 4.

Time (hour)	TEMPERATURE (°F) Thermocouples* 2	11	12	13	ΔT 12-2
0:10	124.7	127.1	130.3	127.5	
0:20	119.4	123.5	122.2	124.4	
0:30	106.4	108.3	110.0	108.7	
0:40	120.2	124.6	125.9	124.8	
0:50	125.2	129.7	130.6	129.7	
1:00	125.7	130.0	130.5	129.7	
Average	120.3	123.9	124.9	124.1	4.6
1:10	126.0	130.3	130.6	129.7	
1:20	127.1	131.7	132.1	131.6	
1:30	127.7	131.9	132.0	131.6	
1:40	127.3	131.3	131.4	130.7	
1:50	127.0	130.9	131.3	130.9	
2:00	127.2	130.9	131.4	130.9	
Average	127.0	131.2	131.5	130.9	4.5

ΔT = the highest temperature variation at the same level.
Note: Each temperature value is an average of ten (10) measurements.
*thermocouple location--see Figure 6A.

$F = \frac{9}{5} C + 32.$

Table 28. Experimental grain moisture content and moisture removed (MR) per hour in experiment 4.

Time hour	Gp lb/h ft^2	MOISTURE CONTENT (% d.b.) inlet dryer	inlet cooler	outlet cooler	ΔMC	MR lb/h ft^2
0:10	840	14.93	14.05	12.17	1.88*	
0:20	840	14.56	14.00	14.08	-0.08*	
0:30	840	14.60	13.22	12.89	0.33	
0:40	840	15.00	12.66	12.35	0.31	
0:50	840	14.76	13.02	12.66	0.36	
1:00	840	14.71	13.25	12.32	0.93	
Average		14.77	13.04	12.56	0.48	4.03
1:10	840	14.73	13.25	12.52	0.73*	
1:20	840	15.18	12.78	12.36	0.42	
1:30	840	14.93	12.83	12.37	0.46	
1:40	840	14.74	12.79	12.84	-0.05*	
1:50	840	14.59	12.87	12.68	0.19	
2:00	840	14.43	13.07	12.60	0.47	
Average		14.78	12.89	12.50	0.39	3.28

* = Discharge value.
ΔMC = Inlet minus outlet cooler grain moisture content (% d.b.).
MR = Moisture removed, lb per hour per square foot.
Gp = Grain flow rate, wet lb per hour per square foot.
1 lb/h ft^2 = 4.902 Kg/h m^2.

Table 29. Heat balance in experiment 4 with a (Ga/Gp) wet ratio of 0.25, during the 2-hour cooling operation.

Time (hour)	HEAT (BTU/h)			Latent/Total Heat Ratio*
	Corn	Air		
	Sensible*	Sensible*	Latent*	
1	5966.01	1910.83	4055.18	0.680
2	5445.53	2163.96	3281.57	0.603

* Values derived from equation 10.

1 BTU/h = 0.293 W.

5.4.1 Comments on Experiment 4

Experiment 4 is similar to experiments 2 and 3. The main objective of this experiment was to study the adsorption of water by the grain during cooling, based on the temperature and the position of the grain inside of the cooler. Other purposes of this experiment were to check the temperature variations at the same level (Table 27) and the temperature difference between inlet grain and outlet air.

Table 24 shows the inlet and outlet air conditions. The inlet relative humidity (RH) decreased during the two-hour cooling operation. However, the humidity ratio (W) increased during the same period, which caused desorption of water during the two-hour cooling period.

Table 25 and Figure 13 show the temperature profile during the two-hour cooling operation. The temperature decreased until 23.6 inches (60.0 cm) from the inlet of the cooler. Adsorption took place between 23.6 inches (60.0 cm) and 28.3 inches (72.0 cm) because of the increase in temperature. Beyond the 28.3 inch mark, the temperature decreased again, which means that desorption of water took place in the last portions of the cooler.

Table 26 shows the outlet grain temperature and the difference ($\Delta T1$) when compared with the laboratory ambient air temperature. If $\Delta T1$ is greater than 10^oF (5.5^oC), the cooling process is not completed. In Table 26 a comparison between inlet grain and outlet air temperature showed that the inlet grain temperature was a few degrees warmer than the surrounding air. Negative sign is due to instead state operation of the dryer and therefore of the grain inlet temperature to the cooler.

Table 27 shows the temperature at three locations at the same level (4.7 inches (12.0 cm)) in the cooling bed. The slight variation is due to non-uniform airflow in the cooler.

Table 28 shows the grain moisture content and moisture removed (MR) during the two-hour cooling operation. The amount of water removed during cooling at the first and second hour was similar and was about 4 lb per ft^2 per hour.

Table 29 shows the heat balance with a Ga/Gp ratio of 0.25 w.b. The latent/total heat ratio stayed positive (0.6), which means that sixty (60) percent of the cooling due to the evaporation process and forty (40) percent was due to sensible heat transfer.

5.5 EXPERIMENT 5

Experiment 5 was conducted on August 10, 1984. The same corn dried in experiment 4 was used in experiment 5; it was dried from about 12 percent moisture content to about 9 percent in a single pass through the dryer and cooler. The grain flow rate (Gp) 480 lb/h ft^2 (2348.6 Kg/h m^2) compared to 840 lb/h ft^2 (4117.6 Kg/h m^2) in experiment 4.

The air and corn conditions are shown in Tables 30, 31, 32, 33, 34, and 35 and in Figure 14.

Table 30. Inlet and outlet air conditions in experiment 5 in which the Ga/Gp ratio value is 0.43 w.b.

		INLET				OUTLET					ΔW	MR
Time	Ga*	Temperature (°F)		R.H.	W	Temperature (°F)			R.H.**	W**		
(Hour)	lb/h ft²	Dry bulb	Wet bulb	%	lb H_2O / lb d.a.	Dry bulb	Wet bulb	Wet** bulb	%	lb H_2O / lb d.a.	lb H_2O / lb d.a.	lb / h ft²
1	206.8	88.4	76.4	59.0	0.0170	136.0	98.1	104.0	34.0	0.0411	0.0241	4.99
2	206.8	88.7	76.7	58.5	0.0172	145.5	102.4	107.5	30.0	0.0455	0.0283	5.86

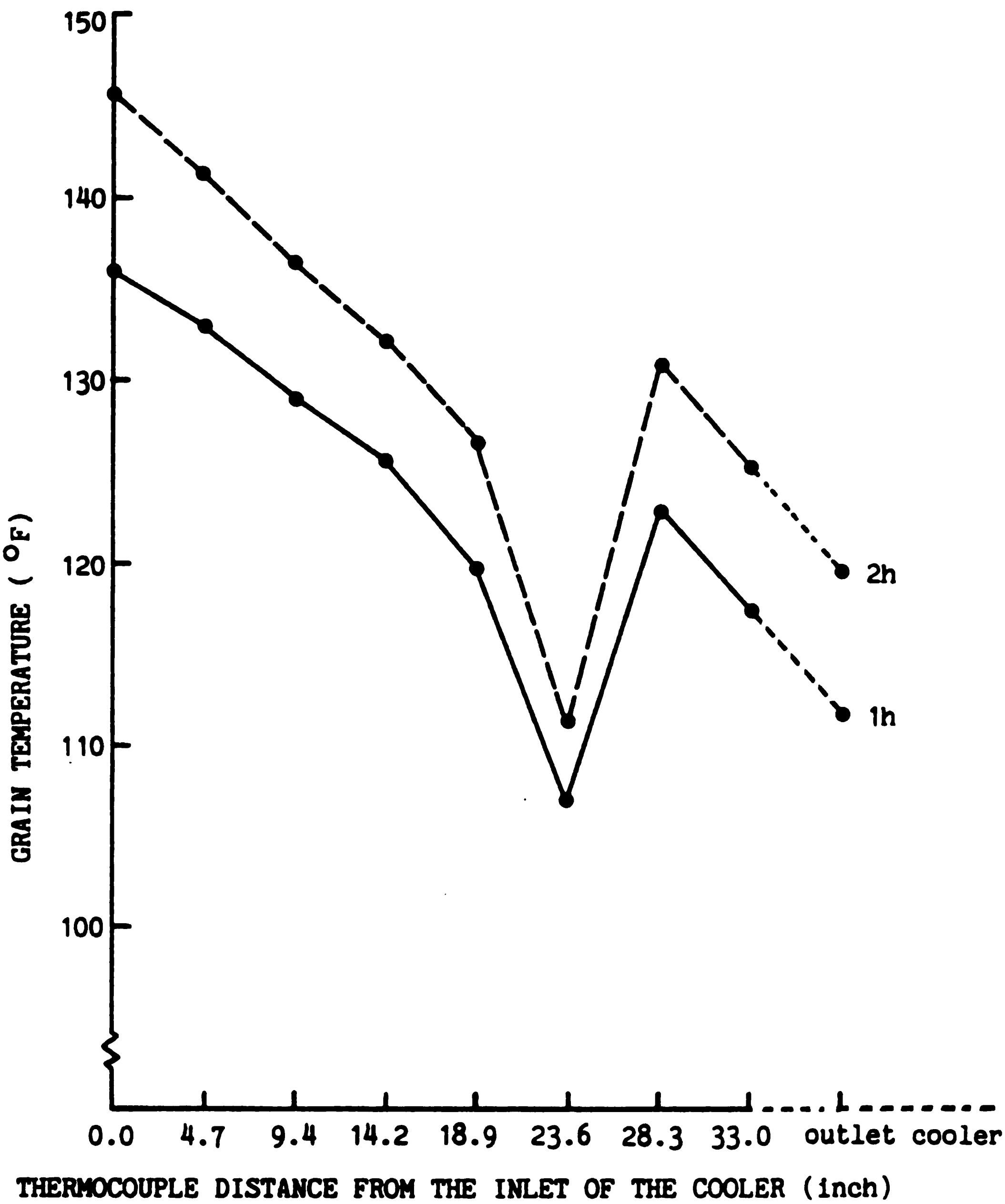
* Air flow rate (Ga).
** Calculated value.
Note: The experimental temperatures are averages of sixty (60) measurements over the 2-hour period.
MR = moisture removed, lb per hour per square foot.
RH = relative humidity, percent.
W = humidity ratio, lb of water per lb of dry air.
1 lb/h ft² = 4.902 Kg/h m² = 0.227 cfm/ft² (at ambient conditions).
1 lb H_2O/lb d.a. = 1,000.0 g H_2O/Kg d.a.
F = (9/5)C + 32.

Table 31. Experimental bed temperatures in the cooling bed and calculated outlet grain temperature in experiment 5.

Time (hour)	TEMPERATURE (^{o}F) THERMOCOUPLES 1	2	3	4	5	6	7	8	Out	Out*	$\Delta T1$ 1-out	$\Delta T2$ 1-out*
0:10	135.4	132.1	127.2	122.1	113.4	100.2	114.5	106.7	97.0			
0:20	136.1	133.3	129.3	126.2	119.7	105.8	122.8	115.7	109.9			
0:30	136.1	133.7	129.8	126.5	120.9	107.4	125.2	119.8	114.8			
0:40	134.7	130.8	127.9	125.8	121.6	109.5	125.8	120.6	116.5			
0:50	136.9	134.3	129.7	125.5	120.0	110.1	123.1	120.4	115.8			
1:00	136.6	133.6	130.2	127.3	122.4	108.4	124.7	120.0	115.3			
Average	136.0	133.0	129.0	125.6	119.7	106.9	122.7	117.2	111.5	101.1	24.5	34.9
1:10	138.7	135.8	131.2	127.4	122.0	110.2	125.5	121.6	115.6			
1:20	158.0	146.8	134.7	128.8	123.6	111.1	126.6	121.8	116.9			
1:30	150.5	151.6	149.1	141.9	129.5	111.3	129.3	123.0	118.3			
1:40	140.9	139.1	136.7	136.1	134.0	113.3	144.4	133.1	120.5			
1:50	142.2	139.2	135.3	130.1	125.3	109.8	131.1	128.8	125.0			
2:00	142.8	135.0	131.0	129.2	124.7	110.8	127.8	123.9	120.6			
Average	145.5	141.2	136.4	132.2	126.5	111.1	130.8	125.4	119.5	104.4	26.0	41.1

* Calculated values of outlet grain temperature (^{o}F).
Note: Each temperature value is an average of ten measurements.
Out means out of the cooler.
$\Delta T1$ means the difference between inlet and outlet experimental grain temperatures.
$\Delta T2$ means the difference between the experimental inlet and calculated outlet grain temperature.

$$F = \frac{9}{5} C + 32.$$



1h = the first hour.
2h = the second hour.

Figure 14. Temperature profile in the cooling bed during cooling in experiment 5.

Table 32. Experimental air and grain inlet and outlet temperatures in experiment 5.

Time (hour)	TEMPERATURE (°F) Grain out	Air in	ΔT1	Grain in	Air out	ΔT2
0:10	97.0	88.3	8.7	139.1	135.4	3.7
0:20	109.9	88.6	21.3	137.3	136.1	1.2
0:30	114.8	88.7	26.1	137.5	136.1	1.4
0:40	116.5	88.5	28.0	140.2	134.7	5.5
0:50	115.8	88.4	27.4	141.6	136.9	4.7
1:00	115.3	88.2	27.1	142.2	136.6	5.6
Average	111.5	88.4	23.1	139.6	136.0	3.7
1:10	115.6	88.9	26.7	141.9	138.7	3.2
1:20	116.9	89.4	27.5	158.3	158.0	0.3
1:30	118.3	88.8	29.5	161.7	150.5	11.2
1:40	120.5	88.9	31.6	143.8	140.9	2.9
1:50	125.0	88.1	36.9	142.4	142.2	0.2
2:00	120.6	88.2	32.4	152.0	142.8	9.2
Average	119.5	88.7	30.8	150.0	145.5	4.5

ΔT1 = the difference between the laboratory ambient temperature and the outlet grain temperature (outlet grain minus inlet air).

ΔT2 = the difference between the inlet grain and outlet air temperatures (grain in minus air out).

$F = \frac{9}{5} C + 32.$

Table 33. Temperature at the same level (4.7 inches (12.0 cm)) from the inlet of the cooler in experiment 5.

Time (hour)	TEMPERATURE (^{o}F)				
	Thermocouples				ΔT
	2	11	12	13	12-2
0:10	132.1	138.4	139.9	138.8	
0:20	133.3	139.5	140.4	139.5	
0:30	133.7	139.8	141.2	140.2	
0:40	130.8	136.4	137.6	136.3	
0:50	134.3	140.1	141.7	140.7	
1:00	133.6	139.7	140.8	139.7	
Average	133.0	139.0	140.3	139.2	7.3
1:10	135.8	142.5	143.7	142.5	
1:20	146.8	153.1	158.9	154.9	
1:30	151.6	164.9	163.5	164.2	
1:40	139.1	145.2	146.0	145.0	
1:50	139.2	145.5	146.5	145.8	
2:00	135.0	141.4	142.8	141.8	
Average	141.2	148.1	150.2	149.0	9.0

ΔT = the highest temperature variation at the same level.
Note: Each temperature value is an average of ten (10) measurements.

$F = \frac{9}{5} C + 32.$

Table 34. Experimental grain moisture content and moisture removed (MR) per hour in experiment 5.

Time (hour)	Gp wet lb/h ft^2	MOISTURE CONTENT (% d.b.) inlet dryer	inlet cooler	mid cooler	outlet cooler	ΔMC1	ΔMC2	ΔMC	MR lb/h ft^2
0:10	480	11.88	10.52	10.00	9.25	0.52	0.75	1.27	
0:20	480	12.35	9.78	9.19	8.90	0.59	0.29	0.88	
0:30	480	12.27	9.65	9.59	8.80	0.06	0.79	0.85	
0:40	480	12.17	10.06	9.16	8.71	0.90	0.45	1.35	
0:50	480	12.51	10.53	9.63	9.32	0.90	0.31	1.21	
1:00	480	12.32	9.15	8.79	8.43	0.36	0.36	0.72	
Average	480	12.25	9.95	9.39	8.90	0.55	0.49	1.04	4.99
1:10	480	13.31	9.61	9.05	8.76	0.56	0.29	0.85	
1:20	480	13.11	9.49	8.84	8.20	0.65	0.64	1.29	
1:30	480	12.02	9.99	8.80	8.70	1.19	0.10	1.29	
1:40	480	12.40	10.99	10.25	9.34	0.74	0.91	1.65	
1:50	480	12.61	12.13	11.44	10.26	0.69	1.18	1.87	
2:00	480	12.46	10.44	10.69	10.11	-0.25	0.58	0.33	
Average	480	12.65	10.44	9.84	9.23	0.60	0.62	1.22	5.86

ΔMC1 = inlet minus mid cooler grain moisture content (% d.b.).
ΔMC2 = mid minus outlet cooler grain moisture content (% d.b.).
ΔMC = inlet minuse outlet cooler grain moisture content (% d.b.).
MR = moisture removed, lb per hour per square foot
mid cooler = 18.9 inches (48.0 cm) from the inlet of the cooler.
1 lb/h ft^2 = 4.902 Kg/h m^2.

Table 35. Heat balance in experiment 5 with a Ga/Gp ratio value of 0.43 w.b., during the 2-hour cooling operation.

Time (hour)	HEAT (BTU/h)			Latent/Total Heat Ratio*
	Corn	Air		
	Sensible*	Sensible*	Latent*	
1	7346.49	2362.48	4984.01	0.678
2	8634.95	2820.00	5814.95	0.673

* Values derived from equation 10.

1 BTU/h = 0.293 W.

5.5.1 Comments on Experiment 5

Experiment 5 was conducted to observe possible water adsorption by the grain during cooling, when the grain flow rate is low. Compared to experiment 4, the inlet corn moisture was lower.

Table 30 shows the inlet and outlet air conditions. The humidity ratio (W) increased during the two-hour cooling operation, which means that the grain lost water to the air during the whole period based on inlet and outlet conditions.

Table 31 and Figure 14 show the grain temperature profile during the two-hour operation. The temperature inside the cooler decreased until 23.6 inches (60.0 cm) from the inlet. From 23.6 inches (60.0 cm) until 28.3 inches (72.0 cm) the temperature increased, showing that adsorption of water by the grain took place. After that, the temperature continued decreasing until the end of the cooling section, indicating desorption again.

Table 32 shows the inlet and outlet air and grain temperatures. As the inlet grain temperature increases, the outlet grain temperature increases also. The difference between the outlet grain and ambient temperature is too large for safe storage, because $\Delta T1$ is greater than $10^{o}F$ ($5.5^{o}C$). The inlet grain temperature is a few degrees higher than the outlet air temperature, as shown in the $\Delta T2$ column in Table 32.

Table 33 shows the temperature variations at the same bed level (4.7 inches (12.0 cm)) from the inlet of the cooler. Non-uniform airflow in the cooler caused a maximum average temperature difference of 8.0°F (4.5°C).

Table 34 refers to the moisture content of the grain at the inlet, at the 18.9 inch (48.0 cm) level and at the cooler outlet. Of the total amount of moisture removed during cooling, half happened in the first 18.9 inches (18.0 cm). The total amount of water removed was greater in experiment 5 (Gp = 480 lb/h ft^2 (2348.6 Kg/h m^2)) than in experiment 4 (Gp = 840 lb/h ft^2 (4117.6 Kg/h m^2)) because of the longer time spent in the cooler by the grain.

Table 35 shows the heat balance and the latent/total heat ratio. Even though the adsorption of water by the grain took place inside the cooler, the latent/total heat ratio remained positive. About 67 percent of the cooling was due to the evaporative process, and the remaining 33 percent due to the sensible heat transfer.

In conclusion, increasing the inlet grain temperature increased the outlet grain temperature. Water absorption took place between 23.6-28.3 inches (60.0-72.0 cm) from the inlet of the cooler.

Moisture removed during cooling increased when the inlet grain temperature was increased. The latent/total heat ratio was not significantly affected.

Comparing experiment 5 with experiment 4, the temperature behaviors are quite similar. In both cases, the absorption occurred at the same interval (23.6-28.3 inches (60.0-72.0 cm) from the inlet of the cooler).

5.6 EXPERIMENT 6

Experiment 6 was conducted on August 25, 1984. Corn previously dried in experiments 4 and 5, was dried from approximately 11 percent to 8.0 percent in a single pass through the dryer and cooler. The bed depth of the cooler was increased from 2.0 ft (60.96 cm) to 3.0 ft (91.4 cm). The number of thermocouples was increased, maintaining the equidistance of 4.7 inches (12.0 cm).

Sample holes were made along the cooling section, starting at 18.9 inch (48.0 cm) from the top, at 4.7 inches (12.0 cm) distance interval.

The air and corn conditions are shown in Tables 36, 37, 38, 39, 40, and 41 and in Figures 15, 16, and 17.

5.6.1 Comments on Experiment 6

The inlet and outlet air conditions are shown in Table 36. The humidity ratio (W) increased during the same test. The amount of water removed was greater during the first two-hour period than during the last two-hour period. This is due to the different drying temperature (400°F (204°C)) during the first and second hours of the test compared to the third and fourth hours (300°F (149°C)). This resulted in different inlet grain temperatures.

Table 37 and Figure 15 show the temperature profile during cooling in experiment 6. During the first two hours,

Table 36. Inlet and outlet air conditions in experiment 6 in which the Ga/Gp ratio value is 0.34 w.b.,

		INLET				OUTLET					ΔW	MR
Time	Ga*	Temperature (°F)		R.H.	W	Temperature (°F)			R.H.**	W**		
(Hour)	lb/h ft²	Dry bulb	Wet bulb	%	lb H_2O / lb d.a.	Dry bulb	Wet bulb	Wet** bulb	%	lb H_2O / lb d.a.	lb H_2O / lb d.a.	lb / h ft²
1	149.6	62.7	58.8	79.0	0.0094	133.1	93.7	93.0	23.0	0.0245	0.0151	2.26
2	149.6	65.3	61.0	79.5	0.0106	129.2	93.5	94.3	29.5	0.0281	0.0175	2.62
3	149.6	69.5	64.1	84.5	0.0130	119.0	89.9	89.0	31.0	0.0219	0.0089	1.33
4	149.6	73.5	66.0	68.0	0.0120	122.5	90.8	90.0	28.0	0.0227	0.0106	1.60

* Air flow rate (Ga).
** Calculated value.
Note: The experimental temperatures are averages of sixty (60) measurements over 3.7-hour period.
MR = moisture removed, lb per hour per square foot.
RH = relative humidity, percent.
W = humidity ratio, lb or water per lb of dry air.
1 lb/h ft² = 4.902 Kg/h m² = 0.227 cfm/ft² (at ambient conditions).
1 lb H_2O/lb d.a. = 1,000.0 g H_2O/Kg d.a.
F = (9/5)C + 32.

Table 37. Experimental bed temperatures in the cooling bed and calculated outlet grain temperature in experiment 6.

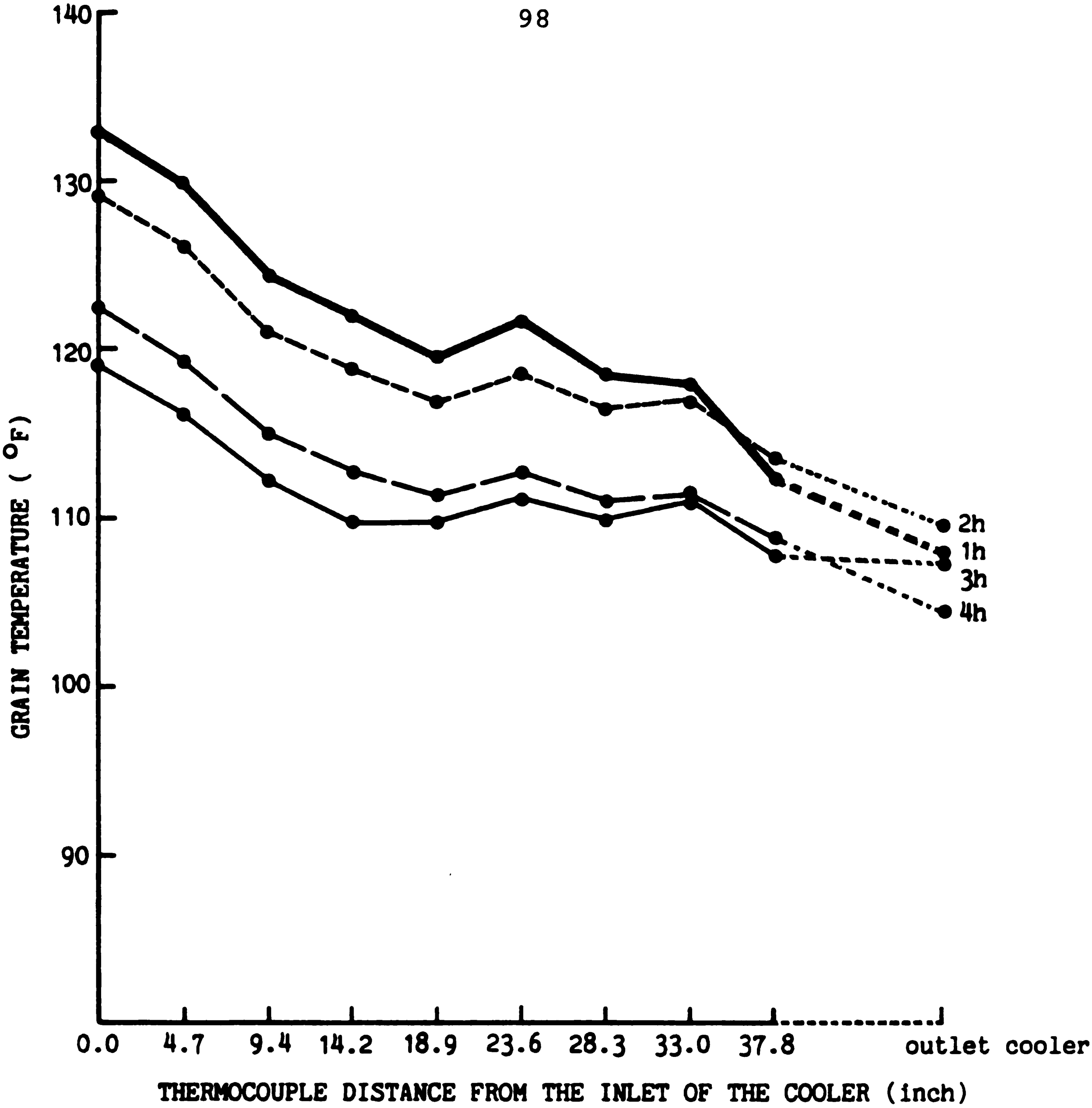
Time (hour)	TEMPERATURE (^{o}F) THERMOCOUPLES													
	1	2	3	4	5	6	7	8	9	10	Out	Out*	ΔT1 1-out	ΔT2 1-out*
0:10	136.3	131.5	125.1	120.9	116.9	116.9	110.1	109.4	101.9	---	---			
0:20	135.9	132.0	126.6	123.8	120.5	121.9	117.4	117.1	109.9	---	---			
0:30	132.0	129.7	125.4	123.2	121.7	124.4	121.9	121.3	115.4	---	106.4			
0:40	132.5	129.0	122.9	120.8	119.0	122.3	121.4	121.8	115.7	---	107.5			
0:50	134.5	131.2	125.7	123.2	119.9	121.8	119.1	118.8	115.1	---	108.4			
1:00	127.5	125.1	120.8	119.9	119.1	122.7	121.3	120.3	116.5	---	109.3			
Average	133.1	129.8	124.4	122.0	119.5	121.7	118.5	118.1	112.4	---	107.9	108.0	25.2	25.1
1:10	128.3	124.7	119.7	117.6	115.2	118.3	117.5	119.2	116.5	---	109.9			
1:20	128.8	125.7	120.7	118.5	115.4	116.9	115.4	115.7	111.7	---	111.0			
1:30	130.2	126.1	120.1	117.7	115.5	117.4	115.2	115.0	111.0	---	108.0			
1:40	131.9	128.6	121.8	119.3	116.8	117.5	115.6	115.1	111.2	---	108.3			
1:50	130.1	128.2	123.2	121.4	119.5	120.8	117.3	117.4	113.7	---	108.2			
2:00	126.1	124.2	120.3	119.1	118.1	120.3	118.1	119.6	116.3	---	111.9			
Average	129.2	126.3	121.0	118.9	116.8	118.5	116.5	117.0	113.4	---	109.6	103.9	19.6	25.3
2:10	121.1	119.5	115.7	115.6	114.8	117.3	116.4	117.6	113.7	---	112.8			
2:20	117.9	115.9	112.7	112.2	111.3	113.6	112.8	114.1	111.0	---	111.4			
2:30	116.8	114.3	110.3	108.9	108.7	110.9	110.0	111.2	107.4	---	108.9			
2:40	117.8	114.6	110.5	108.8	107.4	108.4	107.1	107.7	105.2	---	107.0			
2:50	118.3	115.0	111.0	109.5	107.6	108.6	106.8	107.1	104.4	---	101.8			
3:00	121.8	117.8	112.8	109.9	108.4	109.0	106.8	108.0	104.6	---	101.1			
Average	119.0	116.2	112.2	109.7	109.7	111.3	110.0	111.0	107.7	---	107.2	103.0	11.8	16.0

Table 37. (Continued)

Time (hour)	TEMPERATURE (^oF)													
	THERMOCOUPLES											Out*	ΔT1 1-out	ΔT2 1-out*
	1	2	3	4	5	6	7	8	9	10	Out			
3:10	121.7	118.8	114.5	113.1	110.2	111.3	108.8	108.1	105.4	---	102.8			
3:20	121.6	118.9	114.4	113.1	111.6	112.9	111.8	110.9	109.5	---	102.1			
3:30	124.3	119.6	115.2	113.3	112.2	113.4	111.6	113.0	109.9	---	105.6			
3:40	---	120.1	115.8	112.0	111.7	112.8	111.9	112.4	109.4	---	106.9			
Average	122.5	119.3	115.0	112.9	111.4	112.6	111.0	111.1	108.6	---	104.4	105.2	14.9	17.3

* Calculated values of outlet grain temperature (^oF).
Note: Each temperature value is an average of ten measurements.
Out means out of the cooler.
ΔT1 means the difference between inlet and outlet experimental grain temperatures.
ΔT2 means the difference between the experimental inlet and calculated outlet grain temperature.

$$F = \frac{9}{5} C + 32.$$



1h, 2h, 3h, and 4h mean first, second, third and fourth hours respectively. At 1st and 2nd hours, the air inlet dryer temperature was 400°F and at 3rd and 4th hours it was 300°F.

Figure 15. Temperature profile in the cooling bed during cooling in experiment 6.

Table 38. Experimental air and grain inlet and outlet temperatures in experiment 6.

Time (hour)	TEMPERATURE (^{o}F)					
	Grain out	Air in	ΔT1	Grain in	Air out	ΔT2
0:10	---	62.8		138.0	136.3	
0:20	---	62.5		142.1	135.9	
0:30	106.4	62.4		140.3	132.0	
0:40	107.5	62.3		139.5	132.5	
0:50	108.4	62.7		136.5	134.5	
1:00	109.3	63.4		136.0	127.5	
Average	107.9	62.7	45.2	138.7	133.1	5.6
1:10	109.9	64.0		133.9	128.3	
1:20	111.0	64.7		137.7	128.8	
1:30	108.0	65.0		138.2	130.2	
1:40	108.3	65.4		138.7	131.9	
1:50	108.2	66.0		138.7	130.1	
2:00	111.9	66.7		136.7	126.1	
Average	109.6	65.3	44.3	137.3	129.2	8.1
2:10	112.8	67.3		129.8	121.1	
2:20	111.4	68.2		124.6	117.9	
2:30	108.9	68.9		121.2	116.8	
2:40	107.0	69.8		120.2	117.8	
2:50	101.8	71.0		118.8	118.3	
3:00	101.1	71.7		121.7	121.8	
Average	107.2	69.5	37.7	122.7	119.0	3.7
3:10	102.8	72.5		125.4	121.7	
3:20	102.1	73.2		125.9	121.6	
3:30	105.6	73.9		128.5	124.3	
3:40	106.9	74.2		---	---	
Average	104.4	73.5	30.9	126.6	122.5	4.1

ΔT1 = the difference between the laboratory ambient temperature and the outlet grain temperature (outlet grain minus inlet air).

ΔT2 = the difference between the inlet grain and outlet air temperatures (grain in minus air out).

$$F = \frac{9}{5} C + 32.$$

Table 39. Moisture content changes during the cooling process in experiment 6 with a Ga/Gp ratio of 0.34 w.b.

Time (hour)	MOISTURE CONTENT (% d.b.)						
	Probe Positions						
	Inlet cooler	1	2	3	4	5	Outlet cooler
0:30	7.40	7.12	7.10	7.13	6.99	7.28	7.07
0:40	8.76	7.49	7.89	7.62	7.62	7.24	7.58
0:50	9.34	8.64	8.44	8.65	8.23	7.85	8.44
1:00	7.22	7.06	6.65	6.86	7.23	7.86	7.33
3:10	8.81	8.54	8.75	9.19	9.35	9.19	9.45

Probes 1-5 were placed equidistant 4.7 inches (12.0 cm) starting at 19.9 inches (48.0 cm) from the inlet of the cooler.

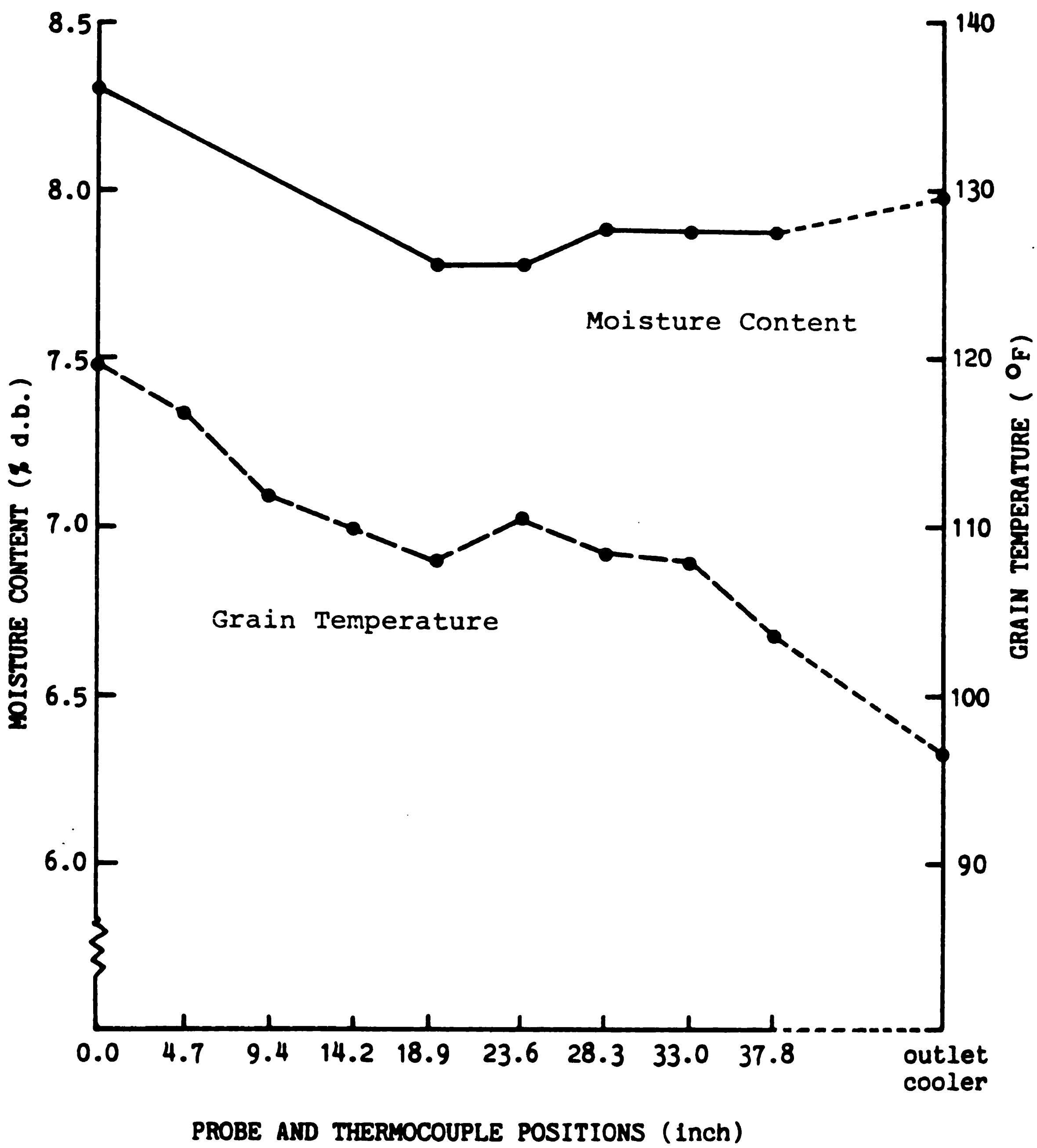


Figure 16. Grain moisture content and temperature profile during a specific cooling period in experiment 6.

Table 40. Experimental grain moisture content and moisture removed (MR) per hour in experiment 6.

Time hour	Gp wet lb/ h ft^2	MOISTURE CONTENT (% d.b.) inlet dryer	inlet cooler	outlet cooler	ΔMC	MR lb/h ft^2
0:10	444	11.57	8.89	8.33	0.56	
0:20	444	9.76	8.45	8.22	0.23	
0:30	444	10.07	7.40	7.07	0.33	
0:40	444	10.91	8.76	7.58	1.18	
0:50	444	11.72	9.34	8.44	0.90	
1:00	444	9.52	7.22	7.33	-0.11	
Average	444	10.59	8.34	7.83	0.51	2.26
1:10	444	11.66	9.12	7.43	1.69	
1:20	444	11.88	9.63	9.01	0.62	
1:30	444	12.11	9.34	8.96	0.38	
1:40	444	11.17	9.20	8.77	0.43	
1:50	444	9.81	7.87	7.75	0.12	
2:00	444	10.05	8.12	7.84	0.28	
Average	444	11.11	8.88	8.29	0.59	2.62
2:10	444	11.43	9.16	8.43	0.73	
2:20	444	9.41	8.65	9.01	-0.36	
2:30	444	12.06	9.33	8.34	0.99	
2:40	444	11.32	10.41	10.35	0.06	
2:50	444	12.03	10.02	9.91	0.11	
3:00	444	11.74	9.98	9.69	0.29	
Average	444	11.33	9.59	9.29	0.30	1.33
3:10	444	10.07	8.81	9.45	-0.64	
3:30	444	9.70	9.03	8.43	0.60	
3:30	444	9.57	8.69	8.72	-0.03	
3:40	444	11.63	9.80	8.29	1.51	
Average	444	10.24	9.08	8.72	0.36	1.60

ΔMC = Inlet minus outlet cooler grain moisture content (% d.b.).
MR = Moisture removed, lb per hour per square foot.
Gp = Grain flow rate, wet lb per hour per square foot.
1 lb/h ft^2 = 4.902 Kg/h m^2.

Table 41. Heat balance in experiment 6 with a Ga/Gp ratio value of 0.34 w.b.

Time (hour)	HEAT (BTU/h)			Latent/Total Heat Ratio*
	Corn	Air		
	Sensible*	Sensible*	Latent*	
1	4771.38	2506.10	2265.28	0.475
2	4919.80	2294.27	2625.55	0.534
3	3120.03	1777.25	1342.78	0.430
4	3367.45	1759.30	1608.15	0.478

* Values derived from equation 10.

1 BTU/h = 0.293 W.

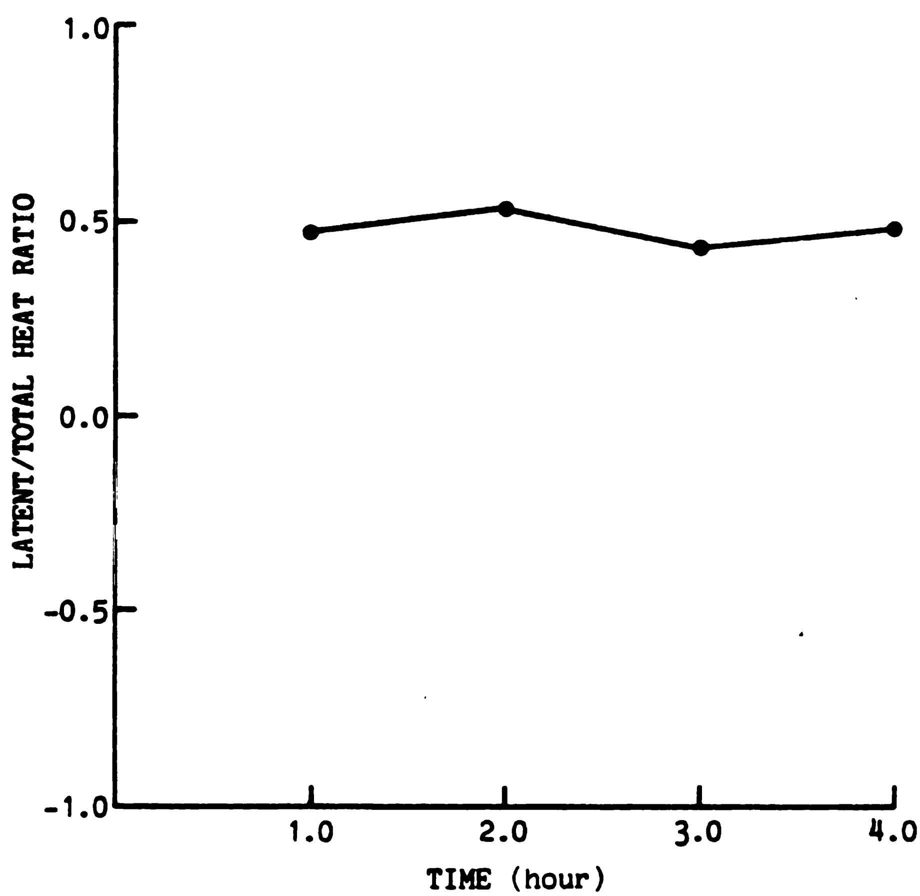


Figure 17. Latent/total heat ratio vs. time during cooling in experiment 6.

the outlet grain temperature was higher than the temperature values of the third and fourth hours. Adsorption of water by the grain occurred from 18.9 inches (48.0 cm) to 23.6 inches (60.0 cm) and from 28.3 inches (72.0 cm) to 33.0 inches (84.0 cm) [both measured from the top of the cooler]. In the rest of the cooler, desorption of water took place. As stated previously, if the temperature decreases during the cooling process, evaporation occurs. If the temperature increases, condensation takes place.

Table 38 shows the air and grain inlet and outlet temperatures. During the first two hours, $\Delta T1$ was greater than during the third and fourth hours. This was due to the higher inlet grain temperature. The difference between inlet grain and outlet air temperature is represented by $\Delta T2$, which is higher during the first two hours (6.9°F (3.9°C)) than during the third and fourth hours (3.9°F (2.2°C)). Again, this was due to the change in inlet grain temperature. The time that the grain was exposed to the air was not sufficient to reach the equilibrium temperature. This is the reason why the inlet grain temperature remains higher than the outlet air value ($\Delta T2$).

Table 39 and Figure 16 show the moisture content and temperature behavior during the cooling process. Both, temperature and grain samples were taken at the same position and at the same time. Both show the desorption and adsorption intervals. The temperature behavior occurred for reasons described previously. Adsorption of moisture by the grain took place at the bottom 23.6 inches (60.0 cm)of the cooler.

Table 40 shows that moisture content of the corn decreased in the cooling process. During the first two hours, the moisture removed was greater than the values found for the next two-hour period. This was due to the higher inlet grain temperature during the first two hours.

Table 41 and Figure 17 show the heat balance. The latent/total heat ratio was not greatly affected when the inlet grain temperature was changed.

In conclusion, experiment 6, with a bed depth of 3.0 ft (91.0 cm) instead of 2.0 ft (61.0 cm) showed that the moisture removal rate decreased in the third foot.

The moisture removal and temperature behavior during cooling in experiment 6 are quite similar to the values of the five previous experiments. The outlet grain temperature was greatly affected by the inlet grain temperature. The additional 1-foot (30.5 cm) bed depth doubled the amount of energy transferred to the air.

5.7 COMMENTS ON EXPERIMENTS 1-6

Table 42 shows a summary of the most important results obtained in experiments 1 to 6. Shown are the inlet and outlet grain temperature difference, the inlet and outlet grain moisture content difference, the moisture removed, and the latent/total heat ratio of the six tests.

Table 42. Major results of tests 1-6.

Experiment Number	ΔT1 ^{o}F	ΔT2 ^{o}F	ΔMC % d.b.	MR lb/h ft^2	Latent/Total heat ratio
1	14.9	25.3	0.63	5.85	0.750
2	14.1	13.8	0.48	4.62	0.724
3	15.8	10.0	0.46	4.55	0.618
4	14.0	23.9	0.44	3.66	0.642
5	38.0	27.0	1.13	5.43	0.676
6	20.9	39.5	0.44	1.95	0.479

ΔT1 = inlet minus outlet grain temperature.
ΔT2 = outlet grain minus inlet air temperature.
1 lb/h ft^2 = 4.902 Kg/h m^2.

$F = \frac{9}{5} C + 32.$

The air flow rate was varied from 206.8 lb/hft^2 in experiment 2 to 484.0 lb/hft^2 in experiment 3. The grain cooled faster when the air flow rate was increased. However, less moisture was removed in the cooling process.

The grain flow rate was varied from 840 lb/h ft^2 in experiment 4 to 480 lb/h ft^2 in experiment 5. Decreasing the grain flow rate increased the amount of water removed. Also, the outlet grain temperature was closer to the temperature of the inlet cooling air temperature, and thus better cooling of the grain resulted.

The ratio of the air and grain flow rates (Ga/Gp ratio) affected to outlet grain temperature in the cooler. As the ratio increased from 0.25 (experiment 4) to 0.43 (experiment 5), the amount of water removed doubled.

The difference between the inlet and the outlet grain temperature (ΔT1) increased when the inlet grain temperature was increased. The same trend was observed for the difference between the outlet grain and inlet air temperature (ΔT2). In contrast, increasing the air flow rate decreased the T2 value.

The moisture removal (ΔMC) increased when the grain flow rate was decreased. The moisture removed (MR) decreased when the inlet grain temperature was decreased while it increased when the grain flow rate was decreased.

Moisture content was one of the important factors affecting the latent/total heat ratio; it decreased from 0.750 in experiment 1 (initial grain moisture content about 16.0

percent) to 0.479 in experiment 6 (initial grain moisture content about 9.0 percent). Because of the prevailing air inlet and outlet conditions during which the experiments were conducted, a negative latent/total heat ratio did not appear. However, it was present in the middle sections of the cooler in all experiments.

In experiment 6, the bed depth was changed from 2.0 ft (0.61 m) to 3.0 ft (0.91 m). The results showed a decrease in the amount of water removal in the third feet as compared to the first and second feet of the cooling bed. The outlet grain temperature was greatly affected by the inlet grain tmperature; the additional 1-foot bed depth doubled the amount of energy transferred to the air, compared with the first and the second feet.

The inlet cooler grain conditions are important in the cooling process. Even more important are the air inlet conditions because ambient conditions of high temperature and high humidity can make effective cooling of warm grain an impossible task. Indeed, this is often the case in southern Brazil during the harvest season.

CHAPTER 6

CONCLUSIONS

Cooling of grain after drying and maintaing the grain cool during storage is a necessary practice. During the cooling process the grain may lose or gain water, which will affect cooling efficiency.

Grain is cooled by latent and sensible heat transfer. The cooling rate depends on the inlet air and initial grain conditions. The inlet air temperature and relative humidity determine the outlet grain temperature. Under the conditions in which the counterflow cooling experiments were conducted, limited moisture adsorption was observed.

The major conclusions of this study were:

(1) The counterflow cooler is an effective cooling device for warm grain if certain limitations are considered.

(2) Increasing the inlet grain temperature increased the outlet grain temperature also.

(3) The grain moisture content decreased between 0.5 to 1.0 percent during the cooling process.

(4) An increase in grain flow rate increased the amount of water removed and resulted in less cooling of grain. At high grain velocities, the possibility of desorption

is greater, because the cooler bed temperature remains high.

An increase in air flow rate decreased the amount of water removed, but resulted in faster cooling of the grain. The decrease in desorption is caused by the lower cooler bed grain temperature.

(5) The increase in bed depth decreased the amount of water removed in the third feet as compared to the first and second feet. However, the additional 1-foot bed depth doubled the amount of energy transferred to the air.

Cooling of grain depends on the ambient conditions. Special precaution must be taken where the climatic conditions are unfavorable (high temperature and high humidity). Indeed, this is often the case in southern Brazil during the harvest season.

CHAPTER 7

SUGGESTIONS FOR FURTHER STUDIES

It is suggested that future experimental work in grain cooling after drying include the following topics:

(1) Grain damage during cooling after drying.

(2) Cooling behavior for other grain species than corn.

(3) Cooler types besides counterflow.

(4) A wider range of inlet air temperature and humidity and of grain temperatures and moisture contents.

(5) A simulation model to predict the cooling behavior based on climatic and grain conditions.

(6) An economical analysis to compare different cooler types.

(7) Development of equipment and methods which will improve the cooling efficiency and grain quality during cooling.

REFERENCES

American Society Heating, Refrigerating and Air-Conditioning Engineers. 1981. Handbook Of Fundamentals. Vol. 1, ASHRAE, New York, N.Y.

Anuario Estatistico do Brasil. 1980. Fundacao Instituto Brasileiro de Geografia e Estatistica. Rio de Janeiro.

Bakker-Arkema, F. W. 1979. Testing of commercial crossflow dryers. ASAE Paper No. 79-3521, St. Joseph, MI.

Bakker-Arkema, F. W. 1984. Personal information.

Brooker, D. B., F. W. Bakker-Arkema, and C. W. Hall. 1981. Drying Cereal Grain. AVI: Westport, CT.

Calderwood, D. L. 1966. Use of aeration to aid rice drying. Trans. ASAE, Vol. 9, pp. 893-895.

Calderwood, D. L. and B. D. Webb. 1971. Effect of the method of dryer operation on performance and on the milling and cooking characteristics of rice. Trans. ASAE, Vol. 14, pp. 142-146.

Chau, N. N. and O. R. Kunze. 1982. Moisture content variation among harvested rice grains. Trans. ASAE, Vol. 25, pp. 1037-1040.

Chung, D. S. and H. B. Pfost. 1967. Adsorption and desorption of water vapor by cereal grains and their products. Trans. ASAE, Vol. 10, pp. 552-575.

Converse, H. H., D. B. Sauer, and T. O. Hodges. 1973. Aeration of high moisture corn. Trans. ASAE, Vol. 16, pp. 696-699.

Food and Agriculture Organization. 1978-1982. FAO Production Yearbook, Vol. 32, 33, 34, 35, and 36. Rome, Italy.

Fortes, M., M. R. Okos, and J. R. Barret, Jr. 1981. Heat and mass transfer analysis of intra-kernal wheat drying and rewetting. J. Agric. Eng. Res., Vol. 26, pp. 109-125.

Foster, G. H. 1964. Dryeration--A new corn drying process. AMS 532, U.S. Department of Agriculture, Washington, D.C.

Foster, G. H. 1967. Moisture changes during aeration of grain. Trans. ASAE, Vol. 10, pp. 344-351.

Gustafson, R. J., A. Y. Mahamoud, and G. E. Hall. 1983. Breakage susceptibility reduction by short-term tempering of corn. Trans. ASAE, Vol. 26, pp. 918-922.

Henderson, S. M. 1952. A basic concept of equalibrium moisture. Agr. Eng., Vol. 33, pp. 29-31.

Henderson, S. M. 1954. The causes and characteristics of rice cracking. Rice J., Vol. 57, pp. 16-18.

Hodges, T. O., H. H. Converse, and D. B. Sauer. 1971. Some effects of cooling rates on quality of high moisture corn. Trans. ASAE, Vol. 14, pp. 649-655.

Holman, J. P. 1981. Heat Transfer. Fifth Edition. McGraw-Hill, New York, N.Y.

Kalchick, S. V. 1977. Drying of soybeans in a pilot-scale concurrent flow dryer. Unpublished M.S. Thesis, Michigan State University, East Lansing, MI.

Kunze, O. R. and C. W. Hall. 1965. Relative changes that causes brown rice to crack. Trans. ASAE, Vol. 8, pp. 396-399, 405.

Kunze, O. R. and C. W. Hall. 1967. Moisture adsorption characteristics of brown rice. Trans. ASAE, Vol. 10, pp. 448-453.

Lerew, L. E. 1972. A Fortran Psychrometric Model. M.S. Thesis, Michigan State University, East Lansing, MI.

Patterson, R. L. 1969. Airflow-Pressure Drop Characteristics of Packed Beds of Biological Particles. Unpublished M.S. Thesis, Michigan State University, East Lansing, Michigan.

Rodrigues-Arias, J. H. 1956. Desorption Isotherms And Drying Rates Of Shelled Corn In The Temperature Range of 40 to 140^{o}F. Unpublished Ph.D. Thesis, Michigan State University, East Lansing, MI.

Sabbah, M. 1971. Convective Heat Transfer Coefficient and Tempering Effects on Cooling Rate of Shelled Corn. Unpublished Ph.D. Dissertation, Purdue University, Purdue, Indiana.

Sabbah, M. A., G. H. Foster, C. G. Haugh, and R. M. Peart. 1972. Effect of tempering after drying on cooling shelled corn. Trans. ASAE, Vol. 15, pp. 763-765.

Sorenson, J. W., Jr., N. K. Person, Jr., W. E. McCune, and P. Hobgood. 1967. Design method for controlled-environment storage of grain. Trans. ASAE, Vol. 10, pp. 366-369.

Souza, O. W. 1978. Equalization of moisture content of wheat before drying. Anais do III seminaria nacional de Armazenagem. lompanhia Paranaense de silos e Armazens--COPASA. Curitiba, PR.

Thompson, R. A. and G. H. Foster. 1967. Dryeration--high speed drying with delayed aeration cooling. ASAE Paper No. 67-843, St. Joseph, MI.

Thompson, T. L. 1972. Temporary storage of high-moisture shelled corn using continuous aeration. Trans. ASAE, Vol. 15, pp. 333-337.

United States Department of Agriculture. 1968. Safe corn storage period. Agricultural Research, Vol. 16, p. 10.

United States Department of Agriculture. 1983. Agricultural Statistics, Washington. D.C.

Walker. L. P. 1978. Process Analysis Of A Multistage Concurrent Rice Dryer. Unpublished Ph.D. Thesis, Michigan State University, East Lansing, MI.