EFFECTS OF AIRFLOW RATES ON COOLING TIME AND TEMPERATURE DISTRIBUTION IN AERATED WHEAT

By

DAVID REID EPPERLY

Bachelor of Science
in Agricultural Engineering
Oklahoma State University
Stillwater, Oklahoma
1983

Master of Science
Oklahoma State University
Stillwater, Oklahoma
1985

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 1989

EFFECTS OF AIRFLOW RATES ON COOLING TIME AND TEMPERATURE DISTRIBUTION IN AERATED WHEAT

Thesis Approved:

Thesis Advisor

Dean of the Graduate College

ACKNOWLEDGEMENTS

There have been many people who have directly or indirectly assisted me in the completion of this segment of my life and education. First of all, I would like to thank the U.S. Department of Agriculture for the National Needs Ph.D. Fellowship I received, because without it I probably would not be where I am now.

I would like to sincerely thank my major advisor, Dr. Bobby Clary, for his excellent advice, patience and assistance throughout the entire course of study. I also enjoyed the many extracurricular activities we encountered throughout the years I have known him (fishing, eating, drinking, consulting and other things not to be mentioned here).

Dr. Marvin Stone was another person who bestowed an abundant supply of advice in the completion of this endeavor (typically providing far more than enough advice). Appreciation is also expressed to my other committee members, Dr. Gerrit Cuperus, Dr. Willard Downs and Dr. Gary Foutch for their advice, patience and assistance.

Thanks is also extended to Wayne Kiner and the staff at the Agricultural Engineering Laboratory for their much needed assistance, and notably Bruce Lambert for his help in setting up the instrumentation for this investigation.

There were also several others that indirectly helped me through this ordeal. First, I cannot forget my mother and family for their generous support. I would also like to thank Stan Clark for providing a place to go and

unwind on weekends and after a long day of work, mentally and physically. And last but not least, to Pamela Atherton for no specific reason, but for numerous smaller considerations (she will get the message).

Finally, I would like to dedicate this dissertation to my father, the late Jean R. Epperly. I regret that he was not here to see me through my Ph.D. program, but know that he would be proud of my achievements.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table		Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

LIST OF SYMBOLS

A_{cum}	cumulative amount of air used to aerate grain, m^3
B	intercept in mathematical models
C_g	specific heat of grain, cal/g·°C
E	coefficient for enthalpy term, dimensionless
ΔH	maximum enthalpy difference between air entering and leaving the grain mass, cal/g
k_g	thermal conductivity of grain, cal/s·m·°C
L	total depth of grain, m
M	slope in mathematical models
M_w	grain moisture content, % w.b.
Δmc	change in moisture content, % w.b.
P	porosity, dimensionless
Q	volumetric flow rate of air, m^3/hr
Q_a	aeration rate, L/s·m^3
q'	electrical heat input, cal/s·m
T	temperature, °C
T_o	initial grain temperature, °C
T_{final}	final grain temperature, °C
T_{db}	dry-bulb temperature, °C
T_{wb}	wet-bulb temperature, °C
T_{dbc}	dry-bulb temperature of air in environmental chamber, °C
T_{wbc}	wet-bulb temperature of air in environmental chamber, °C

T_{dbe} dry-bulb temperature of air exiting columns, °C

T_{wbe} wet-bulb temperature of air exiting columns, °C

T_1 grain temperature at time Θ_1, °C

T_2 grain temperature at time Θ_2, °C

ΔT differential between initial and final grain temperatures, °C

W mass of grain to be cooled, kg

X distance from bottom of grain mass, m

y variable in Schumman's equation

z variable in Schumman's equation

β Ratio of orifice diameter to pipe diameter, dimensionless

Φ variable in Schumman's equation

ρ_a air density, g/m^3

ρ_b bulk density, kg/m^3

ρ_s particle density, kg/m^3

Θ time, hr

Θ_c time correction factor, dimensionless

Θ_L time for leading edge of cooling front to move out of grain mass, hr

Θ_T time for trailing edge of cooling front to move out of grain mass, hr

Θ_{LL} time for leading edge of cooling front to reach a given location at a certain aeration rate, hr

Θ_{LT} time for trailing edge of cooling front to reach a given location at a certain aeration rate, hr

CHAPTER I

INTRODUCTION

Approximately 800 million bushels of wheat are harvested each year in the Southern Great Plains. In Oklahoma, about 33% of wheat is maintained in on-farm storage (Anderson, 1988). Because temperatures, humidity and harvest conditions are favorable for insect and mold development in stored grain, this region is considered a high-risk storage area (Storey, *et al.*, 1979).

Stored grain insects can damage hard red winter wheat by causing weight loss, lower test weight, reduction in grade, decrease in germination and nutritive value, and by increase in contamination. Recent changes in the Federal Grain Inspection Service (FGIS) grading practices have resulted in grain containing 32 insect damaged kernels/100 gram sample being designated as sample grade (Federal Register, June 30, 1987). Furthermore, the Food and Drug Administration (FDA) must declare this grain as unfit for human consumption, restricting it to livestock feed which discounts price. Also, the Environmental Protection Agency (EPA) has removed heavily used pesticides from the market. As a result, the potential for monetary loss of on-farm and commercial stored grain has increased dramatically.

Harein (1982) reported that annual storage losses due to insects is at least 10 percent. In this region, this could amount to 80 million bushels or over $300 million per year.

In the Oklahoma/Texas region, the stored grain system is primarily regulated by grain temperatures. In this area, wheat is harvested during the hot summer months and typically enters storage about 35°C (95°F) (Cuperus *et al.*, 1986). This temperature is above the upper development threshold for most stored grain insects and acts as a deterrent to infestations as long as the grain mass remains at or above 35°C (95°F). These high summer temperatures also result in the rapid breakdown of grain protectants (Abdel-Kaddel *et al.*, 1979, Thorpe and Elder, 1982).

In the fall when the grain begins to cool and grain protectants have become ineffective through degradation, there is potential for tremendous populations of insects and molds to develop. Fall air temperatures of September and October slowly cool grain temperatures to 20° to 30°C (68° to 86°F), which is ideal for stored grain insect development causing insect populations to increase rapidly (Epperly *et al.*, 1987). As outside temperatures drop below the temperature of the grain mass, convection currents result in moisture migration to the cooler grain located near the top surface at the center of the bin. These convection currents and moisture migration produce high grain moisture areas which are favorable for growth and reproduction of stored grain insects and molds. Unless grain temperatures are reduced below the critical level of 15°C (60°F), insect and mold population growth will continue throughout the winter.

Aeration and grain turning have been used to control temperature and moisture migration in grain throughout the United States. Studies at Oklahoma State University (Cuperus *et al.*, 1986) and in Australia (Evans, 1983) have indicated that effective use of aeration systems to rapidly drop the grain mass temperature during the fall months not only produces an environment to discourage infestations, but can be fatal to most insects. They believe that aeration becomes effective in reducing existing stored grain insect populations when the temperature drop in the grain mass exceeds a threshold level in either amount or rate of temperature drop. If stored grain temperatures are lowered and maintained at low levels, the grain will remain at a safe temperature until summer. Stored grain insects acclimate to low grain temperatures when those temperatures are reduced slowly. The effects observed by these researchers are apparently related to the rate of temperature reduction in the grain bin.

Aeration poses no chemical or environmental problems and is significantly less costly than conventional chemical control (Epperly *et al.*, 1987). After grain temperatures drop below 15°C (60°F), they remain low well into the summer months. Aeration has been shown to save one to three fumigations per year and eliminate the need to turn grain. Aeration decreases off farm inputs including pesticides and energy while reducing grain loss, resistance buildup and worker exposure to fumigants.

Cold weather frontal systems reaching Oklahoma in October and November typically produce temperatures below 10°C during the night time, but usually last only two to five days. This allows about 25 to 60 hours of available aeration time per frontal system. The "standard" air flow rate has been about 1.34 $L/s{\cdot}m^3$ (0.1 cfm/bu), which requires 120 to 150 hours of aeration to completely cool the grain mass (Noyes and Clary, 1985). Using higher aeration rates, the grain mass can be completely cooled during one cold weather front. If these higher airflow rates are to be used it will be necessary to predict the total cooling time. However, with present technology the cooling times and temperature gradients cannot be accurately predicted. The purpose of this study is to establish a means to accurately predict these variables.

CHAPTER II

OBJECTIVES

The objectives of this study were to:

1. Determine the rate at which the leading and trailing edges of a cooling front propagate through a grain mass in relation to different aeration rates.

2. Develop a mathematical model to predict the temperature profile in the cooling zone of aerated wheat.

3. Determine the thermal conductivity, specific heat, bulk density, particle density and porosity of the wheat used in the study.

CHAPTER III

REVIEW OF LITERATURE

Aeration in General

The practice of aerating stored grain was established in the United States during the early 1950's and is now an accepted quality-maintenance measure. Aeration development was coincident with the building of reserve stocks of grain following World War II. Large flat storages were used to hold much of the reserve grain, and aeration was first developed for this type of storage. The experience with aeration in flat storages was so favorable that the practice was soon adapted to silos and upright storages at grain elevators and to larger farm-type grain bins.

Initially, aeration was used to cool the center of the grain mass and thereby prevent moisture migration from the warm grain to the cold surface layer. Robinson *et al.* (1951) explains that in the fall and winter when the bin wall and the grain near the wall becomes colder than the grain at the center of the bin, convection currents within the bin are created which result in the transfer of moisture from the comparatively warm central mass of grain to the cold upper surface around the center of the bin. The slow upward moving air in the central portion of the grain mass rises in temperature from contact with the comparatively warm grain and at the same time, the absolute humidity of the air is increased by moisture removed from the grain. When the rising air comes in contact with the cold grain near the top surface, some of the moisture condenses, thus raising the moisture content of the whole mass of grain. In fact, there is actually a slight decrease in moisture content from some distance below the surface down to the floor.

Aeration for Insect Control

The two major factors affecting the prevalence of stored grain insects are temperature and moisture conditions. Most of these insects are thought to be of subtropical origin and have developed no known tolerance to low temperatures. For each species of insect there is a particular zone of temperature and moisture within which the capacity for population increase is greatest. Grain temperatures around 15° to 18°C (60° to 65°F) are considered the danger point. At these or higher temperatures, severe damage to stored grain from insects is expected, whereas below this level no serious damage is likely. Also, grain temperatures above 35°C (95°F) are unfavorable to most insects (Cotton, 1963; Bishop, 1959; Surtees, 1963, 1965). Insects generally prefer moist grain with moisture contents 12 percent or higher. Grain with moisture contents below 12% is less desirable for insect growth and reproduction (Bishop, 1959; Hunter and Taylor, 1980; Evans, 1982, 1983; Ghaly, 1984).

The use of aeration to cool grain in order to manage stored grain insects has been investigated in Australia (Sutherland *et al.*, 1971; Ghaly, 1984), England (Burgess and Burrell, 1964; Burrell, 1967; Armitage and Stables, 1984), Israel (Navarro *et al.*, 1969, 1973; Donahaye *et al.*, 1974) and the United States (Johnson, 1957; Cuperus *et al.*, 1986; Epperly *et al.*, 1987). Burges and Burrell (1964) aerated 6,500 tonne of malting barley and stated that cooling the grain by aeration to 20°C (68°F) greatly reduced insect risk.

They added that after completion of aeration, the grain temperature is considered safe if the cumulative daily heat production of the insects remains negligible. Generally, 17°C (63°F) was considered safe.

Two different aeration tests were conducted by Burrell (1967), a small-scale and a large-scale test. The small-scale test consisted of two 8-tonne bins of barley which were infested with insects and aerated with refrigerated air, lowering the grain mass temperature to the 3° to 4°C (37° to 39°F) range. Of the 3,400 adult insects added to the two bins, only seven live and 32 dead insects were found in the six tonnes sieved. It was thought that the insects might have been stimulated by air movement or temperature to migrate from the bins. The large-scale test consisted of a 140-tonne bin heavily infested with insects and aerated with refrigerated air to 5° to 10°C (40° to 50°F). The total number of live insects in 16 samples fell by 271 from 2,071, and the number of dead rose by 180 in 20 days. Cooling can be used to prevent insect infestations from building up in bulk grain. However, where a heavy infestation is already present, cooling is unlikely to destroy all insects unless the grain can be kept cool for a period of many months.

Sutherland (1968) aerated 2,700 tonnes of heavily infested wheat to cool the grain mass to 8.3°C (47°F). Less than one live insect per 45 kg (100 lb) of grain was found by careful sieving during out-loading. He stated that his investigation had shown how aeration alone could reduce insect activity and consequent moisture migration and mold formation, and that under suitable conditions aeration can eliminate the need for insecticides.

Navarro *et al.* (1969) observed 1,142 tonnes of aerated wheat for 22 months. They cooled the grain mass from 26.8°C -32.2°C to 10.2°C -13.8°C and reported that most of the grain-infesting insect species were dead at the end of the 22-month storage period. Armitage and Stables (1983) experimented with two aerated and two non-aerated 30-tonne bins of wheat infested with stored grain insects. Temperatures in the aerated bins reached 5°C and below. More insects exited out of aerated than non-aerated bins, and most escaped from the most heavily infested bin. The number of live insects were considerably lower in the aerated than in the non-aerated bins. Similarly, there were fewer live insects in aerated bins, but not significantly fewer than in non-aerated bins. He emphasized the importance of cooling the grain mass quickly before sizable infestations can arise.

Cuperus *et al.* (1986) conducted a three-year study in Oklahoma in which they observed several on-farm grain bins, both aerated and non-aerated. Substantial differences were found between aerated and non-aerated grain bins for abundance of insects. Stored grain insect mortality was demonstrated when grain temperatures dropped below 15°C (60°F) for extended periods of time. They also observed that after cooling the grain mass to about -7°C (20°F) in February, the mean grain temperature remained at 2°C (36°F) in April, 13°C (56°F) in July and 18°C (65°F) in October without any further aeration. Grain samples taken in April contained no live insects compared to 114 live adult secondary insects and 4 live adult primary insects per 1 kg (2.2 lb) sample taken in October. This showed that aeration can have residual control effects that extend well into the warm season.

Models

When considering the cooling rate of a grain mass, there are two general approaches. The first assumes that no mass transfer takes place between the grain and the cooling medium. In an ideal case, the cooling zone is of negligible thickness and the maximum temperature change in the cooling air occurs throughout the cooling period (Foster, 1967). The temperature rise in the air is equal to the temperature drop in the grain. When a heat-balance equation is written for the ideal case, the two temperature terms are equal and drop out. The unit amount of air required to cool a unit amount of grain is simply a ratio of the specific heat of the grain to the specific heat of the air.

One of the earliest important papers on the topic of heat transfer in a fixed bed was published by Schumann (1929). He analytically solved the cooling rate of a bed of broken solids through which air passed at a constant rate. He developed a two-equation heat transfer model that would predict the temperature history of any point in the bed. The model was restricted to systems where the thermal properties are constant, for noncompressible fluids and where the solid particles are small enough that there is no temperature gradient within the particles at any time.

Furnas (1930) later extended Shumann's (1929) model to larger airflow rates and bed-depths and applied the solutions to beds of iron balls. The Schumann (1929) deep bed analysis is exact for systems where the thermal conductivity of the bed particles is large and their size is small, but these conditions do not hold for most beds of biological particles, adds Bakker-Arkema *et al.* (1974).

Bakker-Arkema and Bickert (1966) worked with the deep-bed cooling of beets and developed a model based on Schumann's (1929) analysis to predict the temperature in a deep-bed as a function of time and position. The assumptions made in developing the model were that no mass transfer takes place between the beets and the cooling source, there is no temperature gradient in the individual beets and the air velocity in all interstices of the deep bed were to be constant. When theoretical and experimental cooling rates were compared, the real cooling rate was considerably higher than the predicted rate. They stated that the difference was due to the effect of mass transfer on the cooling rate. The result was a decrease in both the cooling air and beet temperatures, both factors contributing to an increased cooling rate.

Several other authors also discussed the need for the consideration of latent heat transfer (Boyce, 1966; Burrell and Laundon, 1967; Foster, 1967; Moysey, 1969; and Person *et al*, 1966). As Foster (1967) explains, to raise the temperature of the air and maintain or increase the relative humidity, the absolute humidity (mass of water per mass of air) must be increased. In aeration the increase must come from moisture removal from the grain. Furthermore, the grain must supply the heat for evaporating the moisture. Thus, the moisture removable incident to cooling reduces the amount of sensible heat exchange required and lowers the quantity of cooling air required to effect a given temperature change in the grain.

There have been numerous drying models developed that, obviously, include moisture changes (Barre *et al.*, 1971; Baughman *et al.* 1971; Henderson and Henderson, 1968; and Bloome and Shove, 1971, 1972). Only a few people have derived models for cooling grain masses with moisture content changes included (Boyce, 1966; Sutherland *et al.*,1971; Ingram, 1979; and Bakker-Arkema *et al.*, 1967). Boyce (1966) developed a model designed mainly for thin layer drying of grain, but stated that grain cooling could also be solved using the same equations. His was one of the first attempts at writing a semi-equilibrium model of a deep bed. The model consisted of the summation of the heat and mass transfer rates of several thin layers. In semi-equlibrium models, grain and air in each thin layer are assumed to come to temperature equilibrium over the simulation time interval while moisture transfer is predicted through a thin layer or diffusion equation. His computed results were not in reasonable agreement with experimental observations for drying, but he did not mention comparisons for cooling.

Sutherland *et al.* (1971) used an equilibrium analysis with the assumptions that the heat and mass transfer coefficients between air and grain are infinite, there is no diffusion of heat or mass in the airflow direction, the voids in the grain bed were considered to be straight and parallel channels and the air moves uniformly through a uniform cylindrical bed of grain. A computer program was developed that predicted the leading and trailing edges of cooling or heating fronts with either wetting or drying of the grain. They concluded that their model predicted times and front shapes for the equilibrium case reasonably, but the effects of finite transfer and diffusion coefficients should be included to treat the subject adequately.

Ingram (1979) used the method of characteristics to solve heat and mass transfer equations for cooling and drying. He compared the results with those of finite difference solutions and stated that they gave close agreement. The results were best when considering low airflow rates and the agreement was less satisfactory at higher airflow rates.

Bakker-Arkema *et al.* (1967) conducted numerous studies on the cooling of a wet bed of cherry pits using a three-equation analysis; one equation each for product temperature, air temperature and specific humidity of the air. The effect of several parameters (airflow, convective mass and heat transfer coefficients, inlet air conditions, porosity, specific heats and heat of vaporization) on the cooling rate was studied using their model.

Non-equilibrium simulation models describe both heat and mass transfer through rate equations. Simplifying equilibrium assumptions are not made. The most widely known of these types of models is the Michigan State University grain drying simulator, summarized by Bakker-Arkema *et al.* (1974) and Brooker *et al.* (1974). One rate equation each was used to determine grain temperature and moisture content, and air temperature and absolute humidity. Heat transfer was predicted through heat transfer coefficients, while mass transfer was predicted using a mass transfer coefficient and either an empirical thin layer drying rate equation or a theoretical diffusion rate equation. Morey *et al.* (1978) stated that the MSU model, designed for high-temperature drying simulation, is not feasible for use in low-temperature, low-airflow simulation since the solution of the system of partial differential equations requires excessive computer time requiring short simulation time intervals.

A validation test by Keener *et al.* (1978) compared performance of the MSU model and two variations on the model, the MSU model with a new moisture transfer equation and a new partial differential equation based on a two-lump, thin layer equation. All three models predicted moisture content within about 1.0% w.b. over a 100 hour drying test using airflow rates of 10 to 15 m^3/min·tonne.

Schultz (1984) conducted a comparison of simulation techniques for wheat aeration. He examined the factors of solution method, hysteresis and simulation time interval. Simulation models were developed for each combination of factors and the results were compared to field wheat aeration data to determine the accuracy of grain moisture content and temperature prediction. Equilibrium simulation was patterned closely after methods presented by Thompson (1972) and semi-equilibrium simulation was patterned after Thompson *et al.* (1968). He found both equilibrium and semi-equlibrium simulations were inadequate in moisture content prediction, but a combination of the methodologies provided acceptable predictions. The average temperature could be adequately predicted with equilibrium and combination methods, but not with semi-equilibrium. An increase in simulation time interval had little effect on equlibrium simulation results, and hysteresis was found to be a critical factor in predicting adsorption.

Temperature and Moisture Fronts

When cool air is drawn through a bin of warm grain, all the grain does not cool at once. Actually, a step change in the state of air flow into a grain mass causes the formation of 3 zones (say, A, B and C), separated by 2 fronts (namely, temperature and moisture) which move through the grain mass in the direction of air flow (Sutherland *et al.*, 1971). A temperature front (heating or cooling) is defined as the zone within the grain mass where the temperature changes from an initial value to a new one caused by the ventilation air. The leading and trailing edges are the top and bottom portions of the front, respectively. In a cooling front, high temperature points move faster than low temperature points, whereas in a wetting front the low moisture content points move faster than high moisture content points. This is how leading and trailing edges of fronts are produced (Sutherland *et al.*, 1983).

In zone A, the grain has reached equilibrium with the entry air and no further change takes place. The temperature of the grain, the entering air and the intergranular air are all equal. The relative humidities of the intergranular air and the entering air are also equal and the grain moisture content has assumed the value which is in equilibrium with this humidity.

In zone C, the grain temperature and moisture content have not changed from the initial values, namely those prior to the step change in the entry air conditions. The temperature of the intergranular air and the air leaving the grain are both equal to the grain temperature. The relative humidity is, in both cases, the value which is in equilibrium with the grain moisture content in zone C.

Zone B, bounded by the temperature and moisture fronts, is of greatest interest, but its conditions are not easily derived. In the faster temperature front the major effect is a change in temperature, but an associated small change in moisture content also occurs. Similarly, in the case of the slower moisture front, there is an associated change in temperature.

Temperature fronts tend to be deep and indistinct. The depth of the fronts depends mainly on airflow rates and the temperature differentials involved (Muir *et al.*, 1987). Sanderson *et al.* (1988a) found that temperature front depths were generally greater than 1.75 m (5.75 ft) and in most cases spanned the entire bed depth (3.5 m (11.5 ft) in their case). They found no noticeable differences in temperature front depths for different ventilation rates for their 3 year study. However, Sutherland *et al.* (1983) and Ingram (1979) stated that if the superficial air velocity in the grain mass was doubled there was almost a doubling of the depth of the temperature front. Burrell and Laundon (1967) had a cooling front depth of 4.3 m (14 ft) resulting from an air velocity of 3 m/min (9.8 ft/min) in wheat of 16.8% moisture, and over 3.05 m (10 ft) in damper wheat.

Various researchers have studied temperature fronts within aerated grain bulks experimentally (Sorenson *et al.*, 1967; McCune *et al.*, 1963; Miller, 1965; Sanderson *et al.*, 1988a, 1988b) and theoretically (Hunter, 1988; Sutherland *et al.*, 1971, 1983). Most of these findings, however, were based on computer simulations with limited data from field experiments. Sutherland *et al.* (1983) state that grain moisture content has little influence on the speed of a temperature front, but temperature plays a dominant role in determining the speed of a cooling front. Also, in a cooling front each point moves at a unique speed whatever the grain conditions are on each side of the front. They developed a computer model using equilibrium theory and simulated front interactions when cooling with high humidity air (Sutherland *et al.*, 1971) and stated that a temperature front travels typically at 1/400 of the face velocity of the air.

Miller (1965) worked in the laboratory with an experimental grain bin to determine the velocities of the leading and trailing edges of a cooling zone in aerated sorghum. He approximated the times for the fronts to pass through the grain mass to be (with flow aeration rates, Q_a, in cfm/bu):

$$\Theta_L = 3.9 \cdot Q_a^{-0.94} \quad (1)$$

$$\Theta_T = 29 \cdot Q_a^{-0.65} \quad (2)$$

However, he pointed out that the results could only be used for the conditions encountered in his tests. The manner in which the aeration rates were determined is thought to be questionable. He used one aeration rate, 1.2 $L/s \cdot m^3$, and used different depths in the grain mass for his different aeration rates.

McCune *et al.* (1963) aerated sorghum at 16.2% moisture content at an aeration rate of 1.6 $L/s \cdot m^3$ (0.12 cfm/bu) with air at approximately 100% RH. Their tests showed that approximately 125 hr were required to cool the grain down 25 C degrees (45 F) (3° higher than the cooling air) and the entire grain mass could be cooled to the entering air temperature in 168 hr.

Hunter (1988) used a relationship between relative humidity and saturation pressure to estimate the dwell state (that prevailing after the passing of the temperature front and before the passing of the moisture front) from the initial seed state and the inlet state. He developed equations for approximating the front speeds and logarithmic slopes for temperature and moisture. He compared his results only with those of Sutherland *et al.* (1983), however, and obtained similar results.

Sanderson *et al.* (1988a) conducted cooling studies in 1983 and 1984 with wheat at initial moisture contents from 15% to 25% w.b. and aeration rates from 0.85 to 23.2 $L/s \cdot m^3$ (0.06 to 1.7 cfm/bu). Their measured cooling times were defined as the duration of forced ventilation required to lower the top layer of the bin from its initial temperature to where it levels off at a value dictated by incoming air conditions during ventilation. Their cooling times are approximations, as it was difficult to obtain an exact cooling time due to fluctuating ambient air conditions and the exponential nature of the cooling curve, and comparisons between cooling times in different years should not be made due to the changes in weather from one year to the next. They modified a method of Navarro and Calderon (1982) that approximates cooling time as:

$$\Theta = \frac{W \times \Delta T \times C_g}{Q_a \times \rho_a \times E \times \Delta H} \tag{3}$$

They changed the constant, E, from 0.5 to 0.4 and improved the accuracy for their observed data. The accuracy of this method is limited to the unpredictability of ambient air conditions and, depending on what values are used for the mean ventilation conditions, the calculated cooling times can vary considerably.

Sanderson *et al.* (1988b) investigated moisture front movements with temperature front studies. They found that the speed of drying fronts in low temperature grain drying bins was not linearly proportional to airflow rate. A doubling of the airflow rate resulted in up to 2.5 times increase in measured drying front speed.

Several factors are thought to change the time required to cool grain. Some factors are also thought to determine the final temperature the grain mass reaches. The most obvious factor affecting cooling time is aeration rate. The change in moisture content is probably the second most important factor.

If some drying takes place due to evaporative cooling, the total cooling time is reduced. Burrell and Laundon (1967) state that a moisture reduction of 0.5% will produce one-third of the total heat loss. Foster (1967) states that heat to evaporate moisture can account for about half of the cooling and the air required for cooling the grain is reduced proportionately. Kline and Converse (1961) found the aeration time required to cool wheat 8.3 C (15 F) degrees with a moisture content reduction of 0.3% was 160 hrs in the summer, compared to a total cooling time of 310 hrs for a moisture reduction of 0.1% in the winter with the same airflow rate and temperature reduction. Person *et al.* (1966) added that the actual reduction in the cooling time as a result of the reduction in moisture content of the grain could not be predicted.

The initial moisture content of the grain is also thought to effect cooling time, but the initial and final temperatures of the grain do not seem to effect cooling time (Moysey, 1969; Burrell and Laundon, 1967; and Navarro *et al.*, 1973). Grain at two different initial temperatures, 30°C (85°F) and 15°C (60°F) were cooled simultaneously and about the same time was required to cool all grain to the aeration air temperature (MRR No. 178, 1960).

The fact that aerated grain does not reach the dry-bulb temperature of the cooling air has been observed by Boyce (1966), Person *et al.* (1966), Sorenson *et al.* (1967), Sutherland *et al.* (1971) and others. They have observed that high moisture grain nearly reaches the wet-bulb temperature of the entering air. Person *et al.* (1966) adds, within certain air dry-bulb temperature and grain moisture content limits, grain temperature can be controlled entirely by the specific humidity of the conditioned air entering the grain mass.

The amount of temperature drop of the grain mass may not affect the amount of time required to cool grain. Studies conducted by Pabis and Henderson (1962) indicate that after only a short time the temperature of a single grain approached that of the adjacent air stream. Burrell and Laundon (1967) also state that heat exchange between the grain and air passing through it at 2.7 to 3.0 m/min (9 to 10 ft/min) is almost instantaneous.

Another factor affecting cooling time is a loss of efficiency during the last stages of cooling (Moysey, 1969). Foster (1967) and Burrell and Laundon (1967) found as the cooling zone moves out of the wheat, the rate of heat removal drops and cooling time is increased proportionately. Sanderson *et al.* (1988a) also mentioned exponential nature of the cooling curve.

Changes in Moisture Content with Aeration

Several investigators have reported there is always an initial drop in moisture content of the grain while cooling regardless of the entering air relative humidity (Sorenson *et al.*, 1967; McCune *et al.*, 1963; Foster, 1967; and Sanderson *et al.*, 1988a, 1988b). The amount of moisture reduction is usually between 0.2% and 1.0% in moisture content, depending on grain and aeration air properties. Burrell and Laundon (1967) reported an average fall of about 0.5% in the moisture content of grain per 24 hr of refrigeration. Metzger and Muir (1983) found airflow rates of 0.5 to 3.0 $L/s{\cdot}m^3$ (0.04 to 0.22 cfm/bu) resulted in moisture content reductions of 0.5 to 0.7 percentage points. Moysey (1969) calculated that for most cases, the cooling process will produce a moisture reduction of 0.25% to 0.75% in moisture content and stated that his experience showed that to be true. Foster (1967) both cooled and warmed a small bin of wheat in the laboratory. In three tests, the wheat moisture content was reduced 0.44% to 0.52% when the wheat was cooled from 27°C to 10°C (80°F to 50°F). When the wheat was warmed from 10°C to 27°C by aeration, its moisture content was increased 0.50% to 0.67%. Wheat at initial moisture levels of 11% and 13.5% was used and moisture losses were calculated from the difference in absolute humidity of the air entering and leaving.

Sanderson *et al.* (1988b) observed a mean drop in moisture content of 0.9% as the initial cooling front passed through the grain bulk. They demonstrated the potential for moisture loss in the initial cooling front in Figure 1. Ventilation air entering at condition 1 removes energy and moisture from the grain as it travels through the grain bulk exiting in

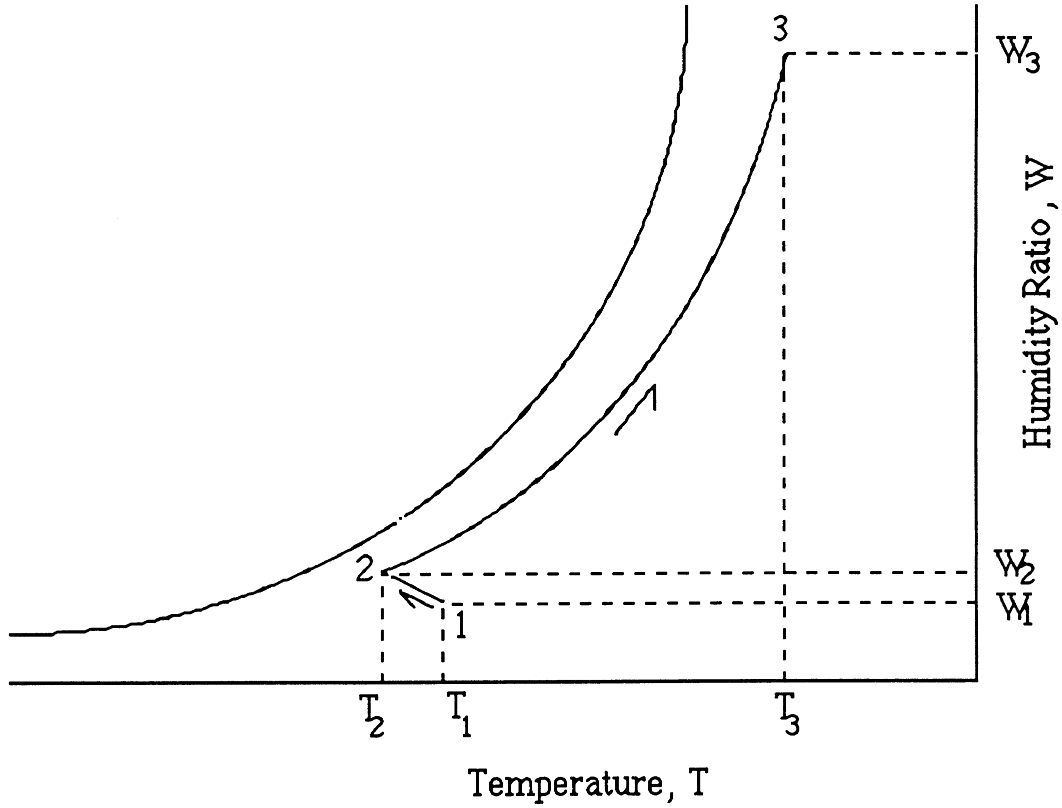

Figure 1. Schematic psychrometric chart showing ventilation air conditions during the initial cooling of damp grain (point 1, air entering grain; 2, air leaving drying front; 3, air leaving temperature front)

equilibrium with conditions of the initial grain bulk (point 3 in Figure 1). The amount of moisture removed in the cooling front is the difference in humidity ratio of the ventilation air between points 2 and 3 in Figure 1 (W_3-W_2) and is limited by the thermal energy available in the grain at the start of ventilation. After the initial cooling front has traversed the grain bulk the ventilation air exits the grain bulk at temperature T_2 (Figure 1). The only drying occurring is in the drying front and is shown as the difference in absolute humidities of the ventilation air between points 1 and 2 in Figure 1 (W_2-W_1). The amount of moisture carried out per unit mass of ventilation air can be higher during the initial cooling process (process 2 to 3) than for the adiabatic drying in the drying front (process 1 to 2) but, again, it is limited by the thermal energy available in the grain at the start of ventilation. They add that the moisture loss in the cooling front occurs throughout the grain bulk because it is dependent on energy in the grain rather than energy in the air, as is the case with drying in the drying front.

Sorenson *et al.* (1967) and Sanderson *et al.* (1988b) stated the variables affecting the magnitude of the drop in moisture content during cooling include initial grain temperature and moisture content as well as wet-bulb temperature of the ventilation air. Foster (1967) said that the moisture change during aeration is incident to the temperature change and proceeds at the same rate.

Grain Properties

In order to accurately predict heat and mass transfer in grain masses one must have an accurate means to derive thermal properties of the grain. Some properties are dependent on temperature, some on moisture content, some on both and some are independent (Boyce, 1965). The main properties examined will be thermal conductivity (k_g), specific heat (C_g), bulk density (ρ_b), particle density (ρ_s) and porosity (P).

The thermal conductivity of wheat is dependent on moisture content. There are several methods of determining the thermal conductivity of grains. Some researchers used a steady state approach with concentric cylinders or spheres (Bakke, 1935 and Oxley, 1944) and others used a transient heat flow method (Hooper and Chang, 1953; Hooper and Lepper, 1950; and Kazarian and Hall, 1965).

Kazarian and Hall (1965) determined that the thermal conductivity of soft white wheat was linearly dependent on moisture content. Their regression equation was:

$$k_g\ (\mathrm{Btu/hr{\cdot}ft{\cdot}^{\circ}F}) = 0.0676 + 0.000654\ M_w \tag{6}$$

Chuma *et al.* (1981) also determined a linear formula for thermal conductivity as:

$$k_g\ (\mathrm{W/m{\cdot}K}) = 0.144 + 0.0006\ M_w \tag{7}$$

The specific heat of wheat is also dependent on moisture content of the product. The specific heat of grain is usually determined by the method of mixtures or with an ice calorimeter. Kazarian and Hall (1965) determined a regression equation for soft white wheat using the method of mixtures as:

$$C_g = 0.334 + 0.00977\ M_w \tag{8}$$

Disney (1954) determined the specific heat of Bersée wheat at a moisture content range of 7.7% to 23.7% using an ice calorimeter. The regression equation obtained was:

$$C_g = 0.263 + 0.01036\ M_w \tag{9}$$

He also determined regression equations for other moisture content ranges.

Pfalzer (1951) determined the specific heat of hard wheat for moisture contents ranging from 0% to 16% using the method of mixtures. Three different samples were analyzed with different linear equations for each sample:

$$C_g = 0.283 + 0.00724\ M_w \tag{10}$$

$$C_g = 0.301 + 0.00733\ M_w \tag{11}$$

$$C_g = 0.288 + 0.00828\ M_w \tag{12}$$

Mohensin (1980) collected wheat specific heat data from several different sources and presented the following equation:

$$C_g\ (\text{kJ/kg}\cdot\text{K}) = 1.258 + 0.01131\ M_w \tag{13}$$

Other investigators have determined the specific heat for wheat at specific conditions but will not be reviewed in this discussion (Muir and Viravanichai, 1972; Babbit, 1945; Moote, 1953) .

Bulk density is defined as the weight of a mass of intact individual units of the material packed in a given volume (including pore space) by a specific method (Mohensin, 1980). The bulk density of soft white wheat remains relatively constant for moisture contents from 0% to 10% with an average value of 750 kg/m^3 (46.8 lb/ft^3). Above 10% moisture content, the density decreases by 3.7 kg/m^3 (0.23 lb/ft^3) for a 1% increase in moisture content (Kazrian and Hall, 1965). The USDA standard bulk density for wheat is 769 kg/m^3 (48.0 lb/ft^3) (Agricultural Statistics, USDA, 1952).

Particle density refers to the weight per unit net volume of the solids within each unit of the material (Mohensin, 1980). Porosity is simply the ratio of the pore volume to the total volume of a material. Porosity can be calculated directly from bulk density and particle density as in the following equation:

$$P = 1 - \frac{\rho_b}{\rho_s} \tag{14}$$

CHAPTER IV

EQUIPMENT USED

Aeration System

Storage Bin

The storage bin used in this research was a metal bin located in the Oklahoma State University Agricultural Engineering Laboratory in Stillwater, Oklahoma. The bin was constructed of corrugated metal and was 1.83 m (6 ft) in diameter and 3 m (10 ft) high (Figure 2). Inside the bin were three small diameter columns made of PVC air duct 30.5 cm (12 in) in diameter and 3 m (10 ft) high. The inside surface of the columns had ribs at regular intervals made of silicon to inhibit the airflow from concentrating along the inside walls. The large bin and its wheat served as an insulator for the smaller test columns in that the larger bin would be aerated at the same rate as the test columns and the temperature fronts in the entire grain mass would move at approximately the same speed, reducing radial temperature gradients in the columns. The bin and columns were equipped with perforated sub-floors 15.2 cm (6 in) above the bottom of the bin and were filled to a 2.74 m (9 ft) depth with Chisholm hard red winter wheat.

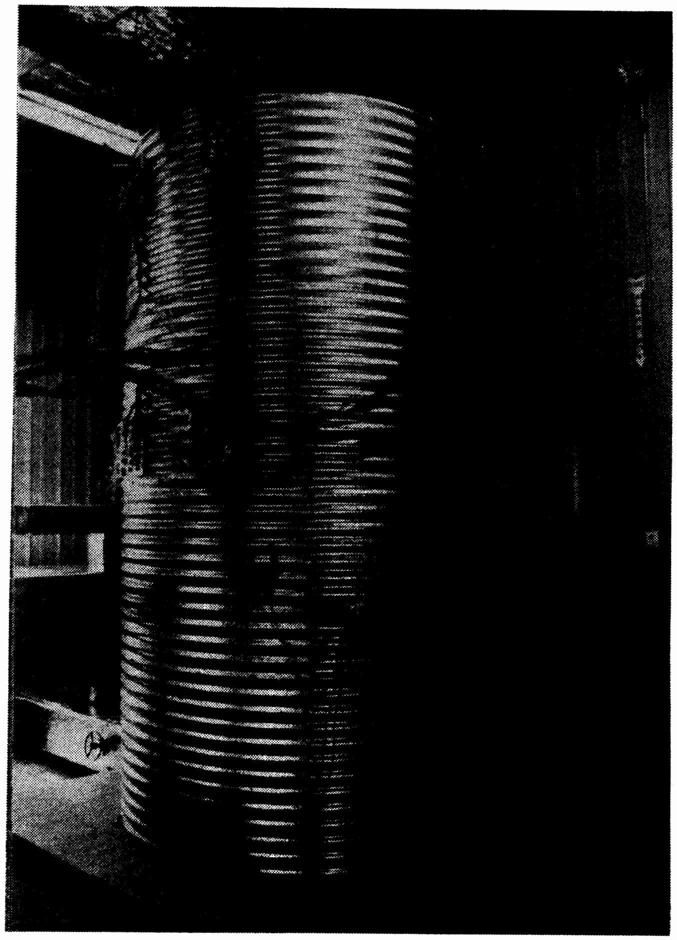

Figure 2. Large grain bin

Aeration Supply

An Aminco-Aire unit was used to condition the aeration air (Figure 3). The unit was capable of providing 472 L/s (1000 cfm) of air at a range of 8% to 99% RH and 9° to 71°C (48° to 160°F). The conditioned air was supplied through an insulated duct to an environmental chamber 1.2 m (4 ft) high by 1.2 m (4 ft) deep by 2.4 m (8 ft) wide and was insulated with 5 cm (2 in) of foam insulation (Figure 4). The supply air for the conditioning unit was recirculated from the environmental chamber along with supplemental room air which entered through a damper installed in the ducting.

Two different fans were used to supply the conditioned air to the grain. A smaller centrifugal fan capable of providing 120 L/s (250 cfm) at a pressure differential of 7.5 cm (3 in) of water was used for lower aeration rates. A larger pressure blower capable of providing 700 L/s (1500 cfm) at a pressure differential of 35 cm (14 in) of water was used for higher aeration rates and for rewarming the grain (Figure 5).

Air Metering

The fan delivered air to a plenum measuring 30 cm (12 in) high by 30 cm (12 in) deep by 60 cm (25 in) wide with several air outlets. Air was metered to the larger bin from the plenum using calibrated orifice plates. Two different sizes of supply pipes, a 10.2 cm (4 in) I.D. and a 5 cm (2 in) I.D. PVC pipe, and two different size orifices for the larger pipe were used. The orifices were calibrated using a 75 mm diameter ISA 1932 nozzle on a fan-test apparatus. The calibration data for the orifices is included in

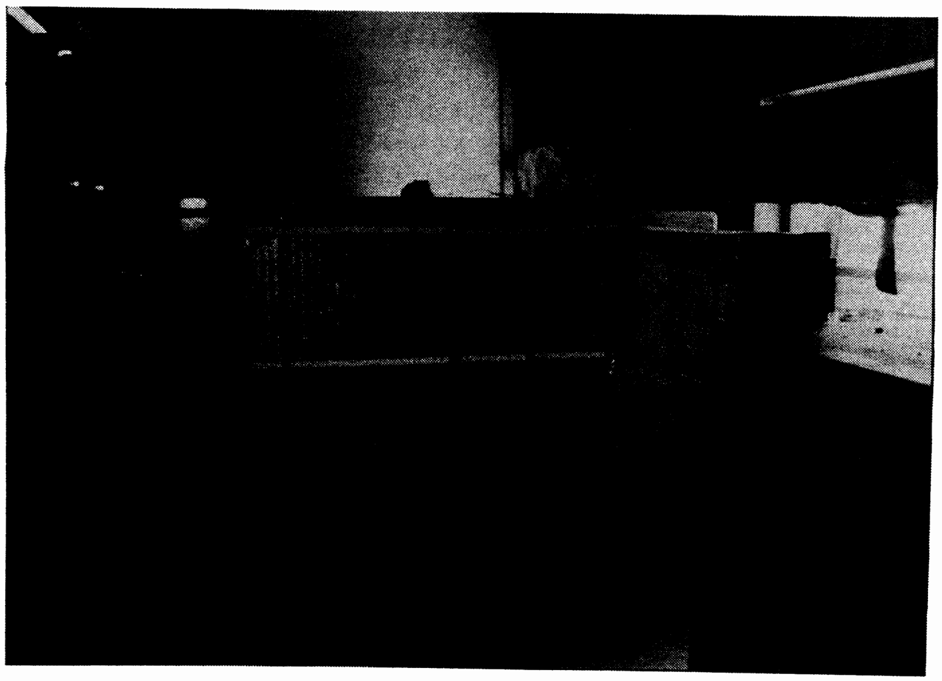

Figure 3. Aminco-Aire unit

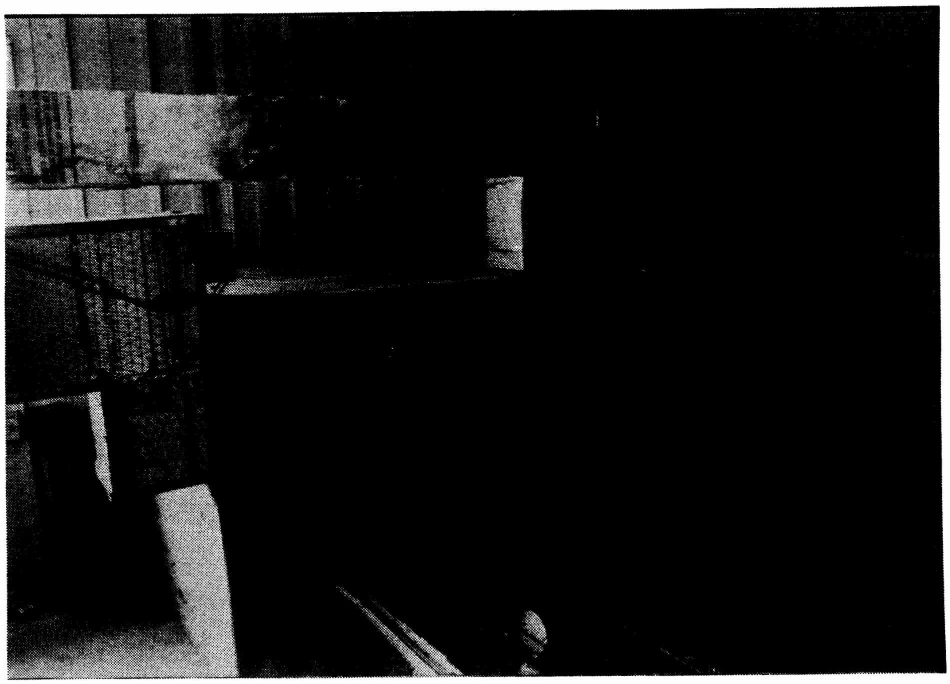

Figure 4. Environmental chamber and conditioned air supply ducts

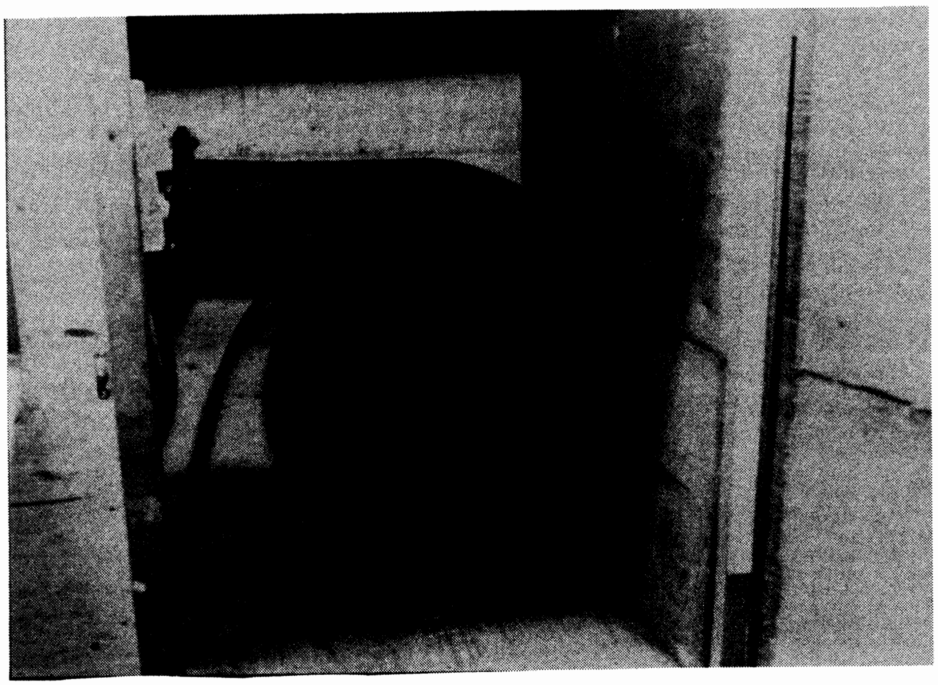

Figure 5. Fan used for aeration tests

Appendix A. A Dwyer Magnehelic® pressure gage with a range of 0 to 500 mm (2 in) of water was used to determine the airflow rate (Figure 6). A gate valve in the downstream side of the orifice plate was used to regulate the airflow (Figure 6).

Airflow to the three smaller columns were metered using factory calibrated Dwyer Ratemaster® Series RM rotometers. Four different rotometers per column were used in order to accurately control the wide range of airflow rates. Three rotometers ranged in airflow rates from 0 to 0.4 L/s (0.8 cfm) and one ranged from 0 to 4.7 L/s (10 cfm) (Figure 7). The four rotometers were connected to a manifold and the conditioned air was supplied to the columns through 2.5 cm (1 in) PVC pipes. The supply pipes were surrounded by an insulated duct extending from the environmental chamber to the large grain bin (Figure 6). A small circulation fan forced conditioned air from the environmental chamber into the insulated supply pipe duct to minimize heat exchange from the supply pipes.

Data Acquisition

Temperature Measurement

Grain and air temperatures were measured by thermocouples. Temperatures in the smaller columns were measured with 30 ga. copper-constantan (Type T) thermocouples placed along the centerline of the columns at 5 cm (2 in) intervals and held in place by securing them to 1.3 cm (0.5 in) square wooden dowels. The thermocouples extended from the sub-floor of the columns to the top of the grain mass. The grain temperatures in the large bin were measured along the centerline of the bin at

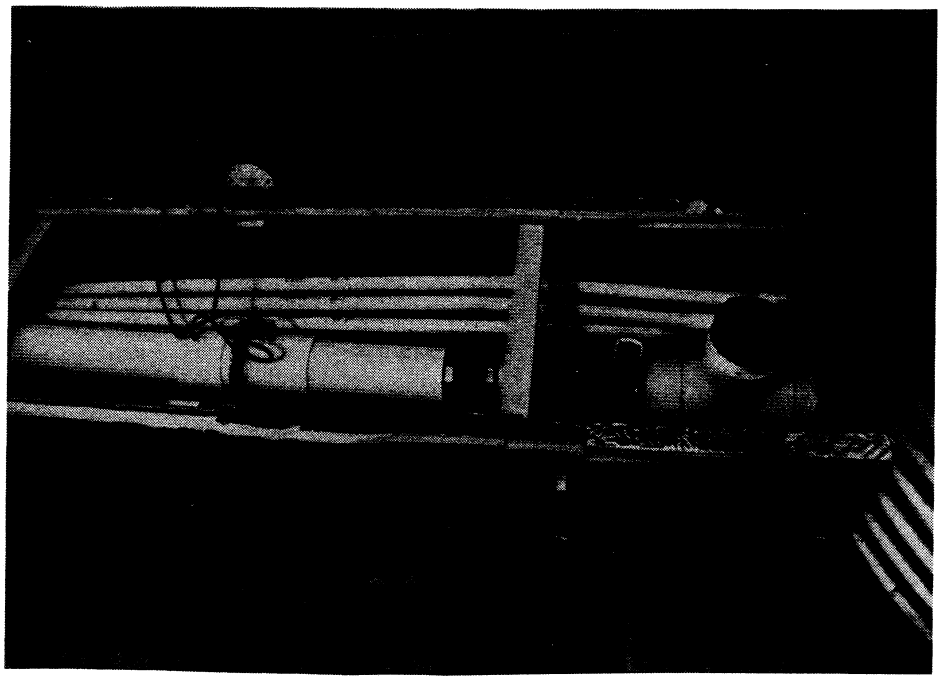

Figure 6. Supply duct, orifice, gate valve, and Y-pipe

Figure 7. Bank of rotometers

15.2 cm (6 in) intervals with 24 ga. iron-constantan (Type J) thermocouples. The horizontal temperature profile of one column was measured using 36 ga. copper-constantan (Type T) thermocoulpes spaced at 2.5 cm (1 in) intervals connected to a 10 mm (3/8 in) diameter wooden dowel approximately 122 cm (48 in) above the column sub-floor.

The wet-bulb and dry-bulb air temperatures at the exit of the columns and in the environmental chamber were measured with 24 ga. copper-constantan (Type T) thermocouples. The wet-bulb temperatures were obtained using wet-bulb thermometers (Figure 8) in the columns with small 15 cm (6 in) electric fans blowing air across the wick. The wet-bulb temperature of the environmental chamber air was measured using an outlet of an unused rotometer blowing on the wick . From the wet-bulb and dry-bulb temperatures, the relative humidity of the air was calculated using Bosen's (1960) equations:

$$A=33.8639\cdot((0.00738\cdot T_{db}+0.8072)^8-0.000019\cdot|1.8\cdot T_{db}+48|+0.001316) \quad (15)$$

$$B=33.8639\cdot((0.00738\cdot T_{wb}+0.8072)^8-0.000019\cdot|1.8\cdot T_{wb}+48|+0.001316) \quad (16)$$

$$C=B-0.662\cdot(T_{db}-T_{wb}) \quad (17)$$

$$RH=100\cdot(C/A) \quad (18)$$

Dataloggers and Computer

Three dataloggers were used to read temperature data with one datalogger being used per column. The three dataloggers used were a 60-channel Doric Digitrend 220 Multipoint Recorder, a 60-channel Hewlett Packard 3497A Data Acquisition/Control Unit and a 60-channel Acurex Autodata Ten/5 Calculating Datalogger. The dataloggers were calibrated

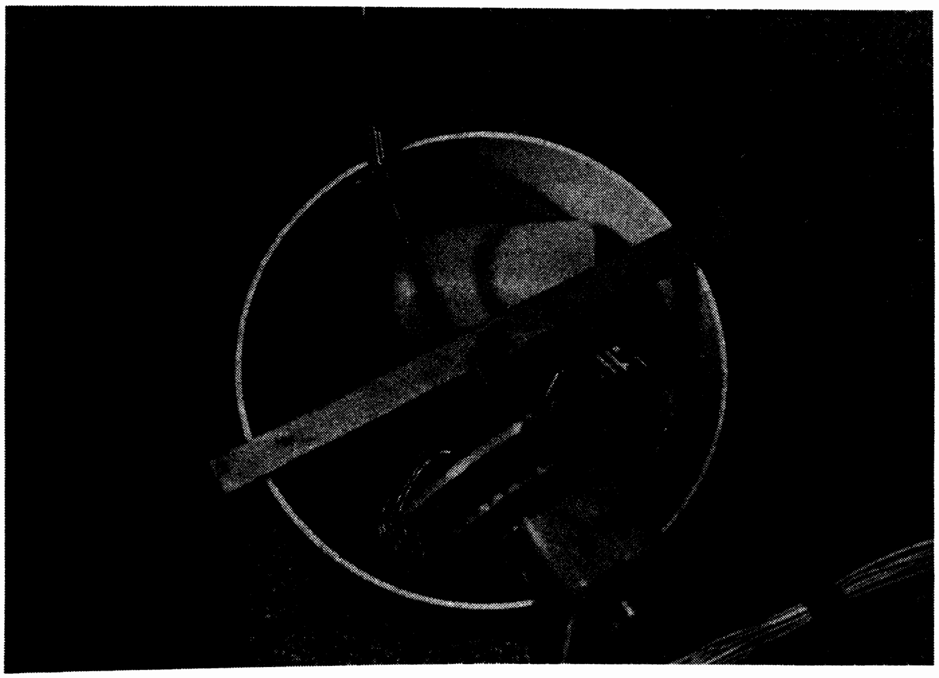

Figure 8. Wet-bulb thermometer and ventilation fan for exiting air conditions

using an ice bath. All three dataloggers were interfaced to a Executive XT-10, IBM-compatible computer (Figure 9). A computer program (Program 1, Appendix B) was written in GW-Basic language that would acquire thermocouple readings from the dataloggers every 30 minutes, convert voltages to temperatures (in the Hewlett Packard's case), convert air wet-bulb and dry-bulb temperatures into relative humidities, print the results to the computer screen and record the data on a floppy disk. Computer programs were also written to extract individual temperature readings from a specific thermocouple over the entire aeration period (Program 2, Appendix B), or to extract all temperature readings for a specific test column and specific time (Program 3, Appendix B).

There were not enough channels in the dataloggers to record the thermocouple temperatures in the large bin and the horizontal profile of the test column. Therefore, this data was recorded manually. The horizontal grain temperatures were read from a 10-channel Omega 2176A digital thermometer (Figure 10) and the grain temperatures from the large bin were read using a Fluke Model 51 hand-held digital thermometer.

Grain Property Measurements

Moisture Content

A grain sampling probe was built to extract grain samples for determination of moisture contents. The probe was constructed in two 145 cm (57 in) sections and marked at 15.2 cm (6 in) intervals to gauge depth of the probe in the grain mass (Figure 11). The probe obtained approximately 25 grams of wheat per sample and the samples were weighed using electronic scales graduated to 0.01 gram.

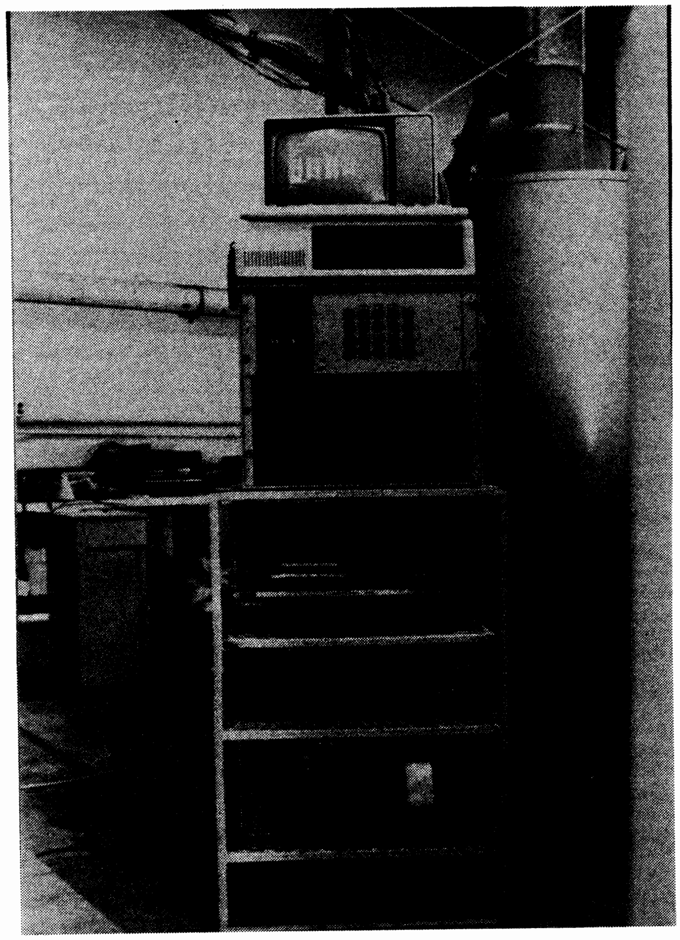

Figure 9. Computer interfaced to three dataloggers

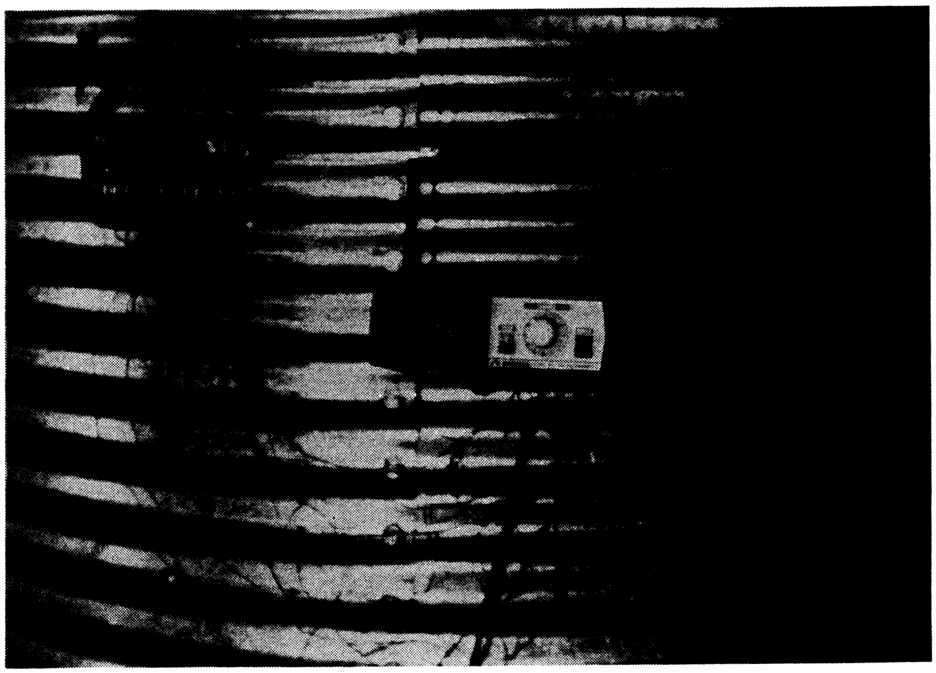

Figure 10. 10-channel temperature thermometer

Figure 11. Grain probe sampler

Thermal Conductivity

The apparatus used for the grain thermal conductivity tests was designed after Kazarian and Hall's (1965). It consisted of a section of 10.2 cm (4 in) I.D. PVC pipe 30 cm (12 in) in length with a rubber cap on one end. A 22.8 cm (9 in) length of bare resistance wire, 1.68 ohm/cm (4.27 ohm/ft), was connected at the axis of the cylinder between two 10 ga. solid copper wires. Power for the heater wire was supplied by a variable DC current supply. A 36 ga. copper-constantan (Type T) thermocouple was placed approximately 4 mm (1/64 in) from the heater wire over a single layer of electrical tape located at the middle of the heater wire. Thermocouple temperatures were read from a hand-held digital thermometer and voltage and amperage readings were taken from DVM's (Figure 12).

Bulk Density

Bulk densities were determined using a standard 0.95 L (1 qt) grain test weight apparatus, a wooden slat and a funnel with a gate in the outlet. The mass of the grain was measured using electronic scales.

Specific Heat

The specific heat of the wheat was determined using a 0.47 L (1 pt.) Thermos® container as the calorimeter. A 36 ga. copper-constantan (Type T) thermocouple with a hand-held digital thermometer was used to determine the grain and water temperatures. The masses were measured with electronic scales.

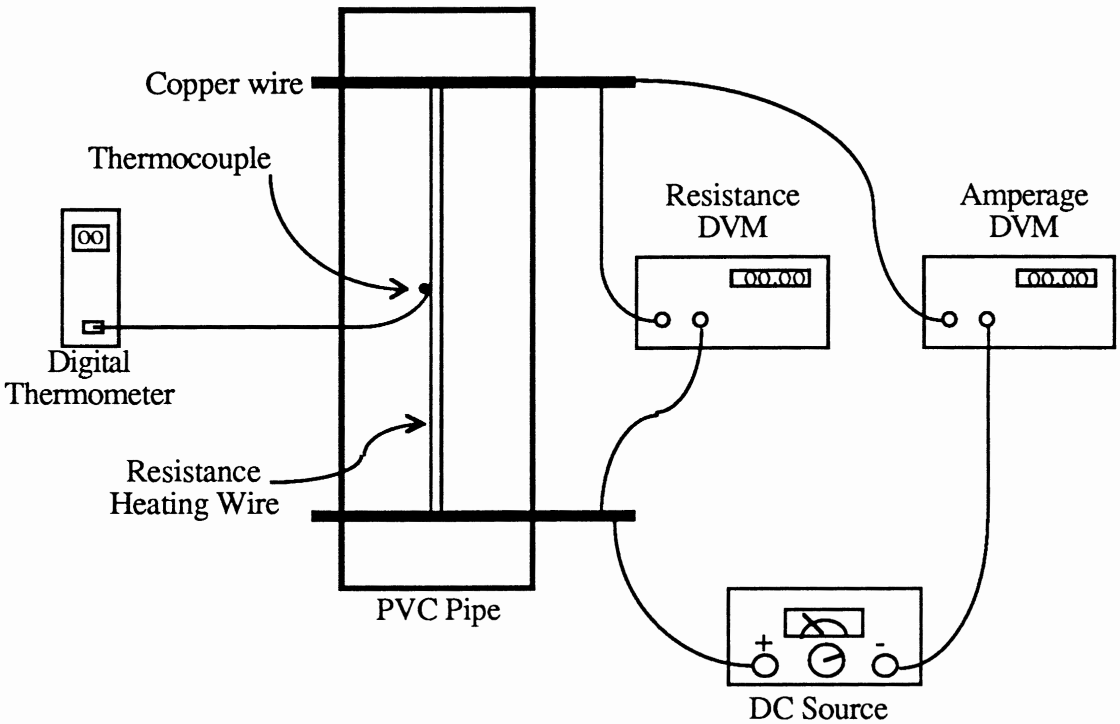

Figure 12. Schematic of thermal conductivity testing apparatus

CHAPTER V

PROCEDURES

Preliminaries

Six different airflow rates were used in this study. They were 0.67, 1.34, 2.68, 5.36, 8.04 and 10.72 L/s·m^3 (0.05, 0.1, 0.2, 0.4, 0.6, and 0.8 cfm/bu). Each airflow rate was replicated three times by aerating the three columns simultaneously at each aeration rate.

The bin and columns were initially filled to the 2.74 m (9 ft) level with Chisholm hard red winter wheat. The wheat was grown in the 1988 growing season at Stillwater, OK, and was cleaned to remove fines and foreign materials. The wheat was initially at about 12.5% moisture content (w.b.) and ranged from 25° to 30°C (77° to 86°F).

A preliminary test was performed to determine if there were temperature gradients across the diameter of the columns, to determine if the temperature front movements in the large bin and the test columns proceeded at the same rates and to perform a general test of all the equipment simultaneously. The airflow rate used for this test was 5.36 L/s·m^3 (0.4 cfm/bu). The same procedure was used for this test as for the remainder of the tests, explained in detail later.

Aeration Tests

Fan, Orifice and Rotometer Use

Because of the wide range in airflow rates used in this experiment, two different fans, three different orifice sizes and a total of twelve rotometers were used. The smaller 120 L/s (250 cfm) fan was used for the three lower aeration rates. The larger blower was used for the three higher aeration rates because the pressure drop across the rotometers was too high for the smaller fan.

The 5 cm (2 in) supply pipe with an orifice plate having a ß (ratio of orifice diameter to pipe diameter) of 0.5 was used to meter air to the large bin at the two lowest aeration rates. The 10.2 cm (4 in) supply pipe with an orifice having a ß of 0.5 was used for the middle two aeration rates and an orifice with a ß of 0.66 was used for the two highest aeration rates. Appendix A contains a complete listing of the specifications for all of the orifice plates.

In order to obtain accurate airflow rates to the test columns over the entire aeration range, one larger and three smaller rotometers were used per column in parallel to regulate the aeration rates. One small rotometer was used for each of the two lowest aeration rates; two small rotometers for the third lowest rate; three small rotometers for the next higher rate; and one large and one small rotometer each was used for the two highest aeration rates.

General Procedures

The order of aeration was determined by random number generation. The order of aeration was 2.68, 1.34, 0.67, 8.04, 5.36 and 10.72 L/s·m^3 (0.2, 0.1, 0.05, 0.6, 0.4 and 0.8 cfm/bu).

The entire grain mass was initially warmed to about 35°C (95° F) with air within 5% to 10% RH of the equilibrium relative humidity of the wheat. This warm-up was done to simulate summer harvest conditions. The wheat was allowed to set for 4 to 8 hours to ensure moisture equilibrium had been reached in the grain.

Moisture samples were then taken in each test column with the grain sampler. The samples were taken starting at 7.6 cm (3 in) above the perforated floor and at each 15.2 cm (6 in) interval above that, giving a grain sample from the center of each 7.6 cm (6 in) section of the grain mass. The grain samples were labeled and the moisture contents (w.b.) were determined using the oven-dry method of ASAE Standard S352.1.

The air conditioning unit was set for the lowest temperature it could attain at a RH within 5% to 10% of the equilibrium relative humidity of the wheat, usually about 9°C (48°F) and 60% to 70% RH, and allowed to stabilize. The water bottles used for the wet-bulb temperatures in the environmental chamber and on top of the columns were filled with deionized water, the thermocouples were inserted in the wicks, the smaller circulation fans at the top of the columns were turned on and sheet metal lids were placed on top of the columns (Figure 13). A tube from the outlet of an unused rotometer was used to supply air to the wet-bulb thermometer in the environmental chamber (Figure 14). The top opening in the Y-fitting (Figure 6) on the supply tube to the large bin was then opened to let the air escape into the atmosphere instead of going into the bin plenum. Next, the fan was turned on and the desired airflow rate into the large bin was obtained by adjusting the gate valve until the correct pressure difference across the orifice was reached (Figure 6). After setting the airflow rate, the cap was replaced on the Y-fitting and the airflow rate rechecked.

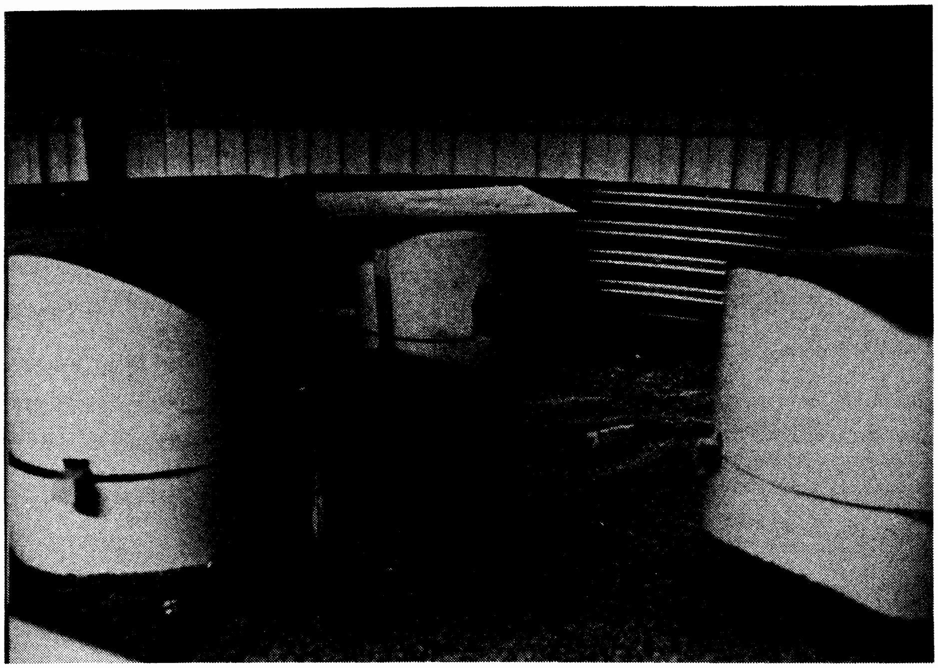

Figure 13. Top view of test columns

Figure 14. Wet-bulb thermometer in environmental chamber

The rotometers were set to the desired airflow rate for each column with the datalogger for that column being started immediately after airflow had begun. The computer collected data from the dataloggers every thirty minutes and stored the data on a floppy disk.

Thermocouple readings were manually recorded for the temperature profiles in the large bin and the horizontal temperature profile in the column. These readings were taken periodically throughout the aeration test with the time interval varying with each aeration rate.

The temperature data was monitored on the video screen and when the grain temperatures near the top of the grain mass ceased to lower, the aeration fan was left on for a short period longer to ensure complete cooling and the fan and dataloggers were stopped. The wheat was allowed to set for 4 to 8 hours to ensure moisture equilibrium had been reached in the grain. Grain moisture content samples were again taken as before and the moisture losses were calculated using the moisture content data taken before aeration.

The grain was rewarmed again and moisture samples were taken. Grain was added to the test columns to replace that removed by sampling and the water bottles for the wet-bulb thermometers were again checked and refilled with fresh water. If necessary, the aeration fans were exchanged and different supply pipes and/or orifice plates were installed for the next test.

Grain Properties

Bulk Density

All grain properties were evaluated with wheat at about 24°C (75°F) and at a moisture content of 13.2% (w.b.). The bulk density was determined using a standard 0.95 L (1 qt) grain test weight apparatus. The grain was placed in a funnel and allowed to drop into the "bucket" from a height of about 7.6 cm (3 in) above the top of the bucket. The wheat was then leveled using a wooden slat and weighed on electronic scales. The bulk density was determined from the average of 20 samples.

Particle Density and Porosity

The particle density was estimated using DeVoe *et al.*'s (1985) data. They determined the particle density of 20 samples of Chisholm wheat using a He-air pyconometer. The wheat was grown in the 1983 growing season at five locations throughout the state of Oklahoma. The porosity of the grain was then determined from the values of bulk and particle density.

Specific Heat

The specific heat of wheat was determined using the method of mixtures similar to that of Kazarian and Hall (1965). The wheat samples were held at room temperature, approximately 21°C (70°F). About 70 gm (2.5 oz) of ice water was placed in the Thermos® calorimeter and allowed to warm to approximately 2.5°C (36°F). A 50 to 60 gm (2 oz) sample of wheat was then dropped directly into the water in the calorimeter and the calorimeter was shaken to agitate the grain-water mixture. Equilibrium was generally reached in less than one minute, but the temperatures were continuously recorded for 2 to 3 minutes longer. Twelve samples were taken to determine the specific heat of the wheat.

Thermal Conductivity

The transient heat flow in an infinite mass, initially at a uniform temperature, heated by a line heat source of constant strength, was chosen for determining the thermal conductivity of the wheat. Hooper and Lepper (1950) determined that thermal conductivity can adequately be found using the solution for the general partial differential equation for the temperature distribution in an infinite cylinder, which is:

$$k_g = \frac{q' \ln(\Theta_2 / \Theta_1)}{4\pi (T_2 - T_1)} \tag{19}$$

The amount of current to use and the duration of the tests were first determined from the work of Kazarian and Hall (1965). A current of 0.6 amps was found to cause a temperature rise of about 15.5°C (28°F) after 10 minutes of heating. Temperature rise between 1 minute and 10 minutes was around 6°C (11°F).

After determining the current and heating time to be used, a sample of grain was placed in the test apparatus cylinder and allowed to reach equilibrium with room temperature, about 24°C (76°F). The electric circuit was closed and temperature rise was recorded for the time interval between 1 and 10 minutes. After each test, the grain was removed from the cylinder and kept at room temperature for 10 to 15 minutes. Ten determinations of thermal conductivity were made for the wheat.

CHAPTER VI

RESULTS AND DISCUSSION

Preliminaries

A preliminary test was performed to determine if there were any horizontal temperature gradients across the test columns and whether the temperature profile throughout the large bin and the test columns were similar throughout the aeration period. If there was a "non-zero" horizontal temperature gradient across the test column then a larger size column would have to be used or the walls of the columns would have to be made rougher. The temperature profiles are desired to be similar throughout the large bin and the test columns to minimize radial heat transfer between them. An aeration rate of 5.36 $L/s{\cdot}m^3$ (0.4 cfm/bu) was used for the test run.

The horizontal temperature profile across one of the test columns at various time periods is shown in Figure 15. The temperatures early in the aeration were all within ±0.25°C of each other. Later in the aeration period the temperatures differed less than ±1°C with temperatures being within ±0.5°C of each other again in the latter stages of aeration. These temperature differences are acceptable since the error of the thermocouples alone is ±0.8°C and there were no extreme temperature gradients near the walls of the column.

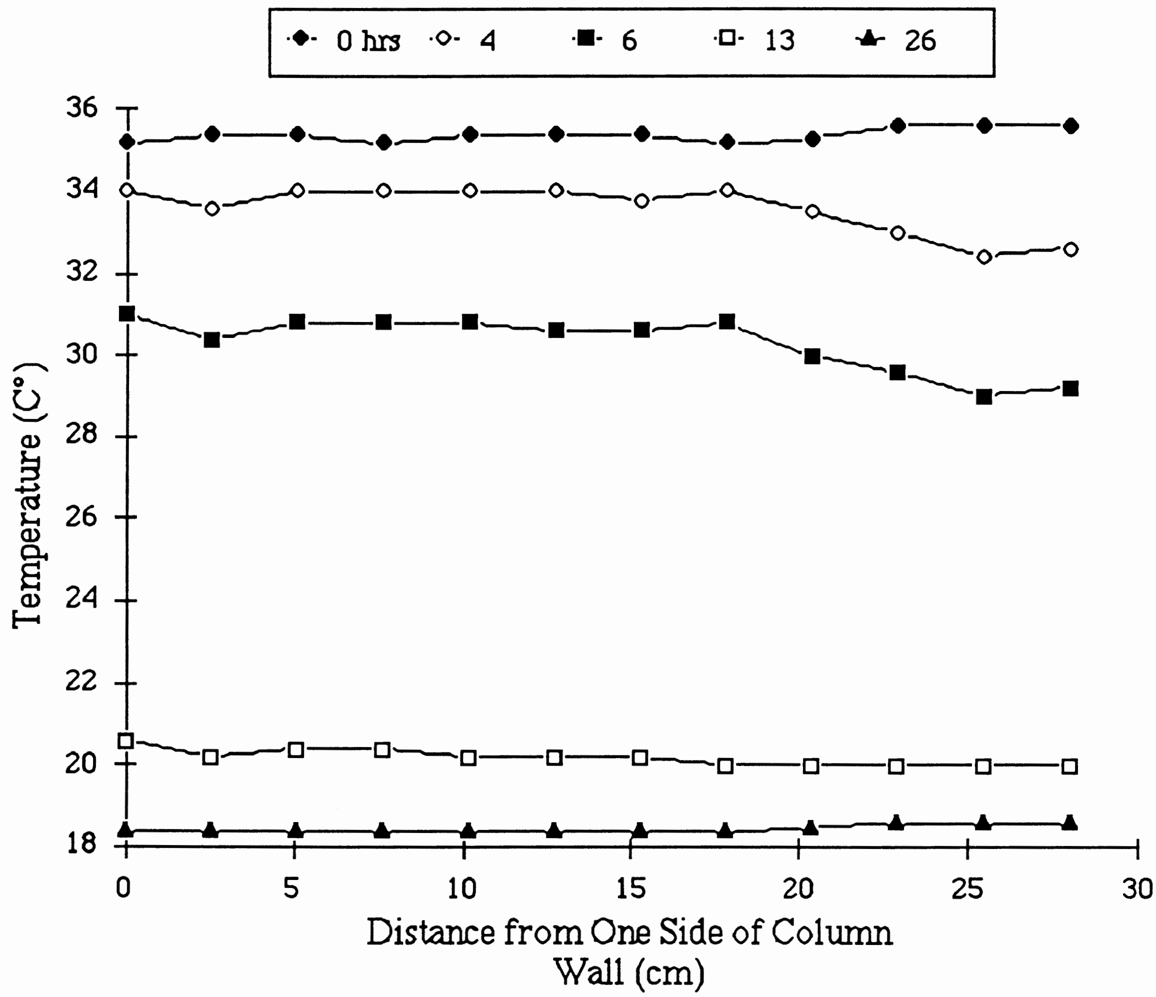

Figure 15. Horizontal temperature profile across one of the test columns at various time periods

Temperature profiles of the large bin and a test column at different time periods are shown in Figure 16. Initially temperatures throughout the center of the two differed less than ±0.8°C of each other. During most of the aeration period the temperatures differed less than ±2°C with wider differences occurring in the later stages of aeration. These differences are also acceptable taking into consideration thermocouple error and the fact that the two sets of temperatures were determined using different thermocouple readout devices.

Grain Properties

Bulk density, particle density, porosity, specific heat and thermal conductivity were determined for the grain used in the experiments. The raw data for the grain properties given in Appendix C. The average values for the parameters were calculated and the results were:

ρ_b = 797.3 kg/m^3 (49.8 lb$_m$/ft^3)

ρ_s = 1440 kg/m^3 (90.3 lb$_m$/ft^3)

P = 0.448

C_p = 0.420 cal/g·°C (0.420 BTU/lb$_m$·°F)

k_g = 0.0372 cal/s·m·°C (0.0899 BTU/hr·ft·°F)

Data taken from ASAE Standard D243.2 show ranges for specific heat and thermal conductivity as:

C_p: 0.30 - 0.52 cal/g·°C

k_g: 0.0306 - 0.0380 cal/s·m·°C (0.74 - 0.92 BTU/hr·ft·°F)

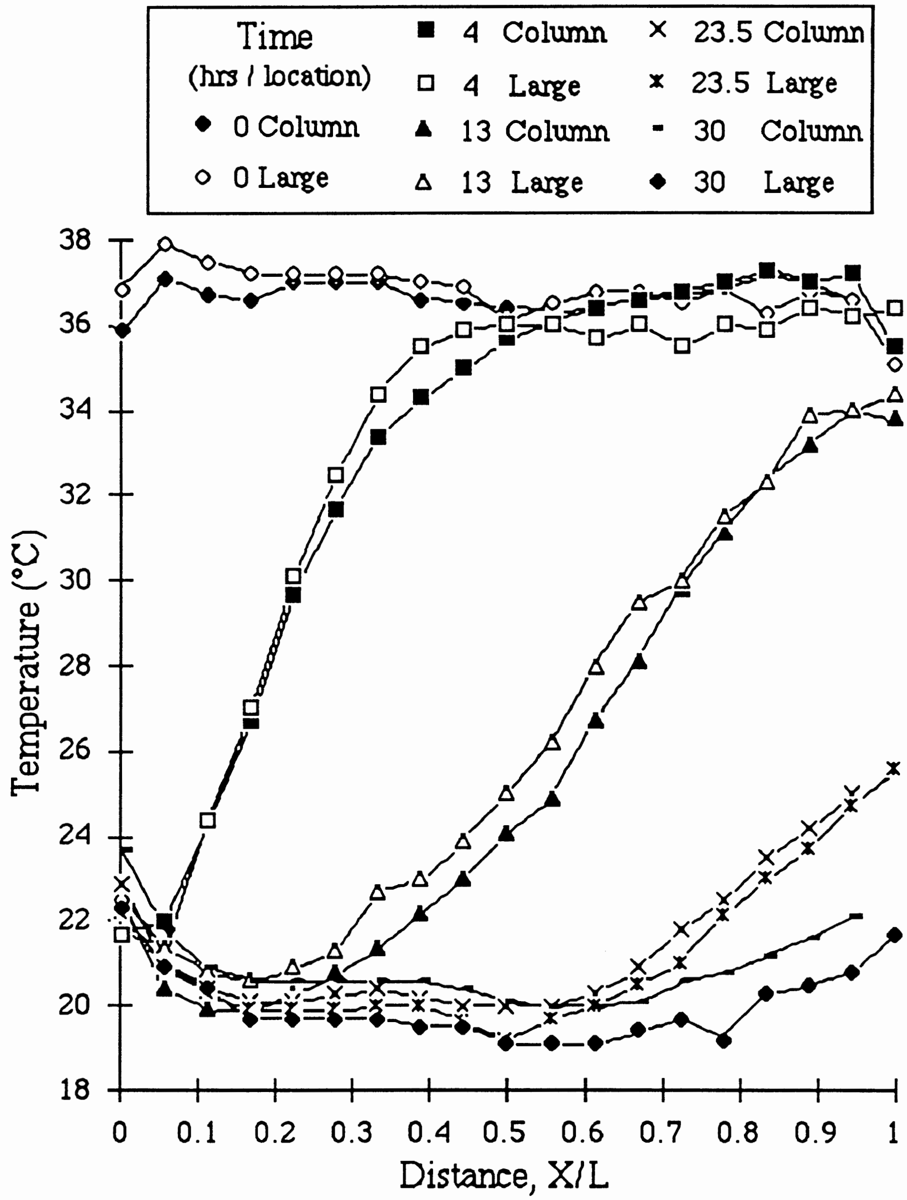

Figure 16. Temperature profile of the large bin and a test column at different time periods

The raw data for the grain properties are shown in Appendix C.

Cooling Times

When cooling grain with aeration there is a leading edge and a trailing edge associated with the cooling front. The leading edge of the front is the temperature interface at which the grain temperature just begins to drop. The trailing edge of the front is the first point below the cooling zone (in a pressure aeration system) in the grain mass that is at the same temperature as the entering air.

The times for the leading and trailing edges of the cooling fronts to exit from the grain mass were first determined. In order to determine these times, temperature data for each thermocouple depth was extracted from the raw temperature data for the entire aeration period. Temperature profile as a function of time for each aeration rate and each test column are shown in Figures 17 through 34. Only the top four of five thermocouple readings were used to determine the times. The leading edge was defined as the time at which the top, or near the top thermocouple first started to drop in temperature. The trailing edge was difficult to determine because of the exponential behavior of the temperature vs. time curve at the last stages of aeration. Therefore, the trailing time was defined as when:

$$\frac{T_o - T}{T_o - T_{final}} \geq 0.95 \qquad (20)$$

The uppermost thermocouple readings could not be used for some of the time determinations for the four lower aeration rates. The airflow was low enough that heat transfer from the surroundings caused the grain

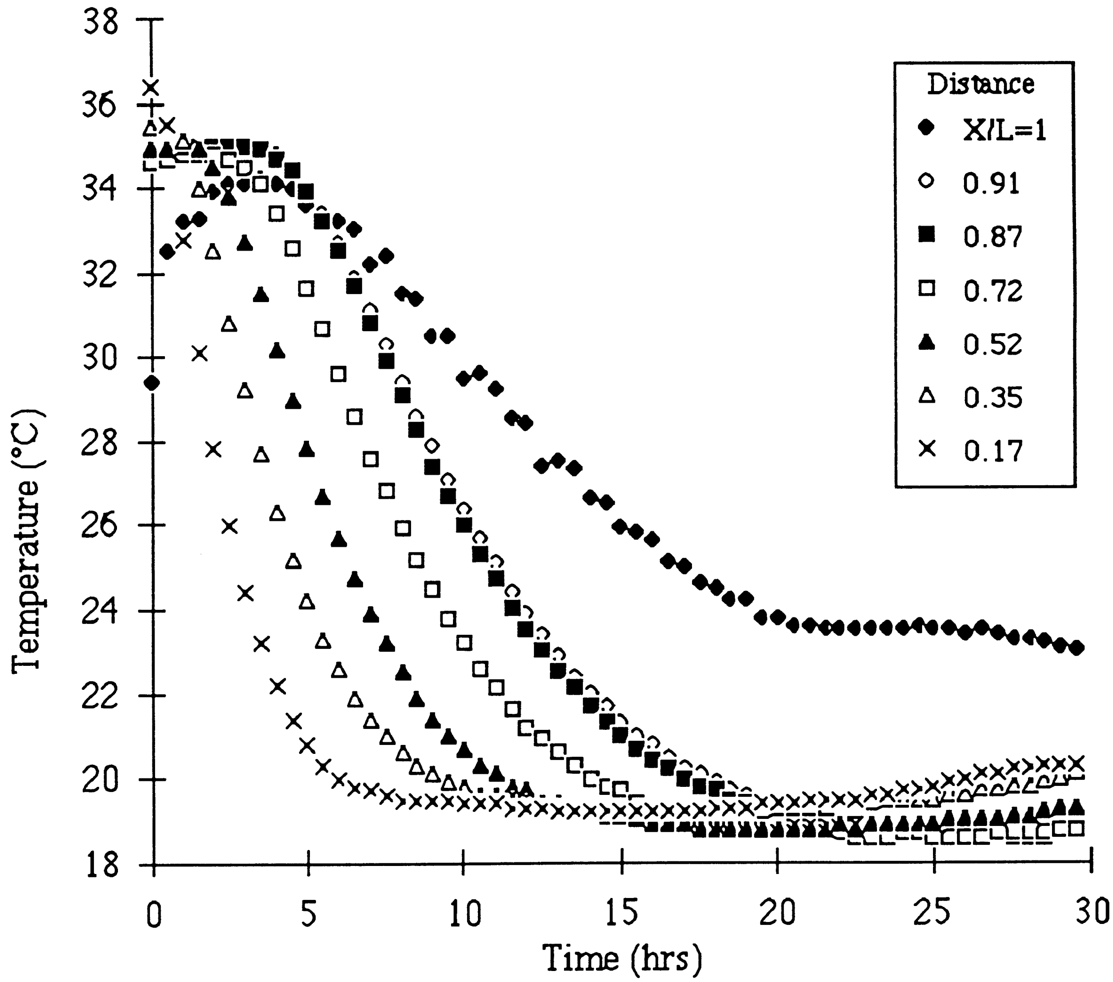

Figure 17. Temperature profile vs. time for column #1 and an aeration rate of 10.72 L/s·m^3

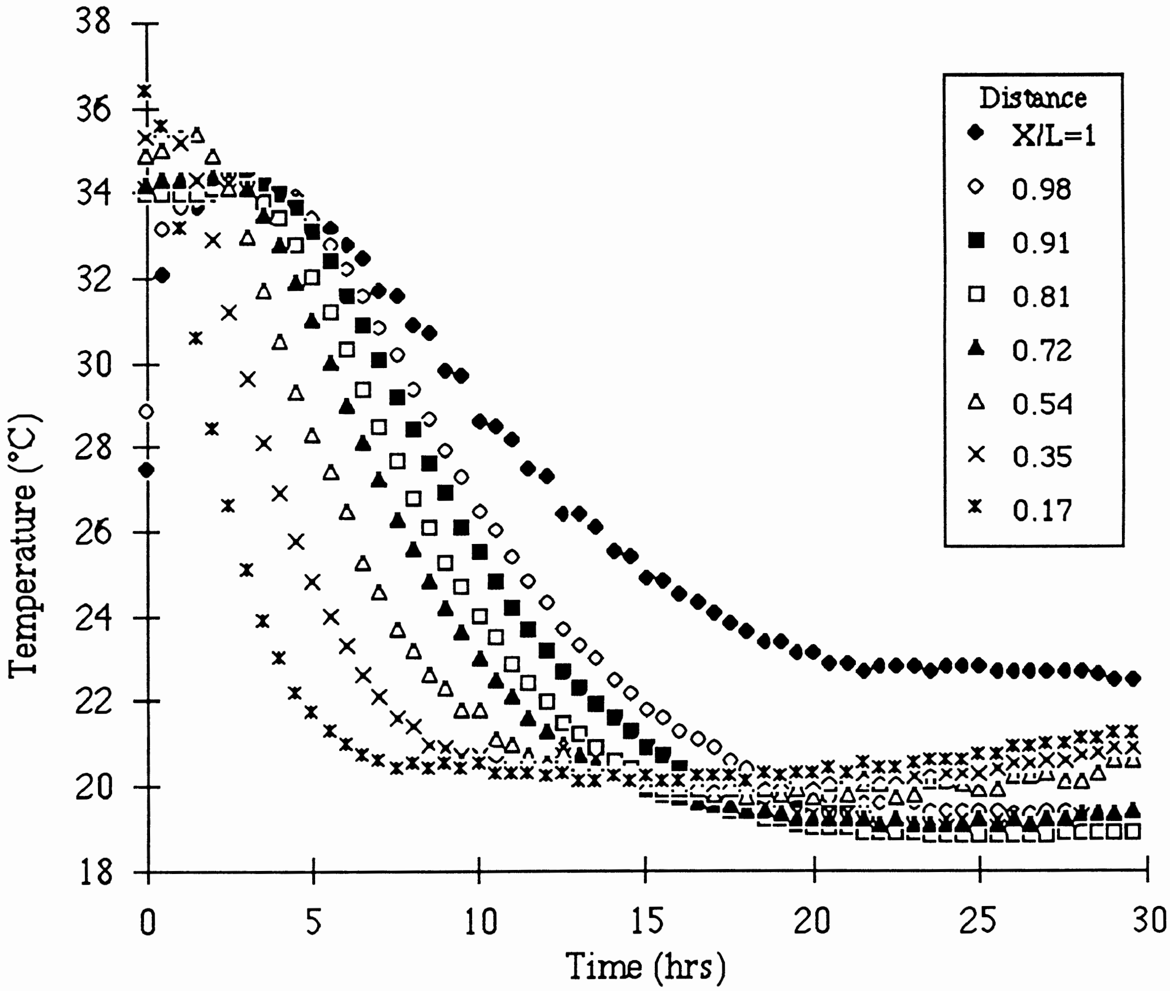

Figure 18. Temperature profile vs. time for column #2 and an aeration rate of 10.72 L/s·m³

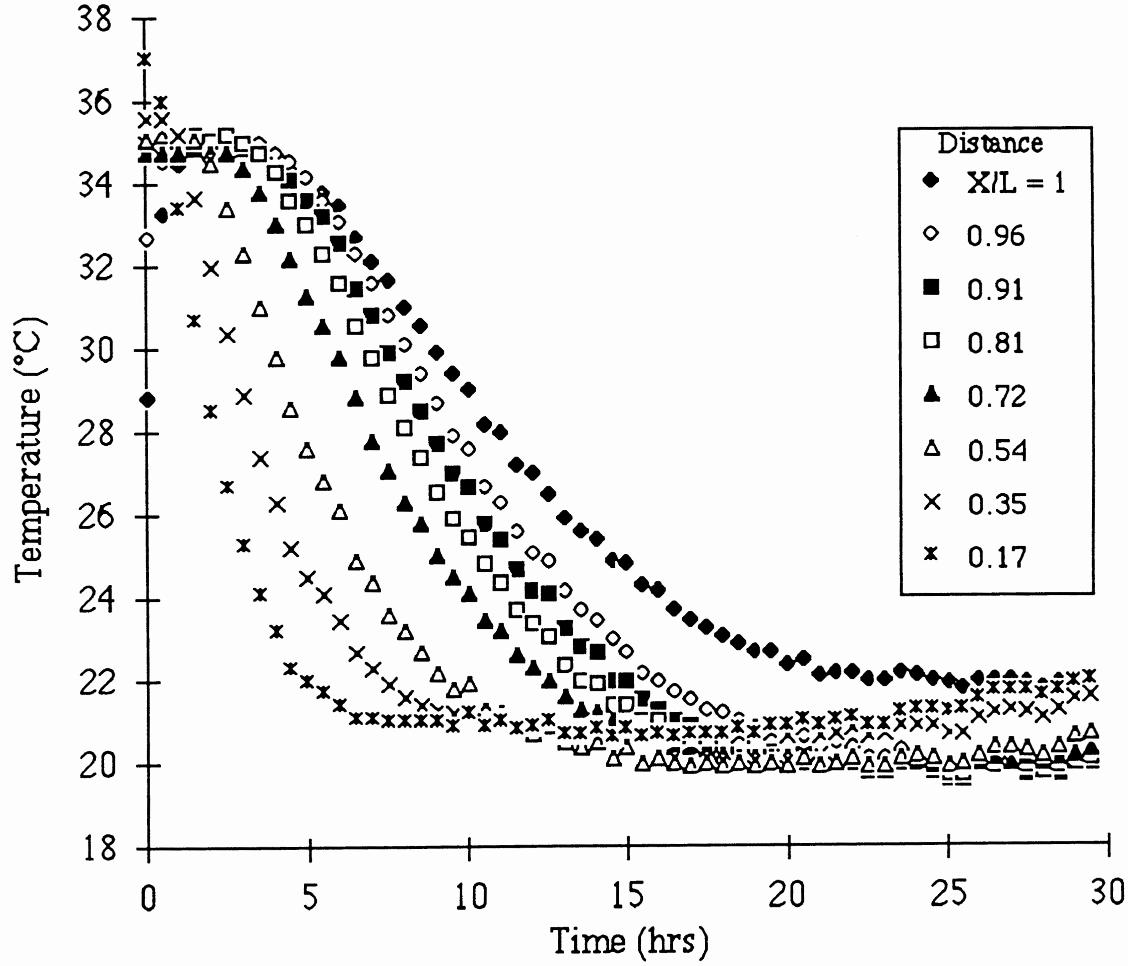

Figure 19. Temperature profile vs. time for column #3 and an aeration rate of 10.72 L/s·m^3

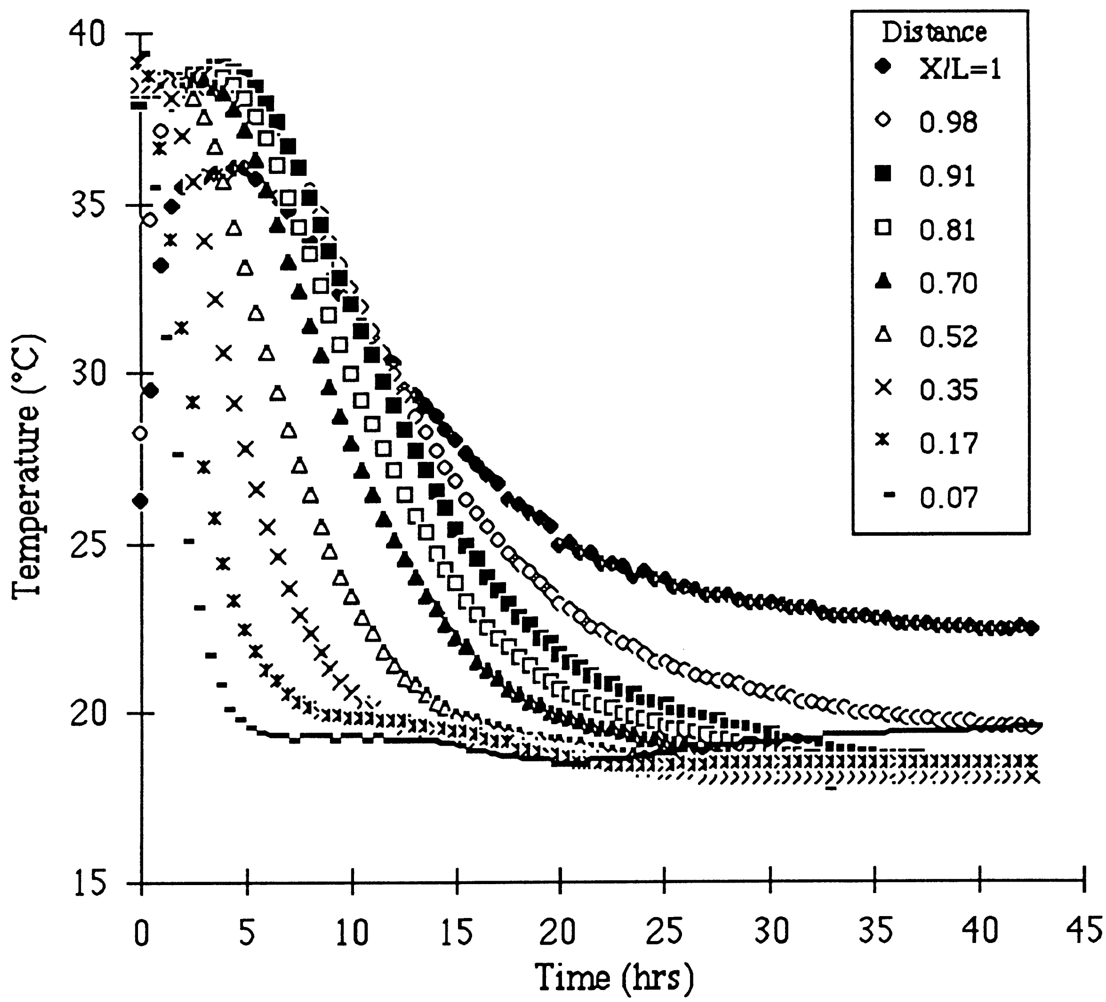

Figure 20. Temperature profile vs. time for column #1 and an aeration rate of 8.04 L/s·m^3

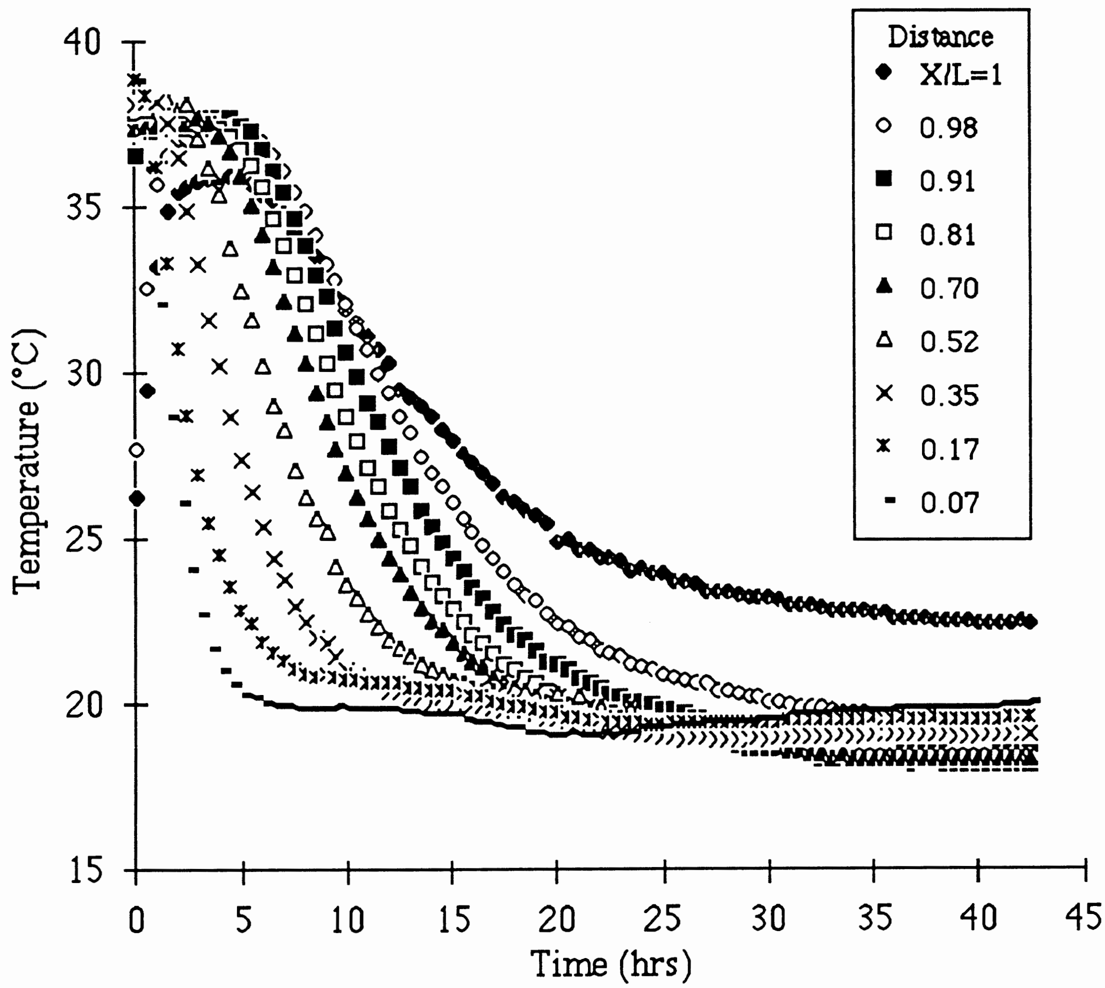

Figure 21. Temperature profile vs. time for column #2 and an aeration rate of 8.04 L/s·m^3

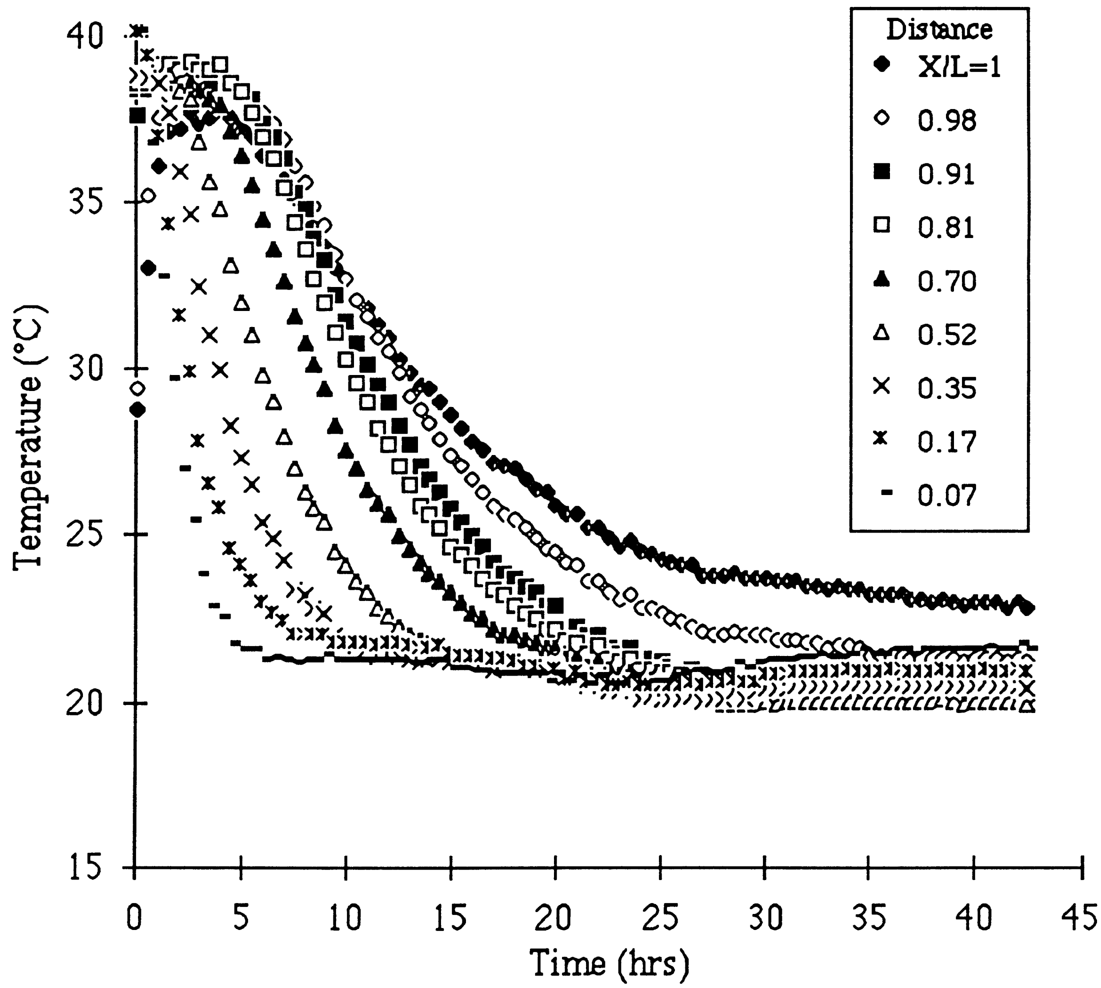

Figure 22. Temperature profile vs. time for column #3 and an aeration rate of 8.04 L/s·m³

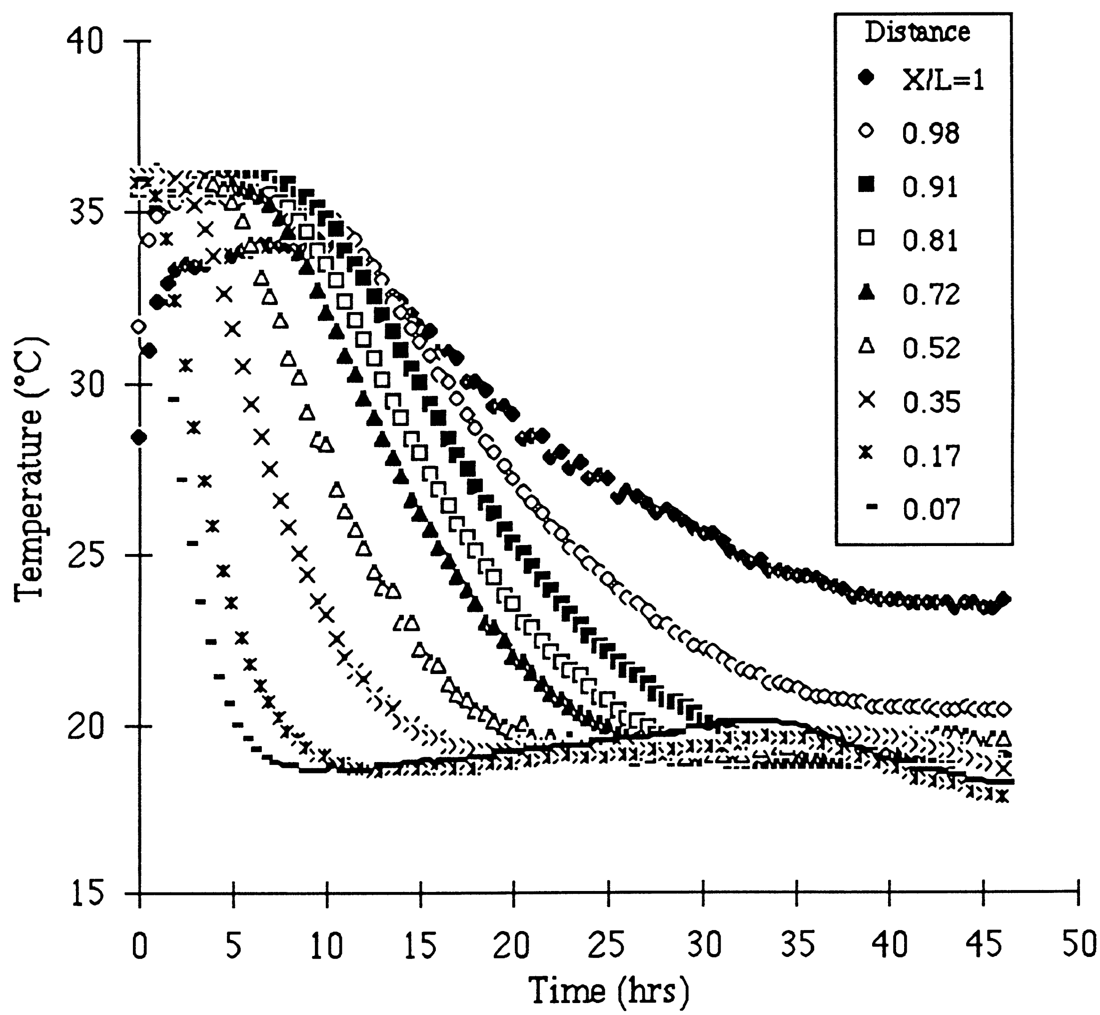

Figure 23. Temperature profile vs. time for column #1 and an aeration rate of 5.36 L/s·m^3

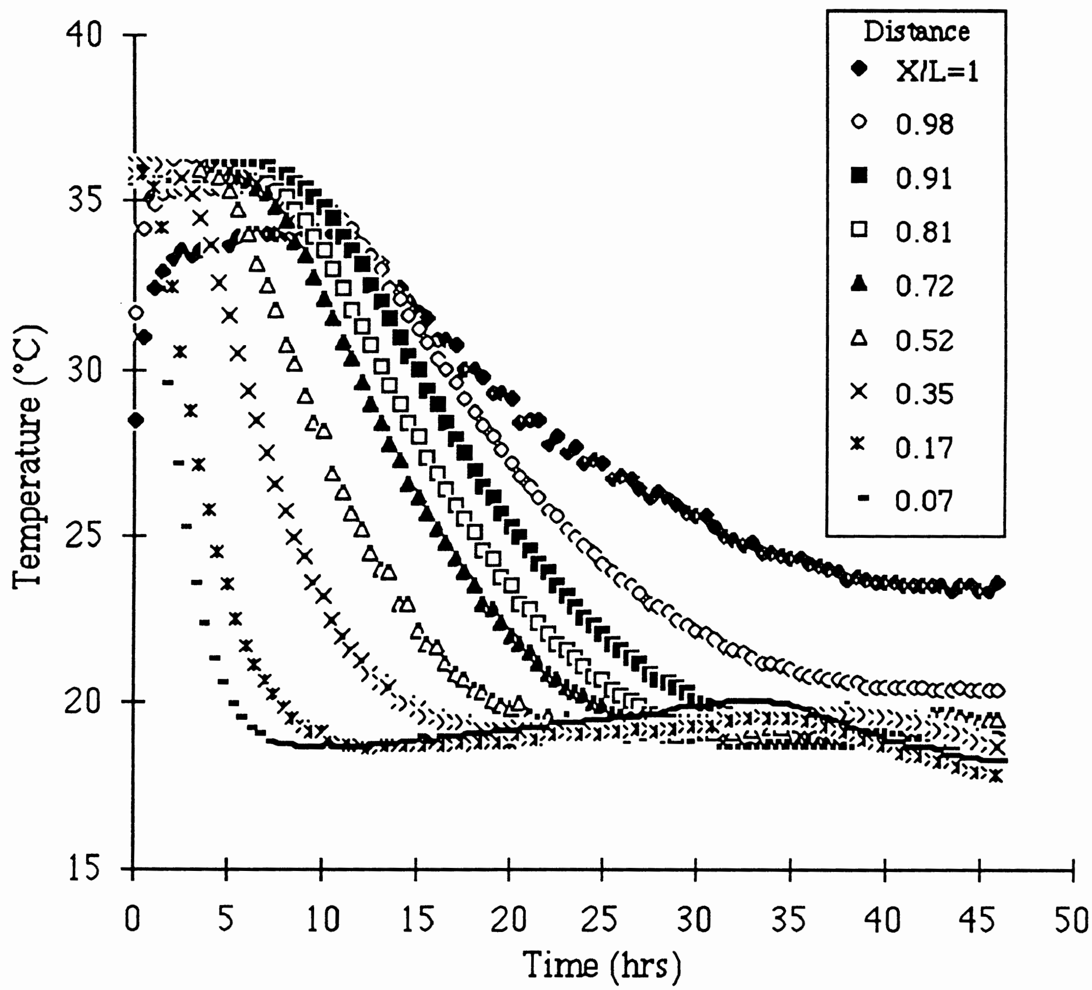

Figure 24. Temperature profile vs. time for column #2 and an aeration rate of 5.36 L/s·m³

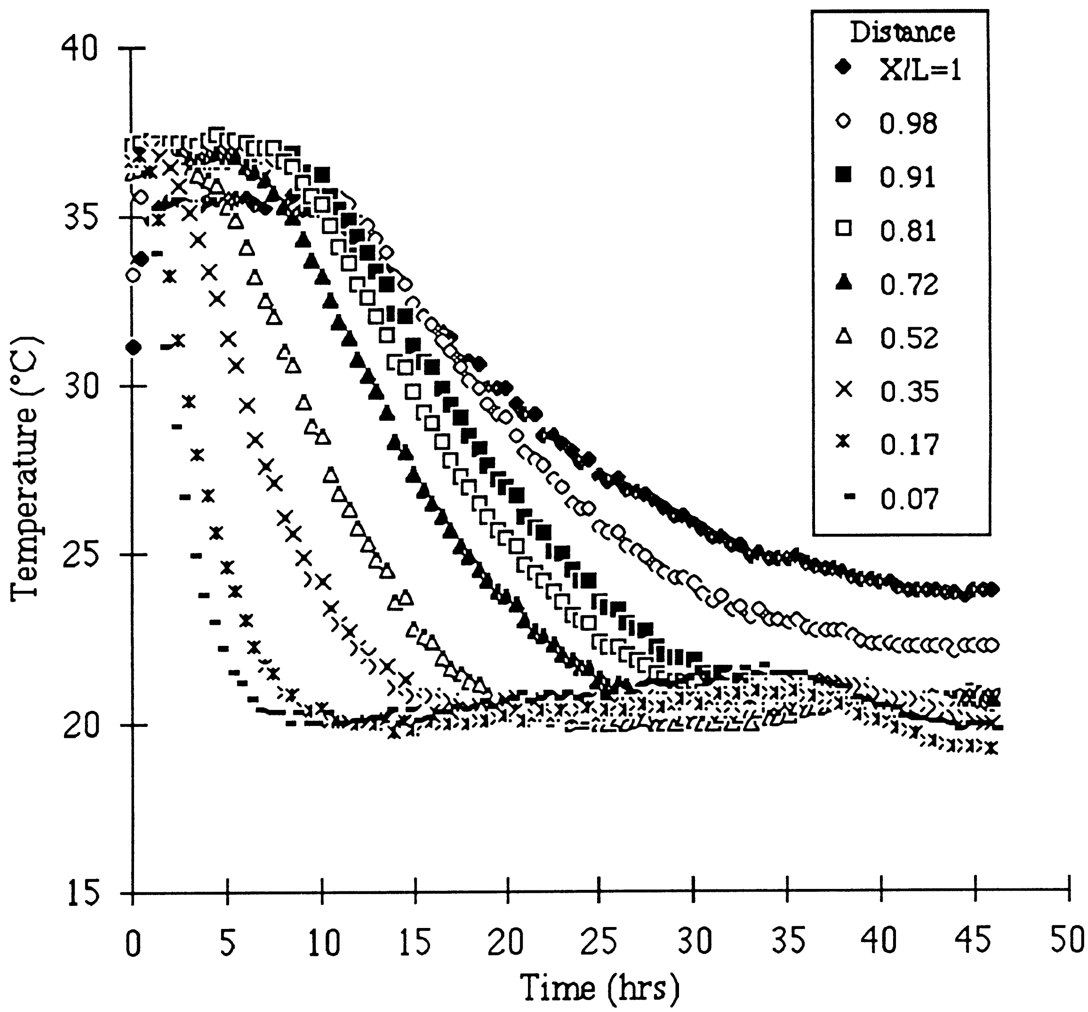

Figure 25. Temperature profile vs. time for column #3 and an aeration rate of 5.36 L/s·m^3

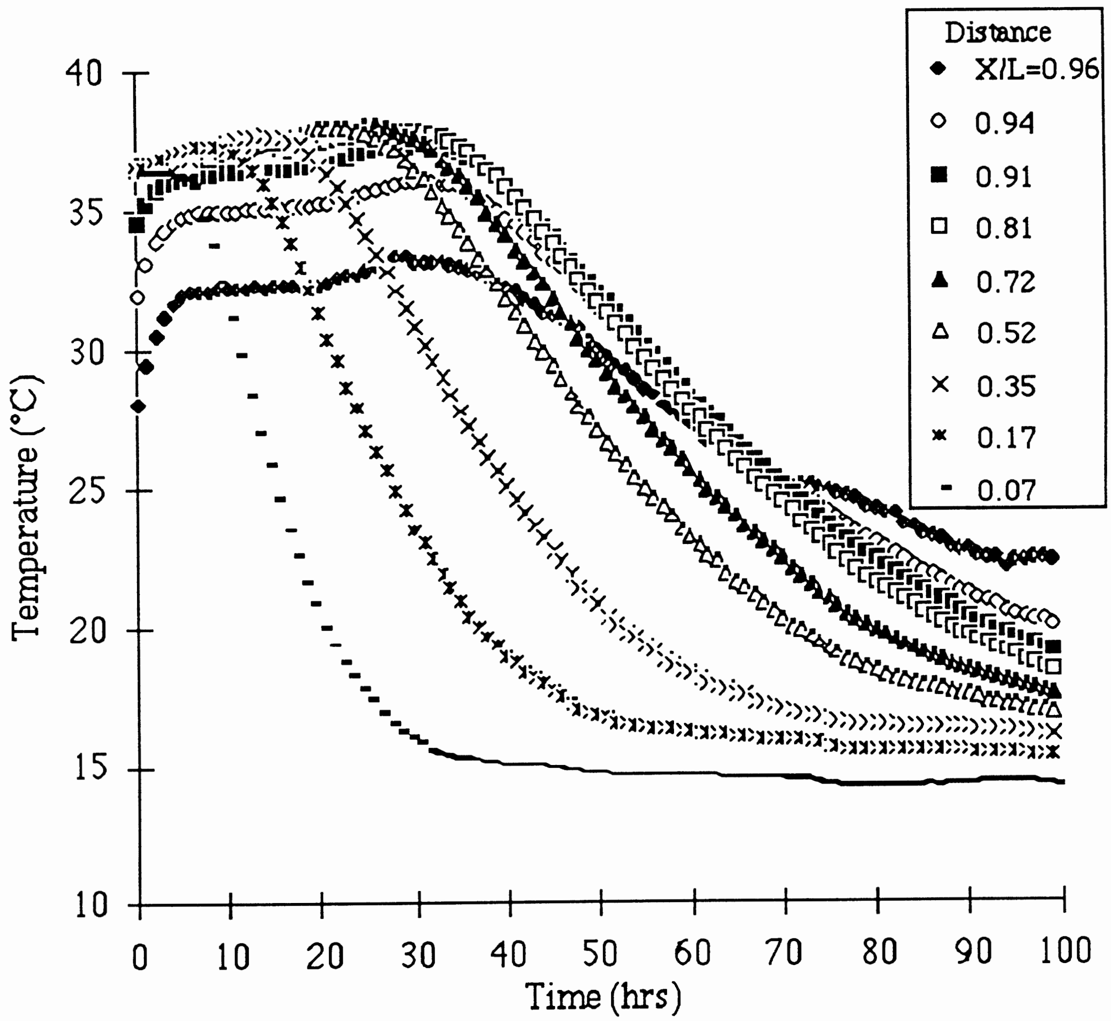

Figure 26. Temperature profile vs. time for column #1 and an aeration rate of 2.68 L/s·m^3

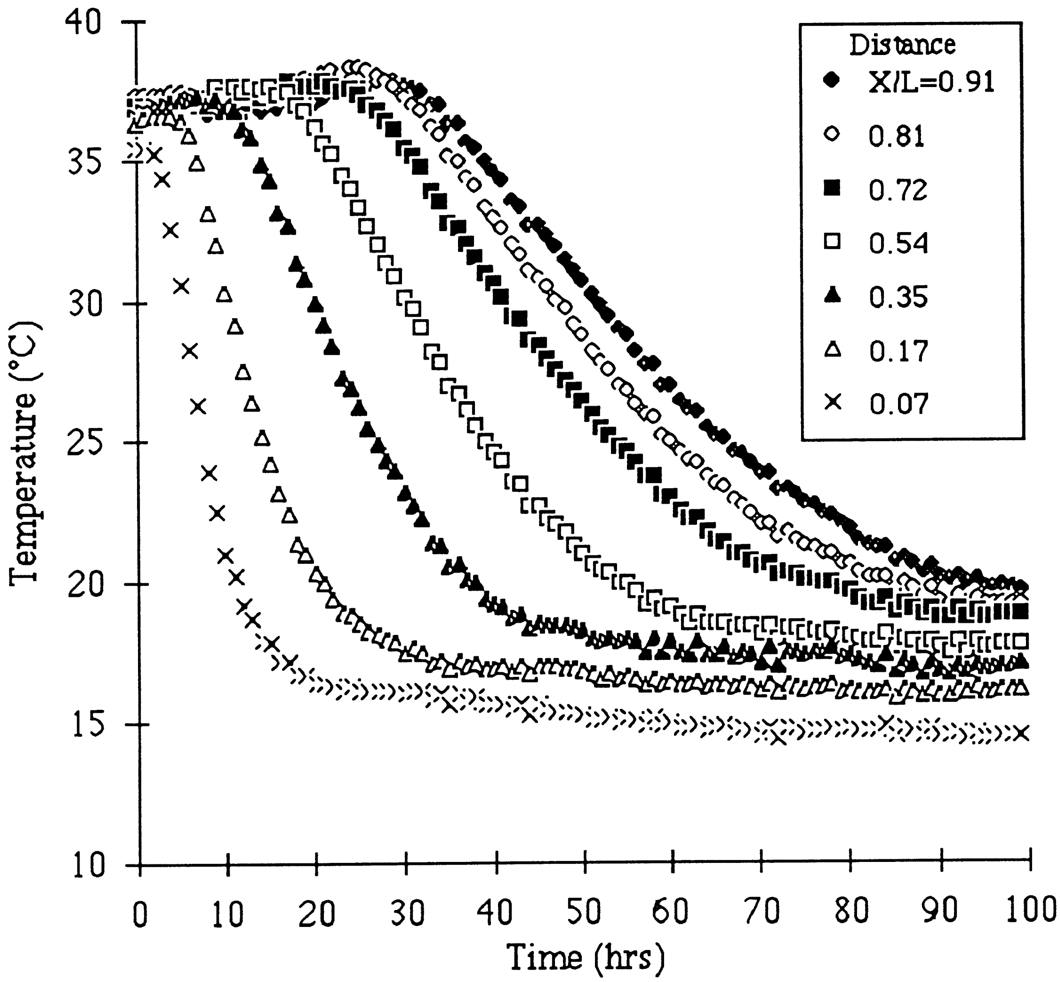

Figure 27. Temperature profile vs. time for column #2 and an aeration rate of 2.68 L/s·m³

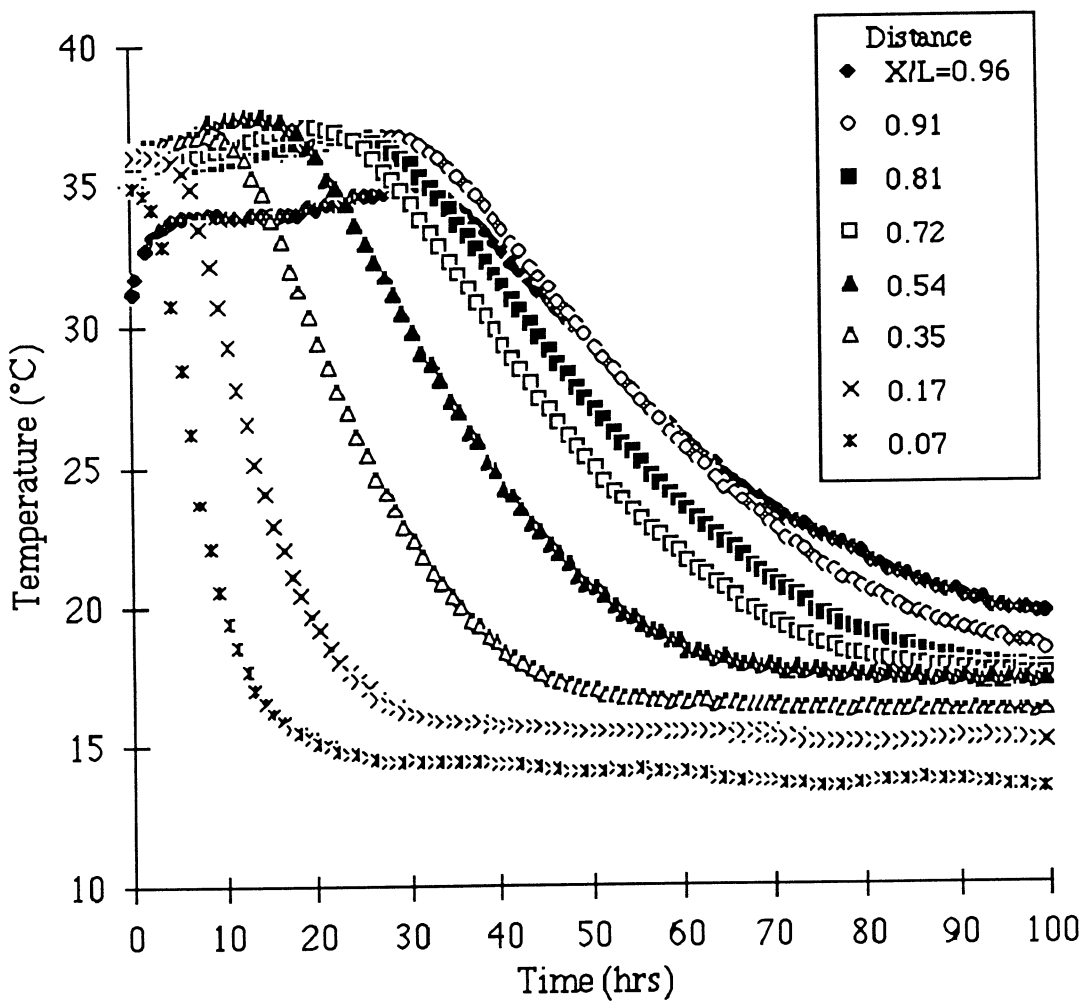

Figure 28. Temperature profile vs. time for column #3 and an aeration rate of 2.68 L/s·m^3

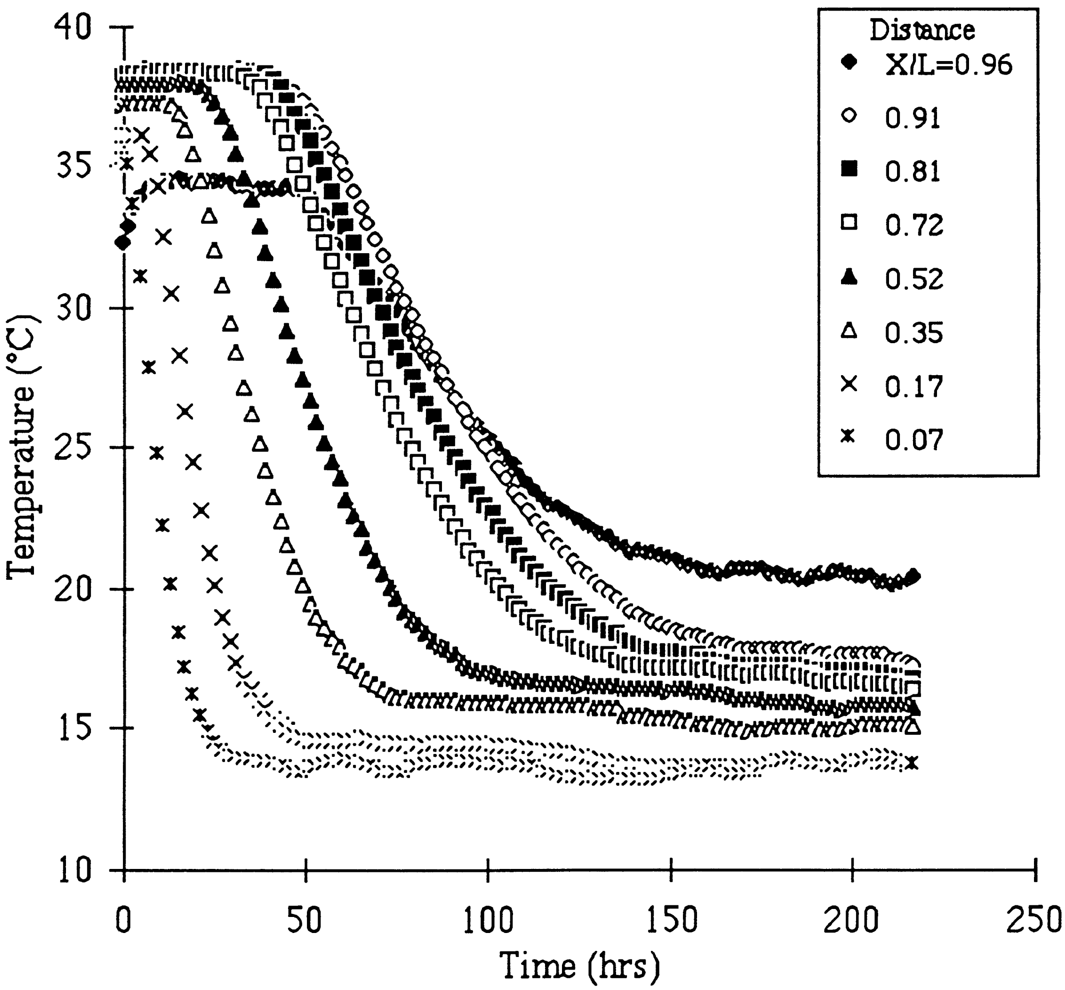

Figure 29. Temperature profile vs. time for column #1 and an aeration rate of 1.34 L/s·m³

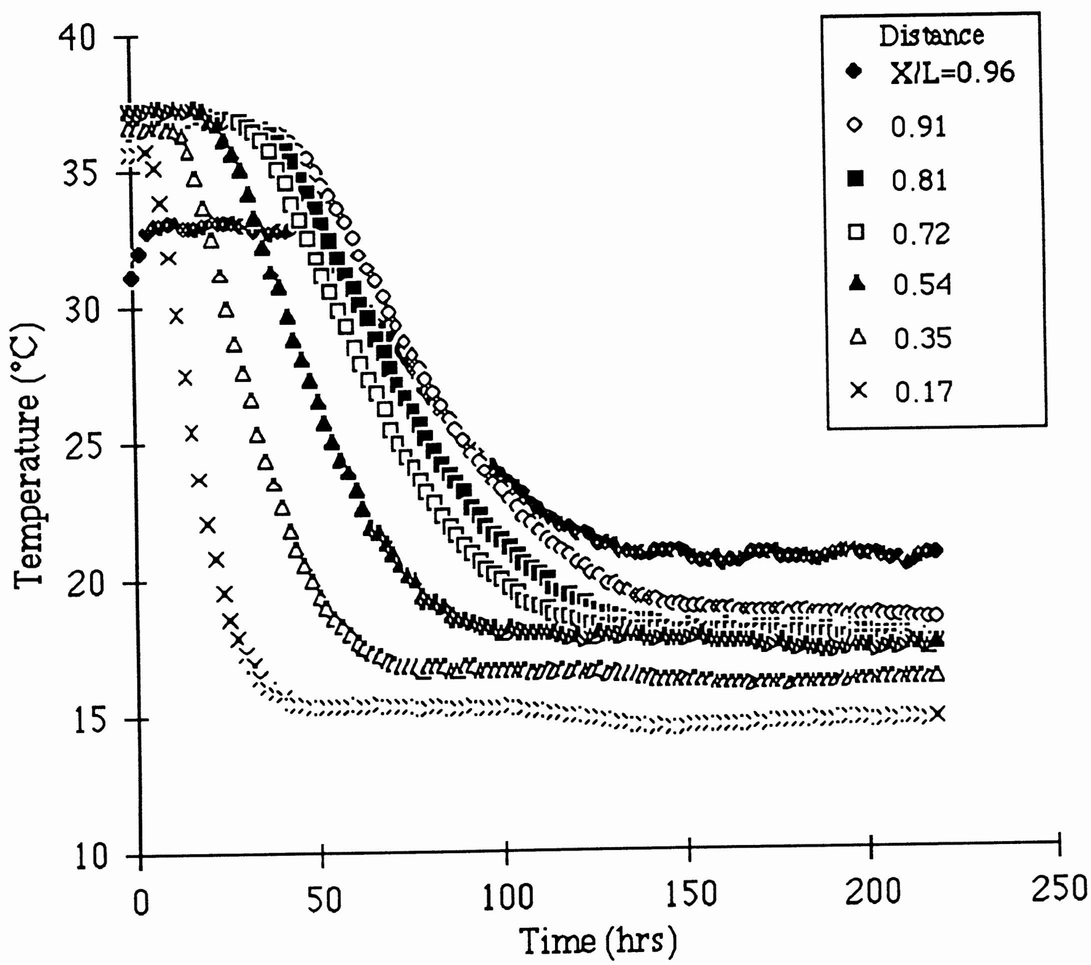

Figure 30. Temperature profile vs. time for column #2 and an aeration rate of 1.34 $L/s{\cdot}m^3$

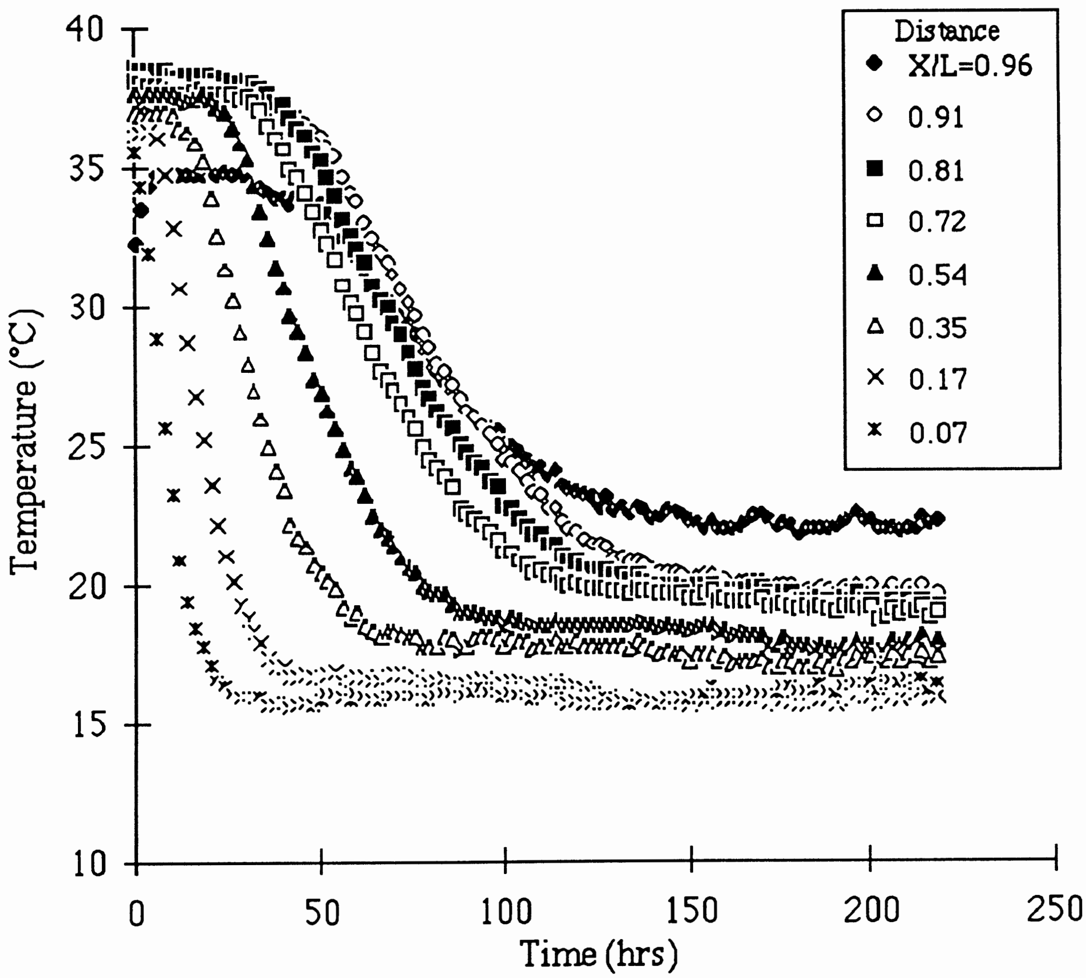

Figure 31. Temperature profile vs. time for column #3 and an aeration rate of 1.34 L/s·m^3

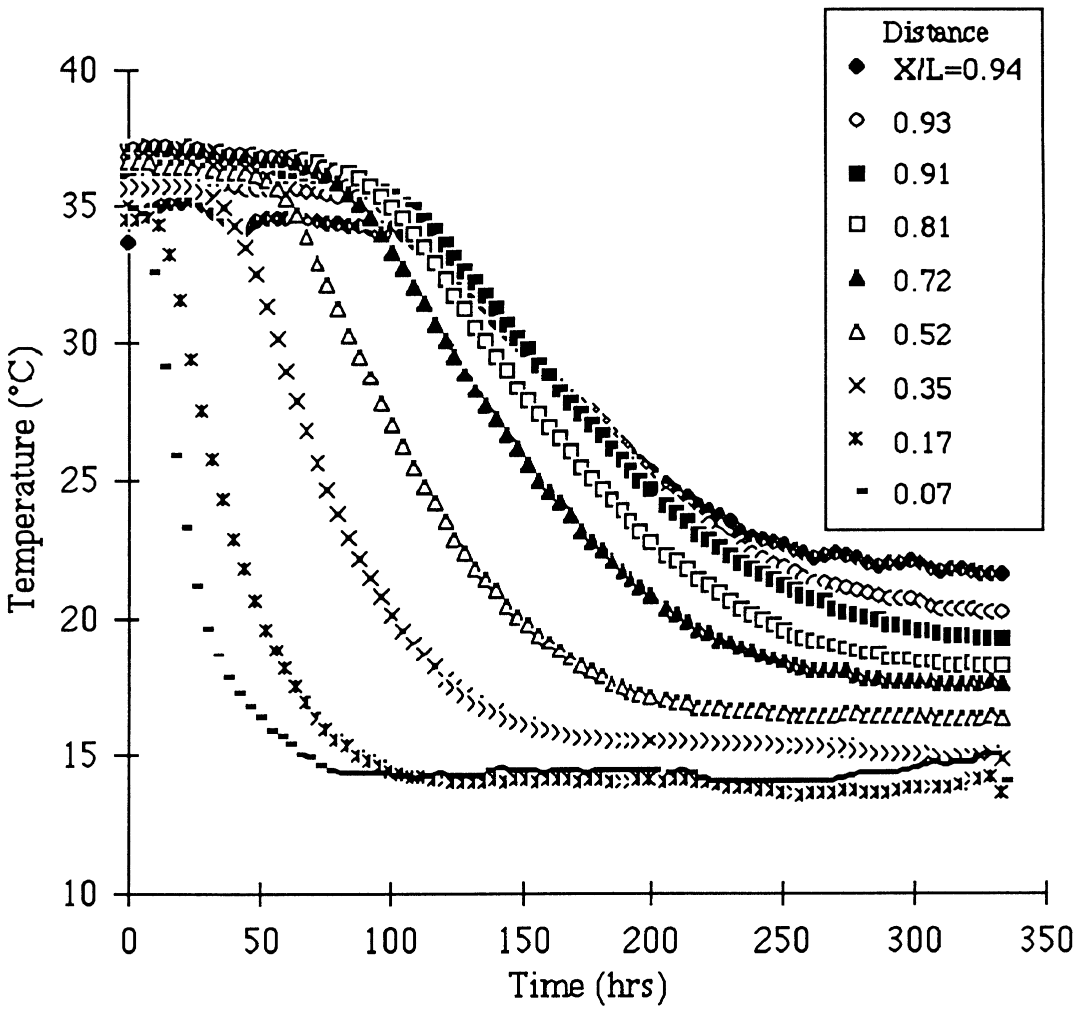

Figure 32. Temperature profile vs. time for column #1 and an aeration rate of 0.67 L/s·m3

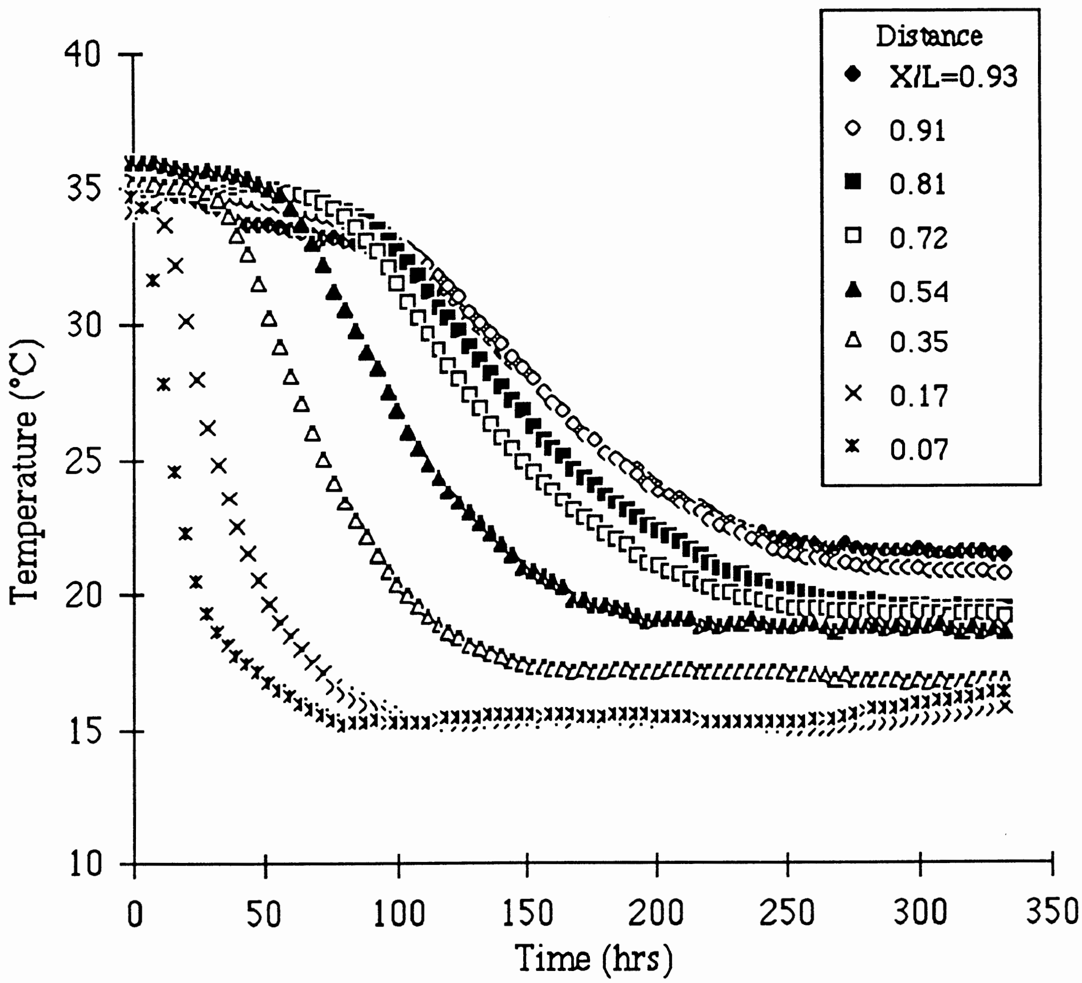

Figure 33. Temperature profile vs. time for column #2 and an aeration rate of 0.67 L/s·m3

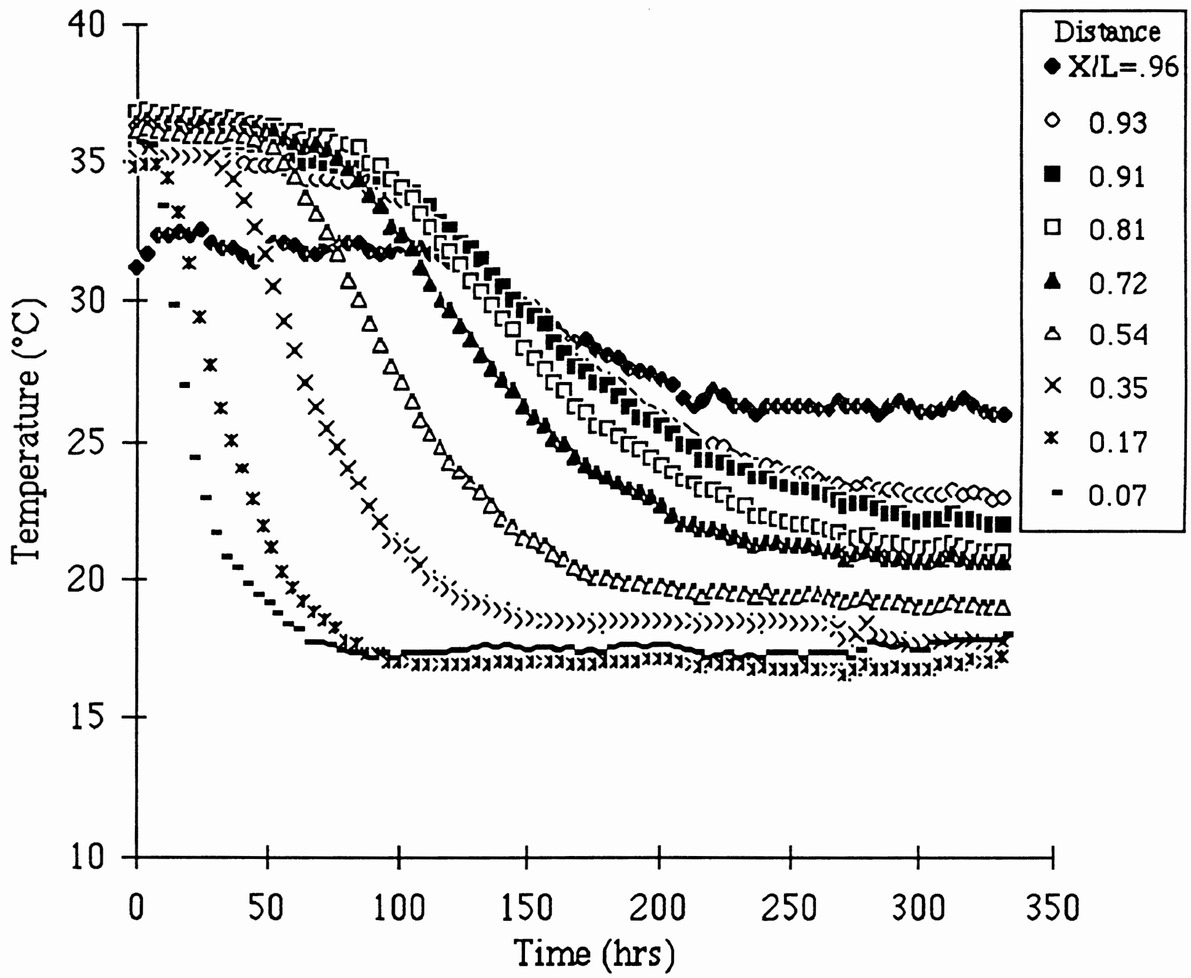

Figure 34. Temperature profile vs. time for column #3 and an aeration rate of 0.67 L/s·m^3

temperatures near the top of the grain mass to fluctuate with room temperature. The second, third and sometimes fourth thermocouple from the top, in the case of the lowest aeration rate, were used to determine the time for the leading and trailing edges to exit the grain mass.

The times for the leading and trailing edges of the cooling fronts to move out of the grain mass for each aeration rate and test column are given in Table I. The aeration fan was left on longer than the time for the trailing edge of the cooling front to exit the columns to ensure total cooling. The cumulative amount of air used during aeration, A_{cum}, was therefore determined because it could be a factor in the amount of change in moisture content.

The temperature drop, ΔT, in the grain mass was calculated as the average of all temperatures throughout the column before aeration began and the average of all temperatures in the column at the time the trailing edge exited the grain mass. The difference between the two average temperatures is the average temperature drop and is shown in Table I.

The moisture losses for each column and each airflow rate were determined. The raw moisture content data is given in Appendix D. The change in moisture content was determined by averaging the moisture contents at all locations in the column before and after aerating and taking the difference of the two averages. The gain in moisture content from rewarming was determined in the same manner. The moisture losses are shown in Table I.

TABLE I

SUMMARY OF AERATION RESULTS

Aeration Rate	Column Number	Trailing Edge	Leading Edge	Cumulative Air Use	Moisture Loss	Temperature Drop
Q_a (L/s·m^3)		Θ_T (hr)	Θ_L (hr)	A_{cum} (m^3)	Δmc (%w.b.)	ΔT (°C)
10.72	1	21.5	4.0	40.10	0.72	15.7
10.72	2	20.5	4.0	40.10	0.35	14.8
10.72	3	20.0	4.0	40.10	0.94	14.8
8.04	1	32.5	5.5	43.33	0.78	19.2
8.04	2	32.5	5.5	43.33	1.21	17.9
8.04	3	32.5	4.5	43.33	0.68	17.6
5.36	1	38.5	9.0	31.27	0.96	17.3
5.36	2	37.5	10.0	31.27	0.84	16.3
5.36	3	38.0	8.0	31.27	0.78	15.7
2.68	1	93.0	32.5	33.81	0.70	19.3
2.68	2	88.5	32.0	33.81	0.82	18.2
2.68	3	90.0	30.0	33.81	0.75	18.0
1.34	1	151.5	47.0	37.13	0.54	20.3
1.34	2	144.0	47.5	37.13	0.66	18.6
1.34	3	144.5	46.5	37.13	0.77	18.1
0.67	1	274.5	104.0	28.38	0.94	18.5
0.67	2	270.0	104.5	28.38	0.73	16.6
0.67	3	274.5	110.0	28.38	0.95	15.7

Statistical Analysis

Statistical analyses were performed on the data using SAS (1988). All statistical analyses are included in Appendix E. An analysis of variance (AOV) was first performed to determine if there were any significant differences in time for the trailing edge, Θ_T, or the leading edge, Θ_L, to exit the grain mass at different aeration rates (Appendix E1, 2). In both cases the effect of the aeration rate was highly significant with Pr>F = 0.0001 for each case (the null hypothesis, H_o, for each case was that the difference between the means was zero and α of rejection was 0.05).

Other researchers have indicated that the amount of moisture content loss and temperature change would affect the cooling time. The effect of these parameters on the time for the trailing edge, Θ_T, and the leading edge, Θ_L, to exit the grain mass were determined (Appendix E3-6). The differences in the amount of moisture content loss did not significantly affect Θ_T or Θ_L (Pr>F = 0.78 and Pr>F = 0.72, respectively). The differences in the amount of temperature drop occurring in these tests also did not significantly affect Θ_T or Θ_L (Pr>F = 0.40 and Pr>F = 0.54, respectively). The differences in the magnitude of the moisture content losses and temperature drops occurring in this study were relatively small. If the differences were greater, the effects of these parameters on the time for the two edges of the cooling front to exit the grain mass would probably increase because of effects of evaporative cooling.

The factors that were thought to affect the amount of moisture content change were statistically analyzed, also (Appendix E7-9). None of the factors of aeration rate, differences in the change in temperature or total amount of air used in these tests during aeration had a significant influence on the amount of moisture content loss with Pr>F = 0.49, 0.91 and 0.56, respectively. The cumulative amount of air used during aeration, A_{cum}, was considered for moisture content loss because the aeration fan was left on longer than the time for the trailing edge, Θ_T, to exit the grain mass for each test.

One other comparison made was whether there was a correlation between the temperature drop and aeration rate (Appendix E10). The amount of temperature drop could be somewhat controlled by the initial temperature of the grain and the conditions of the aeration air. It was attempted to try to keep the amount of temperature drop constant, however, when the larger blower was used as the aeration fan the temperature of the aeration air could not be lowered as much as when the smaller fan was used. Statistically, there was a significant difference between the amount of temperature drop and the aeration rate ($Pr>F = 0.0026$). A Duncan's Multiple Range Test was performed on the data and is given in Appendix E11. The ranking of aeration rates, in descending order of the means of temperature drop, was 1.34, 2.68, 8.04, 0.67, 5.36 and 10.72 $L/s{\cdot}m^3$. There were four different groupings of means which are not significantly different (see Appendix E-11).

Aeration rate was the only variable having a statistically significant affect on the time for the trailing edge, Θ_T, and the leading edge, Θ_L, to exit the grain mass. Therefore, the data was plotted (Figures 35 and 36) and fitted to a regression equation with time as a function of aeration rate only. Do to the exponential nature of the process, the best fit was in log-log form (Appendix E12-13) and the equations for Θ_L and Θ_T are:

$$\Theta_L = 72.2 \cdot Q_a^{-1.21} \qquad (R^2 = 0.98) \qquad (21)$$

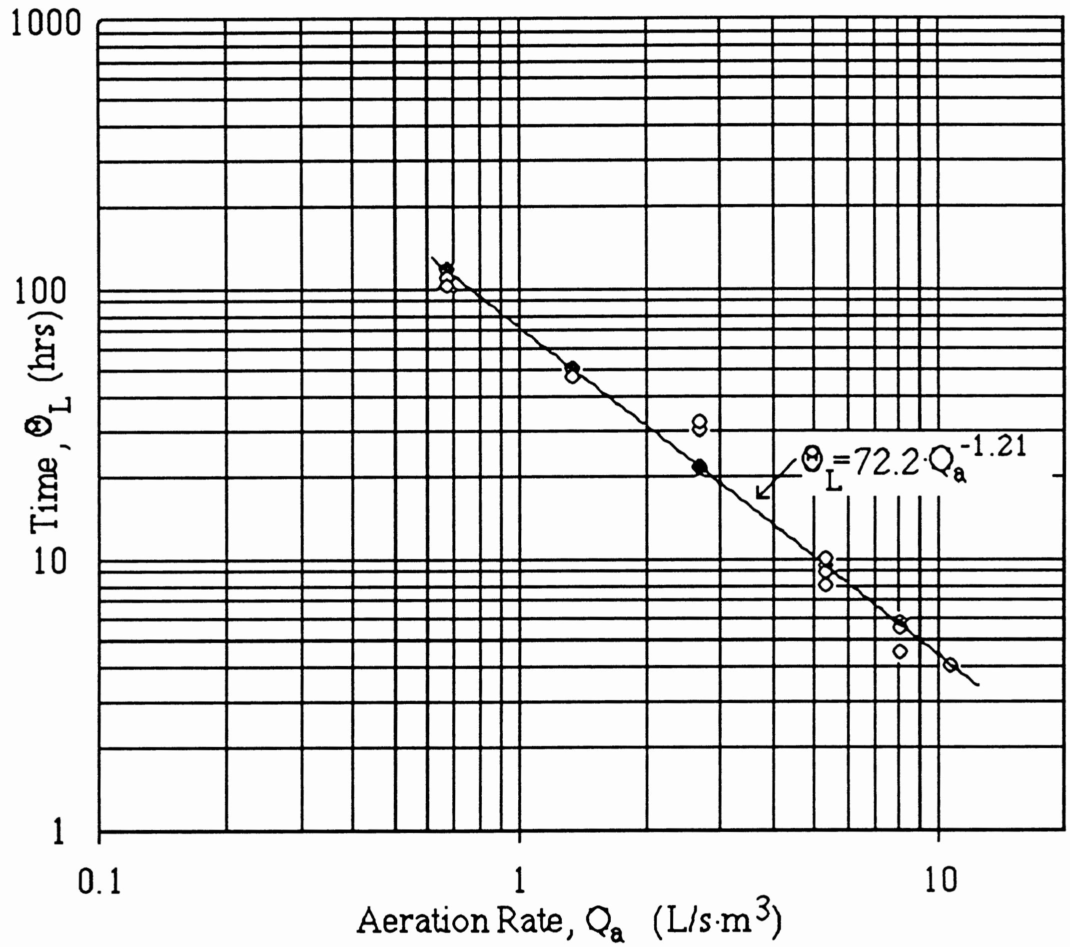

Figure 35. Time for the leading edge of the cooling front, Θ_L, to exit the grain mass as a function of aeration rate, Q_a

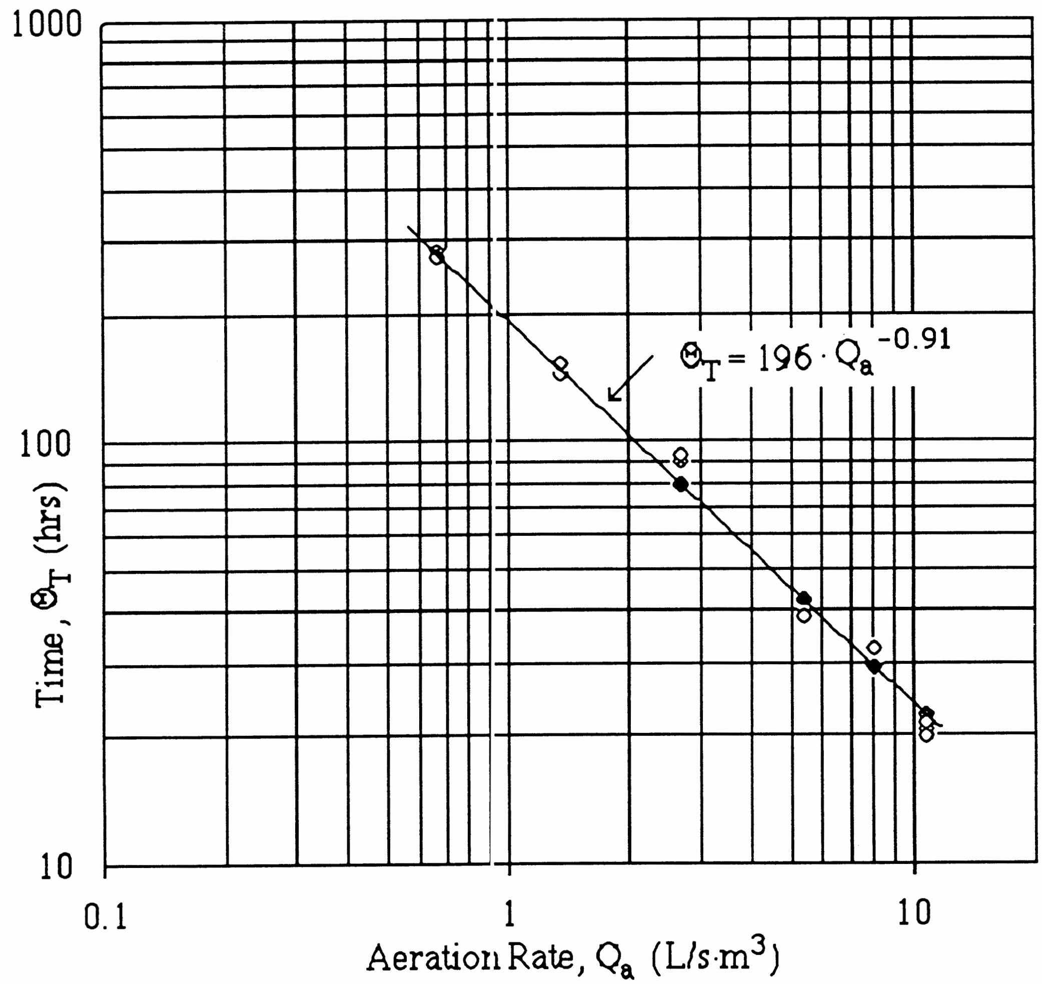

Figure 36. Time for the trailing edge of the cooling front, Θ_T, to exit the grain mass as a function of aeration rate, Q_a

$$\Theta_T = 196 \cdot Q_a^{-0.91} \qquad (R^2 = 0.99) \qquad (22)$$

These equations are in the same form as Miller's (1965), but the constants in the equations are different and the slopes in his equations are considerably less in magnitude. However, his equations were developed for grain sorghum, the manner in which the aeration rates were determined is questionable and he stated that the equations may be valid only for the conditions encountered in his tests.

Mathematical models were developed for predicting the time for the leading and trailing edges of the fronts to reach a given location, X/L, in the grain mass. First, the temperature data was analyzed to determine the time for the fronts to reach certain locations in the test columns. Eight to ten data points were taken per column and aeration rate. The data was plotted and mathematical models were developed for the determination of time to reach a given location for each aeration rate (Figures 37 and 38). The best fit for all cases was again in log-log form. The general form of the equations was:

$$\Theta = B \cdot (X/L)^M \qquad (23)$$

The values of equation parameters for the leading and trailing edges of the cooling front are given in Table II and the AOV's are given in Appendix E14-25.

It was observed that there was a functional relationship between the values of the intercepts, B, and the aeration rate, Q_a. Also, the values of the slopes, M, were only slightly different at the different aeration rates, Q_a. The intercepts, B, and slopes, M, for each edge of the cooling front were plotted as a function of the aeration rate, Q_a (Figures 39 and 40). Regression

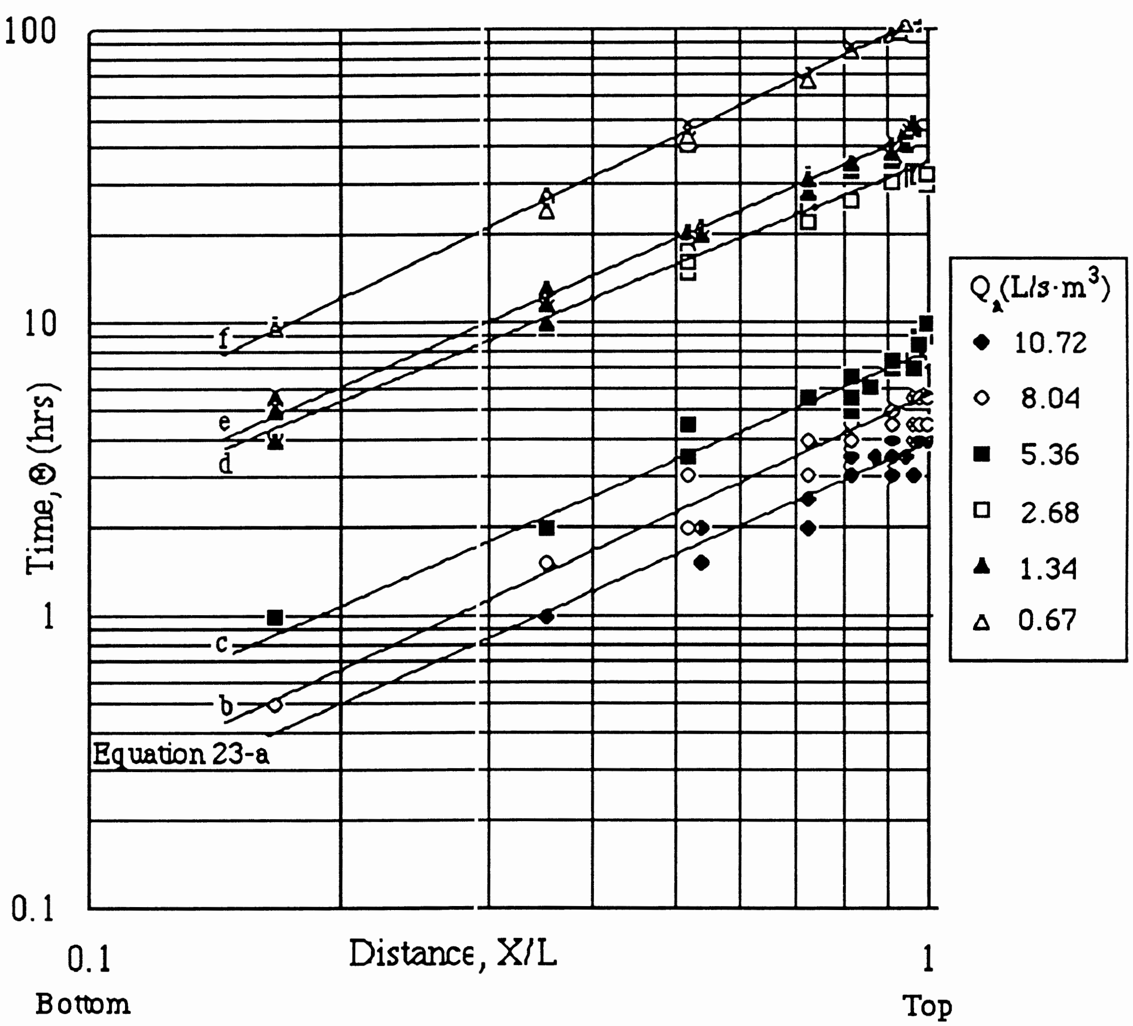

Figure 37. Plot of time for the leading edge of the cooling front to reach a certain distance for each aeration rate with best fit equations for the data from Table II

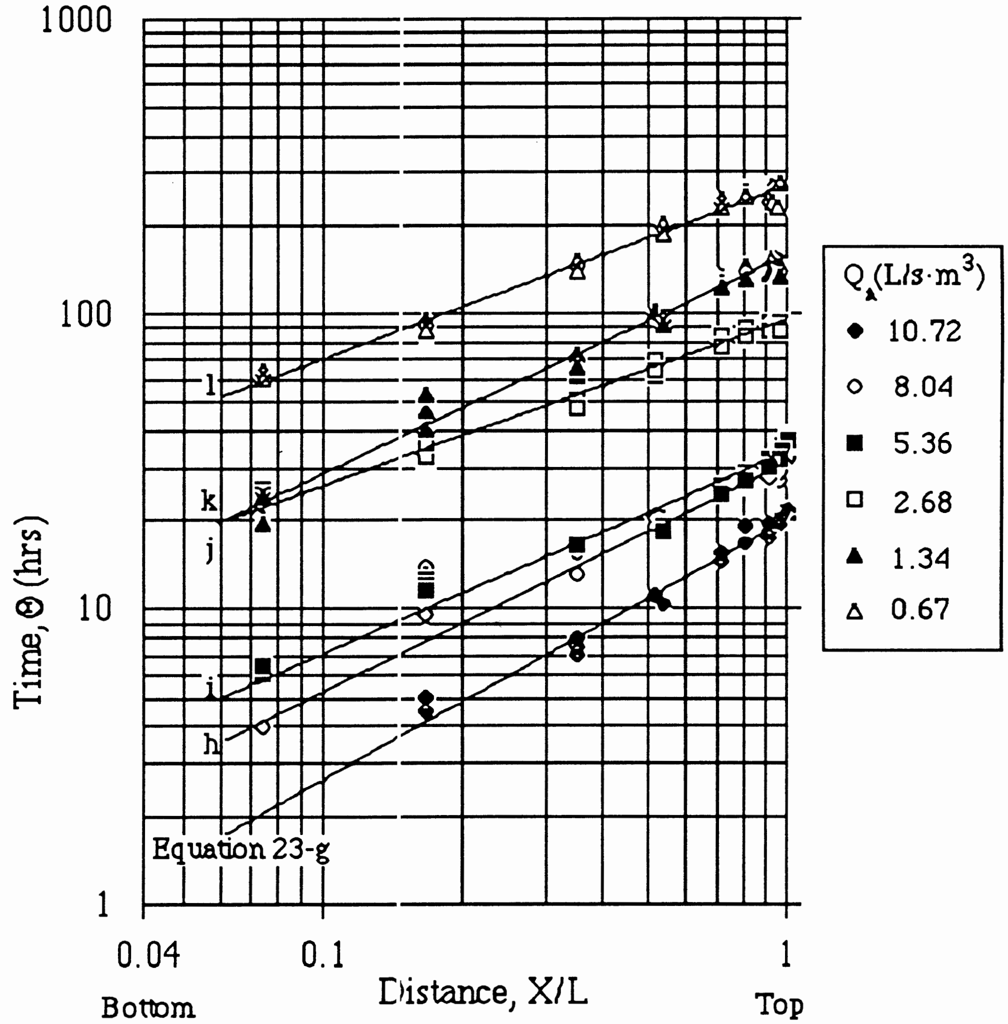

Figure 38. Plot of time for the trailing edge of the cooling front to reach a certain distance for each aeration rate with best fit equations for the data from Table II

TABLE II

VALUES OF EQUATION 23 PARAMETERS FOR LOCATION OF THE LEADING AND TRAILING EDGES OF THE COOLING FRONT

Aeration Rate (L/s·m^3)	Front Edge	Equation 23-( )*	Intercept B	Slope M	R^2
10.72	leading	a	3.90	1.22	0.97
8.04		b	5.46	1.28	0.97
5.36		c	8.09	1.22	0.98
2.68		d	32.99	1.13	0.99
1.34		e	45.98	1.29	0.99
0.67		f	110.90	1.39	0.99
10.72	trailing	g	20.0	0.84	0.98
8.04		h	31.4	0.71	0.95
5.36		i	33.3	0.63	0.97
2.68		j	92.6	0.53	0.99
1.34		k	153.5	0.74	0.98
0.67		l	276.6	0.59	0.99

* Refers to Figures 37 and 38

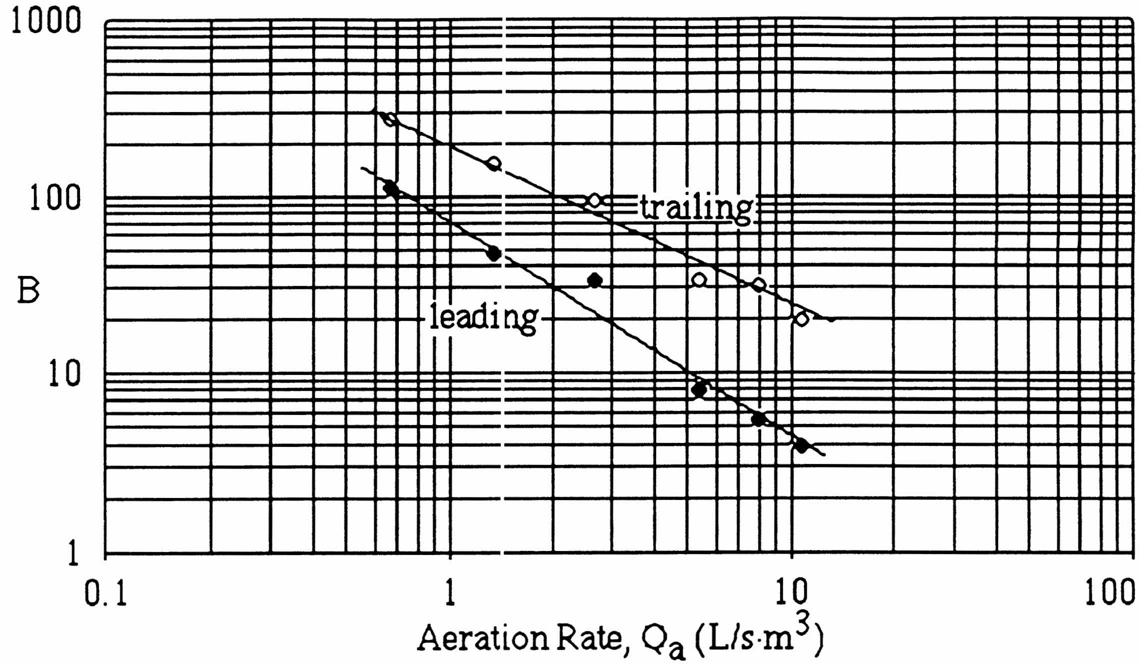

Figure 39. Plot of the B coefficients vs. aeration rate, Q_a, for equation 23 for both the leading and trailing edges of the cooling front

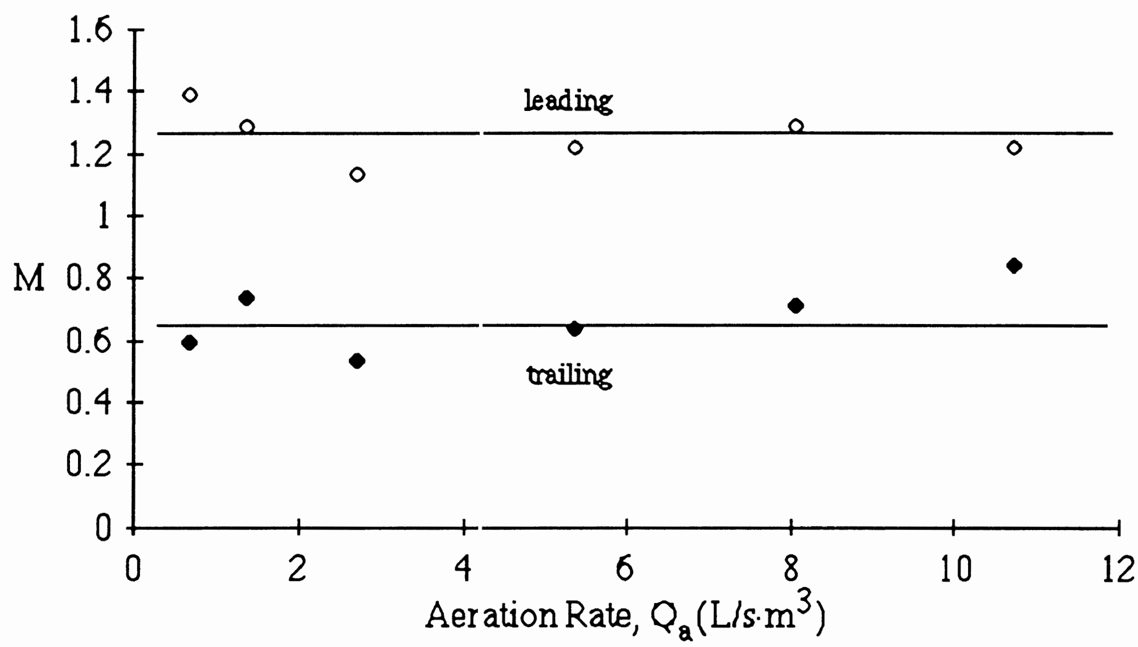

Figure 40. Plot of the M coefficients vs. aeration rate, Q_a, for equation 23 for both the leading and trailing edges of the cooling front

models for the intercepts, B, as a function of the aeration rate, Q_a, for both edges of the cooling front were best fit in the log-log form and were:

Leading:

$$B = 72.1 \cdot Q_a^{-1.21} \qquad (24)$$

Trailing:

$$B = 204 \cdot Q_a^{-0.98} \qquad (25)$$

A statistical analysis was performed to determine if the differences between the slopes, M, for the different aeration rates, Q_a, was zero and is given in Appendix E26-27. There was not enough statistical evidence at an α of 0.05 to reject the null hypothesis that the differences between the slopes was zero for each case ($Pr>F=0.52$ for the leading and $Pr>F=0.14$ for the trailing edge). Therefore, the slope, M, was not a function of aeration rate, Q_a, and the average value for the slope for the leading edge was 1.26 and for the trailing edge was 0.65.

By evaluating the relationships developed for the intercepts, B, and the slopes, M, the individual equations from Table II can be combined into one equation for each edge of the cooling front that would predict the time for the leading or trailing edge of the temperature front to reach a given location at a certain aeration rate. The form of the equations is:

$$\Theta = B_1 \cdot Q_a^{M_1} \cdot (X/L)^{M_2} \qquad (26)$$

where B_1 and M_1 are obtained from equations 24 and 25 and M_2 from the average values of the slope, M.

Regression analyses were performed on the data with the AOV's given in Appendix E28-29. The equations that predict the time for the leading,

Θ_{LL}, or trailing, Θ_{LT}, edge of the temperature front to reach a given location at a certain aeration rate are:

$$\Theta_{LL} = 72.1 \cdot Q_a^{-1.20} \cdot \frac{X}{L}^{1.26} \qquad (R^2 = 0.97) \qquad (27)$$

$$\Theta_{LT} = 204 \cdot Q_a^{-0.98} \cdot \frac{X}{L}^{0.65} \qquad (R^2 = 0.97) \qquad (28)$$

The models are plotted along with the experimental data to compare the results (Figures 41 and 42).

Comparison of Results With Other's Results

Other investigators have reported cooling times during aeration (Sanderson *et al.*, 1988a; Burrell and Laundon, 1967; McCune *et al.*, 1963). Their results are given in Table III along with the predicted values using equation 28. The calculated results are within 8% of the observed values with the exception of Burrell and Laundon's (1967) which reported extrapolated results. The manner of determining the total cooling times were obviously different, also. Miller (1965) used one aeration rate, 1.2 L/s·m^3, and used different depths in the grain mass for his different aeration rates. Therefore, Miller's (1965) aeration data can be used for comparisons using the form of equations 23 and 26. Equations 27, 28 and 23, using an aeration rate of 1.34 L/s·m^3 from Table II, are compared with his results in Table IV. Using the equations for 1.34 L/s·m^3 gave the best comparisons. The differences between the observed and calculated results for the trailing edge data ranged from 0.4% to 11% and for the leading edge ranged from 2% to 30%, however the 30% difference was only 1.5 hrs.

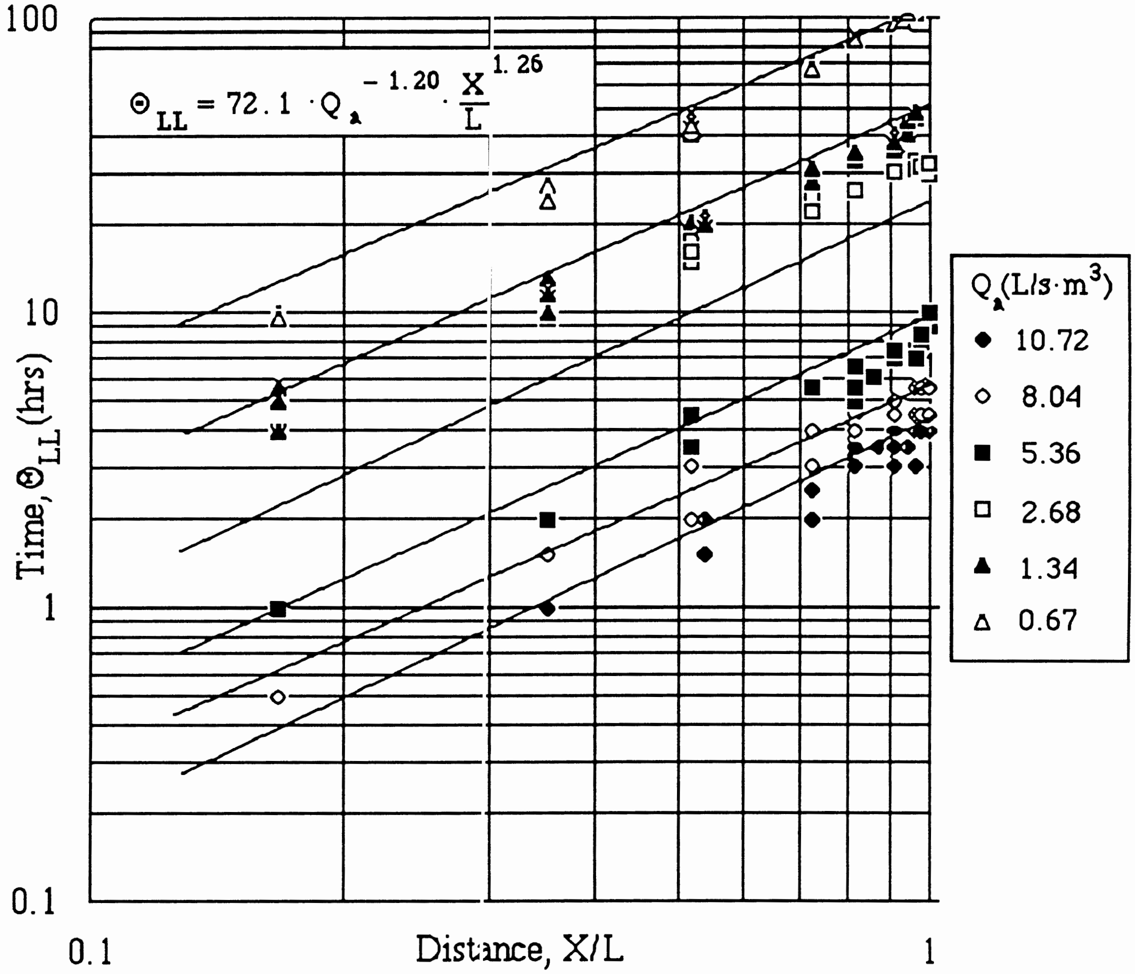

Figure 41. Plot of time for the leading edge of the cooling front to reach a certain distance for each aeration rate with best fit equation 27 for the data

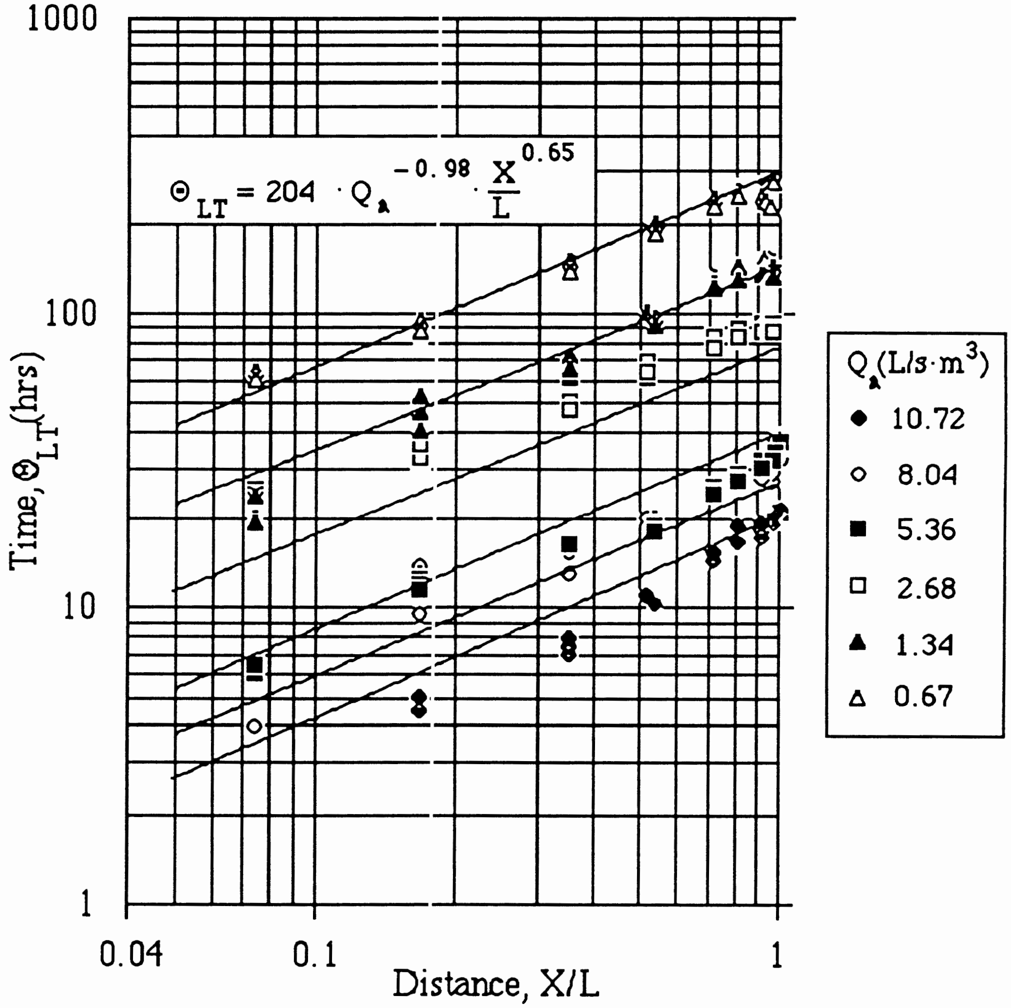

Figure 42. Plot of time for the trailing edge of the cooling front to reach a certain distance for each aeration rate with best fit equation 28 for the data

TABLE III

COMPARISON OF COOLING TIME WITH OTHER'S RESULTS

Investigators	Q_a (L/s·m^3)	Observed Θ_T (hr)	Calculated Θ_T (hr)
Sanderson *et al.* (1988a)	23.2	8-10	9.5
	12.2	15-17	17.6
	6.9	30-35	31.0
	3.4	40-60	61.8
	0.85	260	240.0
Burrell and Laundon (1967)	4.7	60*	45.2
McCune *et al.* (1963)	1.6	125	128.0

* Extrapolated data

TABLE IV

COMPARISON OF MILLER'S (1965) RESULTS
WITH COMPUTED RESULTS

Distance	Observed Times by Miller (1965)		Calculated Times			
X/L	Θ_{LL} (hr)	Θ_{LT} (hr)	Θ_{LL}[1] (hr)	Θ_{LT}[2] (hr)	Θ_{LL}[3] (hr)	Θ_{LT}[3] (hr)
0.889	35	132	50.8	160.7	39.0	140.1
0.667	27	110	35.4	133.3	27.3	113.9
0.444	18	84	21.2	102.4	16.2	84.5
0.222	9.5	54	8.9	65.3	6.6	50.7
0.111	4.9	34	3.7	41.6	3.5	30.5

1 Calculated using equation 27
2 Calculated using equation 28
3 Calculated using form of equation 23 and data from Table II for 1.34 $L/s\cdot m^3$

Temperature Distribution

There have been several models developed to determine grain temperature distributions, but most of them have been developed for drying applications (Schumann, 1929; Furnas, 1930; Boyce, 1966; Ingram, 1979; Bakker-Arkema *et al.*, 1966, 1967; Schultz, 1984; Ingram, 1979; etc.). Of the models developed, most either predict the average grain temperature or did not accurately predict the grain temperatures.

Work done by Schumann (1929) and Furnas (1930) gave theoretical solutions to the temperature history of a cold bed of broken solids being heated by a hot fluid. Bakker-Arkema and Bickert (1966) developed a model for cooling sugar beets using this model, but their real cooling rates were considerably higher than predicted rates. They attributed the differences in the results to the lack of the effect of mass tranfer on the cooling time in the model. All of these investigators used the same approach which involves performing a heat balance on a control volume of the product. The partial differential equation developed for the product was:

$$\frac{\partial T_p}{\partial t} + \frac{hA}{\rho_p c_p}(T_p - T_a) = 0 \tag{29}$$

The initial and boundary conditions were that the initial product temperatures were uniform and that the cooling air temperature was constant throughout time. The variables of temperature, position and time were made dimensionless as follows:

$$\Phi = \frac{T_p - (T_p)_{t=0}}{(T_a)_{x=0} - (T_p)_{t=0}} \qquad y = \frac{hA}{\rho_a c_a V_a} x \qquad z = \frac{hA}{\rho_p c_p} t$$

where the variable t is time, A is surface area, V is air velocity, h is the convective heat transfer coefficient and the subscripts "p" for product and "a" for air.

The final solution for the product temperature developed by these researchers was:

$$\Phi(y, z) = e^{-y} \int_{o}^{z} e^{-z} I_o[2\sqrt{yz}]\, dz \qquad (30)$$

The infinite solution of equation 30 is:

$$\Phi = e^{-y-z} \sum_{n=1}^{\infty} z^n M_n(y\, z) \qquad (31)$$

where the M function is defined as:

$$M_o(a) = J_o(2i\sqrt{a})$$

$$M_n(a) = \frac{d^n M_o(a)}{da^n} \qquad (32)$$

The graphical solution to equation 30 is given in Figure 43.

Temperature distribution data was extracted from the main data files for each aeration rate using Program 3 (Appendix B). The temperature profiles were plotted versus location in the grain mass for various instances in time and is shown in Figures 44 through 61. The temperature distributions found in this study are in the same form as that shown in Figure 43. A temperature prediction model was then developed using equation 30.

The variable y is related to the time in the aeration period, Θ, the variable z is related to the position in the grain mass, X/L, and the variable Φ

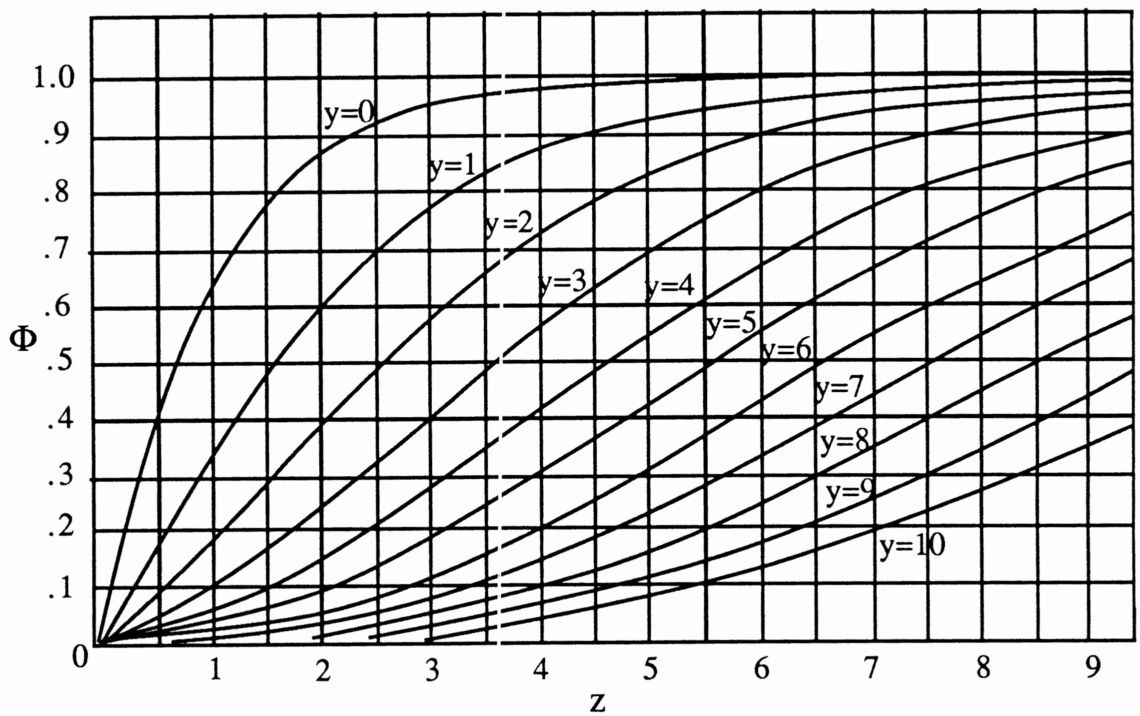

Figure 43. Schumann's (1929) graphical solution to equation 30

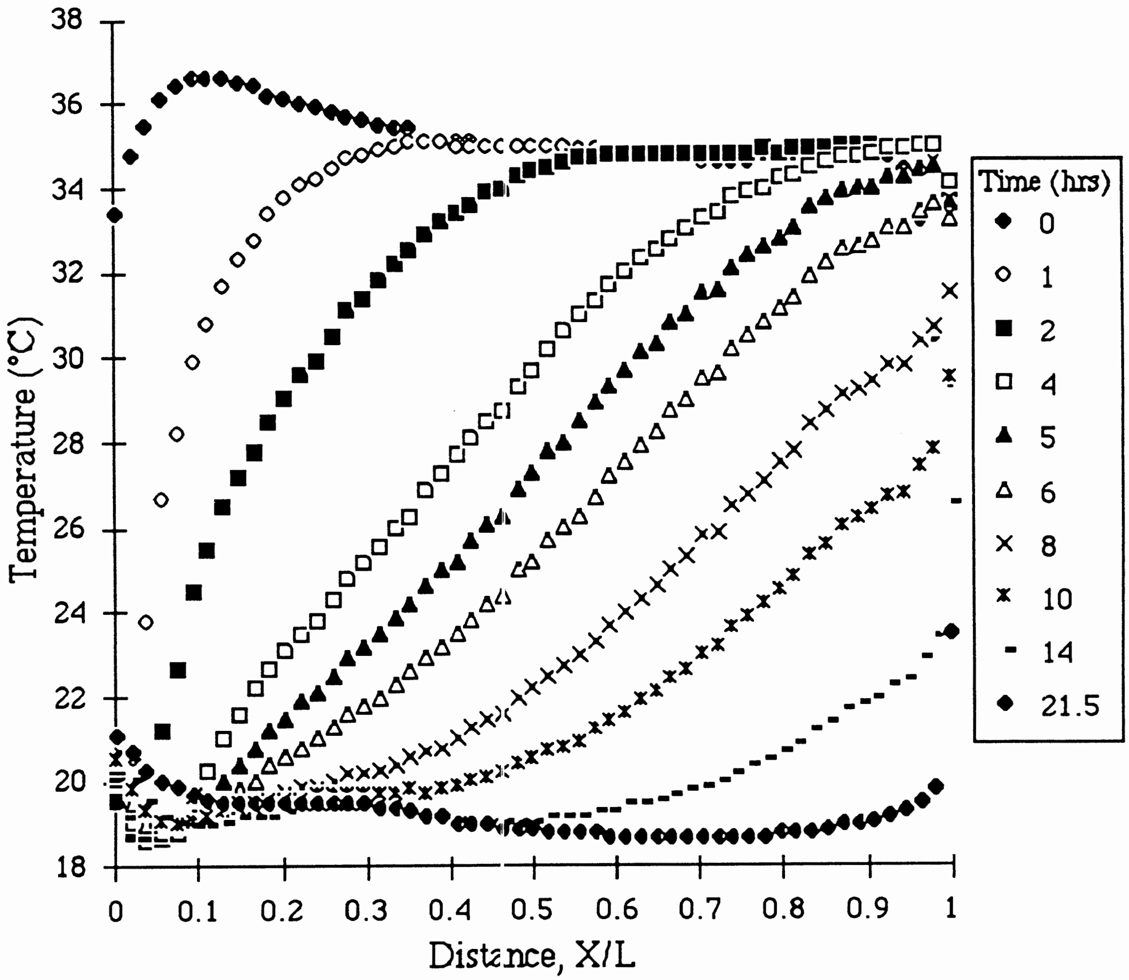

Figure 44. Temperature vs. location in grain mass at different instances of time for column #1 and an aeration rate of 10.72 L/s·m3

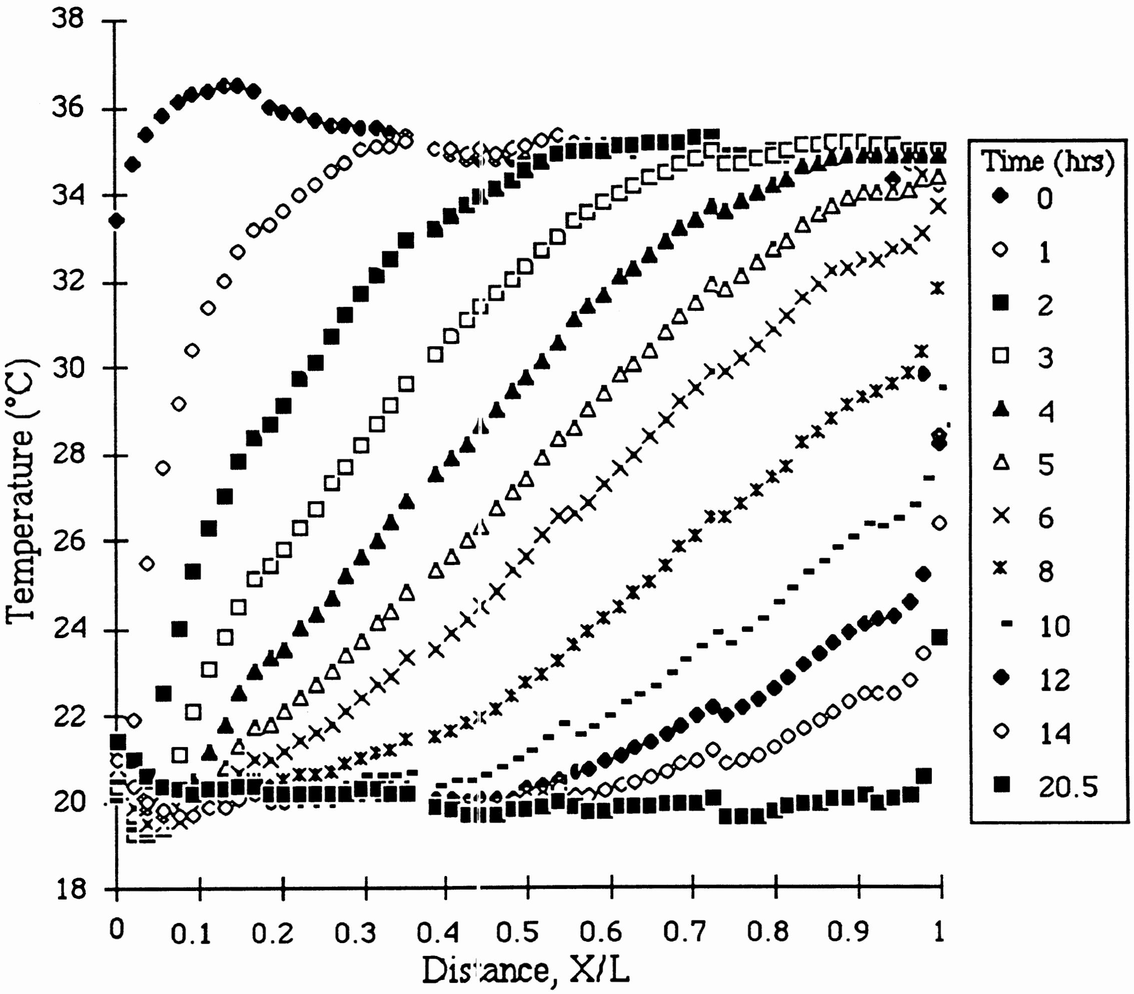

Figure 45. Temperature vs. location in grain mass at different instances of time for column #2 and an aeration rate of 10.72 L/s·m³

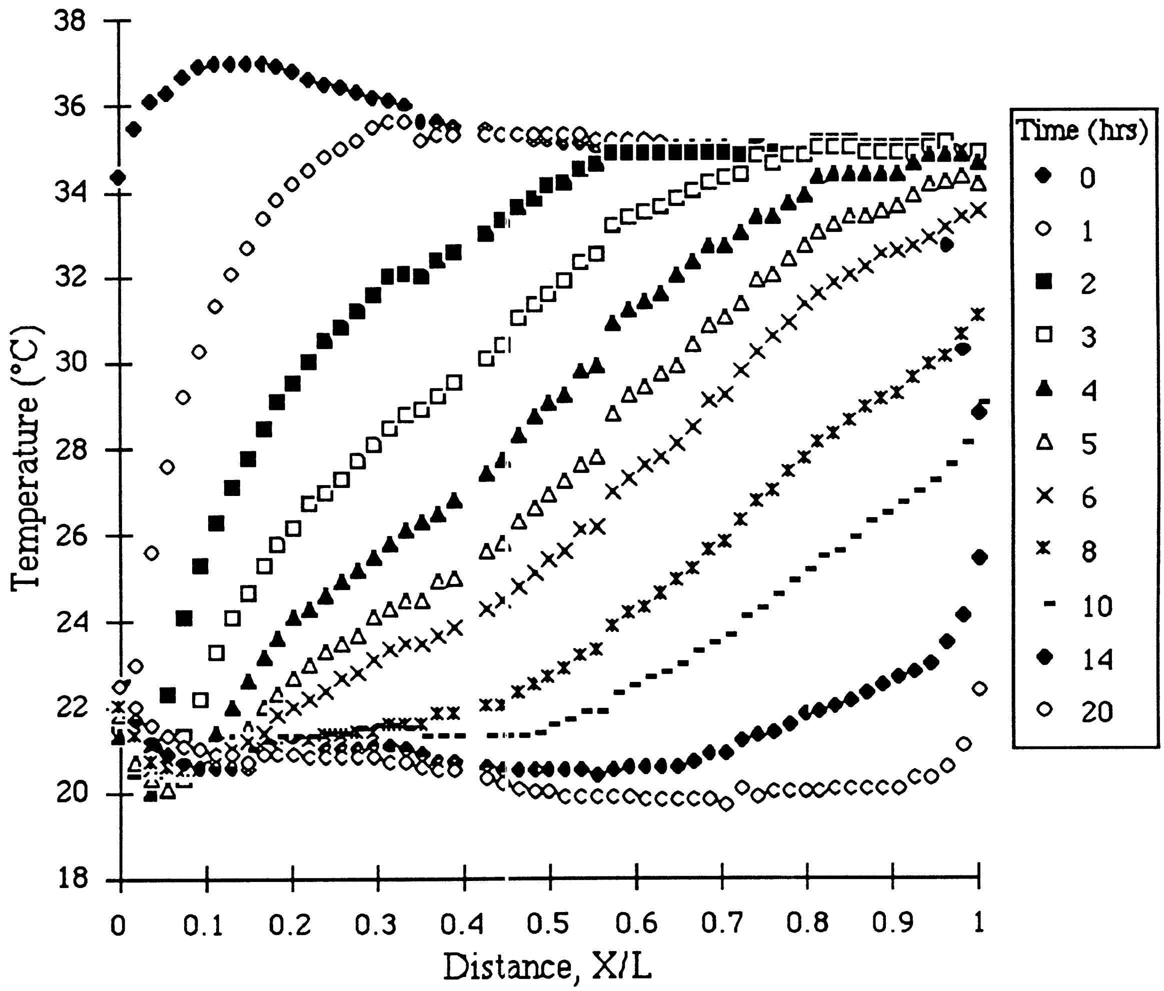

Figure 46. Temperature vs. location in grain mass at different instances of time for column #3 and an aeration rate of 10.72 L/s·m^3

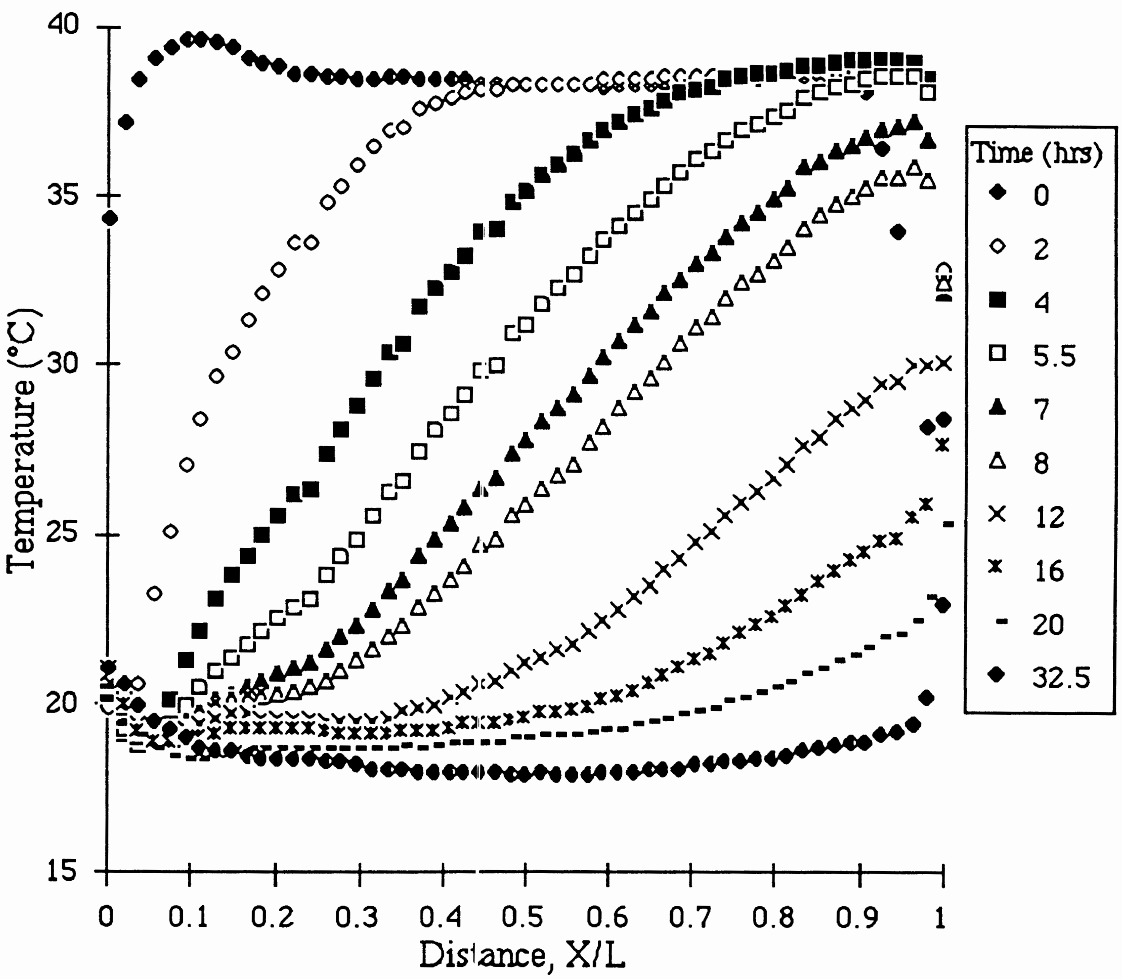

Figure 47. Temperature vs. location in grain mass at different instances of time for column #1 and an aeration rate of 8.04 $L/s{\cdot}m^3$

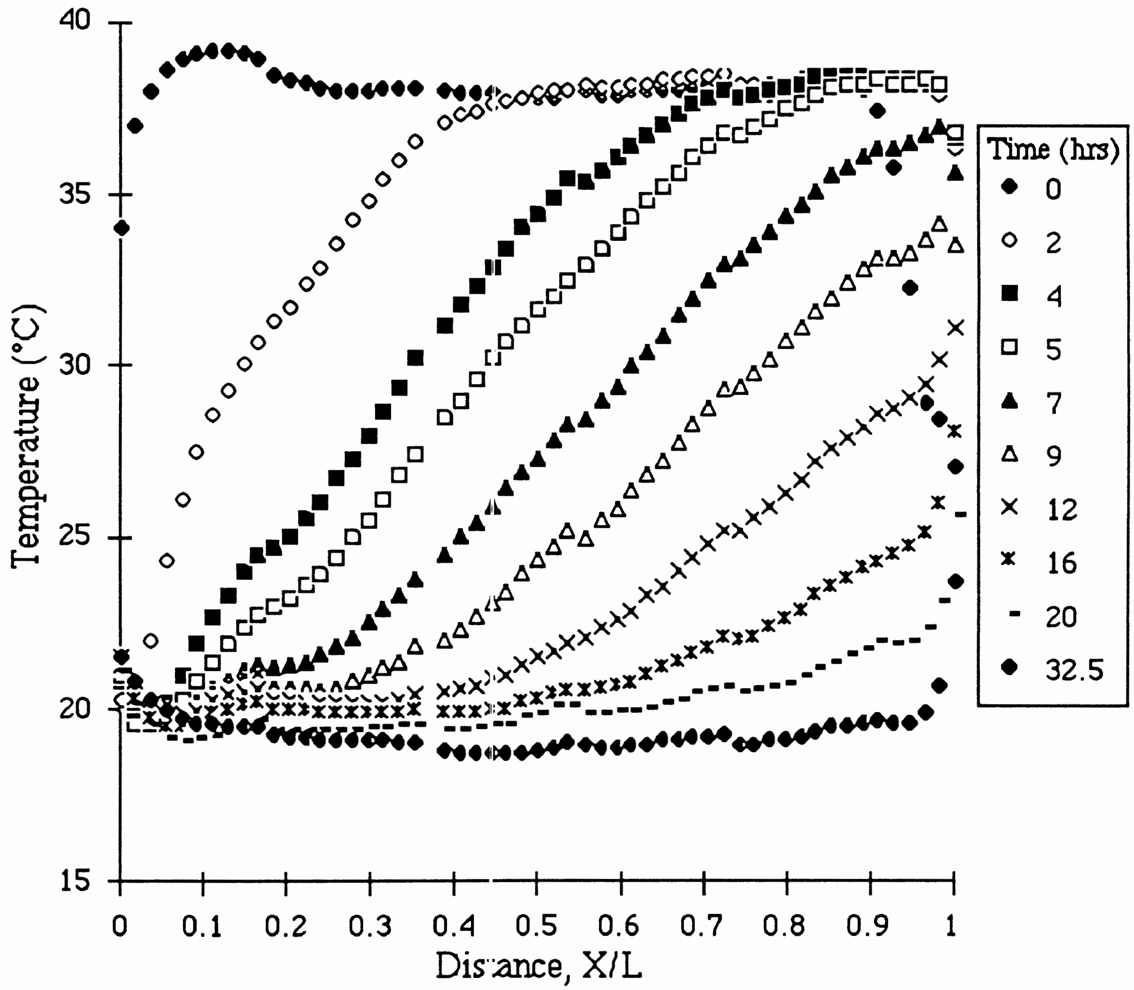

Figure 48. Temperature vs. location in grain mass at different instances of time for column #2 and an aeration rate of 8.04 L/s·m^3

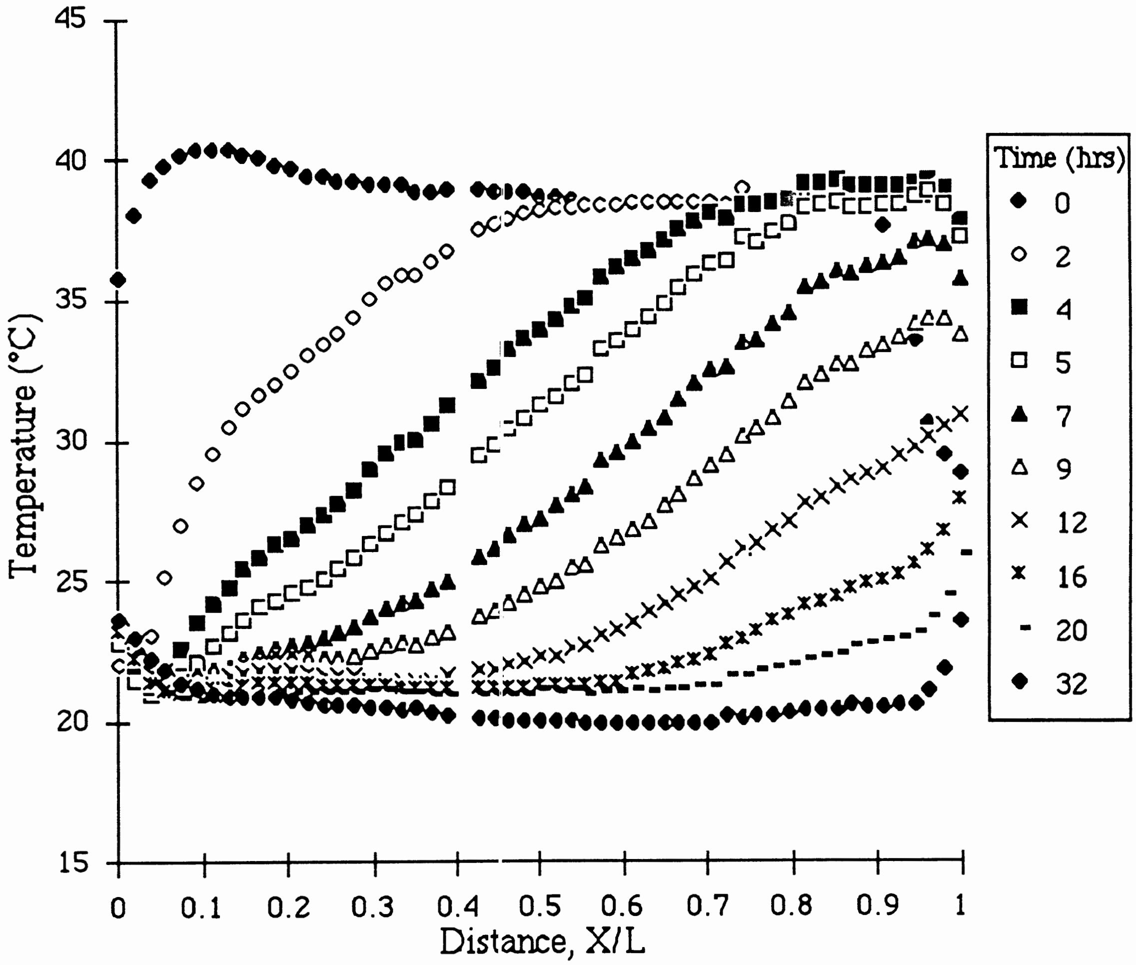

Figure 49. Temperature vs. location in grain mass at different instances of time for column #3 and an aeration rate of 8.04 L/s·m^3

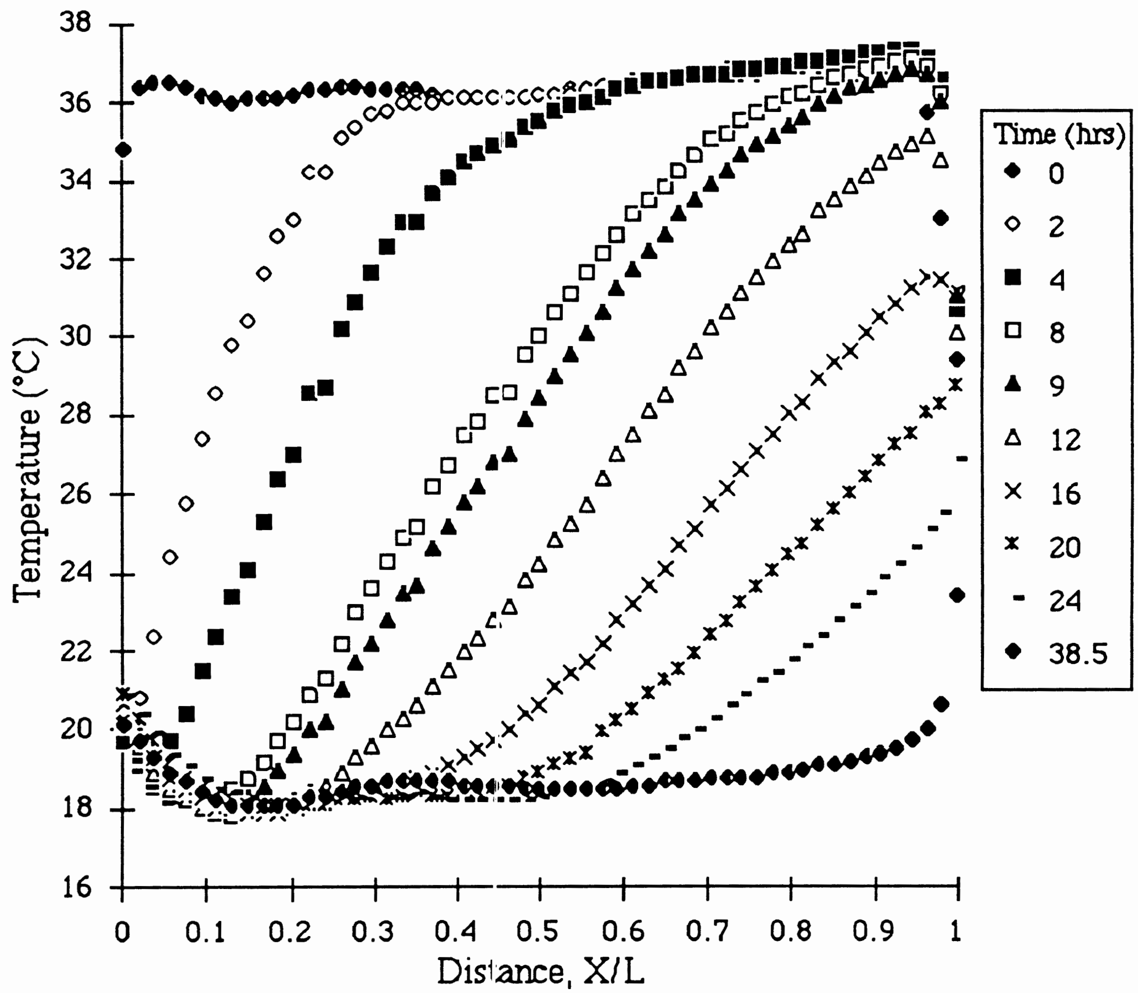

Figure 50. Temperature vs. location in grain mass at different instances of time for column #1 and an aeration rate of 5.36 L/s·m^3

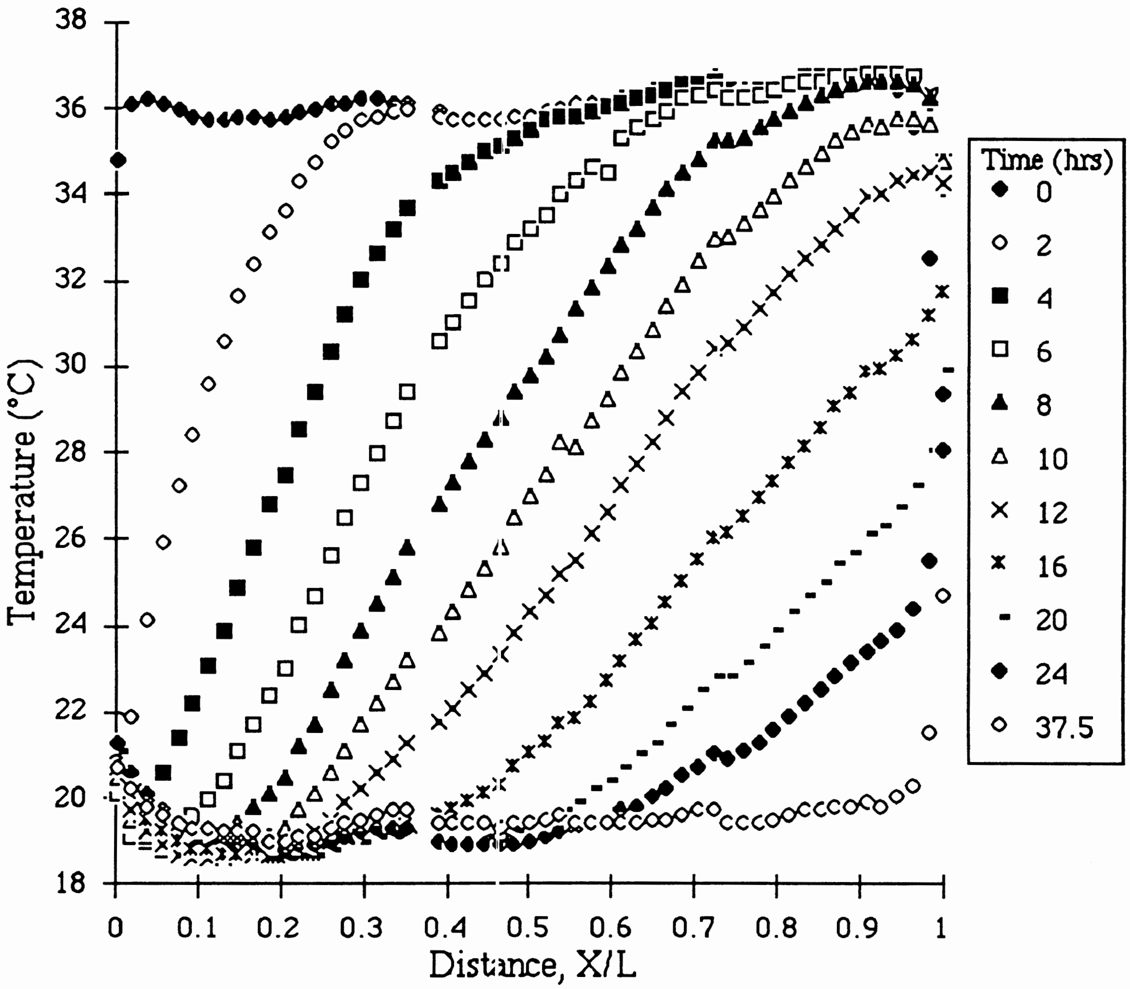

Figure 51. Temperature vs. location in grain mass at different instances of time for column #2 and an aeration rate of 5.36 L/s·m^3

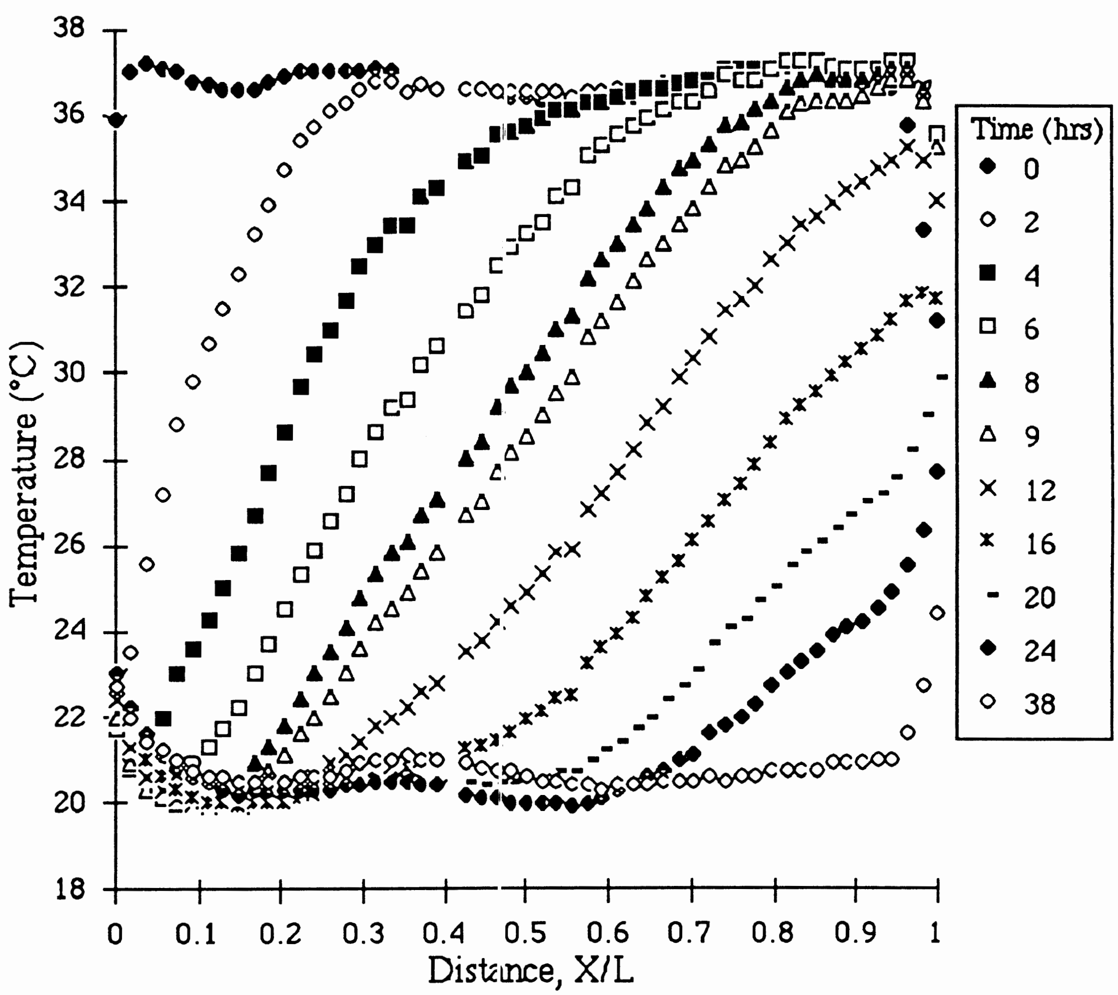

Figure 52. Temperature vs. location in grain mass at different instances of times for column #3 and an aeration rate of 5.36 L/s·m³

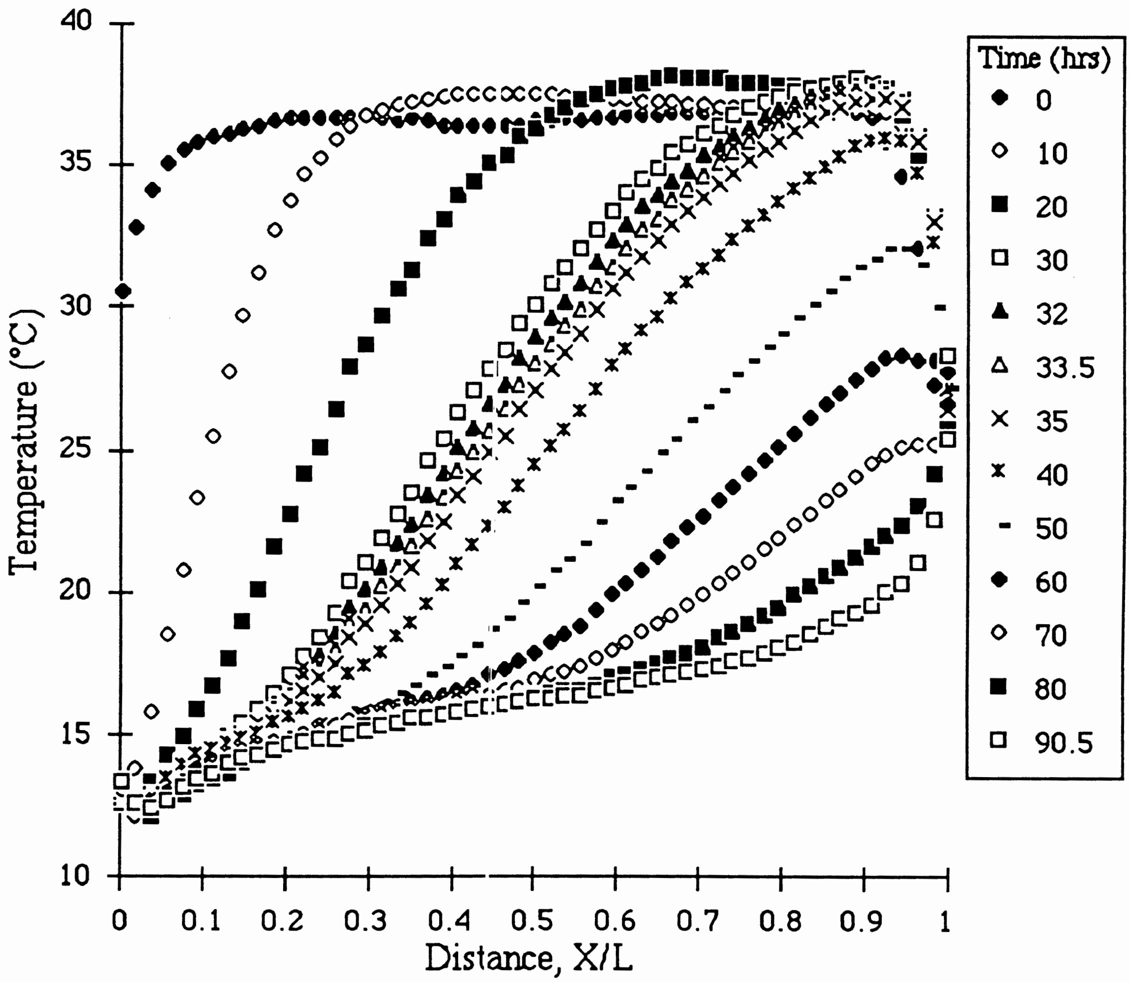

Figure 53. Temperature vs. location in grain mass at different instances of time for column #1 and an aeration rate of 2.68 L/s·m^3

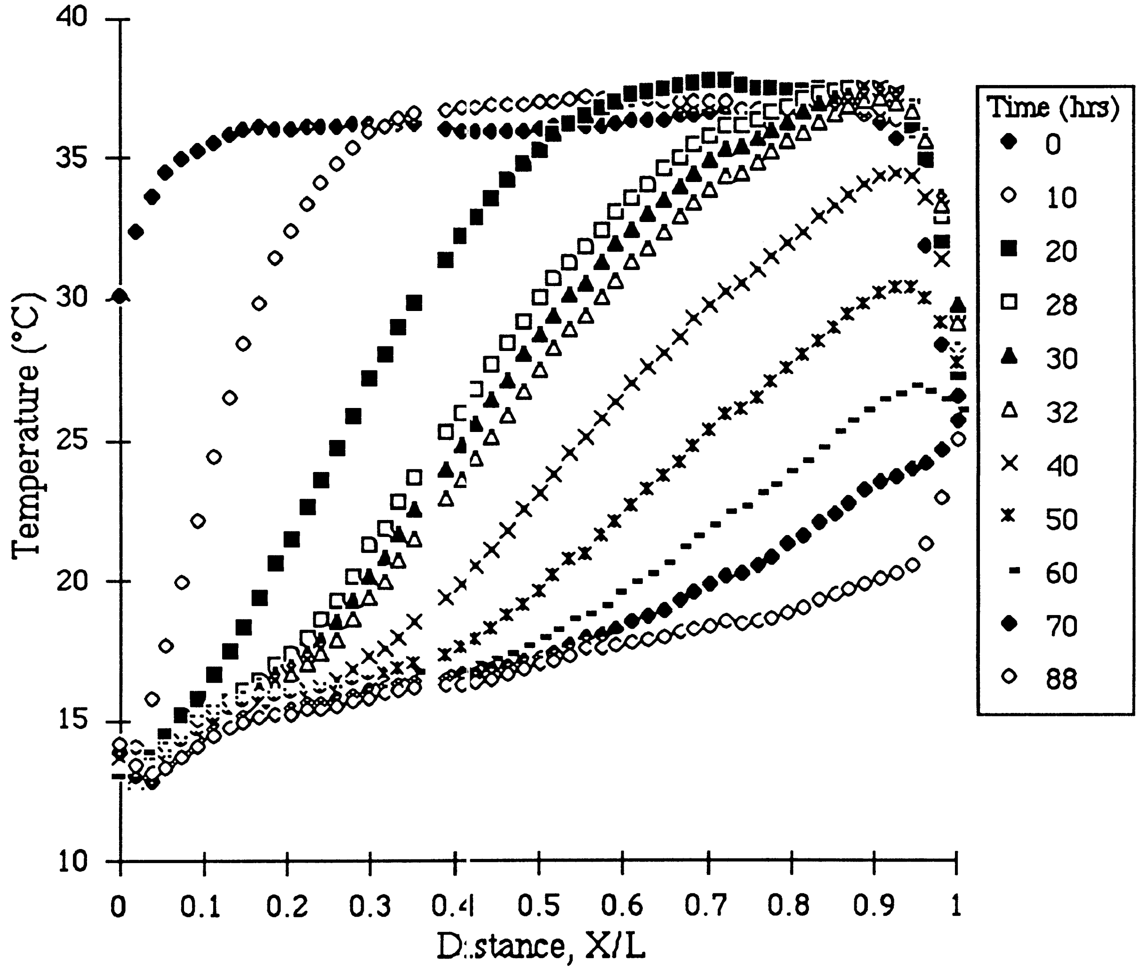

Figure 54. Temperature vs. location in grain mass at different instances of time for column #2 and an aeration rate of 2.68 L/s·m^3

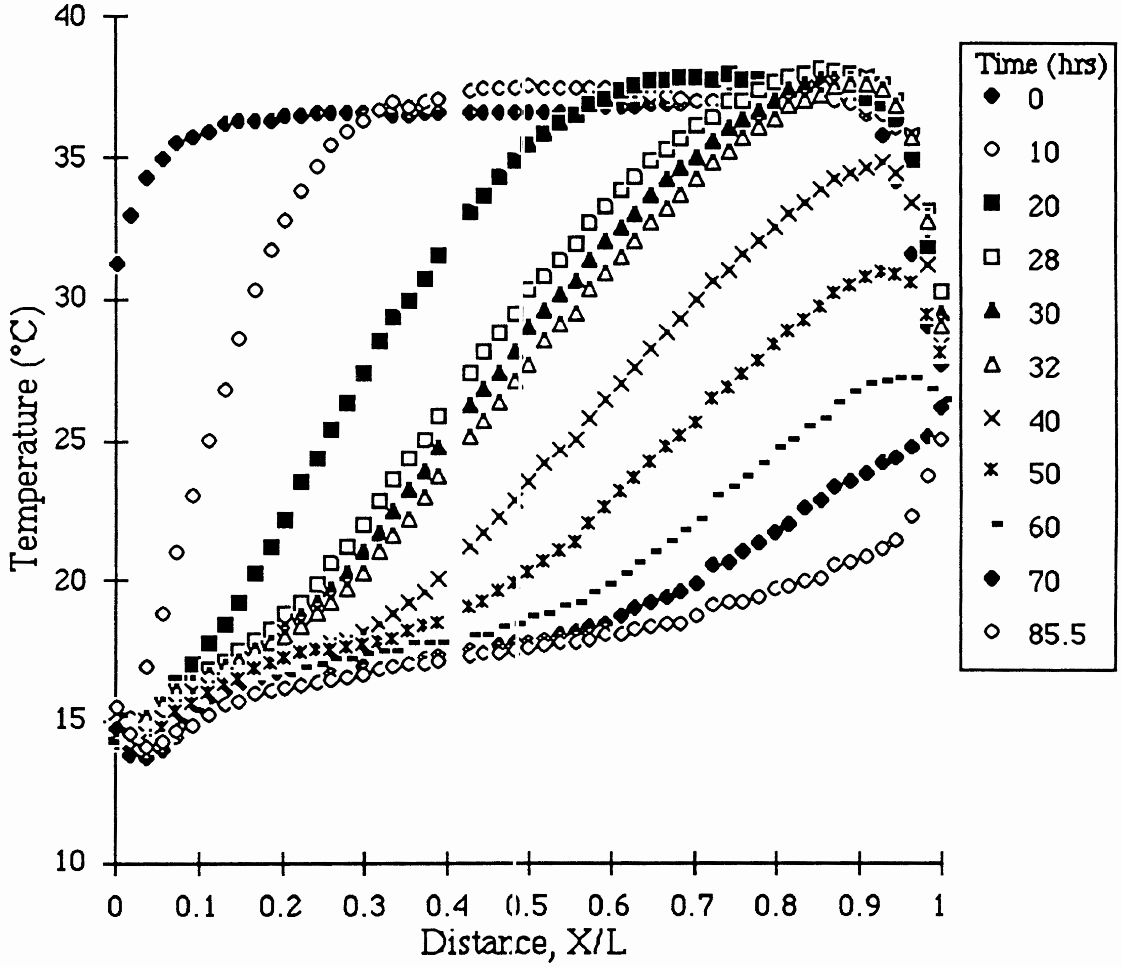

Figure 55. Temperature vs. location in grain mass at different instances of time for column #3 and an aeration rate of 2.68 L/s·m^3

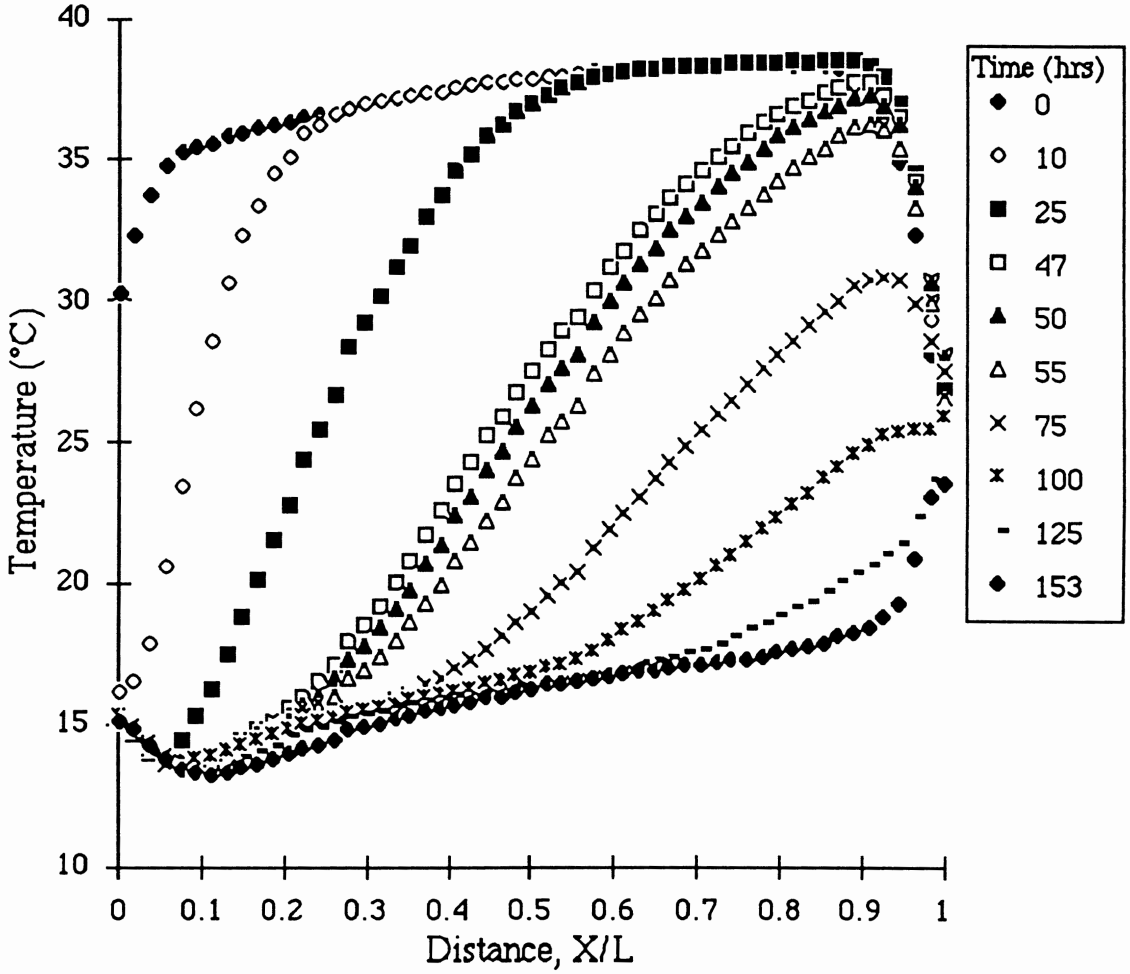

Figure 56. Temperature vs. location in grain mass at different instances of time for column #1 and an aeration rate of 1.34 L/s·m^3

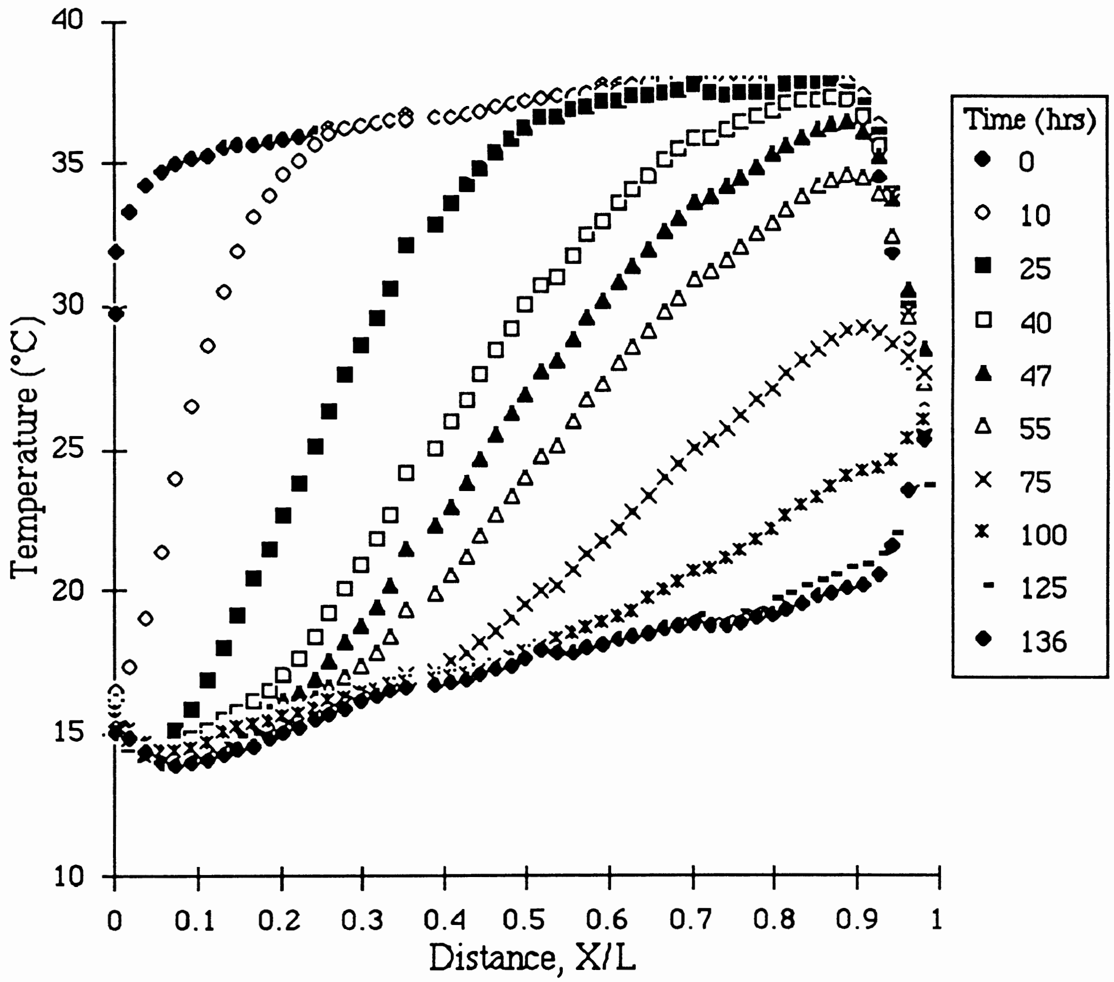

Figure 57. Temperature vs. location in grain mass at different instances of time for column #2 and an aeration rate of 1.34 L/s·m^3

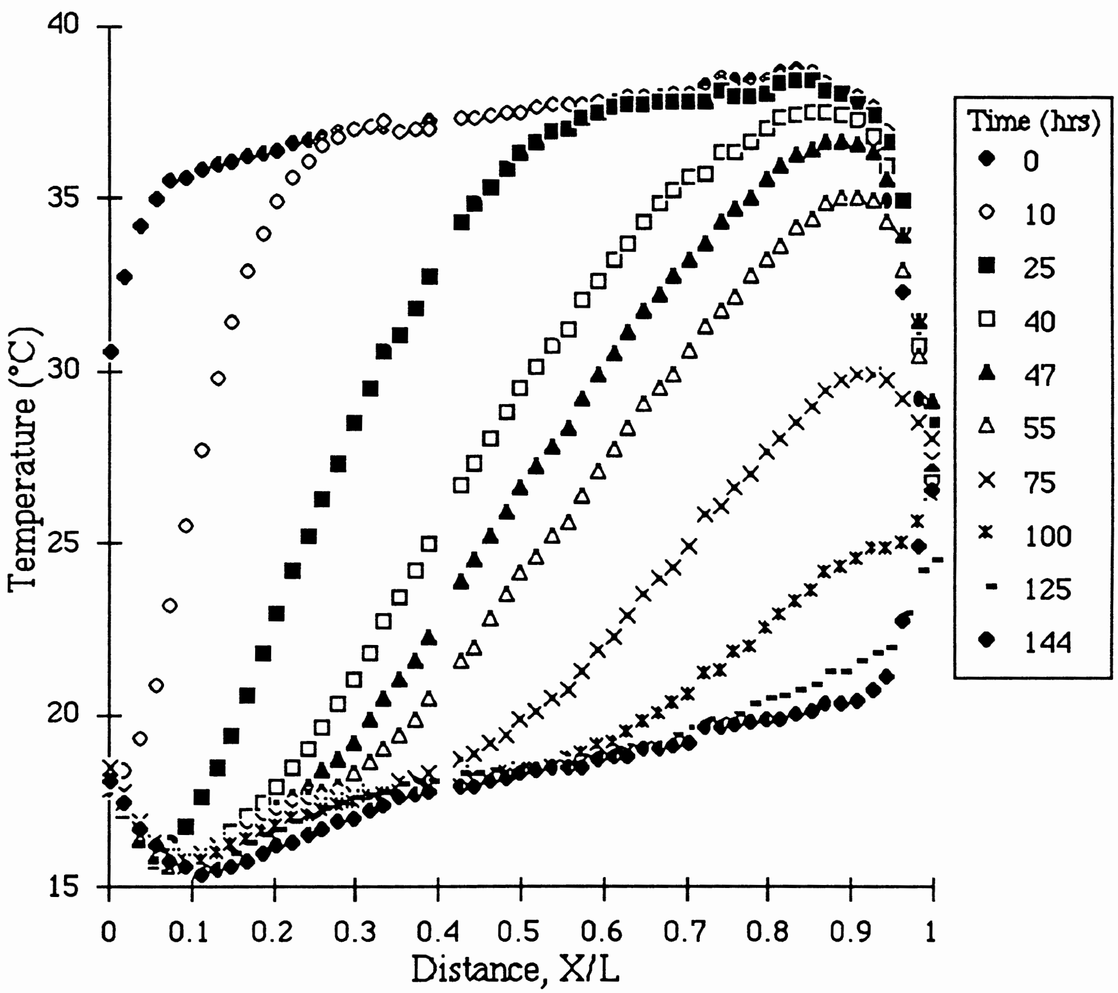

Figure 58. Temperature vs. location in grain mass at different instances of time for column #3 and an aeration rate of 1.34 L/s·m^3

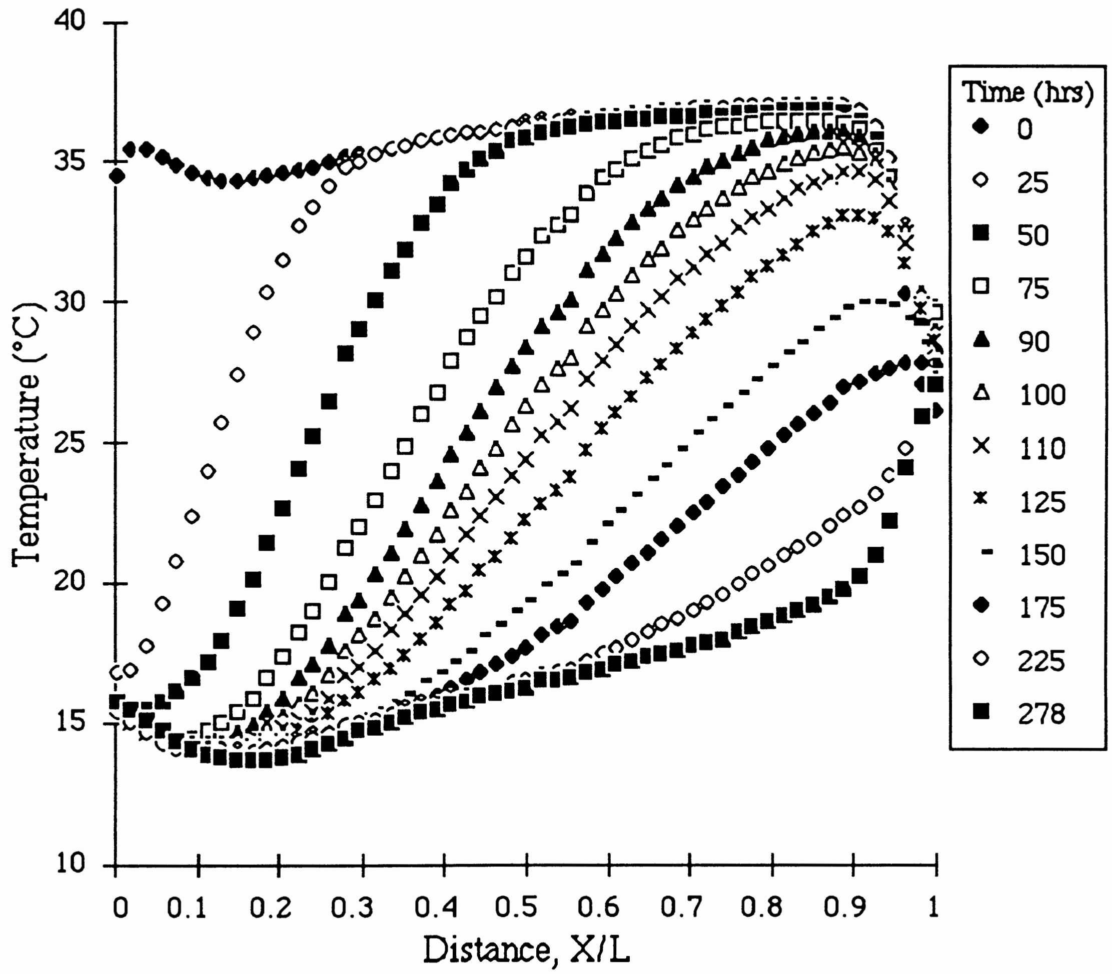

Figure 59. Temperature vs. location in grain mass at different instances of time for column #1 and an aeration rate of 0.67 L/s·m^3

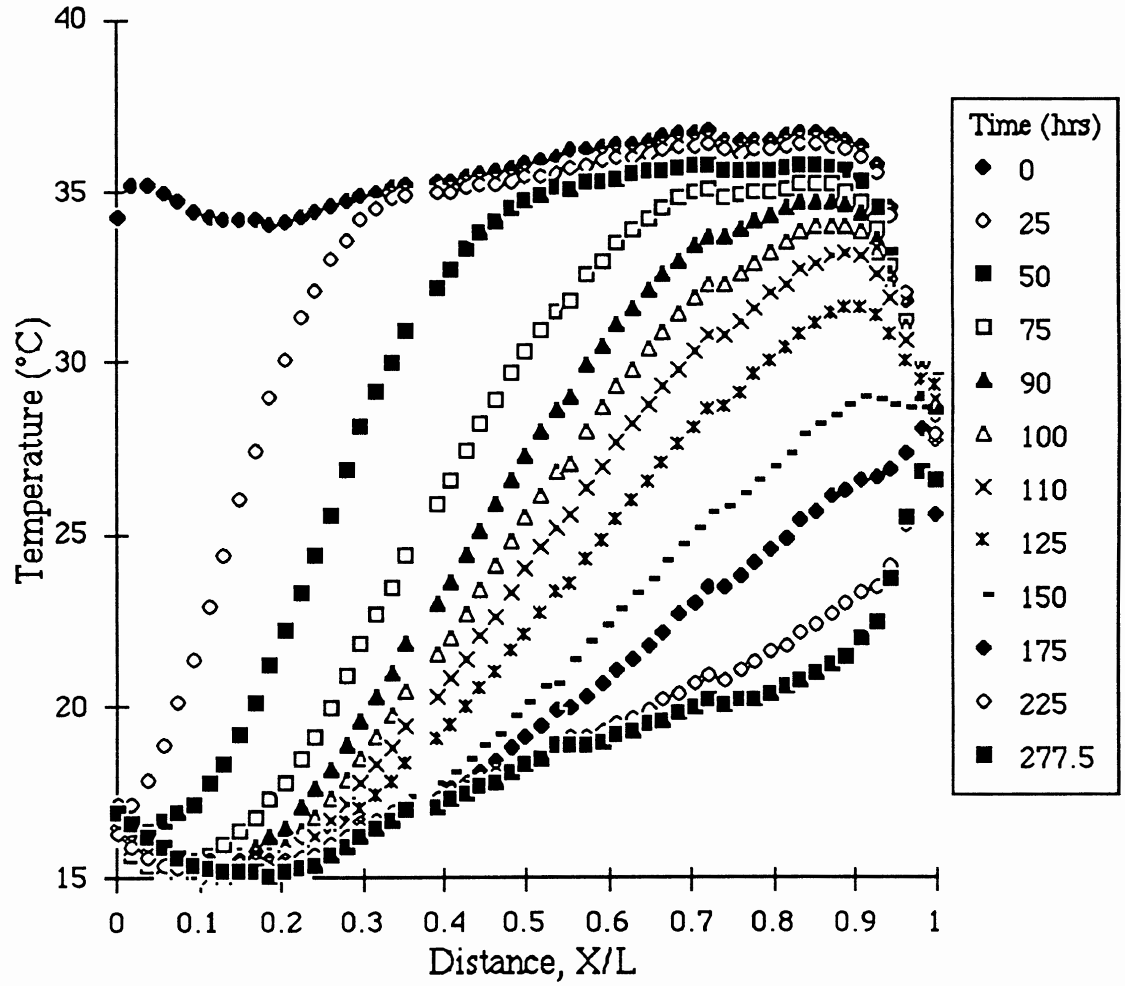

Figure 60. Temperature vs. location in grain mass at different instances of time for column #2 and an aeration rate of 0.67 L/s·m^3

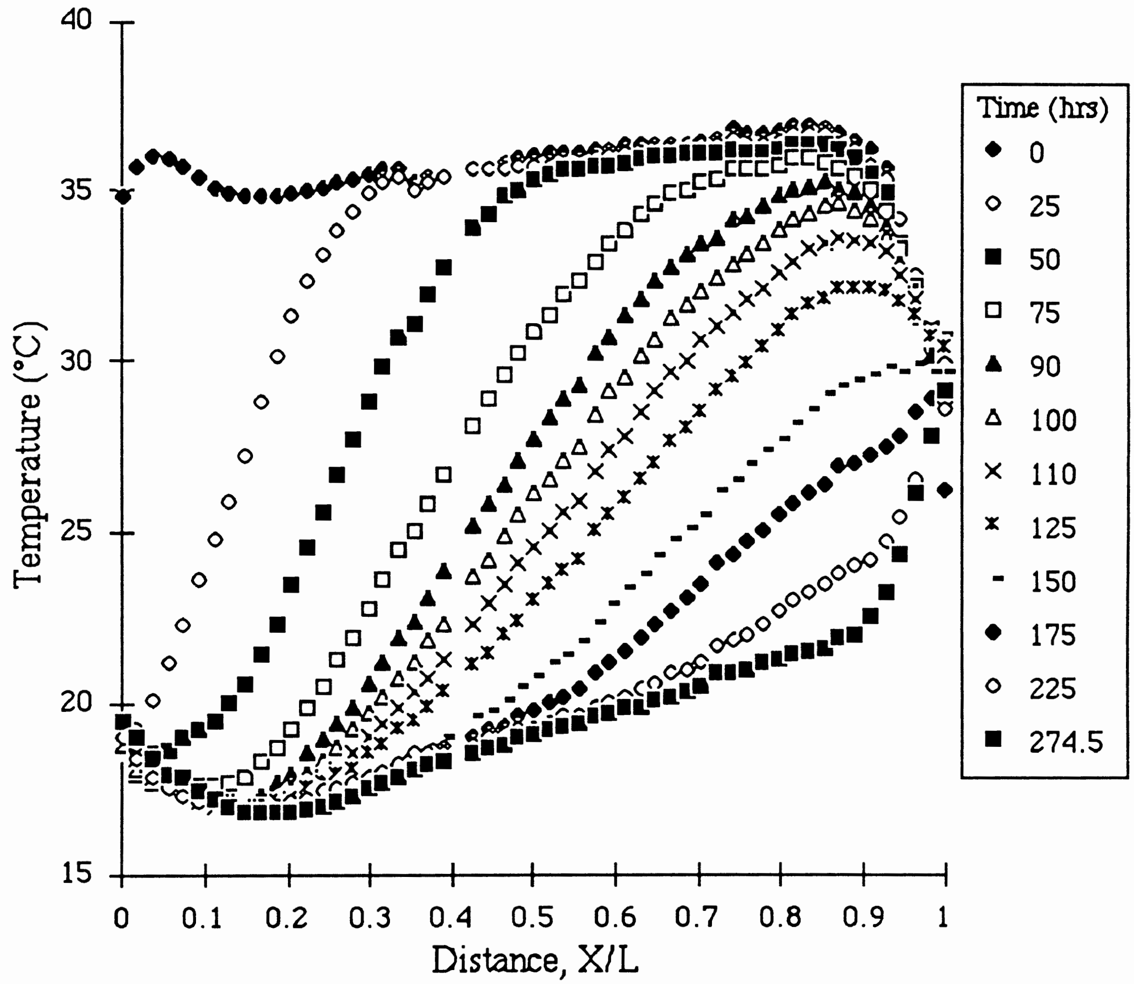

Figure 61. Temperature vs. location in grain mass at different instances of time for column #3 and an aeration rate of 0.67 L/s·m^3

is related to the temperature of the grain. Analogies were made to determine the relationships between the experimental data and equation 30. These analogies were developed using an iteractive approach. The variables of Φ and z were varied in equation 30 until experimental data corresponded to y values. The process was repeated for each aeration rate, Q_a. Correlations between y and Θ were determined using least squares regression analysis.

The conversion from time in aeration, Θ, to y had to be separated into two equations depending on whether the time, Θ, was after or before the leading edge exited the grain mass. Linear relationships were in the form:

$$y = B + M \cdot Q_a \tag{33}$$

and are given in Table V. The intercept, B, and slope, M, for each time period were plotted as a function of the aeration rate, Q_a (Figures 62 through 65). Statistical analyses were performed on the equation parameters to determine if the slopes were different than zero and are given in Appendix E30-33. Using an α of rejection of 0.05, the slope, M, parameter for the time period after the leading edge has exited the grain mass was the only parameter with enough evidence to reject the hypothesis that the slope was zero (Pr>F=0.012). The other parameters, the slope, M, and the intercept, B, for before and the intercept, B, for after the leading edge exits the grain mass, statistically did not have enough evidence to reject the hypothesis that the slopes were not zero (Pr>F=0.055, 0.078 and 0.25, respectively). Therefore, the aeration rate, Q_a, was a factor during the time after the leading edge of the cooling front exited the grain mass only. Mathematical models were developed using the raw data to relate y to Θ_c, the time

TABLE V

VALUES OF EQUATION 33 PARAMETERS FOR CONVERSION OF THE TIME VARIABLE, Θ, TO Y

Aeration Rate ($L/s \cdot m^3$)	Time Period	Intercept B	Slope M
10.72	$\Theta < \Theta_L$	-1.17	4.28
8.04		-1.22	5.02
5.36		-1.19	5.13
2.68		-1.16	4.90
1.34		-0.95	5.14
0.67		-0.94	5.57
10.72	$\Theta > \Theta_L$	3.76	17.02
8.04		4.39	19.15
5.36		4.58	11.69
2.68		3.91	8.73
1.34		4.36	10.11
0.67		4.95	7.04

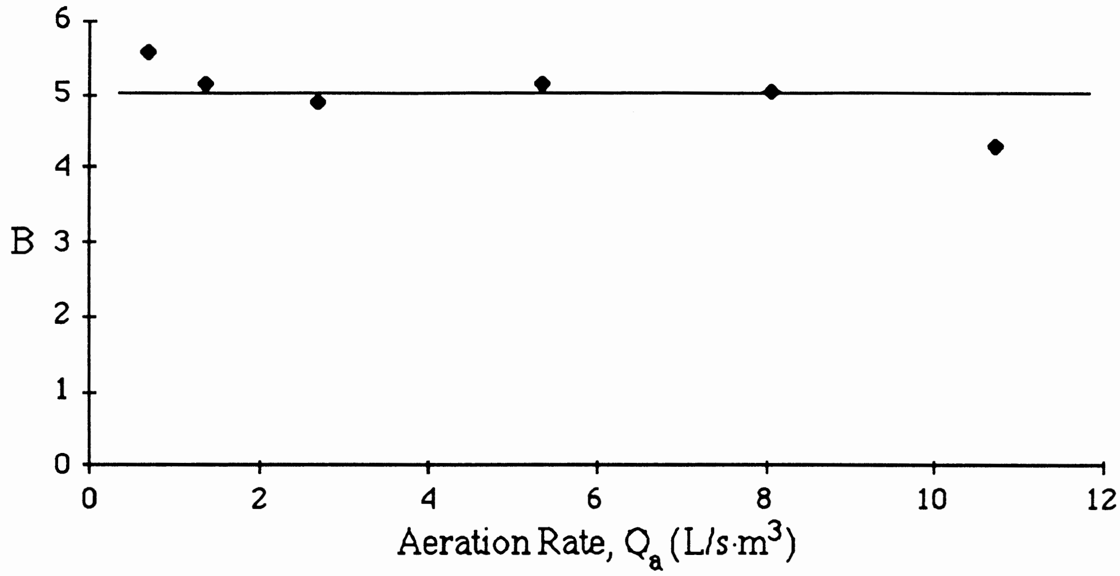

Figure 62. Plot of the B coefficient vs. aeration rate, Q_a, for the form of equation 33 for before the leading edge of the cooling front exits the grain mass

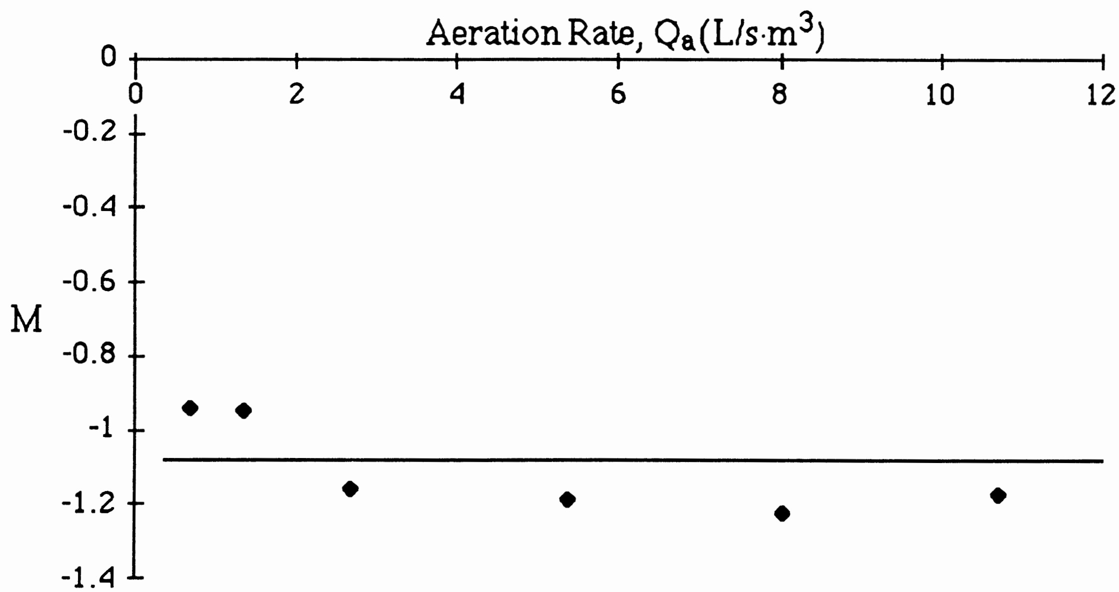

Figure 63. Plot of the M coefficient vs. aeration rate, Q_a, for the form of equation 33 for before the leading edge of the cooling front exits the grain mass

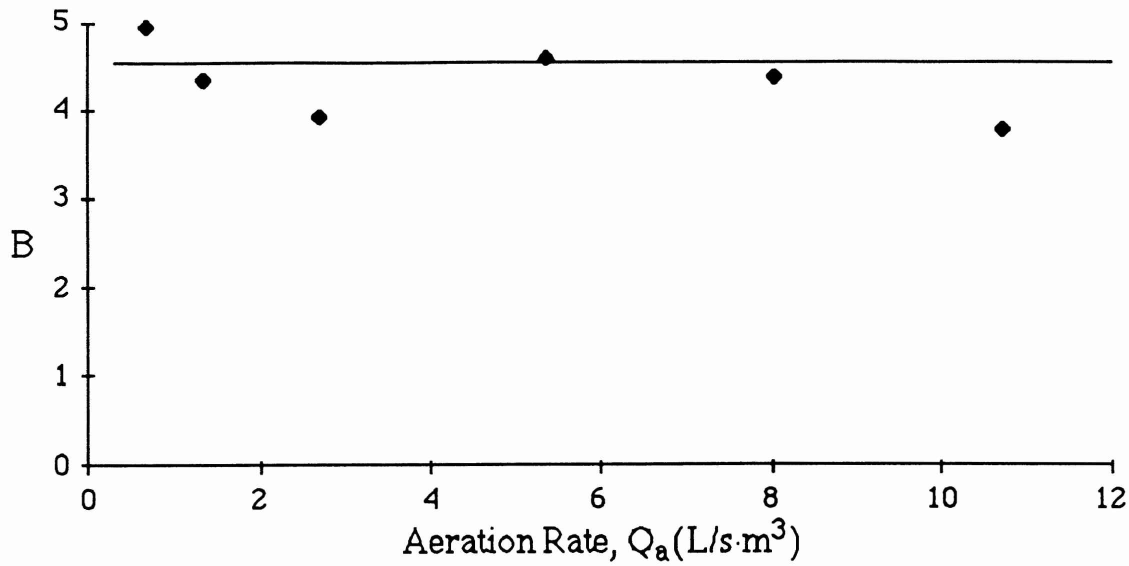

Figure 64. Plot of the B coefficient vs. aeration rate, Q_a, for the form of equation 31 for after the leading edge of the cooling front exits the grain mass

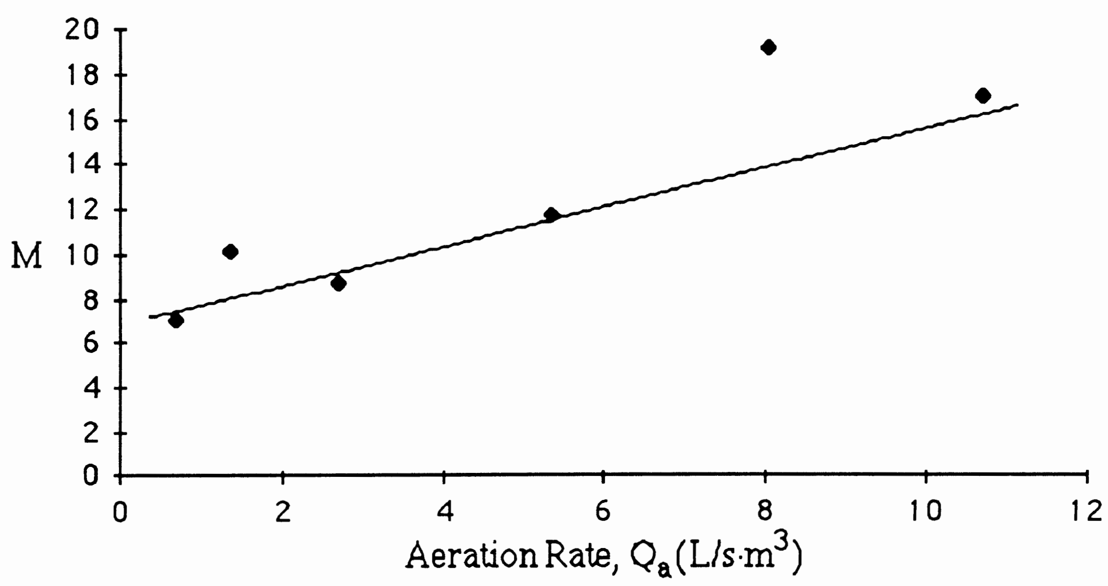

Figure 65. Plot of the M coefficient vs. aeration rate, Q_a, for the form of equation 31 for after the leading edge of the cooling front exits the grain mass

correction factor, and the AOV's are given in Appendix E34-36. The regression equations were:

$$y = 5.03 \cdot \Theta_c - 1.07 \qquad \text{for } \Theta<\Theta_L \ (R^2=0.92) \tag{34}$$

and

$$y = (6.89 + 0.74 \cdot Q_a) \cdot \Theta_c + 4.59 \qquad \text{for } \Theta>\Theta_L \ (R^2=0.96) \tag{35}$$

where the time correction, Θ_c, was:

$$\Theta_c = \frac{\Theta}{\Theta_L} \qquad \text{for } \Theta < \Theta_L \tag{36}$$

and

$$\Theta_c = \frac{\Theta - \Theta_L}{\Theta_T - \Theta_L} \qquad \text{for } \Theta > \Theta_L \tag{35}$$

The variable z was related to the position in the grain mass, X/L, in that z is equal to $10 \cdot (X/L)$. The variable Φ is related to the temperature of the grain where:

$$\Phi = \frac{T - T_{dbc}}{\Delta T} \tag{38}$$

The model using these equations was applied to the temperature distributions measured in the tests. Figures 66 through 71 show the measured and predicted temperature gradients for the aeration rates used in this study. Temperature predictions are generally within 10% of the measured grain temperatures.

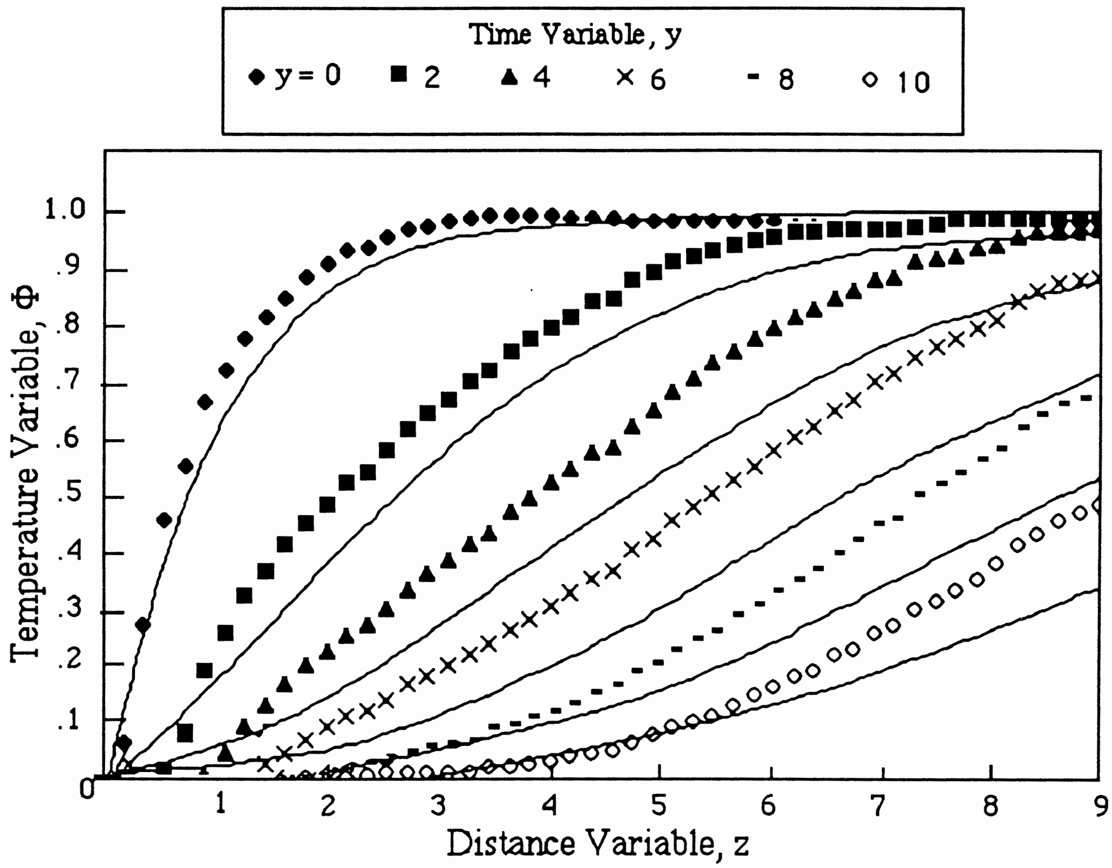

Figure 66. Measured and calculated temperature gradients for an aeration rate of 10.72 L/s·m^3

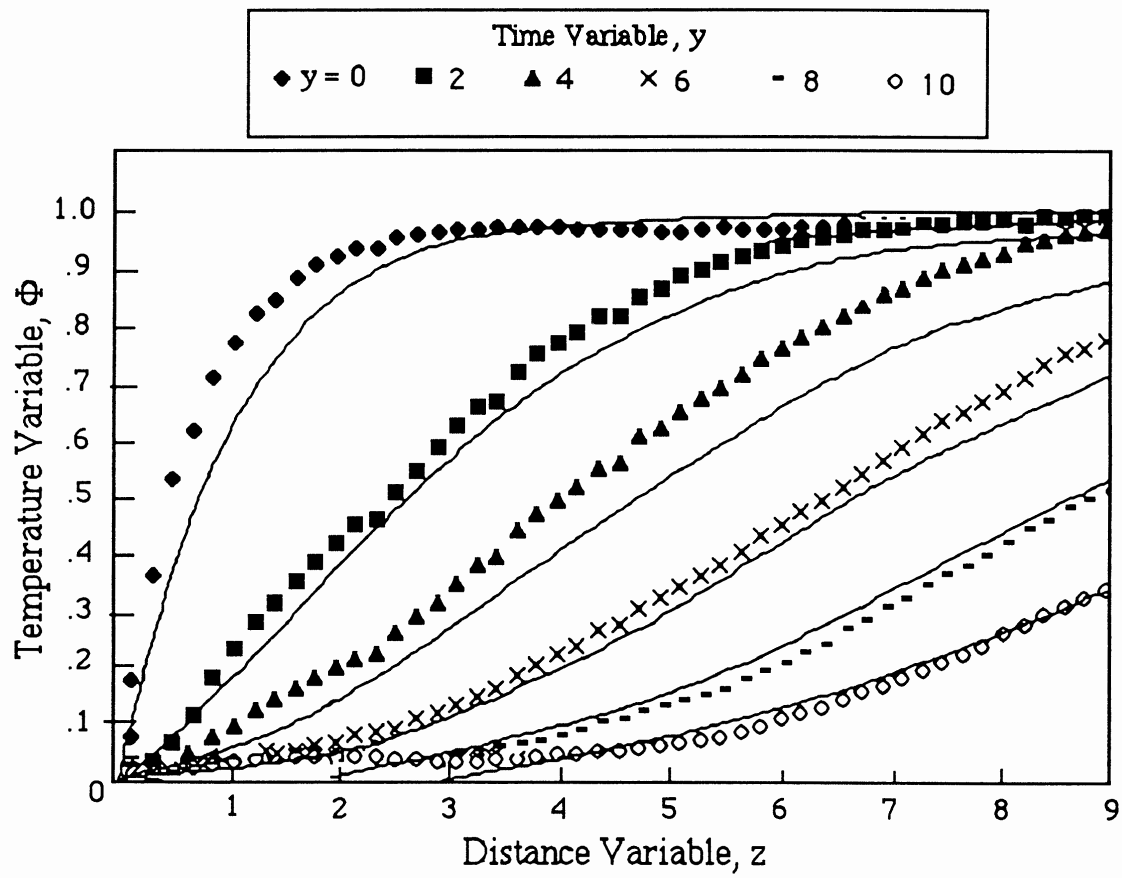

Figure 67. Measured and calculated temperature gradients for an aeration rate of 8.04 L/s·m^3

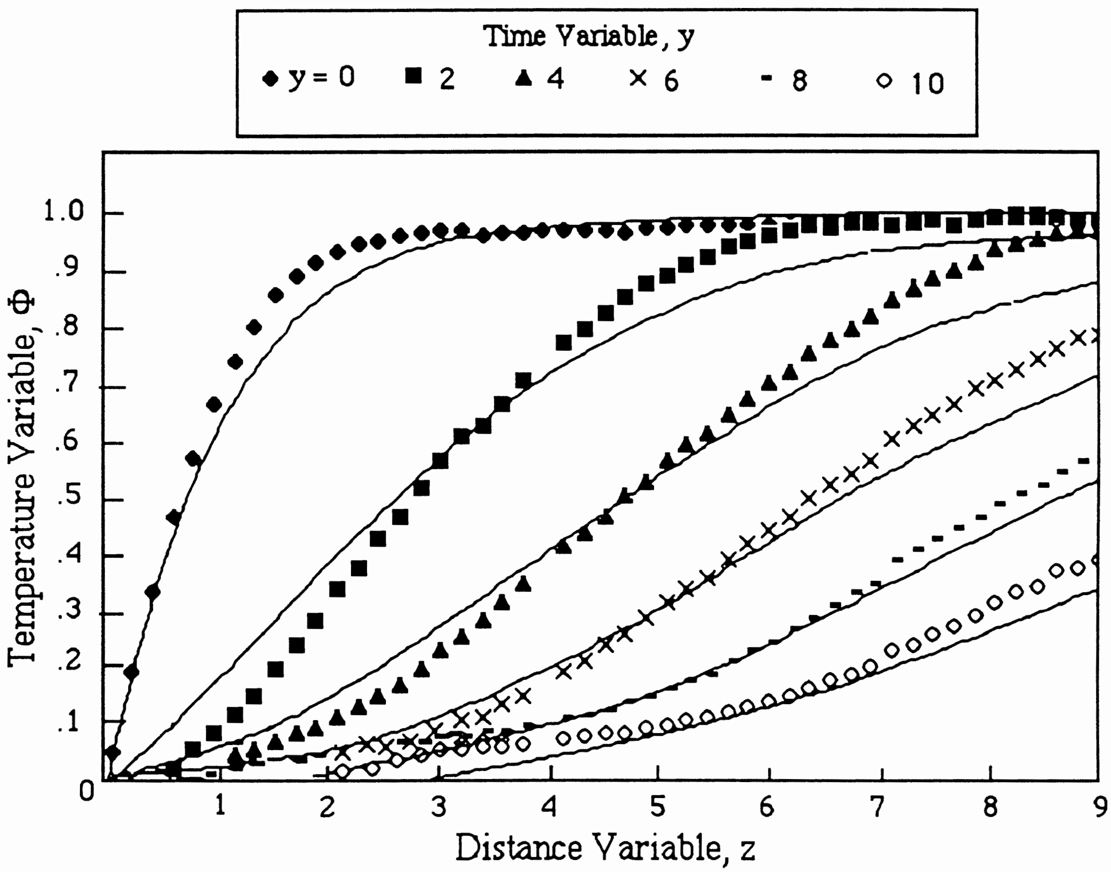

Figure 69. Measured and calculated temperature gradients for an aeration rate of 2.68 L/s·m^3

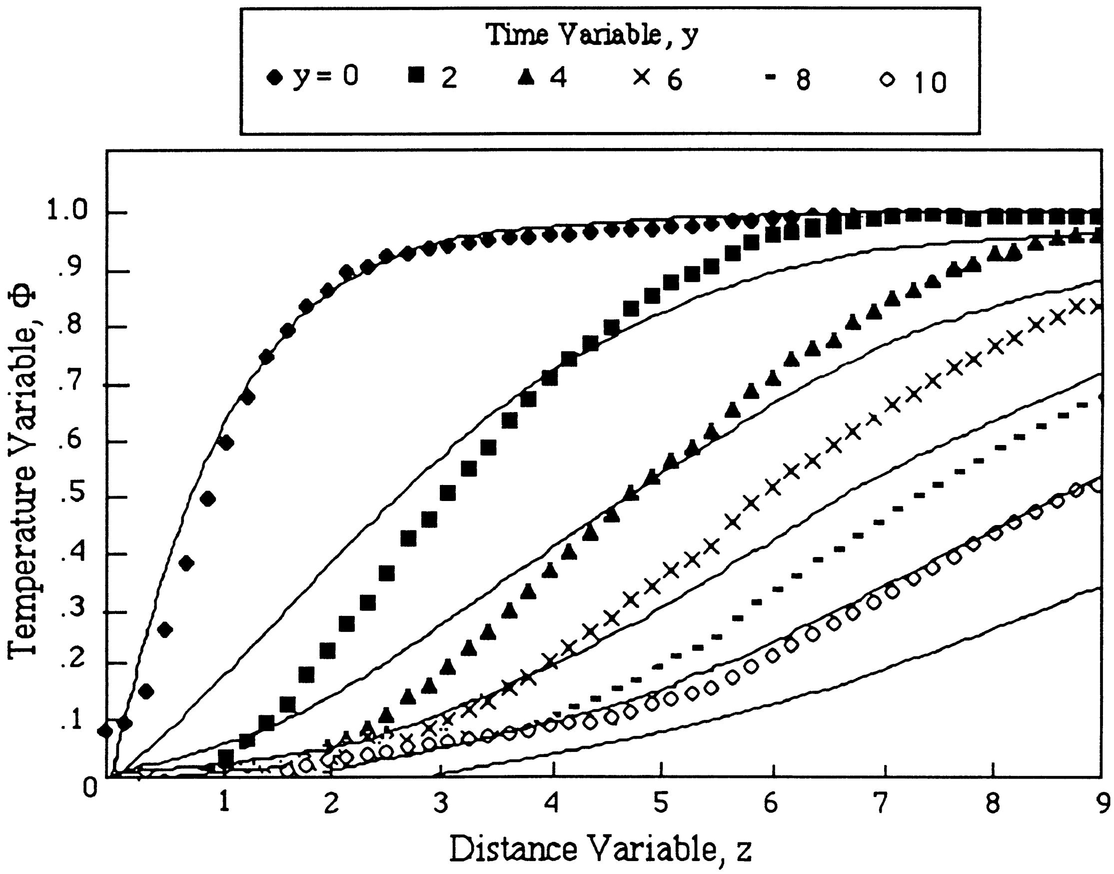

Figure 70. Measured and calculated temperature gradients for an aeration rate of 1.34 L/s·m^3

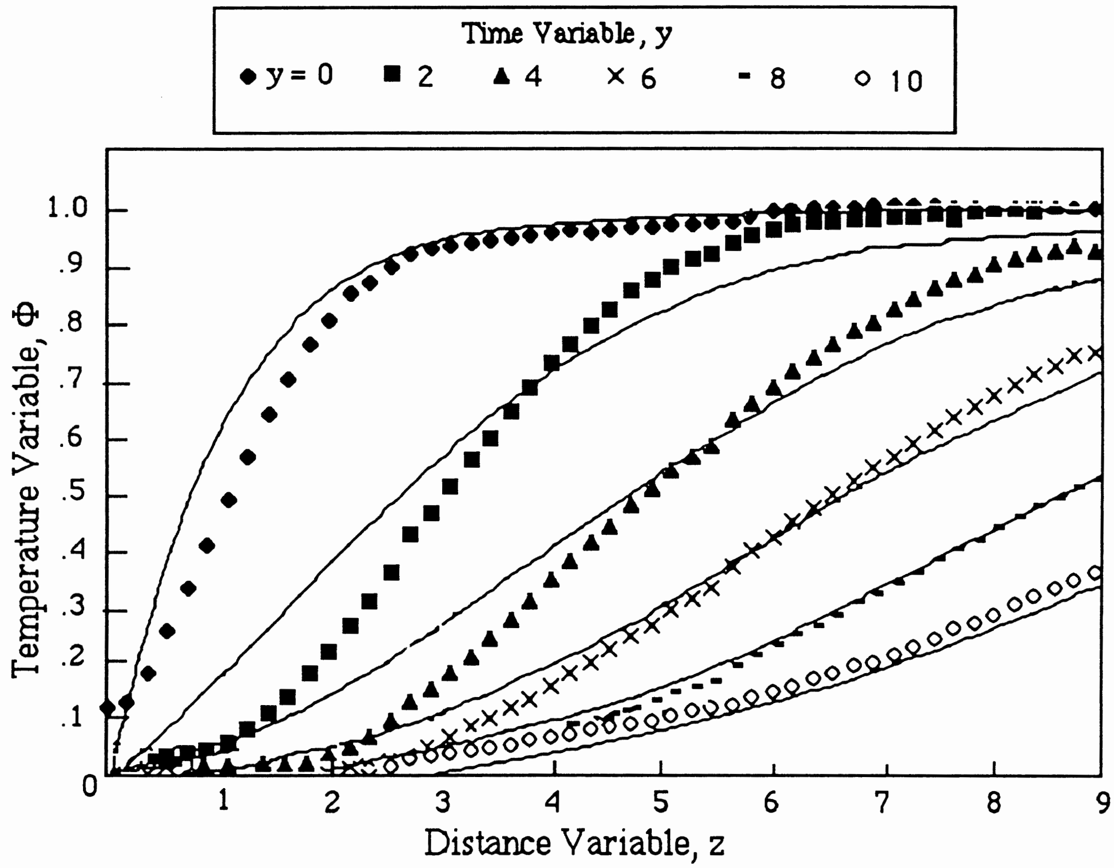

Figure 71. Measured and calculated temperature gradients for an aeration rate of 0.67 $L/s{\cdot}m^3$

Grain Rewarming Results

After each aeration test, the grain mass was rewarmed before beginning the next test. The dataloggers and computer were used to record grain temperatures during the rewarming process. The temperature profile versus time graphs for column #1 for the rewarming runs are given in Figures 72 through 75 (only a partial set of data was taken for run #4, so no graph is given for that run). Also included in the graphs are the dry and wet-bulb temperatures of the air in the environmental chamber, T_{dbc} and T_{wbc}. The aeration rates were not accurately recorded during the rewarming because the rotometer valves were completely opened to obtain the highest airflow possible and the aeration rate did not stay constant. The aeration rate for rewarming run #2 was known to be about 10.6 $L/s{\cdot}m^3$ (0.79 cfm/bu), however.

As compared to the cooling data in Figures 17 through 34, the temperature gradient are greater for rewarming. The reason for this is when air is cooled, it contracts causing the air velocity to decrease, which occurs in the leading edge of the warming front making it move slower. Also, rewetting occured during rewarming causing a latent heat exchange that adds heat to the process.

The final temperature of the grain was always slightly less than the dry-bulb temperature of the air, T_{dbc}, with the grain temperatures being slightly less the farther from the bottom of the grain mass.

During rewarming, the grain mass would always increase in moisture content. Table VI gives the average moisture content increases for each column and rewarming run. The overall average moisture content percent gain was 0.79% (w.b.) with a 95% confidence interval of $0.79 \pm 0.54\%$.

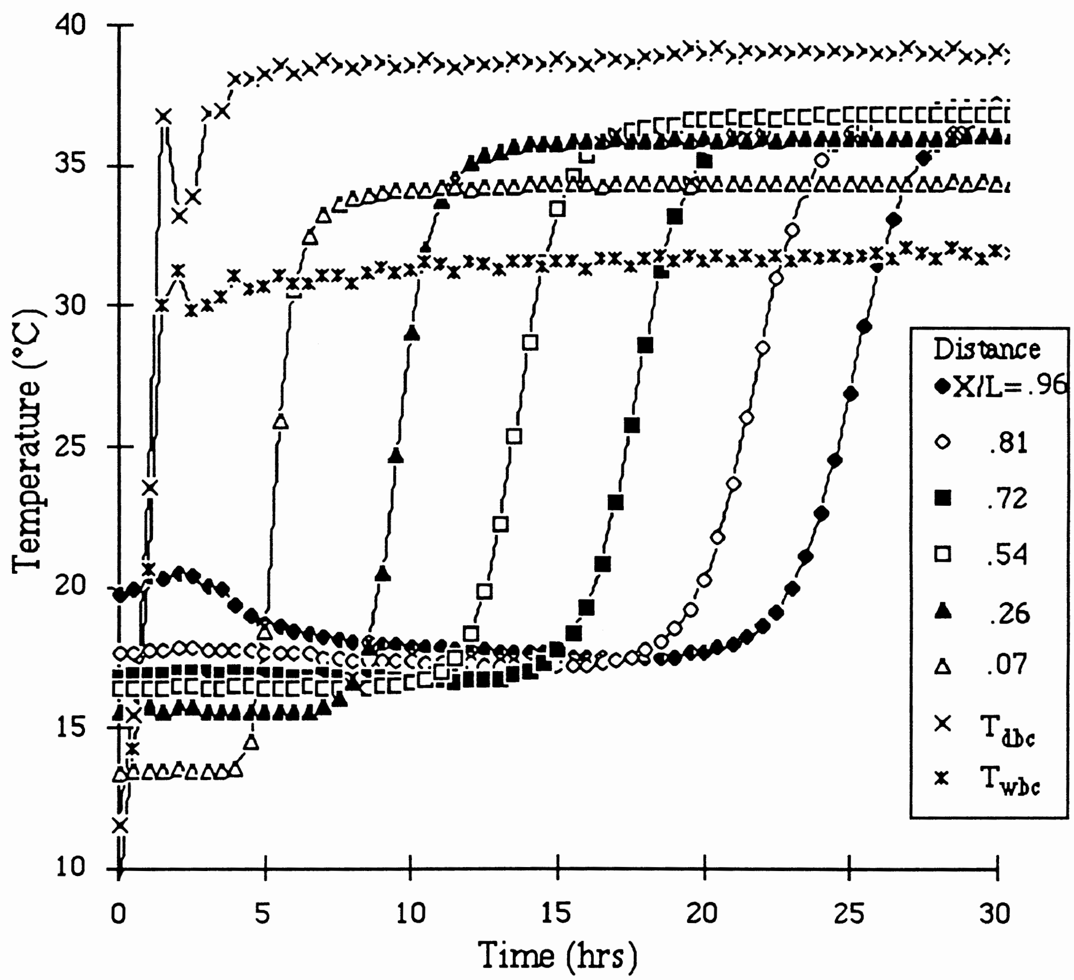

Figure 72. Temperature profile vs. time with entering air conditions for column #1 and run #1 during rewarming

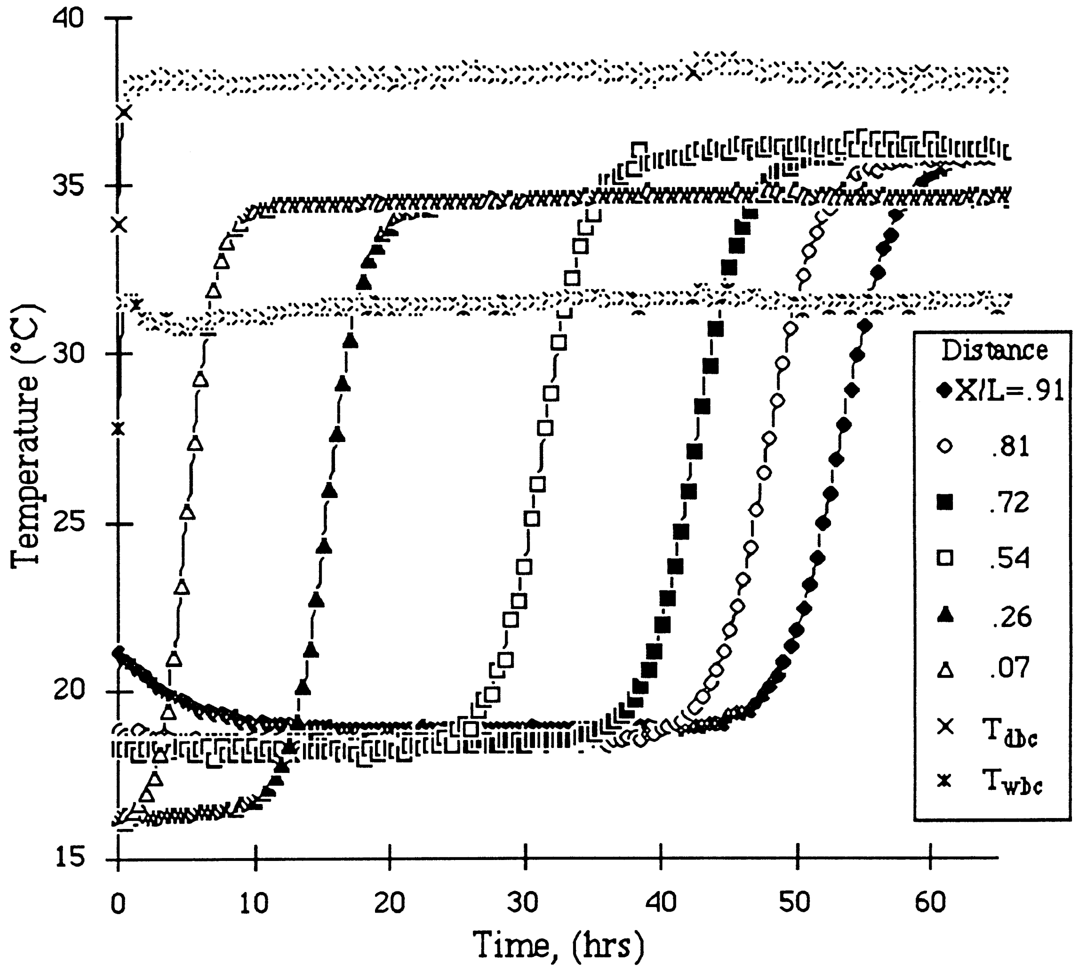

Figure 73. Temperature profile vs. time with entering air conditions for column #1 and run #2 during rewarming

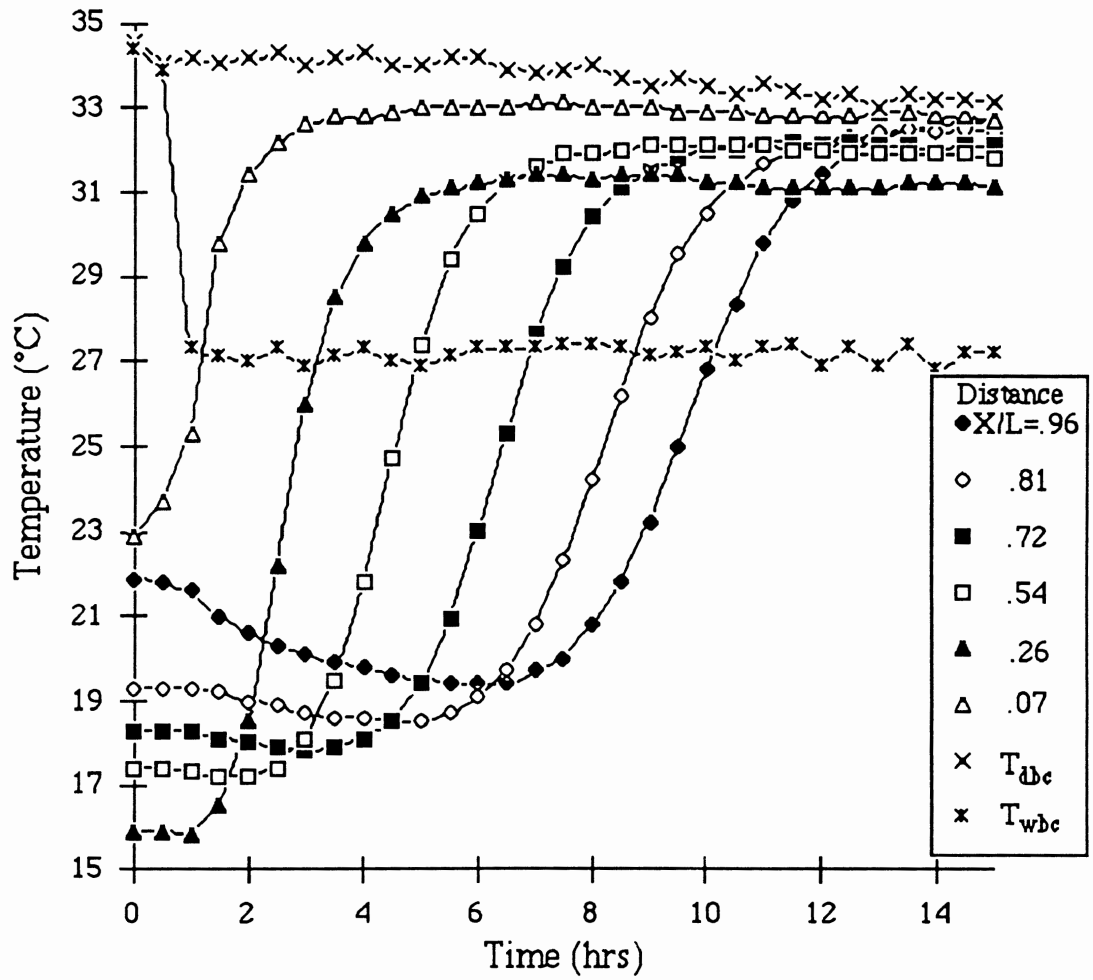

Figure 74. Temperature profile vs. time with entering air conditions for column #1 and run #3 during rewarming

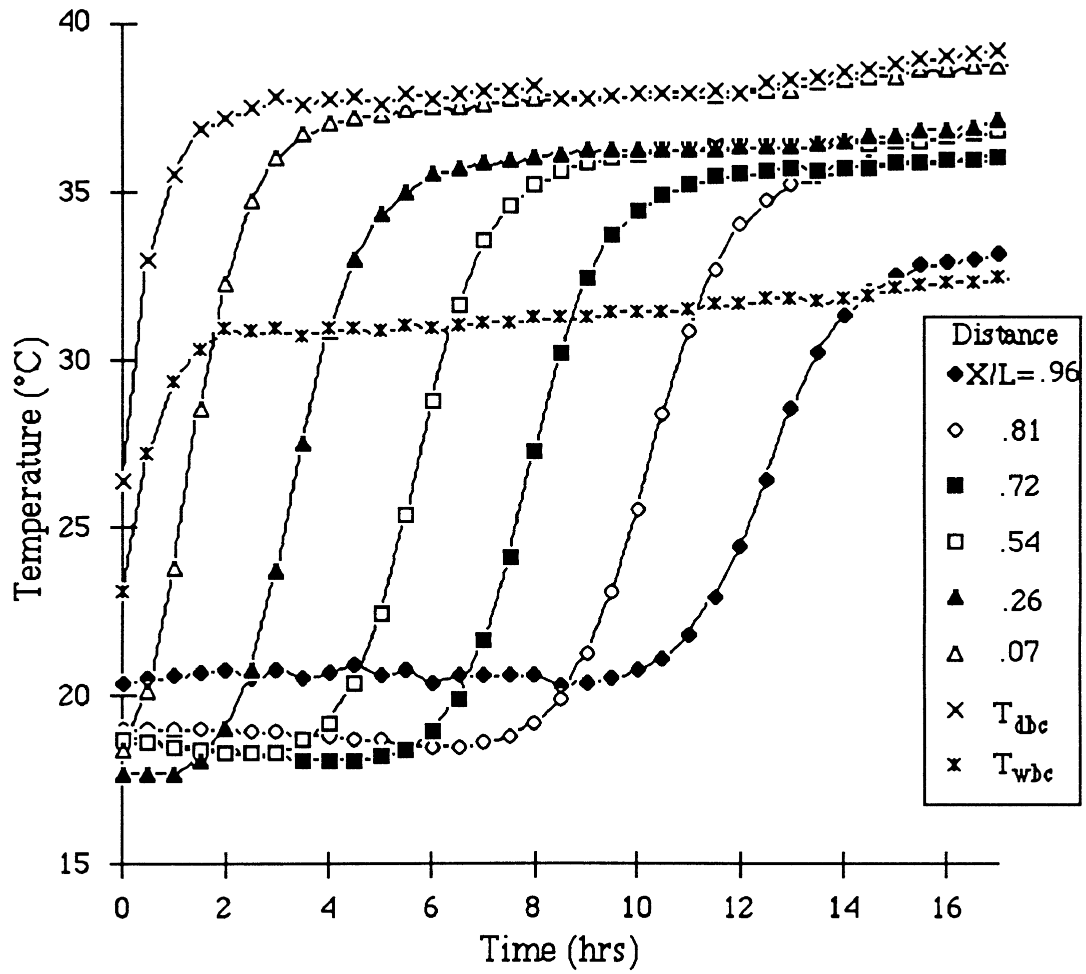

Figure 75. Temperature profile vs. time with entering air conditions for column #1 and run #5 during rewarming

TABLE VI

AVERAGE GAIN IN MOISTURE CONTENT PERCENT FROM REWARMING THE GRAIN MASS

	Column No.			Run
Run No.	1	2	3	Average
1	1.21	1.07	1.07	1.12
2	0.66	0.70	1.11	0.82
3	0.75	0.82	0.59	0.72
4	0.66	0.45	0.26	0.46
5	0.63	1.09	0.80	0.84
			Overall Average = 0.79	

General Observations

Temperature Gradients

The shape of the temperature gradients throughout the grain mass are different before and after the leading edge of the cooling front exits the grain mass. From the start of aeration until the leading edge exits the grain mass, the temperature gradients are concave down as shown in Figures 44 through 61. At the time that the leading edge exits the grain mass the temperature gradient is nearly a diagonal line between the initial grain temperature to the lowest grain temperature, from the bottom to the top of the grain mass. After the leading edge exits until the trailing edge exits, the temperature gradients are slightly concave up. The slopes decrease as time increases with a horizontal temperature profile occurring when the trailing edge exits the grain mass.

Temperature Drops and Rises

There was also a temperature dip near the bottom of the grain mass (Figures 43 through 60). A 2° to 4°C temperature drop occurred in each test about 13 to 36 cm (5 to 14 in) from the bottom of the grain mass in each test, and moved higher in the grain mass with time. The drop in temperature at the bottom of grain bins has been observed by other researchers (Sanderson *et al.*, 1988a and Burgess and Burrell, 1964) and is attributed to evaporative cooling which occurs with the movement of the moisture front.

There was also a slight temperature hump near the bottom of grain mass in some aeration tests before aeration was started as shown in Figures 44 through 61. The temperature rise was generally 2° to 3°C in magnitude and occurred about 13 to 55 cm (5 to 22 in) from the bottom of the grain mass. From observing the order in which the tests were performed, the first two tests had little to no temperature rise while the rise was more prominent the later in the order the test was performed. The temperature rise could be attributed to the moisture content change, or heat of adsorption, which was more pronounced in the lower section of the grain mass.

Final Grain Temperatures

The final grain temperatures compared to the inlet air dry-bulb, T_{dbc}, and wet bulb, T_{wbc}, temperatures for column #2 are given in Figures 76 through 81. The final grain temperature, T_{final}, usually followed the dry-bulb temperature, T_{dbc}, of the aeration air. The final grain temperature was slightly less than the inlet air dry-bulb temperature for the higher aeration rates and greater than the inlet air dry-bulb temperature for the lower aeration rates. Table VII shows the difference between the final grain temperatures and the inlet air dry-bulb temperatures at three different locations in the grain mass for each aeration rate. As the aeration rate decreased, the temperature difference and slope of the final temperature gradient increased. The temperature difference between final grain and inlet air dry-bulb temperatures varied from a few degrees less than inlet air dry-bulb temperature for the highest aeration rate to about 10°C greater than inlet air dry-bulb temperature for the lowest aeration rate. There was almost a flat temperature gradient at an aeration rate of 10.72 L/s·m^3 and a gradient of about 6°C at an aeration rate of 0.67 L/s·m^3.

This phenomenon agrees with theory developed for deep-bed grain drying (Brooker, *et al.*, 1974). It implies that the temperature gradient throughout the grain mas is inversly proportional to the mass flow rate of the aeration air.

A result of this observation would be that when aerating grain, using higher aeration rates will result in lower and more uniform final grain temperatures than aerating with low aeration rates with the same ambient temperatures.

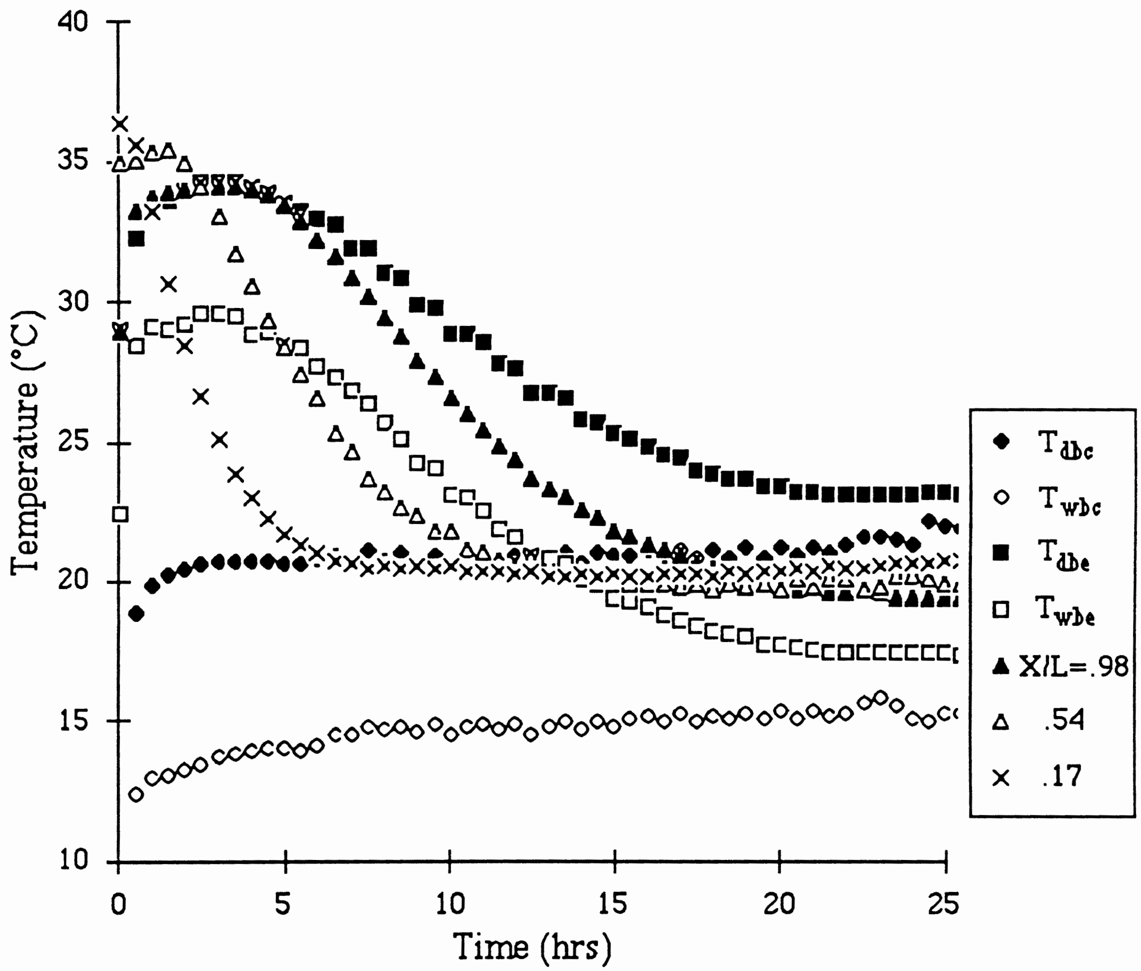

Figure 76. Final grain temperatures compared to the entering air conditions for column #2 and an aeration rate of 10.72 $L/s{\cdot}m^3$

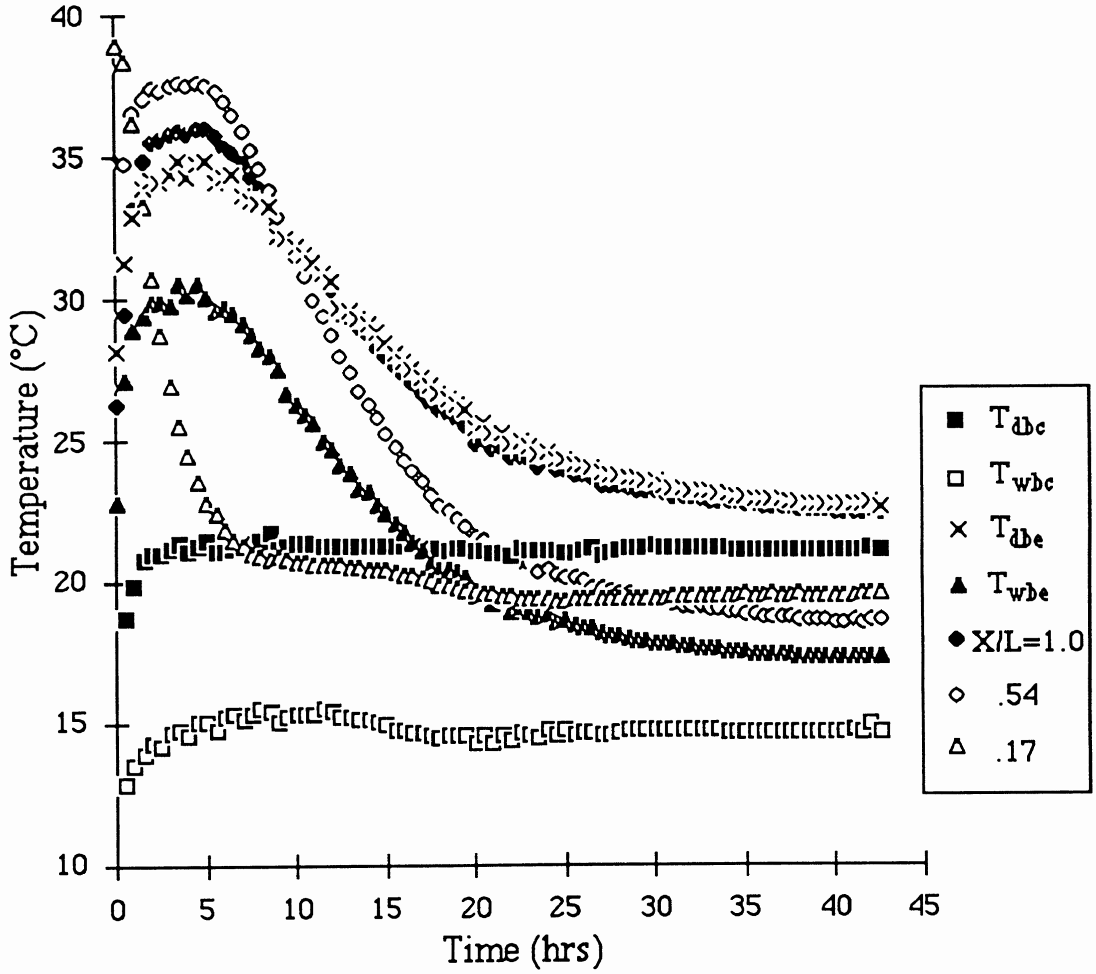

Figure 77. Final grain temperatures compared to the entering air conditions for column #2 and an aeration rate of 8.04 L/s·m^3

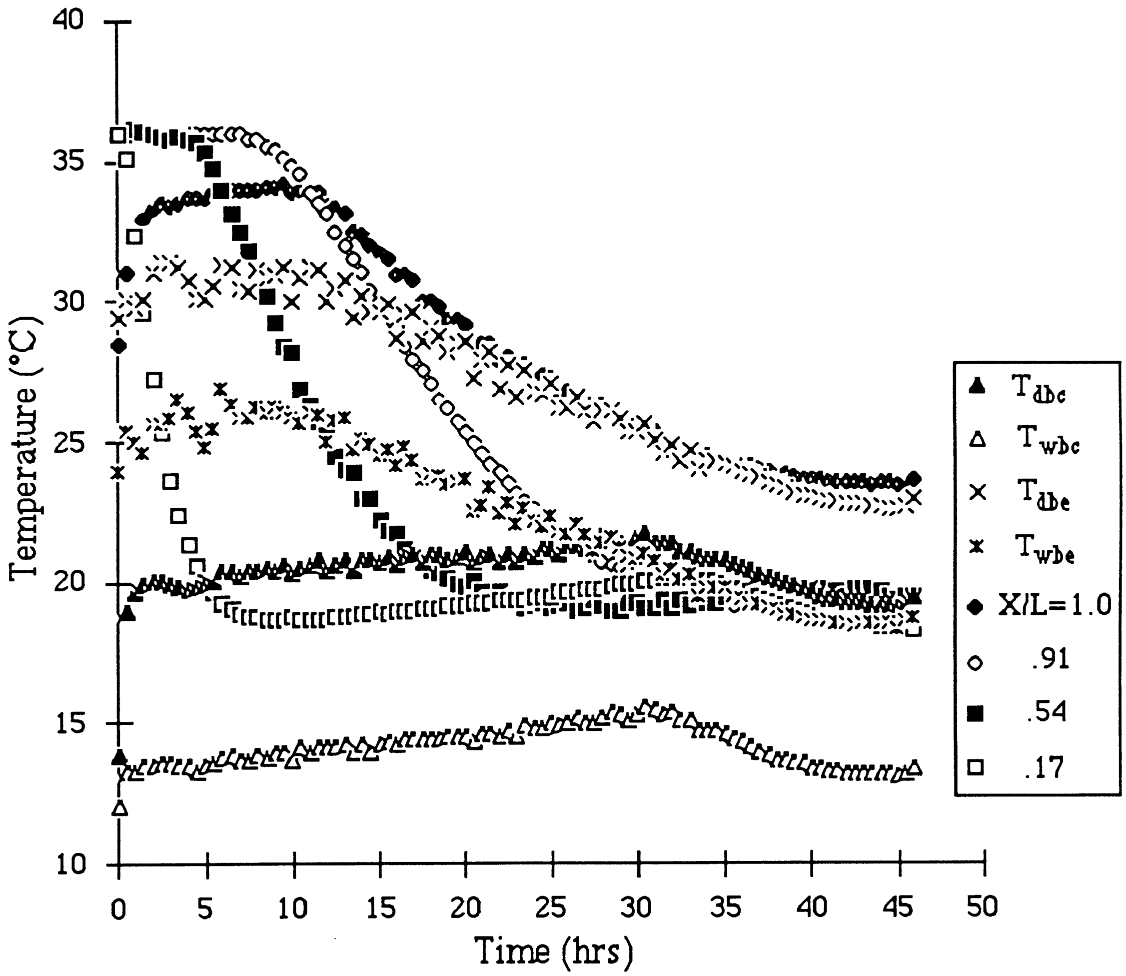

Figure 78. Final grain temperatures compared to the entering air conditions for column #2 and an aeration rate of 5.36 L/s·m^3

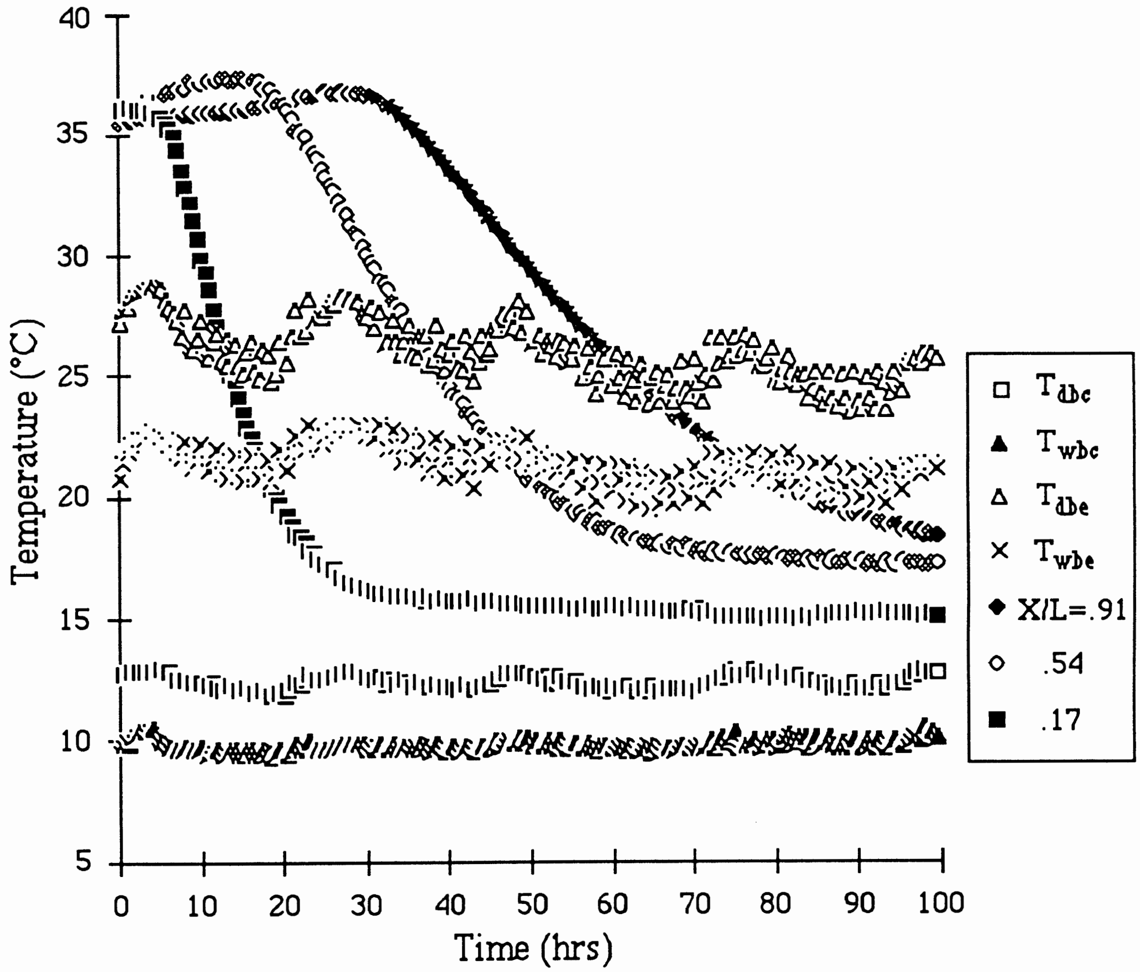

Figure 79. Final grain temperatures compared to the entering air conditions for column #2 and an aeration rate of 2.68 L/s·m^3

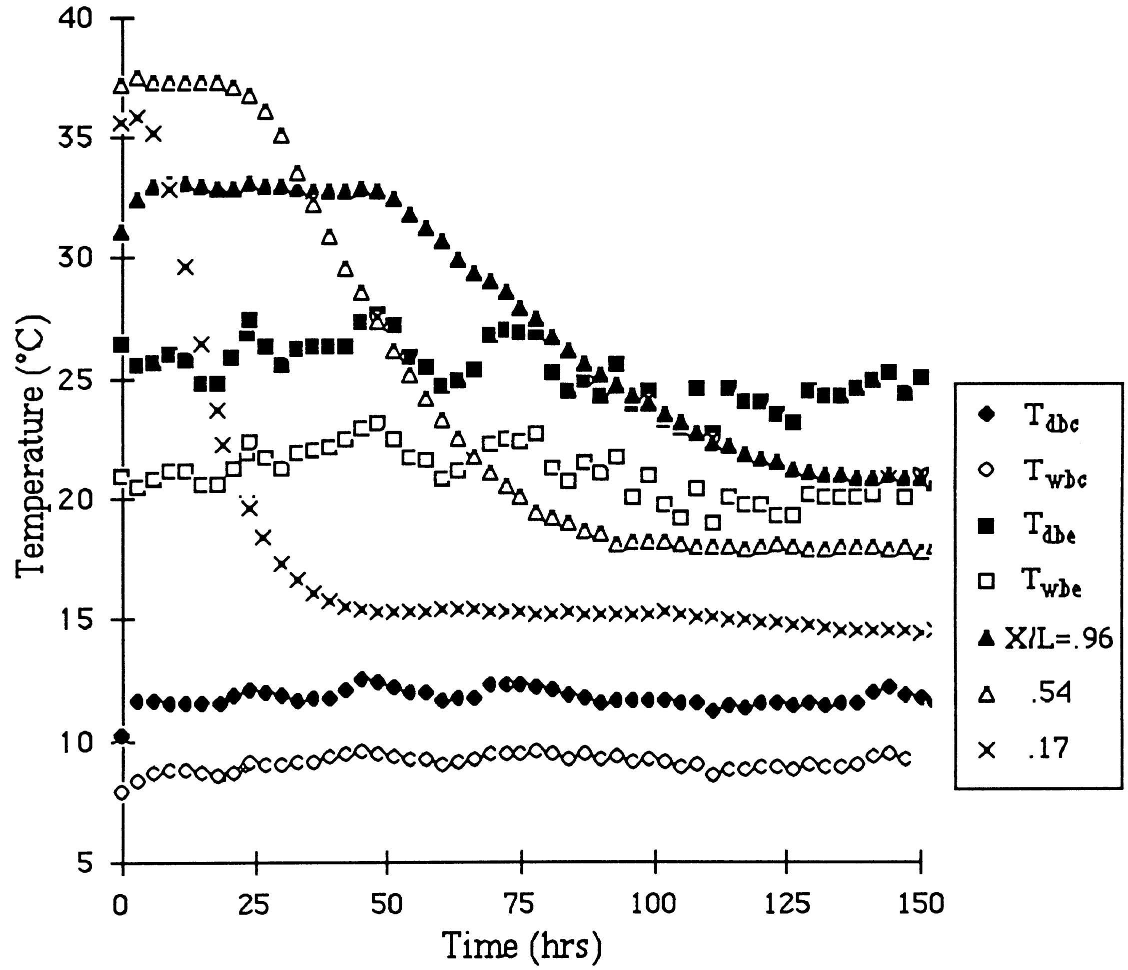

Figure 80. Final grain temperatures compared to the entering air conditions for column #2 and an aeration rate of 1.34 L/s·m^3

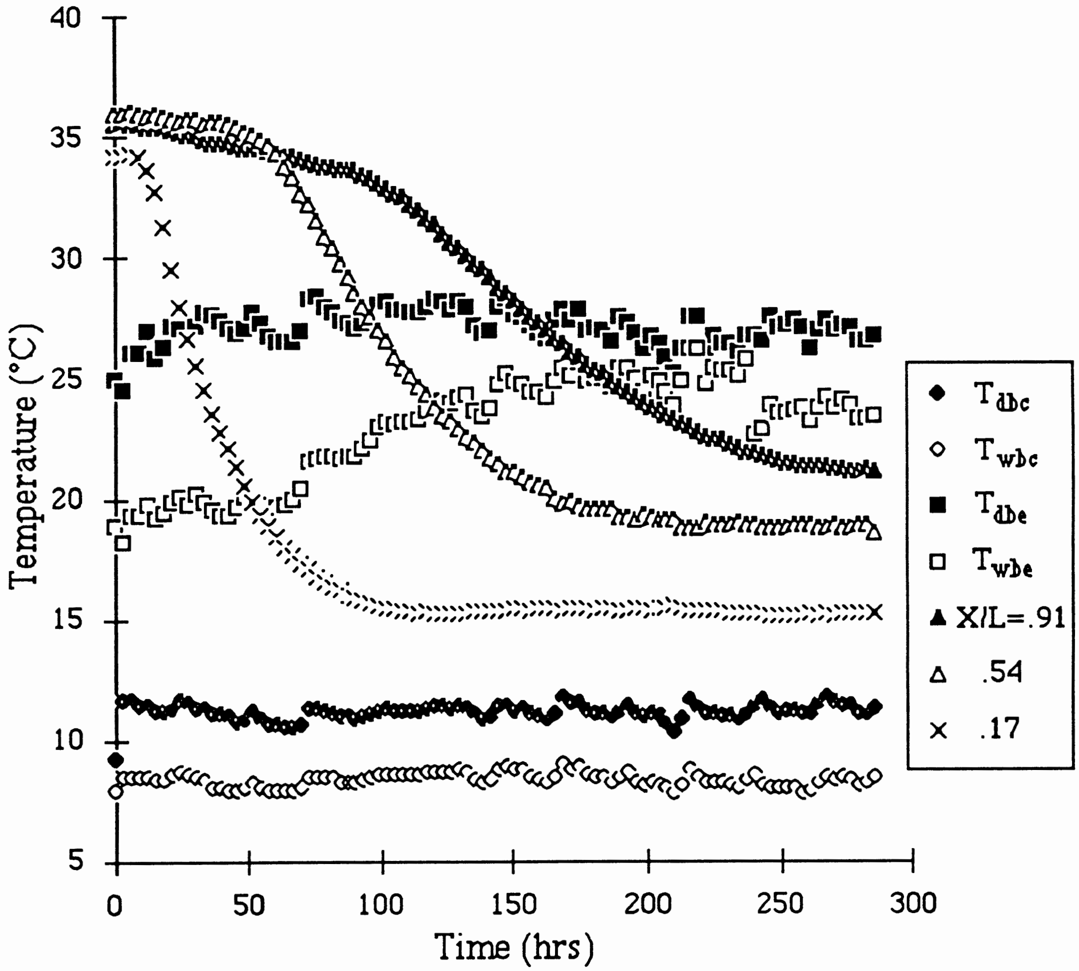

Figure 81. Final grain temperatures compared to the entering air conditions for column #2 and an aeration rate of 0.67 L/s·m^3

TABLE VII

FINAL GRAIN TEMPERATURES IN THE GRAIN MASS AS RELATED TO T_{dbc}

Aeration Rate (L/s·m^3)	Location	T_{final}-T_{dbc} (°C)
10.72	bottom	-1
	middle	-2
	top	-2
8.04	bottom	-1.5
	middle	-1
	top	3
5.36	bottom	-1
	middle	0
	top	4
2.68	bottom	2
	middle	5
	top	6
1.34	bottom	3
	middle	6
	top	9
0.67	bottom	4
	middle	7
	top	10

Changes in Moisture Content

From the statistical analysis given before for the relationship between the moisture content change and aeration rate, none of the factors occurring in these experiments (aeration rate, magnitude of temperature change or total amount of air used during aeration) had a significant effect on the change in moisture content during aeration. The relative humidity of the three lowest aeration rates was from 67% to 72% and the relative humidity of the three higher aeration rates was from 50% to 54%. This is a difference of about 16%, therefore relative humidity differences occurring in these tests do not affect the change in moisture content during aeration. Taking these observations into consideration, a 95% confidence interval for the change in moisture content while cooling with aeration will be $0.78 \pm 0.37\%$ (w.b.). When comparing this to the moisture gain from rewarming, which had a 95% confidence interval of $0.79 \pm 0.54\%$ (w.b.), approximately all the moisture lost while cooling is regained by rewarming. These results agree with those of Foster (1966), Sorenson *et al.* (1967), McCune *et al.*, (1963) and Sanderson *et al.* (1988a, 1988b), which all experienced moisture losses and gains in the ranges given here.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

Aeration tests were performed on hard red winter wheat in an experimental grain bin constructed in the laboratory at Oklahoma State University, Stillwater, Oklahoma. Three small diameter columns inside a larger outer bin were used for the tests and were instrumented with thermocouples to measure temperature distributions. Cooling fronts were forced through the grain mass at six different aeration rates of 0.67, 1.34, 2.68, 5.36, 8.04 and 10.72 $L/s{\cdot}m^3$. The movement of the leading and trailing edges of the cooling fronts were observed and the total cooling times for each aeration rate were determined. Changes in moisture content of the wheat were measured during cooling and rewarming. The grain properties of thermal conductivity, specific heat, bulk density, particle density and porosity were measured for the wheat used in the study.

Conclusions

Analysis of the experimental data led to the following conclusions from this study. They are:

1. The total time required for the leading and trailing edges of the cooling front to exit the grain mass are predicted by the following models:

$$\Theta_L = 72.2 \cdot Q_a^{-1.21} \tag{21}$$

$$\Theta_T = 196 \cdot Q_a^{-0.91} \tag{22}$$

2. The time for each edge of the cooling front to reach a given location in the grain mass are predicted by the following models:

$$\Theta_{LL} = 72.1 \cdot Q_a^{-1.20} \cdot \frac{X}{L}^{1.26} \tag{27}$$

$$\Theta_{LT} = 204 \cdot Q_a^{-0.98} \cdot \frac{X}{L}^{0.65} \tag{28}$$

3. The temperature distribution in the grain mass throughout the aeration period was predicted and is based on Schumann's (1929) equation:

$$\Phi(y, z) = e^{-y} \int_0^z e^{-z} I_0[2\sqrt{yz}]\, dz \tag{31}$$

4. For the conditions prevailing in this study, the total cooling time was not significantly affected by either of the factors of the differences in the amount of drop in moisture content or temperature.

5. The amount of moisture loss occurring during these aeration tests were not significantly affected by aeration rate, the differences in magnitude of temperature drop or total amount of air used during aeration (Pr>F = 0.49, 0.91 and 0.56, respectively) and averaged 0.78% (w.b.). During rewarming of the grain the average moisture content gain was 0.79% (w.b.).

6. More uniform final grain temperature profiles were obtained with the higher aeration rates. The final grain temperature varied with aeration rate. The final grain temperatures being slightly less than the entering air

dry-bulb temperatures for the higher aeration rates and about 10°C greater than the entering dry-bulb temperatures for the lower aeration rates.

Recommendations

Do to empirical nature of the modelling and other limitations occurring in the study, the models developed may not be accurate for other types of applications in aeration. Further research which could be performed to validate whether these results are applicable or to determine if the models need modification are:

1. Perform similar experiments using different bin depth to diameter ratios and determine if the models developed will predict temperature gradients and location of the leading and trailing edges of the cooling fronts during aeration.

2. Perform experiments with intermittent aeration simulating actual field conditions to determine if cooling models developed accurately predict cooling times.

3. Perform aeration tests with different magnitudes of temperature drop during aeration and determine its effect on cooling time and moisture content loss.

Some recommendations resulting from this study are:

1. When cooling wheat by aeration, the use of higher aeration rates (5.36 to 10.72 $L/s{\cdot}m^3$) will require less cooling time allowing the entire grain mass to be cooled during one cold frontal system typical of Oklahoma conditions.

2. The use of higher aeration rates (8.04 to 10.72 $L/s \cdot m^3$ and above) will also result in more uniform final grain temperatures as compared to lower aeartion rates.

3. Rewarming a grain mass using aeration before unloading or resale will result in a gain in moisture content and weight almost equal to the losses occurring in cooling.

REFERENCES

Adel-Kaddel, M. H. K., R. B. Webster, S. R. Loschiavo and F. L. Walters. 1980. Low temperature degradation of malathion in stored wheat. J. Econ. Entomol. 73:654-656.

Anderson, K. B. 1988. Economics of storing grain. In: Stored grain management: Insects, molds, engineering, and economics. Proceedings of Stored Grain Management Satellite Teleconference. Ok. St. Univ. Coop. Ext. Serv. Cir. E-872.

Armitage, D. M. and L. M. Stables. 1983. Effects of aeration on established insect infestations in bins of wheat. Prot. Ecol. 6:67-73.

Babbitt, E. A. 1945. The thermal properties of grain in bulk. Can. J. of Res. F23:388-401.

Bakke, A. L. 1935. Thermal conductivity of stored oats with different moisture content. Plant Physiology. 10:521-524.

Bakker-Arkema, F. W. and W. G. Bicckert. 1966. A deep-bed computational cooling procedure for biological products. Trans. ASAE. 9(6): 834-836, 845.

Bakker-Arkema, F. W. ,W. G. Bicckert and R. J. Patterson. 1967. Simultaneous heat and mass transfer during the cooling of a deep bed of biological products under varying inlet conditions. J. Agric. Eng. Res. 12(4):297-307.

Bakker-Arkema, F. W., L. E. Lerew, S. F. DeBoer and M. G. Roth. 1974. Grain dryer simulation. Agricultural Experiment Station Report No. 224. Michigan State University, East Lansing, MI.

Barre, H. J., C. R. Baughman and M. Y. Hamdy. 1971. Application of a logarithmic model to deep bed drying of grain. Trans. ASAE. 14:864-867.

Baughman, G. R., M. Y. Hamdy and H. J. Barre. 1971. Analog computer simulation of deep bed drying of grain. Trans. ASAE. 14:1058-1064.

Bishop, G. W. 1959. The comparative bionomics of the American *Cryptolestes* (Coleoptera-Cucujidae) that infest grain. Ann. Ento. Soc. of Amer. 52:657-665.

Bloome, P. D. and G. C. Shove. 1971. Near equilibrium simulation of shelled corn drying. Trans. ASAE. 14:709-712.

Bloome, P. D. and G. C. Shove. 1972. Simulation of low temperature drying of shelled corn leading to optimization. Trans. ASAE. 15(2):310-320.

Bosen, J. F. 1960. A formula for approximation of the saturation vapor pressure over water. Monthly Weather Review. 88(8):275-276.

Boyce, D. S. 1965. Grain moisture and temperature changes with position and time during through drying. J. Agr. Eng. Res. 10(4):333-334.

Boyce, D. S. 1966. Heat and moisture transfer in ventilated grain. J. Agric. Eng. Res. 11(4):255-265.

Brooker, D. B., F. W. Bakker-Arkema and C. W. Hall. 1974. Drying cereal grains. Avi. Westport, CT.

Burges, H. D. and N. J. Burrell. 1964. Cooling bulk grain in the British climate to control storage insects and to improve keeping quality. J. Sci. Fd. Agric. 15:32-50.

Burrell, N. J. 1967. Grain cooling studies--II: Effects of aeration on infested grain bulks. J. Stored Prod. Res. 3:145-154.

Burrell, N. J., and J. H. J. Laundon. 1967. Grain cooling studies--I: Observations during a large scale refrigeration test on damp grain. J. Stored Prod. Res. 3:125-144.

Chuma, Y., S. Uchida, K. H. H. and T. Matsuoka. 1981. Bulk physical and thermal properties of cereal grains as affected by moisture content. J. Fac. Agric. Kyushu Univ. 26:57-70.

Cotton, R. T. 1963. Pests of stored grain and grain products. Burgess Publishing Co. Minneapolis, Minn. 318 p.

Cuperus, G. W., P. D. Bloome, R. Noyes and B. Clary. 1986. Stored grain pest management -- A three-year report. Ok. St. Univ. Coop. Ext. Serv. Cir. E-846. pp. 9-18.

DeVoe, D. R., G. H. Brusewitz and M.L. Stone. 1985. Quantitive importance of bulk density when using dielectric measurements to predict percent moisture of hard red winter wheat. ASAE Paper No. 85-3027. Am. Soc. Agric. Eng. St. Joseph, MI.

Disney, R. W. 1954. The specific heat of some cereal grains. Cereal Chemistry. 31:229-334.

Donahaye, E., S. Navarro and M. Calderon. 1974. Studies on aeration with refrigerated air--III: Chilling of wheat with a modified chilling unit. J. Stored Prod. Res. 10:1-8.

Epperly, D. R., R. T. Noyes, G. W. Cuperus and B. L. Clary. 1987. Control stored grain insects by grain temperature management. ASAE Paper No. 87-6035. Am. Soc. Agric. Eng. St. Joseph, MI.

Evans, D. E. 1982. The influence of temperature and grain moisture contents on the intrinsic rate of increase of *Sitophilus oyzae* (L.) (Coleoptera: Curculionidae). J. Stored Prod. Res. 18:55-66.

Evans, D. E. 1983. The influence of relative humidity and thermal acclimation on the survival of adult grain beetles in cooled grain. J. Stored Prod. Res. 19(4):173-180.

Foster, G. H. 1967. Moisture changes during aeration of grain. Trans. ASAE. 10(3):344-347, 351.

Furnas, C. C. 1930. Heat transfer from a gas stream to a bed of broken solids--II. Ind. Eng. Chem. 22(7):721-730.

Ghaly, T. F. 1984. Aeration trial of farm-stored wheat for the control of insect infestation and quality. J. Stored Prod. Res. 20(3):125-131.

Harein, P. K. 1982. Chemical control alternatives for stored grain insects. In: Storage of cereal grains and their products. C. M. Christensen (ED.). Amer. Assoc. Cer. Chem. St. Paul, MN. pp. 319-362.

Henderson, J. M. and S. M. Henderson. 1968. A computational procedure for deep-bed drying analysis. J. Agric. Eng. Res. 13(2):87-95.

Hooper, F. C. and F. H. Lepper. 1950. Transient heat flow apparatus for the determination of thermal conductivities. Amer. Soc. Heat. and Vent. Engr. Trans. 56:309-322.

Hooper, F. C. and S. C. Chang. 1953. Development of the thermal conductivity probe. Amer. Soc. Heat. and Vent. Eng. Trans. 59:463-472.

Hunter, A. J. and P. A. Taylor. 1980. Refrigerated aeration for the preservation of bulk grain. J. Stored Prod. Res. 16:123-131.

Hunter, A. J. 1988. Temperature and moisture front movement in an aerated seed bulk. J. Agric. Eng. Res. 35:113-127.

Ingram, G. W. 1979. Solution of grain cooling and drying problems by the method of characteristics in comparison with finite difference solutions. J. Agric. Eng. Res. 24:219-232.

Johnson, H. K. 1957. Cooling stored grain by aeration. Agric. Engr. 38:238-246.

Kazarian, E. A. and C. W. Hall. 1965. Thermal properties of grain. Trans. ASAE. 8:33-37,48.

Keener, H. M., G. E. Meyer, M. A. Sabbah and R. B. Curry. 1978. Simulation of solar grain drying. Agricultural Engineering Series No. 102. Ohio Agricultural Research and Development Center. Wooster, OH.

Kline, G. L. and Converse, H. H. 1961. Operating grain aeration systems in the hard winter wheat area. Marketing Research Report No. 480. U. S. Department of Agriculture.

McCune, W. E., N. K. Person, Jr. and J. W. Sorenson, Jr. 1963. Conditioned air storage of grain. Trans. ASAE. 6:186-189.

Marketing Research Report No. 178. 1960. Aeration of grain in commercial storage. USDA. 46 pp.

Metzger, J. F. and W.E. Muir. 1983. Aeration of stored wheat in the Canadian Prairies. Can. Agric. Eng. 25(1):127-137.

Miller, J. A. 1965. Effects of aeration time for various airflow rates on properties of effluent air from grain aerated in storage. Unpublished MS thesis. Texas A & M University. College Station, TX.

Mohensin, N. N. 1980. Thermal properties of foods and other agricultural materials. Gordon and Breach. New York, N. Y.

Moote, I. 1953. The effect of moisture on the thermal properties of wheat. Can. J. Tech. 31:57-62.

Morey, R. V., H. M. Keener, T. L. Thompson, G. M. White and F. W. Bakker-Arkema. 1978. The present status of grain drying simulation. ASAE Paper No. 78-3009. Am. Soc. Agric. Eng. St. Joseph, MI.

Moysey, E. B. 1969. Refrigeration of damp grain with natural air. Can. Agric. Engr. 11(1):12-13, 22.

Muir, W. E. and S. Viravanichai. 1972. Specific heat of wheat. J. Agric. Engrg. Res. 17:338-343.

Muir, W. E., D. S. Jayas, M. G. Britton, R. N. Sinha and N. D. G. White. 1987. Interdisciplinary grain storage research at the University of Manitoba. ASAE Paper No. 87-6544. Am. Soc. Agric. Eng. St. Joseph, MI.

Navarro, S., E. Donahaye and M. Calderon. 1969. Observations on prolonged grain storage with forced aeration in Israel. J. Stored Prod. Res. 5:73-81.

Navarro, S., E. Donahaye and M. Calderon. 1973. Studies of aeration with refrigerated air--I: Chilling of wheat in a concrete elevator. J. Stored Prod. Res. 9:253-259.

Navarro, S. and M. Calderon. 1982. Aeration of grain in subtropical climates. FAO Agric. Serv. Bull. No. 52. Rome, Italy.

Noyes, R. T. and B.L. Clary. 1986. Engineering. In: Stored grain management in Oklahoma. Ok. St. Univ. Coop. Ext. Serv. Cir. E-839.

Oxley, T. A. 1944. The property of grain in bulk. Soc. Chem. Indus. J. Trans. 63:53-57.

Pabis, S. and S. M. Henderson. 1962. Grain drying theory--III: The air/grain temperature relationship. J. Agric. Eng. Res. 7(1):21.

Person, N. K. Jr., J. W. Sorenson, Jr. and W. E. McCune. 1966. Thermodynamic considerations in designing controlled storage environments for bulk grain. Trans. ASAE. 9(4):520-523.

Pfalzner, P. M. 1951. Specific heat of wheat. Can. J. Tech. 29:261-269.

Robinson, R. N., W. V. Hukill and G. H. Foster. 1951. Mechanical ventilation of stored grain. Agric. Eng. 32:606-608.

Sanderson D. B., W. E. Muir and R. N. Sinha. 1988a. Intergranular air temperatures of ventilated bulks of wheat. J. Agric. Eng. Res. 40:33-43.

Sanderson D. B., W. E. Muir and R. N. Sinha. 1988b. Moisture contents within bulks of wheat ventilated with near-ambient air: Experimental results. J. Agric. Eng. Res. 40:45-55.

SAS User's Guide. 1988. SAS Institute, Inc. Gary, NC.

Schultz, L. J. 1984. A comparison of simulation techniques for wheat aeration. Unpublished MS thesis. Oklahoma State University. Stillwater, OK.

Schumann, T. E. W. 1929. Heat transfer: A liquid flowing through a porous prism. J. Franklin Ins. 208(5):405.

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. 10(3):366-369.

Storey, C. L., R. D. Speirs and L. S. Henderson. 1979. Insect control in farm-stored grain. USDA Farmers' Bulletin No. 2269. 18 p.

Surtees, G. 1963. Laboratory studies on dispersion behavior of adult beetles in grain.--I: The grain weevil, *Sitophilus granarius* (L.) (Coleoptera: Curculionidae). Bull. Ent. Res. 54:147-157.

Surtees, G. 1965. Ecological significance and practical implications of behavior patterns determining the spatial structure of insect populations in stored grain. Bull. Entomol. Res. 56:201-211.

Sutherland, J. W. 1968. Control of insects in a wheat store with an experimental aeration system. J. Agric. Eng. Res. 13(3):210-219.

Sutherland, J. W., P. J. Banks and H. J. Griffiths. 1971. Equilibrium heat and moisture transfer in air flow through grain. J. Agric. Eng. Res. 16:368-386.

Sutherland, J. W., P. J. Banks and W. B. Elder. 1983. Interaction between successive temperature or moisture fronts during aeration of deep grain beds. J. Agric. Eng. Res. 28:1-19.

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

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

Thorpe, G. R. and W. B. Elder. 1982. Modelling the effects of aeration on the persistence of chemical pesticides applied to stored bulk grain. J. Stored Prod. Res. 18:103-114.

APPENDIXES

APPENDIX A

ORIFICE CALIBRATION DATA

TABLE VIII

ORIFICE PLATE SPECIFICATIONS

Supply pipe size	Orifice diameter	ß	Flow Equation	Standard Error
cm (in)	cm (in)		Q-L/s H-cm (cfm) (in)	
5 (2)	2.54 (1)	0.5	$Q = 4.61 \cdot H^{0.5}$ ($Q = 15.30 \cdot H^{0.5}$)	0.005
10.2 (4)	5 (2)	0.5	$Q = 17.72 \cdot H^{0.5}$ ($Q = 58.84 \cdot H^{0.5}$)	0.163
10.2 (4)	6.77 (2.67)	0.5	$Q = 113.9 \cdot H^{0.5}$ ($Q = 33.30 \cdot H^{0.5}$)	0.080

APPENDIX B

COMPUTER PROGRAMS

Program #1

```
'This program is used to collect data from three dataloggers onto a computer
'floppy disk. The three dataloggers are a ACUREX Autodata 10, Doric and
'Hewlitt Packert 3497A.  The computer used is an Executive XT10 using
'Microsft GWBasic.
'
'________________________________________________________________
'

'-Program initialization
   DEFINT I-K
   DEFSNG M-Q
   DIM DT$(60),DOR(130),SS(60),TEMP(60),TCA(60)
   A$=SPACE$(25)
'-Voltage to temperature conversion for HP datalogger
   A0=.10086091#:A1=25727.94369#
   A2=-767345.8295#:A3=78025595.81#
   A4=-9247486589#:A5=697688000000#
   A6=-26619200000000#:A7=394078000000000#
   DEFFNTEMP(X)=A0+X*(A1+X*(A2+X*(A3+X*(A4+X*(A5+X*
      (A6+X*A7))))))
'-Load link that calls DOS resident driver  ---
   DEF SEG = &H2800
   BLOAD "GPIBBASI.BIN",0
   IE488 = 0
   PRINT "INSERT DATA DISK"
   PRINT "HIT ANY KEY TO CONTINUE ";INPUT$(1)
'-Initialize MBC-488 board
   CMD$ = "SYSCON MAD=3, CIC=1, NOB=1, BA0=&H300"
   A% = 0 : FLAG% = 0 : BRD% = 0
   CALL IE488 (CMD$, A%, FLAG%, BRD%)
'-Initialize HP datalogger
   CMD$="REMOTE 09"
   CALL IE488 (CMD$, A%, FLAG%, BRD%)
   CMD$="CLEAR 09"
   CALL IE488 (CMD$, A%, FLAG%, BRD%)
   A% =12:CMD$="TIMEOUT"
   CALL IE488 (CMD$, A%, FLAG%, BRD%)
   CMD$="OUTPUT 9[$]
   T$="VR5VN1VA1VF1VD5VC0VS0VW0VT3"
   CALL IE488 (CMD$, T$, FLAG%, BRD%)
'-Select disk file names for each datalogger
   NN=0:QQ=0:MM=0
   INPUT "FILENAME FOR ACUREX ";AZ$
```

```
  INPUT "FILENAME FOR DORIC ";DZ$
  INPUT "FILENAME FOR HP ";XZ$
'-Open communication ports for Doric and Acurex dataloggers
  OPEN "COM1:2400,N,8,2" AS #4
  OPEN "COM2:9600,E,7,2" AS #5
'-Open disk files as Random Access files and storing as integers
  OPEN "R",#1,XZ$+".DAT",2
    FIELD#1,2 AS W$
  OPEN "R",#2,DZ$+".DAT",2
    FIELD#2,2 AS DO$
  OPEN "R",#3,AZ$+".DAT",2
    FIELD#3,2 AS AU$
'-Doric and Acurex dataloggers are set to collect data every 30 minutes and
'-send them to the computer
'
'----------DORIC----------
'
'-Input date from datalogger
  Start:
  INPUT#4,HR,MN,SC
  PRINT DATE$,TIME$:PRINT
'-Starting data input loop for Doric datalogger
  J=0
  FOR I=1 TO 127
    INPUT#4, MD
    '-Doric datalogger sends zero's between some observations
      IF MD=0! THEN NEXT I
    J=J+1
    DOR(J)=MD
  NEXT I
'-Print data to screen, convert data to Integer [illegible] store on disk
  FOR I= 2 TO 114 STEP 2
    PRINT USING"######.#";DOR([illegible]
      ID=DOR(I)*10
      NN=NN+1
        LSET DO$=MKI$(ID)
        PUT #2,NN
  NEXT I
'-Use wet-bulb and dry-bulb temperatures to determine relative humidity
  WB=DOR(114):DB=DOR(112)
  GOSUB RELHUM
  PRINT USING"######.#";RH
    NN=NN+1
```

```
      LSET DO$=MKI$(RH*10)
      PUT #2,NN
    PRINT
'
'----------ACUREX----------
'
'-Input date from datalogger
    INPUT#5,A,B,C
'-Starting input data loop for Acurex datalogger
    FOR I=1 TO 59
      INPUT#5,CH,TCA(I)
      PRINT USING "######.#";TCA(I);
      '-Convert to Integer form and store on disk
        IO=TCA(I)*10
          QQ=QQ+1
           LSET AU$=MKI$(IO)
           PUT #3,QQ
    NEXT I
'-Use wet-bulb and dry-bulb temperatures to determine relative humidity
    DB=TCA(56):WB=TCA(57)
    GOSUB RELHUM
    PRINT USING"######.#";RH;
      QQ=QQ+1
      LSET AU$=MKI$(RH*10)
      PUT #3,QQ
'-Determine relative humidity for environmental chamber
    DB=TCA(59):WB=TCA(58)
    GOSUB RELHUM
    PRINT USING"######.#";RH
      QQ=QQ+1
      LSET AU$=MKI$(RH*10)
      PUT #3,QQ
    PRINT
'
'------------HP------------
'
'-Send commands to datalogger to start scan
    CMD$="OUTPUT 9[$]"
    MODE$="AF0AL59"
    CALL IE488 (CMD$, MODE$, FLAG%, BRD%)
'-Start data input loop
    FOR I=1 TO 60
      CMD$="TRIGGER 09"
```

```
      CALL IE488 (CMD$, A%, FLAG%, BRD%)
      CMD$ = "ENTER 09[$]"
      CALL IE488 (CMD$, A$, FLAG%, BRD%)
      SS(I)=VAL(A$)
    NEXT I
'-Set HP back into Remote Mode
    CMD$ = "REMOTE 09[$]"
    CALL IE488 (CMD$, A%, FLAG%, BRD%)
'-Convert voltages to temperatures
'-Convertion is done in groups of 20 channels at a time with the last channel
'-in each group being the temperature compensation term
    II=1:IL=19:IR=20:IO=0
    FOR K=1 TO 3
      FOR I = II TO IL
        RT=SS(IR)*10!
        X=SS(I)
          T=FNTEMP(X)
        J=I-IO
        TEMP(J)=RT+T
      NEXT I
      IR=IR+20: IO=IO+1: II=II+20:IL=IL+20
    NEXT K
'-Converting to Integer form and storing on disk
    FOR I=1 TO 57
      JF=TEMP(I)*10
      PRINT USING "######.#";JF/10;
        MM=MM+1
        LSET W$=MKI$(JF)
        PUT #1,MM
    NEXT I
'-Use wet-bulb and dry-bulb temperatures to determine relative humidity
    DB=TEMP(56):WB=TEMP(57)
    GOSUB RELHUM
    PRINT USING"######.#";RH
      MM=MM+1
      LSET W$=MKI$(RH*10)
      PUT #1,MM
'-Close all data files
    CLOSE #1,#2,#3
'-Doric sends out null line before sending data
    INPUT#4,NUL
'-Return to start of data aquisition
    GOTO Start
```

```
'-Subprogram used to determine relative humidity from wet-bulb and dry-
'-bulb temperatures
 RELHUM:
   A=33.8639*((.00738*DB+.8072)^8.000019*(ABS(1.8*DB+48))+
      .001316)
   B=33.8639*((.00738*WB+.8072)^8.000019*(ABS(1.8*WB+48))+
      .001316)
   C=B-.662*(DB-WB)
   RH=100*(C/A)
  RETURN
 END
```

Program #2

```
'-This is a program to extract data from the original data file.  It will extract
'-all temperature data for the desired column for a specific instant of time.
'
'________________________________________________________________________
'
   START:
   CLS
   K$="      "
   PRINT"INSERT DATA DISK"
   PRINT
   PRINT"WHAT DATA LOGGER ARE YOU USING?"
       PRINT"1-- ACUREX"
       PRINT"2-- DORIC"
       PRINT"3-- HP"
'-There is a different number of readings for the different dataloggers.
             INPUT J
    ON J GOTO ACUREX, DORIC, HP
       ACUREX:  K=61: GOTO FILENAME
       DORIC:   K=58: GOTO FILENAME
       HP:      K=58
'-Setting up the file to read from and to write to and for what hour.
   FILENAME:
            INPUT "WHAT FILE ARE YOU USING ";A$
   CREATE:INPUT "WHAT FILE DO YOU WANT TO CREATE";B$
            INPUT "WHAT HOUR DO YOU WANT TO SEE ";S
   OPEN "R",#1, A$,2
   FIELD#1, 2 AS W$
   OPEN "O",#2,B$
'-Figuring out where to go to in the file and how far to read.
   FIRST=S*2*K+1
   LAST=FIRST+K-1
   G=FIRST
   T=0
   FOR I=FIRST TO LAST
'-Taking out bad thermocouple readings
   IF T=20 AND J=1 THEN GOTO Skip
   IF T=22 AND J=2 THEN GOTO Skip
      GET #1 ,G
      PRINT USING "######.#"; CVI(W$)/10 '-Converting  to real
      PRINT#2 ,T,K$,CVI(W$)/10
   Skip:
    G=G+1
```

```
  T=T+1
NEXT I
CLOSE
PRINT
PRINT "RUN AGAIN (Y/N) ":Y$=INPUT$(1)
   IF Y$<>"Y" THEN END
PRINT "KEEP SAME DEVICE ?":I$=INPUT$(1)
   IF I$="Y" THEN GOTO CREATE
GOTO START
```

Program #3

```
'-This is a program to extract data from the original data file.
'-It will extract all temperature data for a specific instant of time from
'-the desired column.
'
'______________________________________________________________
'
  START:
    CLS
    K$="    "
    PRINT"INSERT DATA DISK"
    PRINT
    PRINT"WHAT DATA LOGGER ARE YOU USING?"
      PRINT"1-- ACUREX"
      PRINT"2-- DORIC"
      PRINT"3-- HP"
'-The different dataloggers have different numbers of readings
        INPUT J
    ON J GOTO ACUREX,DORIC,HP
        ACUREX:  K=61: GOTO FILENAME
        DORIC:   K=58: GOTO FILENAME
        HP:      K=58
'-Setting up which file to read from and write to and for which TC
  FILENAME:
          INPUT "WHAT FILE ARE YOU USING ";A$
  CREATE: INPUT "WHAT FILE DO YOU WANT TO CREATE";B$
          INPUT "WHAT TC NUMBER DO YOU WANT TO SEE ";S
'-Reading and writing the data
  OPEN "R",#1, A$,2
    FIELD#1, 2 AS W$
  OPEN "O",#2,B$
  T=0
  FOR I = 1 TO 100
    FOR JJ=1 TO 8
      GET #1,S
      IF EOF(1) THEN GOTO FINISHED
      PRINT TAB(JJ*8) CVI(W$)/10;  '-Converting from integer to real
     S=S+K
      PRINT#2,T, K$,CVI(W$)/10
     T=T+.5
    NEXT JJ
  NEXT I
  FINISHED:
```

```
   CLOSE
   PRINT
   PRINT "RUN AGAIN (Y/N) ":Y$=INPUT$(1)
     IF Y$<>"Y" THEN END
   PRINT "KEEP SAME DEVICE ?":I$=INPUT$(1)
     IF I$="Y" THEN GOTO CREATE
GOTO START
```

APPENDIX C

GRAIN PROPERTIES

TABLE IX

BULK DENSITY RAW DATA

Bulk Density ρ_b (kg/m^3)
794.3
826.7
796.0
793.6
798.9
800.3
793.4
800.1
797.2
797.4
789.9
794.7
796.0
793.3
792.9
789.6
797.6
800.7
797.2
796.3
Average = 797.3
Std. Dev. = 7.592

TABLE X

PARTICLE DENSITY RAW DATA

Location	Particle Density ρ_s (kg/m^3)
AP	1440
	1460
	1460
	1470
CH	1390
	1390
	1380
	1460
DU	1490
	1500
	1520
	1450
EL	1450
	1460
	1460
	1460
KF	1420
	1420
	1410
	1410
Average	1440
Std. Dev.	36.8

Source: Devoe *et al.* (1985).

TABLE XI

SPECIFIC HEAT RAW DATA

C_p (cal/g·°C)
0.443
0.475
0.450
0.429
0.418
0.409
0.428
0.415
0.425
0.389
0.404
0.350
Average = 0.420
Std. Dev. = 0.0315

TABLE XII

THERMAL CONDUCTIVITY RAW DATA

k_g (cal/s·m·°C)
0.0382
0.0405
0.0366
0.0386
0.0379
0.0361
0.0368
0.0358
0.0361
0.0349
Average = 0.0372
Std.Dev. = 0.00171

APPENDIX D

MOISTURE CONTENT DATA

TABLE XIII

MOISTURE CONTENT[1] DATA FOR AERATION RATE OF 0.67 L/s·m^3

	Column 1			Column 2			Column 3		
Depth[2]	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc
1	11.79	10.89	0.90	12.12	11.05	1.07	12.02	11.18	0.84
2	12.34	10.91	1.43	12.17	11.48	0.69	12.41	11.49	0.92
3	12.45	11.30	1.15	12.46	11.71	0.75	12.98	11.77	1.21
4	12.62	11.45	1.17	12.53	11.77	0.76	13.15	11.85	1.30
5	12.86	11.63	1.23	12.61	11.59	1.02	13.10	11.84	1.26
6	12.80	11.70	1.10	12.63	11.72	0.91	12.98	11.80	1.18
7	12.86	11.74	1.12	12.64	11.81	0.83	12.95	11.85	1.10
8	12.84	11.85	0.99	12.68	11.89	0.79	13.02	12.00	1.02
9	13.01	12.09	0.92	12.70	12.02	0.68	13.06	12.22	0.84
10	12.93	12.36	0.57	12.72	12.49	0.23	13.07	12.49	0.58
11	12.98	12.68	0.30	13.26	12.52	0.74	13.43	12.56	0.87
12	13.24	12.72	0.52	13.39	12.56	0.83	13.45	12.80	0.65
13	13.70	12.76	0.94	13.14	12.60	0.54	13.82	13.19	0.63
14	13.77	12.84	0.93	13.41	13.07	0.34	14.03	13.21	0.82
15	14.09	13.31	0.78	13.79	13.26	0.53	13.96	13.44	0.52
16	14.05	13.12	0.93	13.81	13.19	0.62	14.28	12.88	1.40
17	14.01	13.05	0.96	13.73	12.71	1.02	13.74	12.70	1.04
Av.	13.08	12.14	0.94	12.93	12.20	0.73	13.26	12.31	0.95

[1] Moisture content determined on wet basis.
[2] Numbers represent sample number starting at top of column with number 1 being 7.6 cm deep, 2 being 15.2 cm deep, etc.

TABLE XIV

MOISTURE CONTENT DATA FOR AERATION RATE OF 1.34 L/s·m^3

	Column 1			Column 2			Column 3		
Depth	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc
1	12.53	11.72	0.81	12.29	11.59	0.70	12.21	11.41	0.80
2	12.54	11.72	0.82	12.55	11.94	0.61	12.50	11.61	0.89
3	12.54	11.74	0.80	12.38	11.67	0.71	12.29	11.76	0.53
4	12.47	11.75	0.72	12.25	11.72	0.53	12.20	11.58	0.62
5	12.45	11.75	0.70	12.21	11.61	0.60	12.21	11.52	0.69
6	12.33	11.67	0.66	12.24	11.59	0.65	12.21	11.55	0.66
7	12.23	11.88	0.35	12.28	11.62	0.66	12.23	11.60	0.63
8	12.34	11.89	0.45	12.49	11.72	0.77	12.28	11.80	0.48
9	12.70	12.06	0.64	12.68	11.85	0.83	12.33	11.91	0.42
10	12.87	12.39	0.48	12.67	12.27	0.40	12.90	12.15	0.75
11	12.98	12.76	0.22	12.94	12.30	0.64	12.87	12.24	0.63
12	13.06	12.75	0.31	13.04	12.38	0.66	13.13	12.22	0.91
13	13.19	12.72	0.47	13.21	12.69	0.52	13.32	12.44	0.88
14	13.25	13.10	0.15	13.51	13.08	0.43	13.65	13.30	0.35
15	13.46	13.65	-0.19	13.45	13.25	0.20	13.81	13.05	0.76
16	14.26	13.70	0.56	14.13	13.51	0.62	14.53	13.34	1.19
17	15.08	13.80	1.28	14.84	13.09	1.75	14.99	13.15	1.84
Av.	12.96	12.41	0.54	12.89	12.23	0.66	12.92	12.15	0.77

TABLE XV

MOISTURE CONTENT DATA FOR AERATION RATE OF 2.68 L/s·m^3

	Column 1			Column 2			Column 3		
Depth	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc
1	12.08	11.34	0.74	12.23	11.75	0.48	11.99	12.14	-0.15
2	11.93	11.27	0.66	12.09	11.49	0.60	11.86	11.72	0.14
3	12.00	11.12	0.88	11.91	11.34	0.57	11.91	11.40	0.51
4	11.85	11.04	0.81	12.00	11.37	0.63	11.87	11.30	0.57
5	12.02	11.16	0.86	12.12	11.38	0.74	11.91	11.22	0.69
6	12.38	11.25	1.13	12.03	11.45	0.58	12.01	11.37	0.64
7	12.00	11.29	0.71	12.18	11.44	0.74	12.07	11.42	0.65
8	12.07	11.36	0.71	12.27	11.55	0.72	12.27	11.40	0.87
9	12.22	12.19	0.03	12.22	11.84	0.38	12.21	11.52	0.69
10	12.43	11.76	0.67	12.97	11.81	1.16	12.69	11.58	1.11
11	12.28	11.97	0.31	12.80	11.87	0.93	12.85	11.90	0.95
12	12.62	11.65	0.97	13.11	11.90	1.21	13.00	11.84	1.16
13	12.64	12.01	0.63	13.16	11.96	1.20	13.17	11.98	1.19
14	12.79	11.44	1.35	13.43	11.85	1.58	13.03	12.19	0.84
15	13.05	13.07	-0.02	13.04	12.58	0.46	13.47	12.67	0.80
16	13.37	12.86	0.51	13.64	12.64	1.00	13.65	12.52	1.13
17	13.95	12.92	1.03	13.74	12.78	0.96	14.17	13.22	0.95
Av.	12.45	11.75	0.70	12.64	11.82	0.82	12.60	11.85	0.75

TABLE XVI

MOISTURE CONTENT DATA FOR AERATION RATE OF 5.36 L/s·m^3

	Column 1			Column 2			Column 3		
Depth	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc
1	12.89	11.81	1.08	12.23	11.63	0.60	12.82	12.01	0.81
2	12.91	11.83	1.08	12.78	11.74	1.04	12.96	12.05	0.91
3	13.05	12.05	1.00	12.94	12.12	0.82	13.06	12.22	0.84
4	12.88	12.03	0.85	12.97	12.01	0.96	12.89	12.23	0.66
5	12.96	12.14	0.82	13.01	12.16	0.85	12.90	12.28	0.62
6	13.06	12.28	0.78	13.07	12.29	0.78	12.95	12.27	0.68
7	13.09	12.40	0.69	13.12	12.46	0.66	13.05	12.29	0.76
8	13.16	12.48	0.68	13.13	12.41	0.72	13.10	12.32	0.78
9	13.35	12.69	0.66	13.23	12.49	0.74	13.21	12.38	0.83
10	13.50	12.38	1.12	13.22	12.59	0.63	13.26	12.18	1.08
11	13.75	12.66	1.09	13.14	12.32	0.82	13.08	12.64	0.44
12	13.83	12.61	1.22	13.05	12.55	0.50	13.07	12.60	0.47
13	13.30	12.59	0.71	13.09	12.14	0.95	13.04	12.49	0.55
14	13.25	12.53	0.72	13.06	12.37	0.69	13.22	12.38	0.84
15	13.64	12.79	0.85	13.39	12.31	1.08	13.36	12.54	0.82
16	13.85	12.56	1.29	13.51	12.47	1.04	13.35	12.36	0.99
17	13.56	11.93	1.63	13.46	12.04	1.42	13.22	12.04	1.18
Av.	13.30	12.34	0.96	13.08	12.24	0.84	13.09	12.31	0.78

TABLE XVII

MOISTURE CONTENT DATA FOR AERATION RATE OF 8.04 $L/s{\cdot}m^3$

	Column 1			Column 2			Column 3		
Depth	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc
1	12.63	12.08	0.55	12.61	11.71	0.90	12.85	12.26	0.59
2	12.81	11.94	0.87	12.88	12.00	0.88	13.15	12.43	0.72
3	12.74	12.09	0.65	13.33	12.10	1.23	13.52	12.55	0.97
4	12.69	11.86	0.83	13.33	12.21	1.12	13.31	12.43	0.88
5	12.79	11.92	0.87	13.40	12.20	1.20	13.25	12.43	0.82
6	12.85	12.00	0.85	13.51	12.25	1.26	13.17	12.40	0.77
7	12.98	12.12	0.86	13.47	12.41	1.06	13.19	12.38	0.81
8	13.13	12.20	0.93	13.45	12.43	1.02	13.23	12.41	0.82
9	13.25	12.35	0.90	13.44	12.46	0.98	13.26	12.31	0.95
10	13.09	12.54	0.55	13.64	12.17	1.47	12.88	12.80	0.08
11	12.99	12.45	0.54	13.53	12.19	1.34	13.17	12.75	0.42
12	13.09	12.45	0.64	13.68	12.18	1.50	13.19	12.64	0.55
13	13.25	12.25	1.00	13.53	12.03	1.50	13.17	12.52	0.65
14	13.26	12.16	1.10	13.47	12.15	1.32	13.03	12.16	0.87
15	12.78	12.34	0.44	13.19	12.09	1.10	13.07	12.45	0.62
16	12.96	12.30	0.66	13.03	11.67	1.36	12.81	12.37	0.44
17	13.12	12.11	1.01	13.16	11.75	1.41	12.63	12.00	0.63
Av.	12.97	12.19	0.78	13.33	12.12	1.21	13.11	12.43	0.68

TABLE XVIII

MOISTURE CONTENT DATA FOR AERATION RATE OF 10.72 L/s·m^3

	Column 1			Column 2			Column 3		
Depth	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc	mc_i	mc_f	Δmc
1	12.89	11.88	1.01	12.45	11.97	0.48	13.17	11.86	1.31
2	12.98	12.22	0.76	12.94	12.25	0.69	13.17	12.05	1.12
3	13.05	12.28	0.77	12.96	12.56	0.40	13.37	12.47	0.90
4	12.83	12.06	0.77	13.08	12.40	0.68	13.21	12.37	0.84
5	12.89	12.08	0.81	13.04	12.41	0.63	13.23	12.32	0.91
6	12.88	12.16	0.72	13.01	12.35	0.66	13.16	12.25	0.91
7	12.91	12.15	0.76	12.93	12.41	0.52	13.14	12.20	0.94
8	13.01	12.14	0.87	12.92	12.37	0.55	13.09	12.20	0.89
9	13.14	12.13	1.01	12.90	12.31	0.59	13.04	12.19	0.85
10	12.74	12.27	0.47	12.66	12.43	0.23	13.08	12.31	0.77
11	12.95	12.24	0.71	12.70	12.52	0.18	13.03	12.08	0.95
12	12.84	12.38	0.46	12.66	12.44	0.22	13.08	12.10	0.98
13	12.78	12.39	0.39	12.57	12.34	0.23	12.90	12.15	0.75
14	12.67	12.07	0.60	12.31	12.28	0.03	12.74	11.93	0.81
15	12.77	12.14	0.63	12.25	12.45	-0.20	12.91	12.06	0.85
16	12.65	12.11	0.54	12.29	12.49	-0.20	12.81	12.12	0.69
17	13.12	12.09	1.03	12.48	12.22	0.26	13.39	11.86	1.53
Av.	12.89	12.16	0.72	12.71	12.36	0.35	13.09	12.15	0.94

SAS
E-1
General Linear Models Procedure

Dependent Variable: Θ_T Θ_T vs. Q_a

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	5	140672.278	28134.456	5549.81	0.0001
Error	12	60.833	5.069		
C. Total	17	140733.111			

R-Square	C.V.	Root MSE	Θ_T Mean
0.99957	2.24655	2.25154	100.22222

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Q_a	5	140672.278	28134.456	5549.81	0.0001

SAS
E-2
General Linear Models Procedure

Dependent Variable: Θ_L Θ_L vs. Q_a

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	5	23218.236	4643.647	1932.62	0.0001
Error	12	28.833	2.40278		
C. Total	17	23247.069			

R-Square	C.V.	Root MSE	Θ_L Mean
0.99876	4.58531	1.55009	33.80556

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Q_a	5	23218.236	4643.647	1932.62	0.0001

SAS
E-3
General Linear Models Procedure

Dependent Variable: Θ_L Θ_L vs. ΔMC

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	713.016	713.016	0.08	0.7790
Error	16	140020.095	8751.256		
C. Total	17	140733.111			

R-Square	C.V.	Root MSE	Θ_T Mean
0.00507	93.34172	93.54815	100.22222

Source	DF	Type I SS	Mean Square	F Value	Pr>F
ΔMC	1	713.016	713.016	0.08	0.7790

SAS
E-4
General Linear Models Procedure

Dependent Variable: Θ_T Θ_T vs. ΔMC

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	191.412	191.412	0.13	0.7203
Error	16	23055.657	1440.979		
C. Total	17	23247.069			

R-Square	C.V.	Root MSE	Θ_T Mean
0.00823	112.290	37.970	33.806

Source	DF	Type I SS	Mean Square	F Value	Pr>F
ΔMC	1	191.412	191.412	0.13	0.7203

SAS
E-5
General Linear Models Procedure

Dependent Variable: Θ_T Θ_T vs. ΔT

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	6278.731	6278.731	0.79	0.4001
Error	16	134454.380	8403.399		
C. Total	17	140733.111			

R-Square	C.V.	Root MSE	Θ_T Mean
0.04461	91.46680	91.67005	100.22222

Source	DF	Type I SS	Mean Square	F Value	Pr>F
ΔT	1	6278.731	6278.731	0.79	0.4001

SAS
E-6
General Linear Models Procedure

Dependent Variable: Θ_L Θ_L vs. ΔT

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	554.732	554.742	0.39	0.5405
Error	16	22692.338	1418.271		
C. Total	17	23247.069			

R-Square	C.V.	Root MSE	Θ_L Mean
0.02386	111.40163	37.65994	33.8056

Source	DF	Type I SS	Mean Square	F Value	Pr>F
ΔT	1	554.732	554.742	0.39	0.5405

SAS
E-7
General Linear Models Procedure

Dependent Variable: ΔMC ΔMC vs. Q_a

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	5	0.16484	0.03296	0.95	0.4860
Error	12	0.41780	0.03481		
C. Total	17	0.58264			

R-Square	C.V.	Root MSE	ΔMC Mean
0.28293	23.7865	0.86592	0.78444

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Q_a	5	0.16484	0.03296	0.95	0.4860

SAS
E-8
General Linear Models Procedure

Dependent Variable: ΔMC ΔMC vs. ΔT

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	0.00045	0.00045	0.01	0.9128
Error	16	0.58219	0.03639		
C. Total	17	0.58264			

R-Square	C.V.	Root MSE	ΔMC Mean
0.00077	24.31709	0.19075	0.78444

Source	DF	Type I SS	Mean Square	F Value	Pr>F
ΔT	1	0.00045	0.00045	0.01	0.9128

SAS
E-11
General Linear Models Procedure

ΔT vs. Q_a

Duncan's Multiple Range Test for variable: ΔT

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha = 0.05 df = 12 MSE = 0.91833

Number of Means	2	3	4	5	6
Critical Range	1.702	1.782	1.836	1.865	1.886

Means with the same letter are not significantly different.

Duncan Grouping		Mean ΔT	N	Q_a
	A	19.00	3	1.34
	A			
B	A	18.50	3	2.68
B	A			
B	A	18.23	3	8.04
B				
B	C	16.93	3	0.67
	C			
D	C	16.43	3	5.36
D				
D		15.1	3	10.72

SAS E-12
Analysis of Variance

Dependent Variable: LOG10(Θ_T) Equation (22)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	2.74918	2.74918	1560.292	0.0001
Error	16	0.02819	0.00176		
C. Total	17	2.77737			

Root MSE	0.04198	R-square	0.9898
Dep Mean	1.87761	Adj. R-sq	0.9897
C.V.	2.29676		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	195.807	6.804	149.184	0.0001
Qa	1	-0.9144	0.0231	-39.501	0.0001

SAS E-13
Analysis of Variance

Dependent Variable: LOG10(Θ_L) Equation (21)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	4.82648	4.82648	741.415	0.0001
Error	16	0.10416	0.00651		
C. Total	17	4.93064			

Root MSE	0.08068	R-square	0.9789
Dep Mean	1.24363	Adj. R-sq	0.9776
C.V.	6.48772		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	72.2309	1.0704	62.946	0.0001
Qa	1	-1.21163	0.0445	-27.229	0.0001

SAS E-14
Analysis of Variance

Dependent Variable: LOG10(Θ_L) | Q_a = 10.72 | Θ_L vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	1.91342	1.91342	723.834	0.0001
Error	24	0.06344	0.00264		
C. Total	25	1.97686			

Root MSE	0.05141	R-square	0.9679
Dep Mean	0.37493	Adj. R-sq	0.9666
C.V.	13.71295		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	3.9002	0.1139	45.847	0.0001
X/L	1	1.2146	0.0451	26.904	0.0001

SAS E-15
Analysis of Variance

Dependent Variable: LOG10(Θ_L) | Q_a = 8.04 | Θ_L vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	2.15759	2.15759	792.695	0.0001
Error	24	0.06532	0.00272		
C. Total	25	2.22292			

Root MSE	0.05217	R-square	0.9706
Dep Mean	0.50665	Adj. R-sq	0.9694
C.V.	10.2972		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	5.4605	0.1623	56.253	0.0001
X/L	1	1.2854	0.0456	28.155	0.0001

SAS E-16
Analysis of Variance

Dependent Variable: LOG10(Θ_L) $Q_a = 5.36$ Θ_L vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	2.29720	2.29720	967.151	0.0001
Error	22	0.05225	0.00238		
C. Total	23	2.34945			

Root MSE	0.04874	R-square	0.9778
Dep Mean	0.63904	Adj. R-sq	0.9767
C.V.	7.62653		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	8.0908	0.2418	68.882	0.0001
X/L	1	1.2185	0.0392	31.099	0.0001

SAS E-17
Analysis of Variance

Dependent Variable: LOG10(Θ_L) $Q_a = 2.68$ Θ_L vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	2.09959	2.09959	2182.921	0.0001
Error	25	0.02405	0.00096		
C. Total	26	2.12364			

Root MSE	0.03101	R-square	0.9887
Dep Mean	1.28891	Adj. R-sq	0.9882
C.V.	2.40617		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	32.988	0.5818	196.445	0.0001
X/L	1	1.1346	0.0243	46.722	0.0001

SAS E-18
Analysis of Variance

Dependent Variable: LOG10(Θ_L) $Q_a = 1.34$ Θ_L vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	2.51874	2.51874	1993.907	0.0001
Error	23	0.02905	0.00126		
C. Total	24	2.54779			

Root MSE	0.03554	R-square	0.9886
Dep Mean	1.37963	Adj. R-sq	0.9881
C.V.	2.57619		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	45.978	0.9971	174.595	0.0001
X/L	1	1.2892	0.0289	44.653	0.0001

SAS E-19
Analysis of Variance

Dependent Variable: LOG10(Θ_L) $Q_a = 0.67$ Θ_L vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	2.99296	2.99296	9923.999	0.0001
Error	24	0.00724	0.00030		
C. Total	25	3.00020			

Root MSE	0.01737	R-square	0.9976
Dep Mean	1.74737	Adj. R-sq	0.9975
C.V.	0.99386		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	110.899	1.1507	451.411	0.0001
X/L	1	1.3903	0.0140	99.619	0.0001

SAS E-20
Analysis of Variance

Dependent Variable: LOG10(Θ_T) $Q_a = 10.72$ Θ_T vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	1.20725	1.20725	1153.577	0.0001
Error	26	0.02721	0.00105		
C. Total	27	1.23446			

Root MSE	0.03235	R-square	0.9780
Dep Mean	1.13708	Adj. R-sq	0.9771
C.V.	2.84504		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	19.993	0.3552	167.062	0.0001
X/L	1	0.8436	0.0248	33.964	0.0001

SAS E-21
Analysis of Variance

Dependent Variable: LOG10(Θ_T) $Q_a = 8.04$ Θ_T vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	2.00861	2.00861	508.996	0.0001
Error	28	0.11049	0.00395		
C. Total	29	2.11910			

Root MSE	0.06282	R-square	0.9479
Dep Mean	1.28871	Adj. R-sq	0.9460
C.V.	4.87457		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	31.376	1.0451	101.724	0.0001
X/L	1	0.7085	0.0314	22.561	0.0001

SAS E-22
Analysis of Variance

Dependent Variable: LOG10(Θ_T) $Q_a = 5.36$ Θ_T vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	1.61012	1.61012	995.051	0.0001
Error	28	0.04531	0.00162		
C. Total	29	1.65543			

Root MSE	0.04023	R-square	0.9726
Dep Mean	1.33705	Adj. R-sq	0.9717
C.V.	3.00857		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	33.331	0.7148	161.758	0.0001
X/L	1	0.6343	0.0201	31.544	0.0001

SAS E-23
Analysis of Variance

Dependent Variable: LOG10(Θ_T) $Q_a = 2.68$ Θ_T vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	1.04049	1.04049	2033.144	0.0001
Error	25	0.01279	0.00051		
C. Total	26	1.05329			

Root MSE	0.02262	R-square	0.9879
Dep Mean	1.79154	Adj. R-sq	0.9874
C.V.	1.26272		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	92.573	1.2348	337.213	0.0001
X/L	1	0.5317	0.0118	45.090	0.0001

SAS E-24
Analysis of Variance

Dependent Variable: LOG10(Θ_T) $Q_a = 1.34$ Θ_T vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	2.03884	2.03884	1247.787	0.0001
Error	26	0.04248	0.00163		
C. Total	27	2.08133			

Root MSE	0.04042	R-square	0.9796
Dep Mean	1.95261	Adj. R-sq	0.9788
C.V.	2.07017		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	153.496	3.5279	216.407	0.0001
X/L	1	0.7357	0.0208	35.324	0.0001

SAS E-25
Analysis of Variance

Dependent Variable: LOG10(Θ_T) $Q_a = 0.67$ Θ_T vs. X/L

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	1.32328	1.32328	1852.885	0.0001
Error	26	0.01857	0.00071		
C. Total	27	1.34185			

Root MSE	0.02672	R-square	0.9862
Dep Mean	2.25323	Adj. R-sq	0.9856
C.V.	1.18603		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	276.622	4.2271	365.167	0.0001
X/L	1	0.5938	0.0138	43.045	0.0001

SAS
E-26
General Linear Models Procedure

Dependent Variable: M Leading (from Figure 40)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	0.0042599	0.0042599	0.51	0.5152
Error	4	0.0335147	0.0083787		
C. Total	5	0.0377747			

R-Square	C.V.	Root MSE	M Mean
0.112772	7.29164	0.0915352	1.255343

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Q_a	1	0.0042599	0.0042599	0.51	0.5152

SAS
E-27
General Linear Models Procedure

Dependent Variable: M Trailing (from Figure 40)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	0.0288579	0.0288578	3.48	0.1355
Error	4	0.0331697	0.0082924		
C. Total	5	0.0620276			

R-Square	C.V.	Root MSE	M Mean
0.465242	13.49841	0.0910628	0.6746187

Source	DF	Type I SS	Mean Square	F Value	Pr>F
Q_a	1	0.0288579	0.0288578	3.48	0.1355

SAS E-28
Analysis of Variance

Dependent Variable: LOG10(Θ_{LL}) Equation (27)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	2	52.54935	26.27467	2393.745	0.0001
Error	151	1.65743	0.01098		
C. Total	153	54.20678			

Root MSE	0.10477	R-square	0.9694
Dep Mean	0.99338	Adj. R-sq	0.9690
C.V.	10.54662		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	72.119	2.4712	122.695	0.0001
X/L	1	1.2582	0.0352	35.762	0.0001
Q_a	1	-1.2053	0.0197	-61.046	0.0001

SAS E-29
Analysis of Variance

Dependent Variable: LOG10(Θ_{LT}) Equation (28)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	2	35.74312	17.87156	2764.810	0.0001
Error	168	1.08594	0.00646		
C. Total	170	36.82906			

Root MSE	0.08040	R-square	0.9705
Dep Mean	1.61840	Adj. R-sq	0.9702
C.V.	4.96779		

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	204.343	5.2140	205.817	0.0001
X/L	1	0.6493	0.0175	37.076	0.0001
Q_a	1	-0.9769	0.0145	-67.455	0.0001

SAS
E-30
General Linear Models Procedure

Dependent Variable: M Leading (Shumman)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	0.5760525	0.5760525	7.19	0.0551
Error	4	0.3204123	0.0801031		
C. Total	5	0.8964464			

R-Square	C.V.	Root MSE	M Mean
0.642582	5.653901	0.2830249	5.0058333

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	5.4149	0.1914	28.30	0.0001
Q_a	1	-0.0851	0.0318	-2.68	0.0551

SAS
E-31
General Linear Models Procedure

Dependent Variable: B Leading (from Schumman)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	0.0457935	0.0457935	5.56	0.0778
Error	4	0.0329358	0.0082340		
C. Total	5	0.0787293			

R-Square	C.V.	Root MSE	B Mean
0.581658	8.21683	0.0907412	-1.104333

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	-0.9890	0.0613	-16.12	0.0001
Q_a	1	-0.0240	0.0101	-2.36	0.0778

SAS
E-32
General Linear Models Procedure

Dependent Variable: M Trailing (Shumman)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	94.737636	94.737636	18.82	0.0123
Error	4	20.139551	5.0348878		
C. Total	5	114.87718			

R-Square	C.V.	Root MSE	M Mean
0.824686	18.26129	2.2438555	12.28750

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	7.0419	1.5171	4.64	0.0097
Q_a	1	1.0925	0.2518	4.34	0.0123

SAS
E-33
General Linear Models Procedure

Dependent Variable: B Trailing (from Schumman)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	0.2941898	0.2941898	1.79	0.2518
Error	4	0.6568636	0.1642159		
C. Total	5	0.9510533			

R-Square	C.V.	Root MSE	B Mean
0.309330	9.374667	0.4052356	4.3226667

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	4.6150	0.2740	16.84	0.0001
Q_a	1	-0.0609	0.0455	-1.34	0.2518

SAS E-34
General Linear Models Procedure

Dependent Variable: Y   Leading (from Schumman)   Equation (33)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	1	146.09097	146.09097	795.92	0.0001
Error	70	12.84847	0.18355		
C. Total	71	158.93944			

R-Square	C.V.	Root MSE	Y Mean
0.919161	19.01772	0.4284269	2.2527778

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	-1.0736	0.1283	-8.37	0.0001
Θ	1	5.0281	0.1782	28.21	0.0001

SAS E-35
General Linear Models Procedure

Dependent Variable: Y   Leading (from Schumman)   Equation (34)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	2	152.48714	76.24357	815.34	0.0001
Error	69	6.45230	0.09351		
C. Total	71	158.93944			

R-Square	C.V.	Root MSE	Y Mean
0.959404	13.57421	0.3057966	2.2527778

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	-1.0641	0.0916	-11.62	0.0001
Θ	1	5.5211	0.1405	39.30	0.0001
$\Theta \cdot Q_a$	1	-0.1192	0.0144	-8.27	0.0001

SAS E-36
General Linear Models Procedure

Dependent Variable: Y Trailing (from Schumman)

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Model	2	226.89496	113.44748	228.86	0.0001
Error	68	33.70813	0.49571		
C. Total	70	1260.603			

R-Square	C.V.	Root MSE	Y Mean
0.870653	9.765312	0.7040653	7.209856

Parameter Estimates

Variable	DF	Parameter Estimates	Standard Error	T for Ho: Parameter=0	Prob>|T|
Intercept	1	4.58903	0.1485	30.90	0.0001
Θ	1	6.88941	0.4376	15.74	0.0001
$\Theta \cdot Q_a$	1	0.73641	0.0953	7.73	0.0001

VITA

David Reid Epperly

Candidate for the Degree of

Doctor of Philosophy

Thesis: EFFECTS OF AIRLOW RATES ON COOLING TIME AND TEMPERATURE DISTRIBUTION IN AERATED WHEAT

Major Field: Agricultural Engineering

Biographical:

Personal Data: Born in Kansas City, Kansas, May 28, 1961, the son of Jean R. and Sylvia Epperly.

Education: Graduated from Hydro Public High School, Hydro, Oklahoma, in May, 1979; received Bachelor of Science Degree in Agricultural Engineering from Oklahoma State University in May, 1983; received Master of Science Degree in Agricultural Engineering from Oklahoma State University in May, 1985; completed requirements for the Doctor of Philosophy at Oklahoma State University in December, 1989.

Professional Experience: Teaching Assistant, Department of Agricultural Engineering, Oklahoma State University, January, 1982, to May, 1982, August, 1982, to May, 1983, and January, 1985, to May, 1985; Research Assistant, Department of Agricultural Engineering, Oklahoma State University, August, 1983, to May, 1985; PhD Fellow, Department of Agricultural Engineering, Oklahoma State University, August, 1985, to May 1989.