OPTIMAL SIZING OF A COUNTERFLOW

COOLER FOR FEED PELLETS

By:

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B.S. Biosystems Engineering

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2004

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2008

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COOLER FOR FEED PELLETS

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Acknowledgments

The author would like to thank the following people: his advisor, Dr. Tim Bowser, for his help, support, and patience during the duration of the project, the members of the author's graduate committee, Drs Raymond Huhnke and Danielle Bellmer for their input and recommendations as the author progressed through development of the model included in this research, the personnel currently and formerly employed at Bliss Industries that assisted the author throughout this research, Dr. John te Velde and Miss Carla Beckmann for their assistance in translating a research article originally published in German, and the author's family and fiancé for their invaluable support, assistance, and patience.

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Symbol	Description	Units
T	Air Temperature	^{o}C
Θ	Pellet Temperature	^{o}C
W	Absolute Air Humidity	decimal (kg/kg)
$\overline{M}$	Average Pellet Moisture Content (d. b.)	decimal (kg/kg)
x	Cooler Bed Depth	inches
t	time	seconds
h'	Convective Heat Transfer Coefficient	W/m^2K
a	Specific Surface Area	1/m
G_a	Air Flow Rate	kg/hm^2
G_p	Pellet Flow Rate	kg/hm^2
c_a	Specific Heat of Air	kJ/kgK
c_p	Specific Heat of Pellets	kJ/kgK
c_w	Specific Heat of Water	kJ/kgK
c_v	Specific Heat of Water Vapor	kJ/kgK
h_{fg}	Latent Heat of Vaporization of Water	kJ/kg
L_{bed}	Total Bed Depth	inches
d_{bed}	Cooler or Bed diameter	inches
n_i	Number of Iterations	n/a
n_s	Number of Finite Differences	n/a

Symbol	Description	Units
M_{eq}	Moisture Equilibrium Content (d. b.)	decimal (kg/kg)
D	Diffusivity	m^2/s
F	Linearization Factor	s/in
rh	Relative Humidity	decimal
P_v	Vapor Pressure	N/m^2
P_s	Saturation Pressure	N/m^2
R_v	Ideal Gas Constant for Water	J/kg K
μ_a	Air Viscosity	kg/m s
ρ_b	Bulk Density	kg/m^3
ρ_p	Pellet Density	kg/m^3
d_p	Pellet Diameter	inches
L_p	Pellet Length	inches
r_p	Pellet Radius	inches

1) Introduction

Bliss Industries Inc. currently manufactures and sells a product they call OP><FLO coolers, shown in Figure 1. 1. The OP><FLO coolers use a counter flow process to cool and dry livestock feed pellets immediately after they have been extruded. Warm, high moisture content pellets enter the cooler from above while ambient air is pulled into the cooler from below. The ambient air is gradually warmed as it moves up through the falling product stream. Therefore, when the product enters the cooling chamber it is exposed to the warmest air in the cooler that has the highest moisture carrying capacity. The product is then exposed to gradually cooler air as it makes its way down the cooler. (Bliss Industries Inc., 1999).

Figure 1. 1 An illustration of an OP><FLO cooler currently designed and manufactured by Bliss Industries (Bliss Industries Inc., 1999)

Bliss Industries contacted the Applications Engineering program at Oklahoma State University for assistance. The Applications Engineering program is designed as an outreach program to provide engineering services to small companies in Oklahoma. Bliss Industries needed assistance in sizing their OP><FLO cooler for ambient conditions, desired product flow, and other design parameters. Currently, engineers at Bliss Industries estimate appropriate sizes for this product according to past experience, but this practice occasionally results in models that are not correctly sized, service calls from unsatisfied clients, increased costs, and other difficulties for Bliss Industries personnel. Bliss Industries asked the Applications Engineering program for their help in developing

a system to more effectively determine an appropriate size of an OP><FLO cooler for particular installations.

The Applications Engineer, Mr. Clay Buford, contacted the author's advisor, Dr. Tim Bowser, for help in developing an OP><FLO cooler sizing system. The need for such a system was then presented to the author as a potential topic of research. The author's interest in computer programming, mathematics, and the livestock and feed industries made the decision to pursue this research a simple one.

Dr. Bowser, Mr. Buford, and the author traveled to Bliss Industries on October 6, 2005 and met with Bliss Industries engineers, Patrick Hensley and David Holt, and owner, Bill Bliss. The need for better tools to help optimally size OP><FLO coolers was the main topic of discussion. Bliss Industries had not been able to allocate the time and resources necessary to develop such tools and has requested assistance in this matter. The author agreed to develop a tool to help Bliss Industries determine the optimal size of an OP><FLO cooler.

Mathematically describing what occurs in the OP><FLO cooler and how ambient conditions affect the cooler's operation would be beneficial to Bliss Industries when determining the appropriate cooler size for a client. Estimates of the moisture and temperature profiles of air and pellets inside a cooler would assist Bliss Industries in determining the ability of a cooler to meet the final moisture content and temperature specifications of a client. Development of a model to estimate the heat and moisture transfer that occurs in an OP><FLO cooler would likely involve gradients with respect to multiple parameters. A computer program or model to estimate an appropriate cooler size

based on ambient conditions of operation, type of product being cooled and conditioned, and desired production capacity would meet the needs of Bliss Industries.

In this research the author has combined the efforts of other engineers, modern computer processing capability, simple numerical integration techniques, and easily accessible software to develop a tool to meet the needs of Bliss Industries. This research uses models developed to describe the cooling and drying of grains which have been modified to describe feed pellets. Using these models, the author has developed and tested a system that can be used to estimate the temperature and moisture profiles for feed pellets in an OP><FLO cooler with any given cooler diameter, bed depth, pellet size, air flow, product capacity, input temperature, input moisture content, and ambient conditions.

2) Objectives

The primary objective of this research is to develop a tool that will help Bliss Industries determine the appropriate size for an OP><FLO cooler based on ambient conditions of operation, products to be conditioned (livestock feed pellets ranging from 11/64” to 3/4” in diameter), and desired production measured in tons of product per hour. The tool must be useful, inexpensive, and easily accessible for Bliss Industries. The other main objective of this research is to validate the ability of the tool to accurately describe the cooling process of feed pellets using data from current OP><FLO cooler installations.

3) Literature Review

3.1) Livestock Feed

The feeding of livestock is a large and diverse industry in the United States and worldwide. On average, about 250 million tons of materials are fed to livestock animals each year in the US, and about 600 million tons are fed to livestock worldwide. This includes material fed to cattle, pigs, chickens, sheep, and goats (USDA, 2005).

Most livestock feed is in the form of grains, roughages, compound feed, and additives. Whole grains often include corn, oats, wheat, and barley. Roughages are often celluloid material ranging from hay to cotton seed hulls. Compound feeds are combinations of various processed grains, roughages, and additives that are processed and blended together for optimum nutrition. Compound feed is often fed in the form of meal, crumbles, or pellets. Additives often include protein supplements, trace minerals, oils, or other concentrated nutrients specific to the species and environment.

Feed pellets, the main focus of this research, encompass a significant portion of the livestock feed industry. The United States Department of Agriculture (USDA) conducted a survey of agricultural cooperatives in 2004, and found an estimated 7 billion dollars of livestock feed was sold in the US in 2004. At least 14% of the feed sold was in the form of pellets. This translates into at least one billion dollars of pellets sold in the US. Additionally, these statistics do not account for pellets produced on site at large livestock producers and not sold (Eversull, 2005).

3.2) The Pelleting Process

The purpose of pelletizing grains and roughages for livestock feed is to increase the efficiency, digestibility, and palatability of these foodstuffs. Pellet shaped feed allows for easier and more efficient consumption by the animal. Additionally the process through which the material is steamed, heated, and formed into pellets breaks down the contents of the pellet for palatability and digestion purposes (Harper, 1998).

Producing pellets from feedstuffs is an integral system combining steps of size reduction, conditioning, pelleting, and cooling (Thomas, 1997). During the conditioning step materials are treated with heat, steam, binders, and other additives that allow smaller particles to combine into larger ones. Once the material is conditioned, it passes into a pelletizing mill where it is extruded into cylindrical particles. After the pellets have been extruded they pass into a cooler where the pellets are simultaneously cooled and dried (Robinson, 1983).

The cooling and drying process is a crucial step in the production of feed pellet products. Large amounts of energy and cost have been added to pellets prior to the cooling and drying process (Harper, 1998). Using a dryer that requires a minimal amount of energy input is desirable to keep the production costs of pellets as low as possible. Additionally, when pellets are properly cooled and dried, they are less likely to produce dust, commonly called fines, or spoil from microbial and fungal growth. Fines are undesirable since they require more effort for the animal to consume and are more likely to be wasted. Fines also pose both safety and management issues in handling of the pellets. Fines and spoilage are both problems that can be minimized through proper cooling and drying of pellets.

Various factors affect the cooling and drying process of feed pellets. Very little research appears in the literature specifically on the cooling and drying of feed pellets. However, the studies that can be found in the literature conclude that the behavior of feed pellets can often be closely approximated with expressions developed for grains and oilseeds: Robinson (1983); Biagi (1986); Maier (1988), and the cooling and drying process of grains and other food products is essentially a mass and energy balance (Brooker et al. 1992). Therefore the amount of energy in the air and pellets as well as the amount of moisture in both the pellets and the air directly affect the cooling and drying process. Also the method(s) of heat and mass transfer being employed: conduction, convection, absorption, adsorption, etc. significantly affects the cooling and drying process in foods and grains (Heldman and Lund, 2007). Thus the type of cooler being used and the methods of heat and mass transfer the cooler design employs will impact the cooling and drying process of feed pellets. Finally, if the pellets are cooled too quickly, a dry crust will form on the surface of the pellet that will hinder moisture migration out of the pellet and leave the pellet core soft and moist. Once a pellet with this soft moist core is allowed to reach equilibrium, the pellet will become brittle and produce excess fines (Hensley, 2006). Thus, factors that affect the performance of a pellet cooler can be summarized as: cooler type, air flow rate, air temperature, air humidity, pellet flow rate, pellet temperature, pellet moisture content, and pellet size (Maier, 1988).

There are various types of coolers that can be used to cool and dry pellets once they leave the mill. Some of the classic designs include: vertical style cooler, horizontal or belt style cooler, mixed rotary style cooler, and counter flow cooler (Maier, 1988). All of these designs use air as a convection and advection medium, but each design uses different means of exposing the pellets to the air. The four main methods for exposing pellets to drying air are the same as the four main drying methods used in grains: cross flow, concurrent flow, counter flow and mixed flow (Brooker et al. 1992). Figure 2. 1 shows how each method exposes the product to the cooling air.

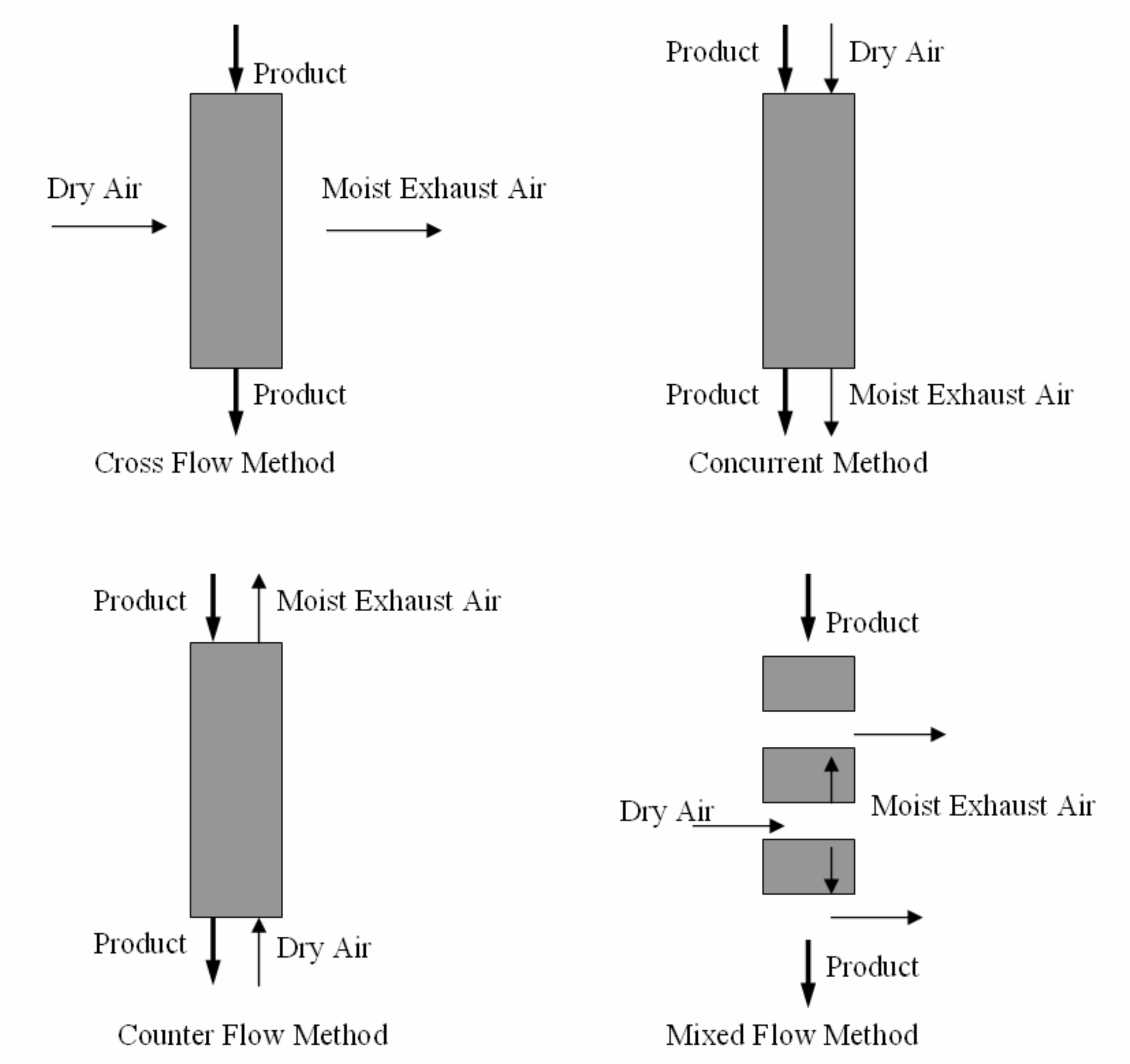

Figure 2. 1 The four major grain drying methods (Brooker et al. 1992)

The various types of cross flow coolers are described in Maier (1988). The cross flow cooler is often implemented in two styles: vertical and horizontal. Both models have large airflow requirements In the vertical model, a product moves by gravity through an air stream which flows perpendicularly through the product stream. The horizontal model takes up large amounts of floor space, and air is drawn up through a perforated conveyor belt that carries the product from the inlet to the outlet of the cooler. To minimize the floor space requirement of horizontal coolers, additional "decks" can be added. Figure 2.2 illustrates the cross flow methods often employed in pellet coolers.

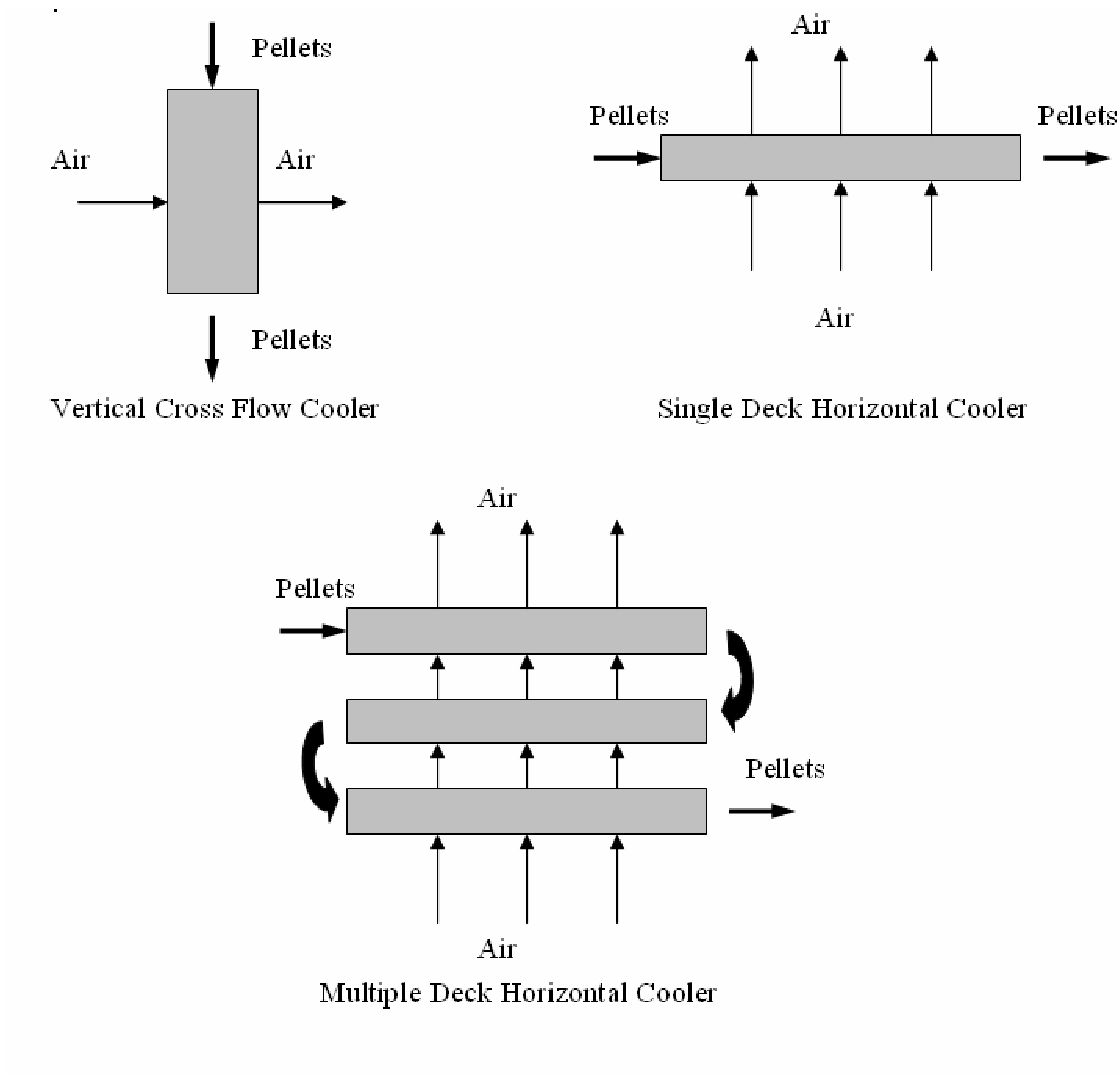

Figure 2. 2 Cross Flow methods of grain and pellet drying and cooling

The concurrent cooler method is used in grain drying and requires a heated air stream to dry the product and a cool air stream to lower the final temperature of the product. Initially the product is conveyed horizontally and heated with high temperature air stream that flows in the same direction as the product stream. After the product has been dried it is then exposed to a stream of cold air to cool the product. This method does require additional energy to increase the temperature of the air, but it does provide excellent uniformity in the drying of the product (Brooker et al. 1992).

The mixed rotary style cooler provides some of the advantages of both horizontal and vertical cross flow coolers. Similar to a horizontal cross flow cooler, control of bed depth and residence time of the pellets in the cooler can be achieved by adjusting the speed of the cooler. However the space requirement of the mixed flow cooler is small similar to the vertical cross flow cooler (Maier, 1988).

The OP><FLO cooler, the topic of this research, incorporates a counter flow design. Maier (1988) and Bliss Industries Inc. (1999) both cite the advantages of counter flow coolers to include: small space, low energy, and low maintenance requirements. An illustration of an OP><FLO cooler is seen in Figure 2. 3:

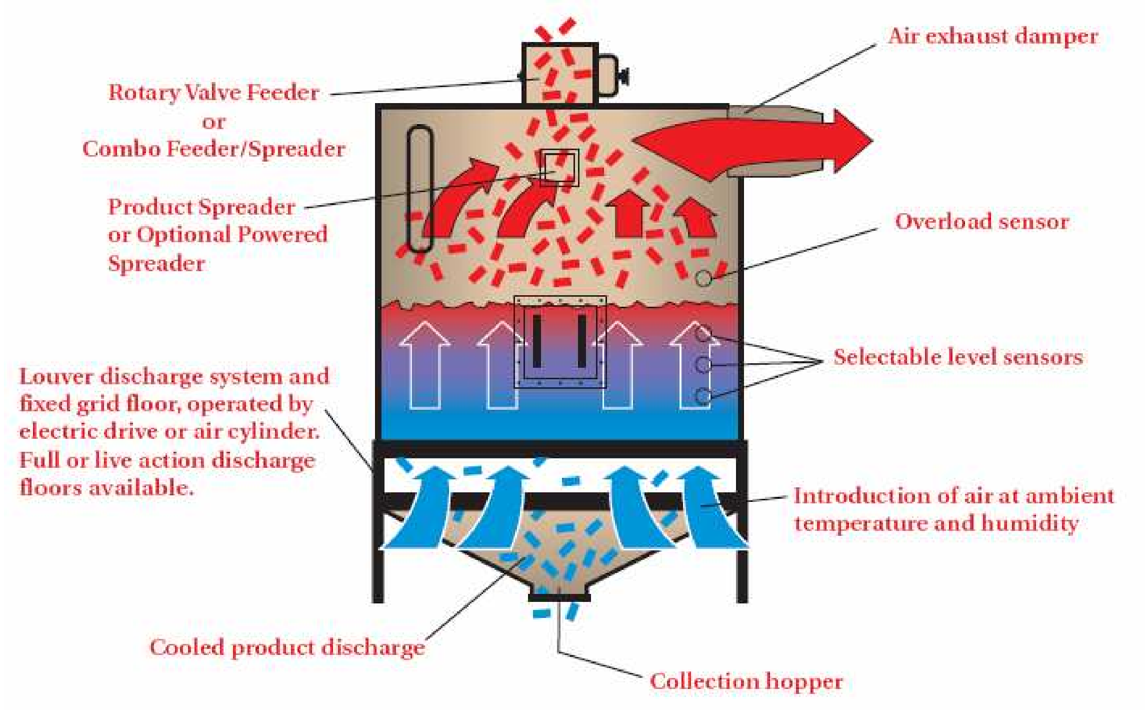

Figure 2. 3 A cross sectional representation of an operating OP><FLO cooler which incorporates a counter flow design (Bliss Industries Inc., 1999).

After the cooling and drying process, any fines that are carried off by the cooling air separated by a cyclone separator and may be returned to the product stream to be conditioned and pelletized again. The cooled and dried pellets are subjected to a sorting process where more fines can be removed from the final product. Finally the pellets are then stored in bins or bagged for transportation (Maier, 1988).

3.3) Mathematical and Computer Models

Models can be useful tools to predict the cooling and drying of livestock feed pellets. A model can be defined as a representation of a process or phenomena. In the case of computer modeling, a computer is used to calculate mathematical approximations that can be used to describe and estimate the behavior of a particular system of interest. Often we can obtain or approximate the rate of change of a particular dependent variable (temperature, concentration, velocity, etc.) with respect to some independent variable (time, distance, etc.). Numerical integration methods, such as the Euler method, can then be used to approximate values for the dependent variable with respect to the independent variable (Davis and Rabinowitz, 1984). Numerical integration computer models can be used in various facets of agricultural and biological engineering such as the heat and mass transport that takes place in a feed pellet cooler.

Mathematical models for counter flow coolers exist in the literature. Some models describe counter flow water cooling towers used in power generation and refrigeration (Ren, 2006; Kloppers and Kröger, 2005), but these models do not address the issue of drying biological material. Other models deal with counter flow cooling of biological material, but do not use air as the cooling medium (Chern, 1989) or do not consider feed pellets (Bruce and Giner, 1993). However, one model in particular focuses specifically on the counter flow cooling and drying of feed pellets. This model was developed to determine the factors that may influence the design of counter flow feed pellet coolers (Maier, 1988). Maier (1988) developed a counter flow computer model almost twenty years prior to this project, but the processing capability of most computers has increased significantly during that time period (Morley and Parker, 2006). The complexity of Maier's (1988) model was limited by the large execution time that would be required on the microcomputers available at that time. However, the work done by Maier (1988) provides an incredible foundation for the development of a model to describe the counter flow cooling and drying process of livestock pellets.

Maier (1988) was able to conclude that the bed depth and residence time are "the most significant design parameters" for a counter flow cooler. Maier (1988) also concluded that initial cooling temperature has a significant impact on the heat and mass transfer phenomena occurring in the cooler, but the initial relative humidity of the cooling air is of “minor importance in the design of a counter flow pellet cooler”(Maier, 1988). The OP><FLO coolers have sensors that determine the bed depth inside the cooler and control systems that keep the bed depth constant (Bliss Industries Inc., 1999). The constant bed depth provides a significant amount of control on the cooling and drying process by regulating the residence time of the pellets in the cooler.

4) The Computer Model

The model developed in this research is designed to operate in Microsoft Excel 2003, simply referred to as Excel. The model used advanced, custom programmed macros and custom programmed functions written in Visual Basic for Applications or VBA. The decision to use Excel and VBA was based on several factors: many small businesses currently use this software for other everyday purposes (Morley and Parker, 2006), Excel and VBA are capable of complex calculations, Excel is capable of displaying information graphically to allow simple interpretation of the modeling process, the use of Excel would prevent the need to purchase costly specialized data analysis software, and the author has considerable experience in custom macro programming in VBA and Excel.

The model developed in this research uses a set of input variables to estimate the temperature and moisture profiles of the air and pellets in the OP><FLO cooler. These input variables are dependent on the need of the client considering the purchase of an OP><FLO cooler and their geographic location. These input variables include desired production capacity, air flow in the cooler, initial temperature and moisture content of the newly formed pellets, pellet dimensions and density, ambient air temperature and relative humidity, and the amount of space available for the cooler in the form of bin diameter and bed depth.

Bliss Industries personnel can assign values for the client's desired production capacity, pellet dimensions, initial pellet moisture content, and initial pellet temperature in appropriate fields in the model. Then they will select an OP><FLO cooler model based on space that a client has available and the client's budget. Values for bin diameter, bed depth, and airflow specific to the selected OP><FLO model will be placed into the model. Finally, appropriate values for average ambient temperature and relative humidity must be determined for the client's geographic location. The model can then provide information about the moisture and temperature profiles of the pellets and the air inside the cooler. Most importantly, the model will provide estimates of the final moisture content and temperature of the pellets as they exit the cooler. Bliss Industries will then be able to adjust values of bed depth, bin diameter, and air flow to determine the optimal size of a cooler to meet the needs of a client.

After an approximate cooler size has been determined for the average ambient conditions of a client's geographic location, the temperature and relative humidity values can be adjusted to determine how well a cooler will perform in extreme, less than ideal conditions such as high humidity or sub-zero temperatures. A client will adjust the airflow in a working OP><FLO cooler to control the final moisture content and temperature of the pellets in varying ambient conditions (Locke, 2008). Therefore, Bliss Industries personnel will be able to adjust the airflow value and use the model to estimate how a cooler will perform in a wide variety of conditions. If the cooler does not perform at an acceptable level in less than ideal conditions, a larger cooler model may be needed.

The calculations in this research are carried out in SI units with the exceptions of bed depth which will be measured in inches and the input variables will use American customary units. These exceptions are for the convenience of Bliss Industries since their literature and equipment are specified in the American customary system.

Bliss Industries provided the author with data from OP><FLO coolers currently in use at various geographic locations. Unfortunately, most of the information was for OP><FLO coolers used to process wood pellets. Since the focus of this research is OP><FLO coolers used for livestock feed pellets, most of the information was not useful. The information that was provided for coolers used on livestock feed pellets can be seen in Appendix A. This information not only provides example values for all input variables for the model, but also provides calibration and validation data.

While the information in Appendix A will be useful for this study, the data provided by Bliss Industries is limited. Information was only provided for three OP><FLO coolers that process feed pellets. Additionally, the data for final moisture content and temperature of the product are based on “customer feedback” (Locke, 2008), and no further information was provided regarding how the data was measured or obtained.

The equations for counter flow cooling of grains and oilseeds can be found in Brooker et al. (1992). These equations use thermodynamic principles to describe the rate of heat and water vapor transport out of the grain particles and into the cooling air. However several studies in the literature conclude that the behavior of livestock feed pellets can be adequately described using approximations developed for grains and oilseeds (Robinson, 1983; Biagi, 1986; Maier, 1988). These conclusions are supported intuitively by the fact that feed pellets are primarily composed of grains and oilseeds. These equations have been successfully implemented in previous computer models for the drying and cooling of grains (Bruce and Giner, 1993) and feed pellets (Maier, 1988). The counter flow equations are:

$$\frac{dT}{dx} = \frac{h'a}{G_a c_a + G_p c_v W}(T - \Theta) \qquad 4.1$$

$$\frac{d\Theta}{dx} = \frac{h'a}{G_p c_p + G_p c_w \overline{M}}(T - \Theta) - \frac{h_{fg} + c_v (T - \Theta)}{G_p c_p + G_p c_w \overline{M}} G_a \frac{dW}{dx} \qquad 4.2$$

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

$$\frac{d\overline{M}}{dt} = \text{A single kernel drying equation} \qquad 4.4$$

Where h' represents the convective heat transfer coefficient measured in W/m^2K, a represents the specific surface area measured in m^{-1}, T represents the temperature of air measured in ^oC, Θ represents the temperature of the pellets measured in ^oC, G_a represents the airflow in the cooler measured in kg/hm^2, c_a represents the specific heat of air measured in kJ/kgK, G_p represents total pellet flow in the cooler measured in kg/hm^2, c_v represents the specific heat of water vapor measured in kJ/kgK, W represents the absolute humidity of air measured in kg/kg, h_{fg} represents the latent heat of vaporization measured in kJ/kg, c_p represents the specific heat of pellets measured in kJ/kgK, c_w represents the specific heat of water measured in kJ/kgK, $\overline{M}$ represents the average moisture content of pellets (dry basis) measured in kg/kg, x represents the bed depth or position in the cooler measured in inches, and t represents time measured in seconds. Equation 4.4 is often presented this way in the literature and defined later since every product will have a different drying equation (Brooker et al. 1992). Since the OP><FLO coolers operate at steady state, it can be assumed that time, t, can be linearly related to position, x. It is also assumed that all four dependent variables of the major dependent variables: T, Θ, W, and $\overline{M}$ are dependent only on x, and are therefore constant across the entire area of the cooler for any value of x.

A set of four differential equations requires four boundary conditions to reach a solution. The boundary conditions used for this model are the air properties entering the bottom of the cooler and the product properties entering the top of the cooler:

$$T(L_{bed}) = T_{ambient} \qquad 4.5$$

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

$$W(L_{bed}) = W_{ambient} \qquad 4.7$$

$$\overline{M}(0) = \overline{M}_{initial} \qquad 4.8$$

An x value of zero is used for the top of the cooler, the point where the product enters the cooler. The value of x increases as the product moves down the column. The value L_{bed} indicates total bed depth. Currently Bliss uses 40-60 inches for L_{bed} in their OP><FLO coolers (Bliss Industries Inc., 1999).

There are several methods available in the literature to describe equation 4.4. Crank (1975), provides a theoretical expression for diffusion in cylindrical particles. Brooker et al., (1992), further refines Crank's (1975) solution to:

$$\overline{M}(t) = M_{eq} + \left(\overline{M}(0) - M_{eq}\right)\left(\sum_{n=1}^{\infty} \frac{4}{\lambda_n^2} \exp\left[-\lambda_n^2 Dt\right]\right) \qquad 4.9$$

Where λ_n represents the roots of the zero order Bessel function, M_{eq} represents the equilibrium moisture content (dry basis), and D represents the diffusivity.

Another method requires the use of finite differences on individual pellets for varying values of pellet radius, r (Maier, 1988). This method uses a theoretical diffusion equation that can also be found in Brooker et al., (1992):

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial r} + \frac{1}{r}\frac{\partial M}{\partial r}\right) \qquad 4.10$$

Where M is the local moisture content (dry basis). To solve equation 4.10, it can be assumed that the surface of the pellet is always at equilibrium with the surroundings and the moisture content of the pellet core does not change. The solution to equation 4.10 can then be used to determine the average moisture content at any value of x within the cooler bed.

Equations 4.9 and 4.10 require an expression for diffusivity, D. Expressions for diffusivity of feed pellets were proposed by both Maier (1988) and Biagi (1986). Biagi (1986) determined experimentally that the diffusivity of feed pellets could be approximated by:

$$D = \left(1.015\times10^{-5}\frac{m^2}{h}\right)\exp\left(\frac{-547K}{\Theta_{abs}}\right) \quad 4.11$$

Maier (1988) concluded a more appropriate diffusivity approximation could be obtained by modifying an expression developed for corn by Chu and Hustrulid (1968):

$$D = C\left(1.513\times10^{-4}\frac{m^2}{h}\right)\exp\left(\left(-5.47+0.45\Theta_{abs}\right)M - \frac{2513K}{\Theta_{abs}}\right) \quad 4.12$$

Maier (1988) proposed using a value of C = 3 for feed pellets.

Both of these methods for estimating drying rates were determined infeasible for this research. Results of numerical integration experiments using equation 4.9 yielded slow drying rates and did not support data provided by Bliss describing the input and output conditions of OP><FLO coolers currently in use. Implementing equation 4.10 would further increase the complexity and run time of the model. A simple drying equation that more closely matched the data provided by Bliss was desired for this research.

Brooker et al., (1992), offers an expression that "is often used in grain drying analysis" and is "analogous to Newton's Law of Cooling":

$$\frac{d\overline{M}}{dt} = k\left(\overline{M} - M_{eq}\right) \quad 4.13$$

where:

$$k = A\exp\left(-\frac{5023R}{\Theta_{abs}}\right) \quad 4.14$$

The drying constant, k, has units of s^{-1} and Θ_{abs} has units of R. The recommended value of the drying coefficient, A, for corn is 0.54 (Pabis and Henderson, 1961).

A more commonly used and simpler form of equation 4.13 can be obtained by assuming that equilibrium moisture content is a constant value (Brooker et al., 1992):

$$\overline{M}(t) = M_{eq} + \left(\overline{M}(0) - M_{eq}\right)\exp[-kt] \quad 4.15$$

Equation 4.15 does not accurately predict the drying of grains due to low initial drying rates (Brooker et al., 1992). However, in OP><FLO and other counter flow coolers, the product is initially exposed to air the highest moisture carrying capacity inside the cooler (Bliss Industries Inc., 1999). This would indicate that M_{eq} is not constant in counter flow coolers. More likely, the value of M_{eq} will be small at low values of x and increase as x increases. Therefore, equation 4.15 was not valid for this research, and the differential form, equation 4.13, should be used with a variable M_{eq}. Using a variable M_{eq} could cause the initial drying rates to increase.

Combining equations 4.4, 4.16, and 4.17 yields:

$$\frac{d\overline{M}}{dx} = A\exp\left(-\frac{5023R}{\Theta_{abs}}\right)\left(\overline{M} - M_{eq}\right)F \qquad 4.\ 16$$

The linearization factor, F, is based on the concept of mass continuity in a steady state device (Cengel and Boles, 2006). It can be assumed that the position in the cooler and time are related linearly by a factor, F that has units of s/in and can be defined as:

$$F = 15971\left(\frac{\rho_B}{G_p}\right) \qquad 4.\ 17$$

In order to implement equation 4.17, it was necessary to describe the equilibrium moisture content of the pellets as a function of bed depth or as a function of other parameters that are only dependent on bed depth. Information in the literature regarding the equilibrium moisture content of livestock feed pellets is scarce. The only available data are sorption isotherms published by Friedrich (1980). Figure 4. 1 shows Friedrich's (1980) sorption isotherms and commonly used expressions for M_{eq} of grains and oilseeds as depicted in Maier (1988).

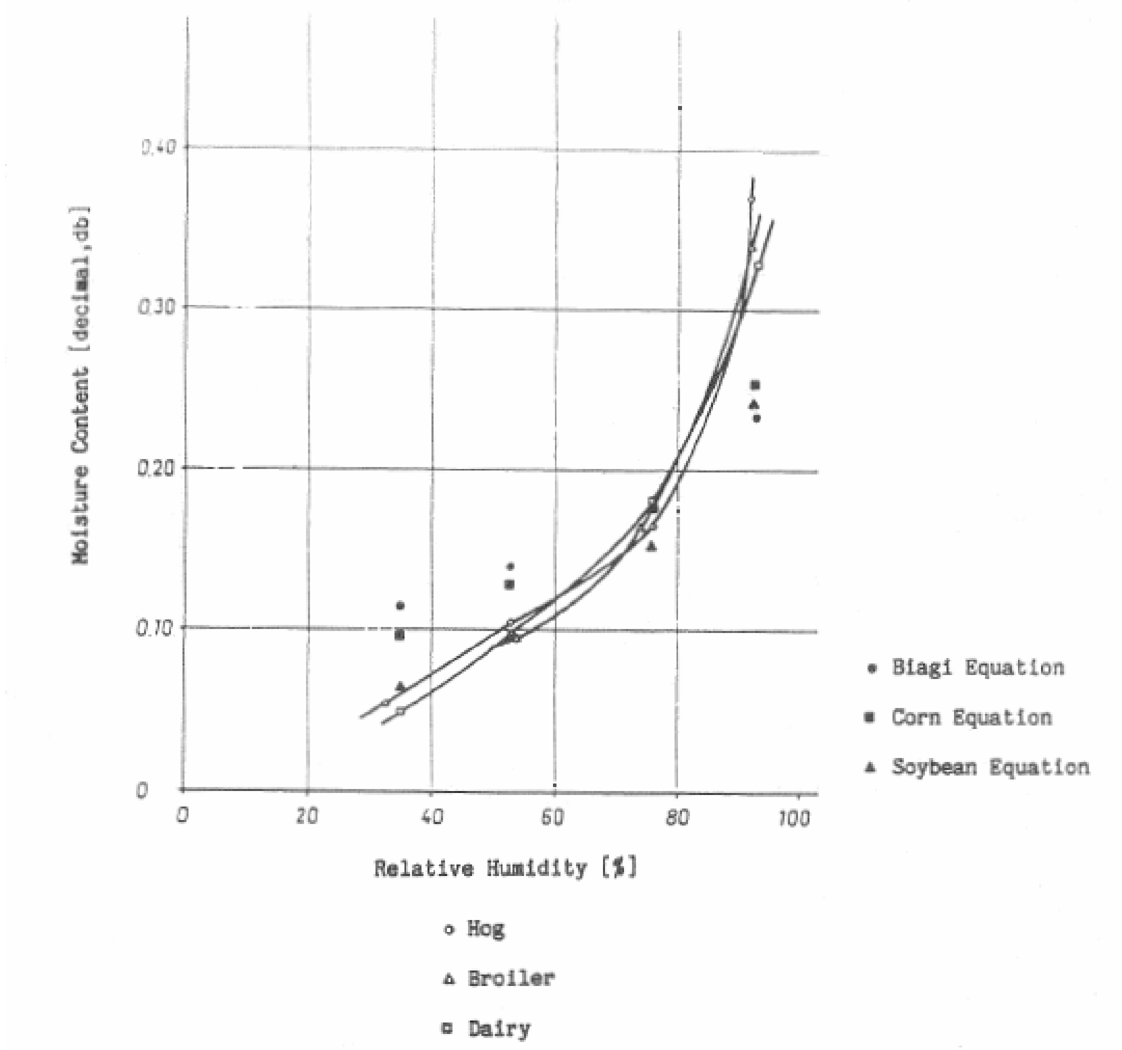

Figure 4. 1 A comparison of sorption isotherms of livestock feed pellets and equilibrium moisture content equations (Maier, 1988)

In Figure 4. 1 Maier (1988) compared the sorption isotherms of hog, dairy, and broiler feed pellets published by Friedrich (1980) with various moisture equilibrium content equations. It can be concluded that the expression for moisture equilibrium content of soybeans closely approximates the moisture equilibrium content of feed pellets (Maier, 1988). The equilibrium content of soybeans can be estimated by (Brook and Foster, 1981):

$$M_{eq} = 0.375314 - 0.066816 \ln(-1.98\,(T + 24.576)\ln(rh)) \quad 4.18$$

Relative humidity, rh, can be defined as the ratio of the amount of water being carried by the air and the total amount of water that the air can carry (Ramaswami et al. 2005). It can also be defined as (ASABE, 2005):

$$rh = \frac{P_v}{P_s} \quad 4.19$$

Where P_v, represents the vapor pressure and P_s represents the saturation pressure. The vapor pressure can be defined as:

$$P_v = \frac{P_{atm} W R_v}{287 + W R_v} \quad 4.20$$

Where the atmospheric pressure, P_{atm}, is in Pa, and R_v is the ideal gas constant for water vapor and has a value of 416.95 J/kgK. The saturation pressure, P_s, can be estimated by (ASABE, 2005):

$$P_s = 22{,}105{,}649.25 + \exp\left(\frac{A + BT + CT^2 + DT^3 + ET^4}{FT - GT^2}\right) \quad 4.21$$

Where A = -27,405.526, B = 97.5413, C = -0.146244, D = $0.12558\text{x}10^{-3}$,

E = $-0.48502\text{x}10^{-7}$, F = 4.34903, and G = $0.39381\text{x}10^{-2}$ (ASABE, 2005).

After obtaining a complete expression for equation 4.4, it was now necessary to define other parameters in the model equations. Values for the specific heat of air, water, and water vapor were readily available in a Thermodynamic text. Since the temperature change of the pellets and air is small in an OP><FLO cooler, constant values for the specific heats of air, water, and water vapor were appropriate. Specific heat values used in this research have units of kJ/kg ^{o}C and were approximated numerically as: c_a = 1.0057 c_v = 1.889 and c_w = 4.186 (Cengel and Boles, 2006).

The specific heat of grains is a function of moisture content, and it seems reasonable that the specific heat of feed pellets is dependent on moisture content as well. It can be assumed that the specific heat of corn kernels will be similar to the specific heat of feed pellets (Maier, 1988). In units of kJ/kg ^{o}C, an appropriate expression for the specific heat of pellets is (Brook and Foster, 1981):

$$c_p = 1.465 + 3.559\overline{M} \qquad 4.22$$

The latent heat of vaporization in grains refers to the amount of energy necessary to vaporize water so that it can be carried out of the grain. The latent heat of vaporization for grains was estimated by (Brook and Foster, 1981):

$$h_{fg} = (2542.1 - 2.384T)(1 + A\exp(-B\overline{M})) \qquad 4.23$$

The latent heat of vaporization is measured in units of kJ/kg, T is in Celsius and the average moisture content is a dry basis decimal. Values for the constants, A and B, are not available for feed pellets, but it can be assumed that pellets will behave similar to corn (Maier, 1988). Thus A = 1.2925 and B = 19.961 (Brook and Foster, 1981).

An expression for the convective heat transfer coefficient, h', in packed beds of cylinders was determined by Barker (1965). A version of Barker's (1965) equation appropriate for grains is (Brooker et al., 1992):

$$h' = AC_aG_a\left(\frac{d_pG_a}{\mu_a}\right)^B \qquad 4.24$$

Where the air viscosity, μ_a, can be calculated as (Brooker et al., 1992):

$$\mu_a = C + DT \qquad 4.25$$

For SI units, the coefficients for grains are as follows: A = 0.2755, B = -0.34,

C = 0.06175, and D = 0.000165.

The specific surface area, a, is defined as the amount of surface area per unit volume of the cooling bed. For cylindrical pellets the specific surface area can be approximated as (Maier, 1988):

$$a = \left(1 - \frac{\rho_b}{\rho_p}\right)\left(\frac{2(r_p + l_p)}{r_pl_p}\right) \qquad 4.26$$

The model developed in this research uses an iterative process to estimate the temperature and moisture profiles inside the OP><FLO coolers. First the bed of feed pellets is divided into a number of equally sized slices, n_s. Then an initial estimate must

be made for the temperature and moisture profiles. Values for T and Θ are initialized as the line between $\Theta_{initial}$ and $T_{ambient}$ using:

$$T(x)\ and\ \Theta(x) = \left(\frac{\Theta_{initial} - T_{ambient}}{L_{bed}} \right) x + T_{ambient} \qquad 4.27$$

Values for the average pellet moisture content and absolute humidity profiles are initialized as constant values of $\overline{M}_{initial}$ and $W_{ambient}$ respectively. Finally derivatives for all moisture and temperature profiles are initialized as a negative 0.1 as an initial estimate since the temperature and moisture of both pellets and air temperature should decrease as x increases (Bliss Industries Inc., 1999).

After defining an initial estimate for the temperature and moisture content profiles, the iterative process can begin. Estimations are calculated for air and pellet properties such as: relative humidity, specific heat, and latent heat of vaporization that are dependent on temperature and moisture content. These properties and the initial values for temperature and moisture can then be used in equations 4.1 – 4.4 to calculate better estimates for the changes in temperature and moisture for both the air and pellets. Numerical integration methods can then be used to obtain new estimates of the temperature and moisture profiles in the cooler. The iterative loop is completed when new estimates of air and pellet properties are calculated from the new estimates of the moisture and temperature profiles.

Convergence for this model is evaluated in two ways: the values for the temperature and moisture content of the product and air do not change between iterations, or the estimated amount of water entering the air is approximately equal to the estimated amount of water entering the product. The iterative loop is repeated a number of times, n_i, that is greater than or equal to the number of bed slices, n_s. Repeating the process until n_i is 250% of n_s will allow the model to approach convergence. Numerical integration experiments using the data in Appendix A indicate an n_s value of 200 is appropriate for most OP><FLO coolers, and the percent difference between the amount of moisture leaving the product and the amount of moisture entering the air will typically range from 1 – 5% for a maximum n_i value of 500 if n_s is 200. Additional iterations will decrease the percent difference between the amount of moisture leaving the product and the amount of moisture entering the air, but to minimize run time of the model a maximum value of n_i = $2.5n_s$ will be used in this research. Therefore, an n_s value of 200 and a maximum n_i value of 500 will be the default values for the model, but the user will have the option of using a more or less slices at their discretion. If the user wishes to use an n_s value other than 200, the value maximum value of n_i will automatically be adjusted accordingly.

The process is iterative process is described graphically in Figure 4. 2:

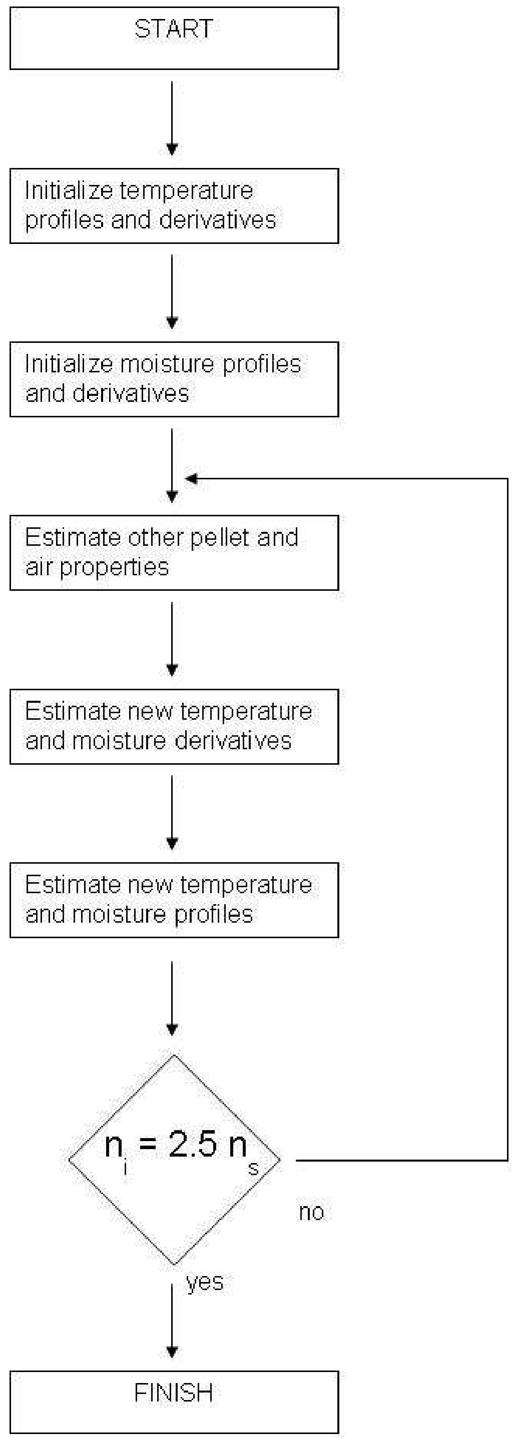

Figure 4. 2 Flow Schematic of the Model Program

This model will require the use of numerical integration techniques. During the iterative loop, equations 4.1, 4.2, 4.3, and 4.4 are used to calculate the derivatives of the dependent variables, air and product temperature and moisture, with respect to the independent variable, bed depth. These derivatives can be used to estimate values for the dependent variables via numerical integration. One simple method for numerical integration is the Euler's method (Ramaswami et al. 2005):

$$y_2 = y_1 + dy_1(x_2 - x_1) \qquad 4.28$$

Where y represents the dependent variable, x represents the independent variable, and dy represents the derivative of y. For small step sizes, Euler's Method will yield reasonable approximations for integration (Davis and Rabinowitz, 1984).

5) Debugging the Model

5.1) Stabilizing the Model

Once expressions and values had been identified for all parameters in the model equations, the model was programmed into an Excel and VBA format. A macro was written to carry out the iterative process discussed previously in Figure 4. 2 and values from Appendix A were placed into the model for testing.

The initial model exhibited one major flaw: the temperature profiles would become unstable and exhibit a diverging sinusoidal response before the model could converge. The pellet temperature, Θ, would show an increase at some point in the cooler, n_j, and then immediately decreased at the next point in the cooler, n_{j+1}. In the next iteration, the next point, n_{j+2}, would show an increase and point n_{j+3} would show a decrease. This divergent phenomenon would proliferate with each iteration until the entire profile for Θ exhibited a sinusoidal pattern. Also, the magnitude of the difference between the increases and decreases would escalate as the value of n_i increased. A comparison of equations 4.1 and 4.2 shows that the values of the air and pellet temperatures are closely linked. So as the pellet temperature values diverged, the air temperature values behaved similarly.

This divergent phenomenon violates the Second Law of Thermodynamics. Specifically the Clausius statement, a significant basis of the Second Law of Thermodynamics, is violated. The Clausius statement infers that heat cannot flow spontaneously from a low temperature body to a higher temperature body without additional work being done to the system (Cengel and Boles, 2006). Once the pellets enter the OP><FLO cooler, no significant work occurs until the pellets exit the cooler. The pellets are exposed to continuously cooler air as they move down the cooler (Bliss Industries Inc., 1999). Therefore, limits were placed on the values of Θ and T in the model to prevent the values of those variables from increasing as the value of x increases. Thus, the model was constrained to obey the Second Law of Thermodynamics.

5.2) Calibrating the Model

The next task in this research was to determine if the model would provide reasonable estimates of the heat and mass transfer occurring in the OP><FLO cooler. Once the model was stabilized, data from Table A-1 was put into the model. The model carried out the iterative process as expected, and estimates of the temperature and moisture profiles were calculated. Unfortunately, this initial numerical integration experiment did not support the data in Table A-1. The estimated moisture loss was approximately 1-2% instead of the 3-4% expected moisture loss reported by Bliss Industries. The process was repeated for data for the information in tables A-2, and A-3. In all cases the model estimated a final moisture content of the pellets that was higher than the expected final moisture content provided by Bliss Industries.

An examination of the model equations and expressions for all of the parameters was conducted. It was determined that the only expression that had not been used in the literature to describe the cooling and drying of feed pellets was equation 4.16, the derivative of moisture content of the pellets with respect to bed depth. All other expressions and equations were derived from thermodynamic principles or were used in computer models describing pellet cooling and drying (Maier, 1988; Biagi, 1986).

The change in moisture content, calculated by equation 4.16, used an empirical drying coefficient, A. Initially a value for whole corn was used for this coefficient. However, the drying rate of whole corn is affected by the presence or absence of the tip cap, pericarp, and hull (Brooker et al., 1992). However, feed pellets are composed of particles of corn and other grains, roughages, and additives. If the tip cap, pericarp, and hull of the corn and other grains are present in pellets, they will likely not have the same effect on drying that is observed in whole kernels. For this research, it was assumed that feed pellets and whole corn have different values for the drying coefficient, A, in equation 4.16.

A simple sensitivity analysis was conducted to determine how changing the value of the drying coefficient would affect the model. Since the OP><FLO cooler in location 1 is operating close to the average capacity for a cooler of comparable size (Bliss Industries Inc., 1999), the model was used to estimate temperature and moisture profiles for location 1 using the values in Table A-1. Since an average pellet length was not provided by Bliss Industries, an average pellet length of 0.75 inches was assumed for location 1 from the author’s experience in feeding livestock. An initial pellet temperature of 180 ^{o}F and an initial pellet moisture content of 12% were used. Also the following values were used: the drying coefficient, A = 0.5, ambient air temperature, $T(L_{bed})$ = 50 ^{o}F, and ambient absolute humidity, $W(L_{bed})$ = 0.006917 kg/kg (which yields the specified relative humidity of 92 % at 50 ^{o}F). Once the model had finished, values for final average moisture content and final product temperature were recorded. The process was repeated

for values of the drying coefficient ranging from 0.5 to 2.5. The process was again repeated using values for ambient temperature of 0 ^{o}F and 100 ^{o}F. Figure 5. 1 illustrates the results of the data collection.

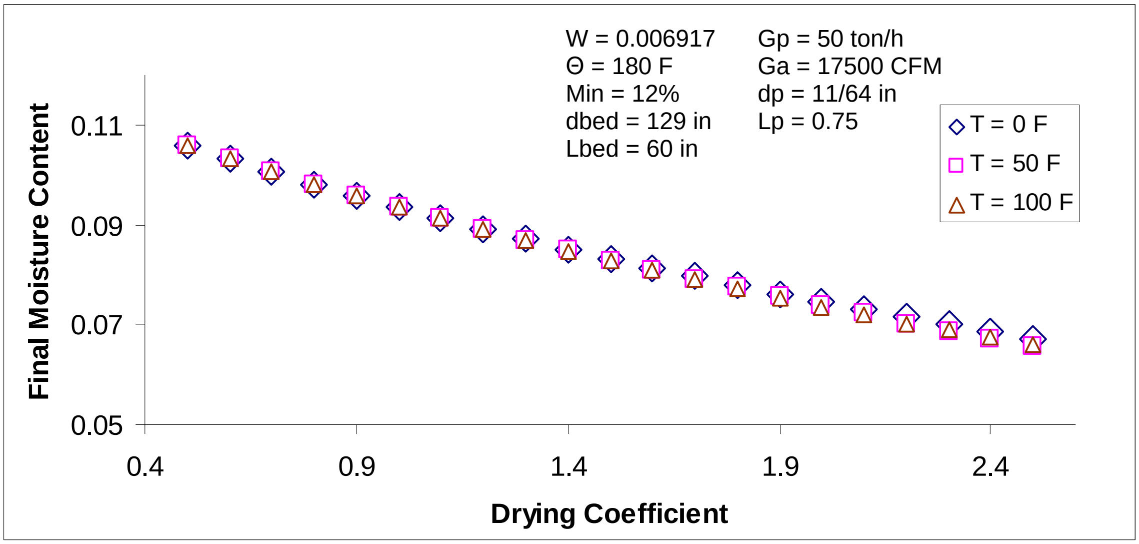

Figure 5. 1 Final moisture content for various drying coefficients and different ambient temperatures

It can be concluded from Figure 5. 1 that ambient temperature has little affect on the estimate of final moisture content of pellets, and according to the final moisture content provided in Table A – 1 (7 – 8 %), the drying coefficient has a value between of 1.5 , where the final moisture content was estimated to be 8.2% and 2.2 where the final moisture content was estimated to be 7.0%.

Other variables were then systematically changed one by one to determine if and how each variable would affect the final moisture content estimate. The process used to produce Figure 5. 1 was repeated for all independent variables in the system: ambient absolute humidity, bed depth, bed diameter, pellet diameter, pellet length, pellet flow rate, air flow rate, initial pellet temperature, and initial pellet moisture content. Each time the process was repeated only one independent variable and the drying coefficient were changed to see how the model performed under various conditions. The results can be seen in Figures 5. 2 – 10.

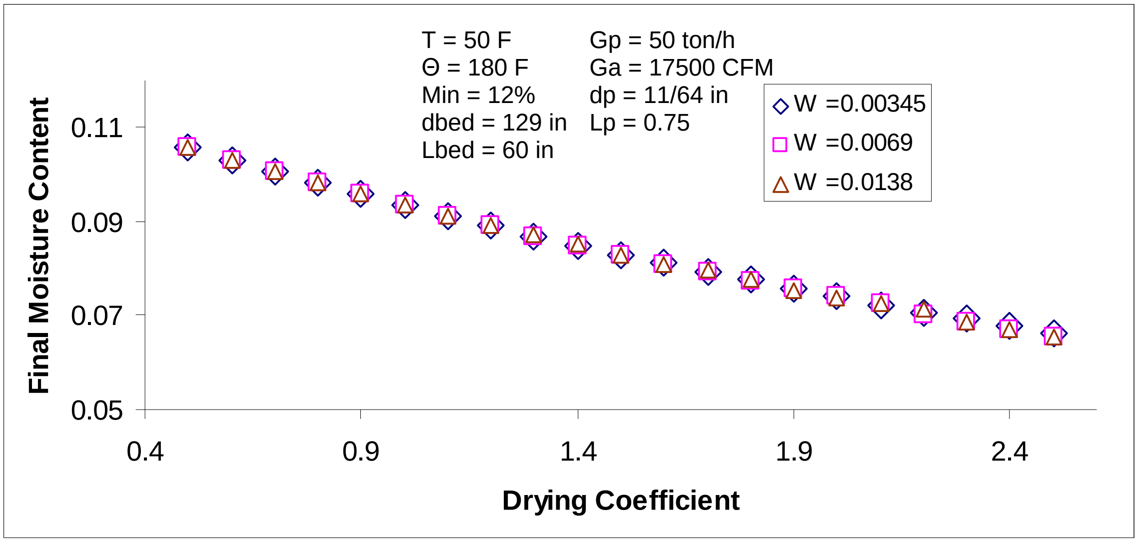

Figure 5. 2 Final moisture content for various drying coefficients and different ambient humidity conditions.

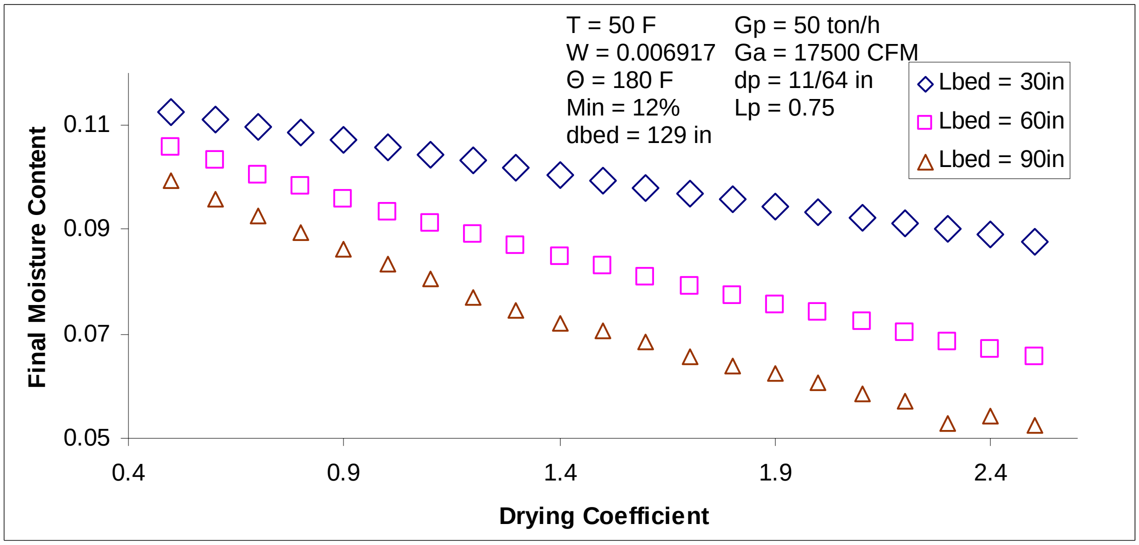

Figure 5. 3 Final moisture content for various drying coefficients and different bed depth values

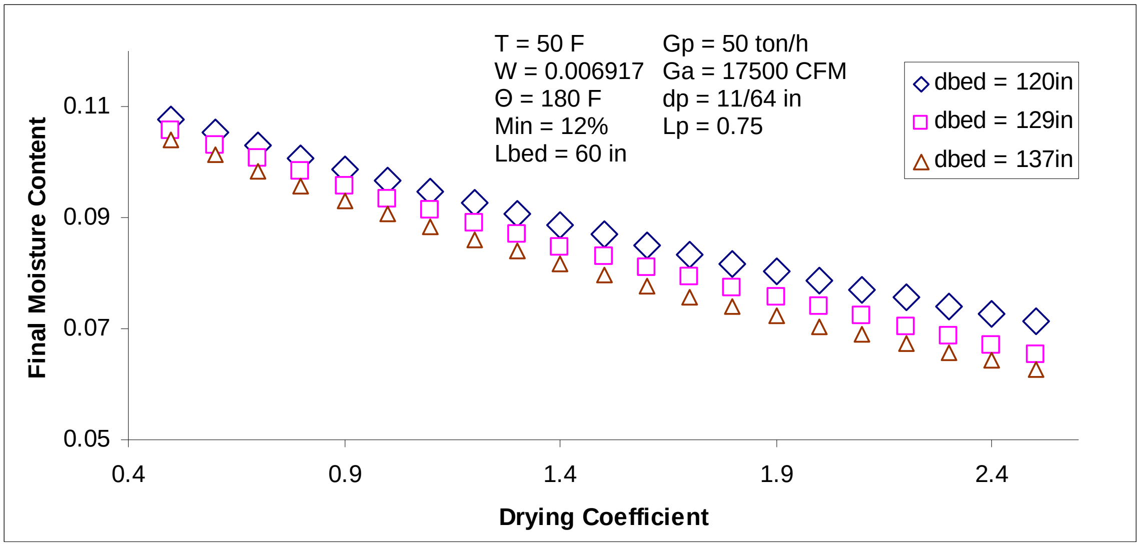

Figure 5. 4 Final moisture content for various drying coefficients and different cooler diameters

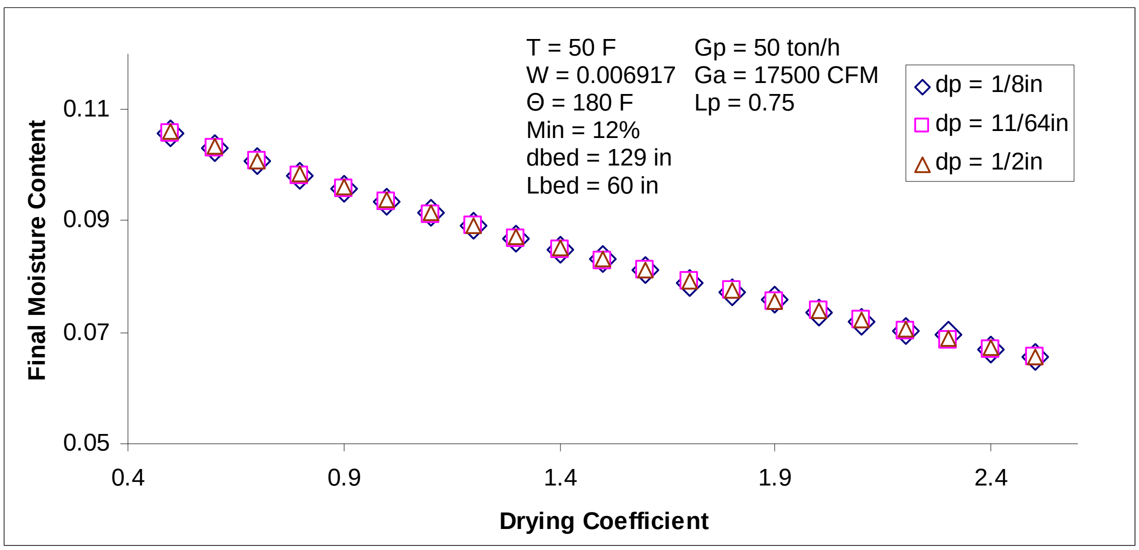

Figure 5. 5 Final moisture content for various drying coefficients and different pellet diameters

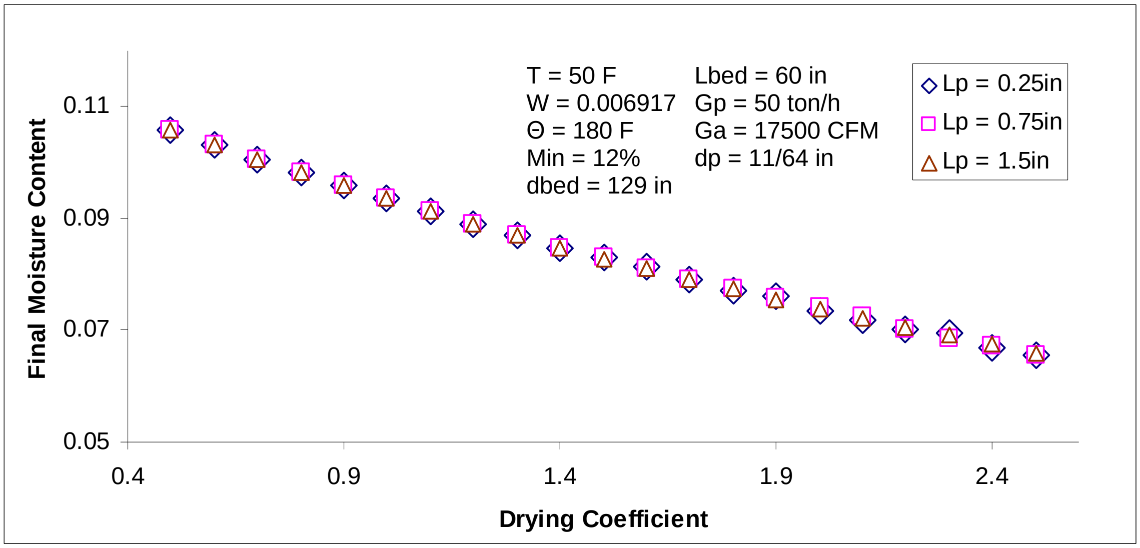

Figure 5. 6 Final moisture content for various drying coefficients and different pellet lengths

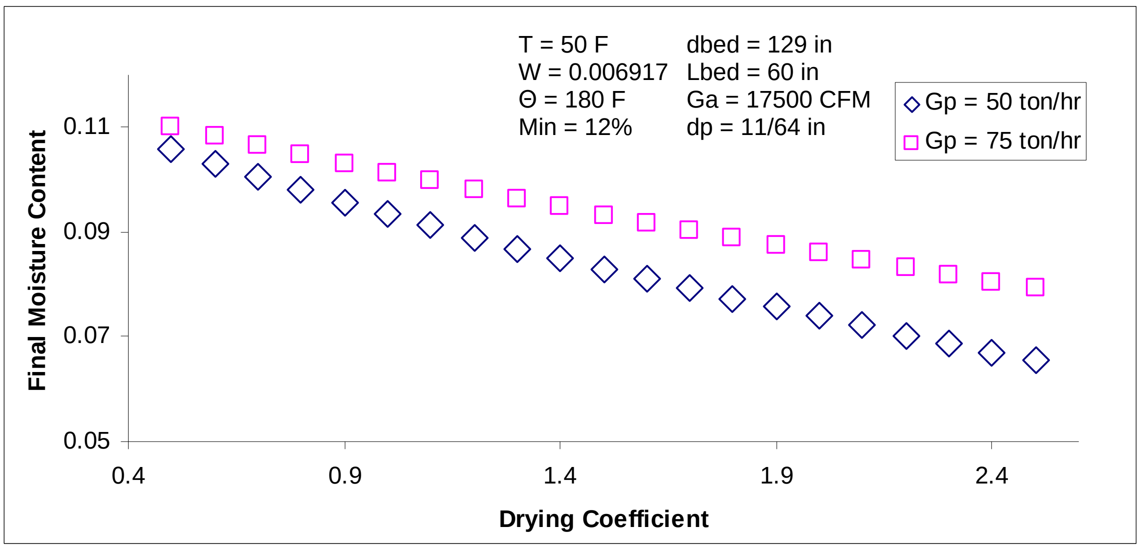

Figure 5. 7 Final moisture content for various drying coefficients and different pellet flow rates

It should be noted that Figure 5. 7 does not contain a data series for 25 tons per hour. The model estimated that the temperature would drop too quickly in this cooler at such a low product flow rate and the pellets would exit at or close to the initial 12% moisture content regardless of the value of the drying coefficient.

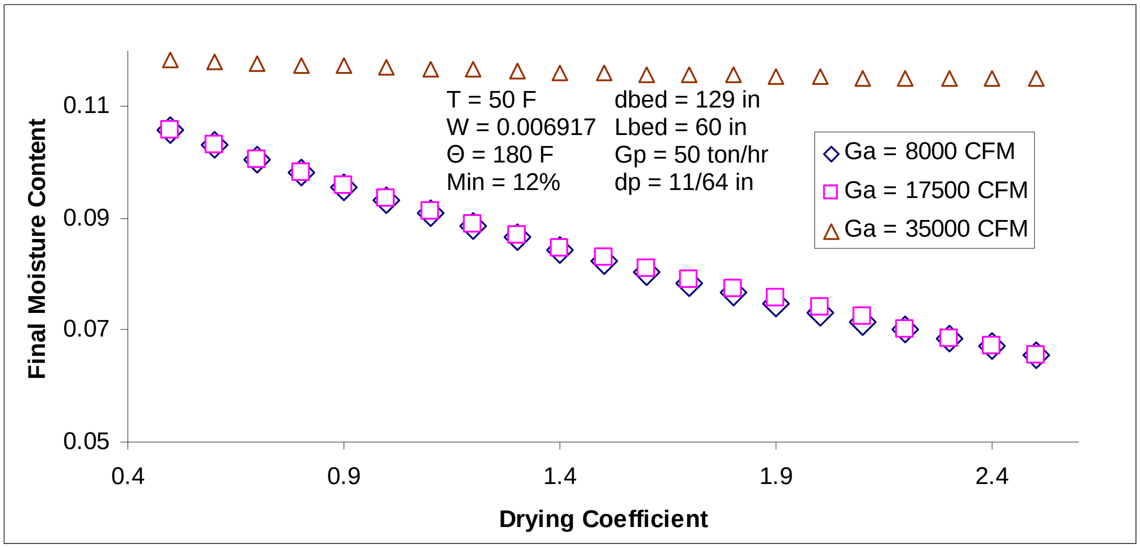

Figure 5. 8 Final moisture content for various drying coefficients and different air flow rates

It should be noted in Figure 5. 8 that an extremely high airflow rate will cool the bed too quickly and minimize moisture loss.

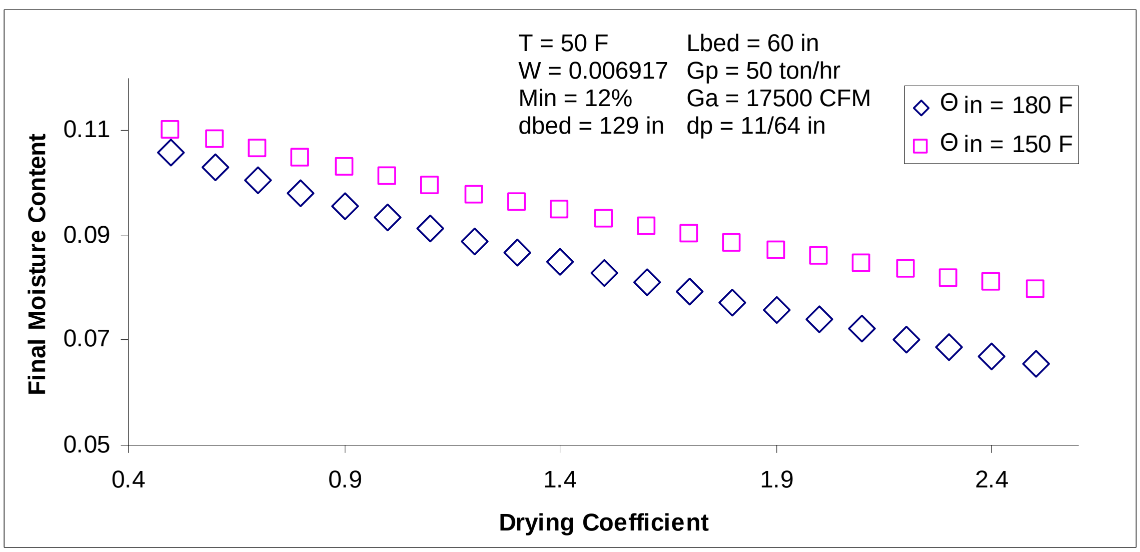

Figure 5. 9 Final moisture content for various drying coefficients and different initial pellet temperatures

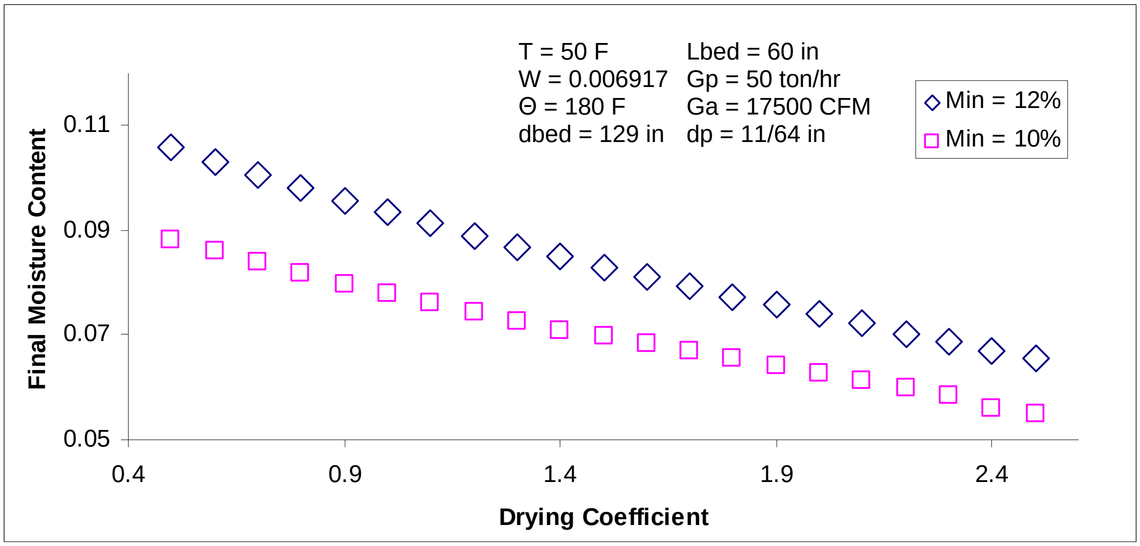

Figure 5. 10 Final moisture content for various drying coefficients and different initial pellet moisture contents

The process was then repeated for a second OP><FLO cooler. The cooler in location 2 is operating closer to average capacity than the cooler in location 3 (Bliss Industries Inc., 1999). Therefore the data in table A – 2 was used in a sensitivity analysis, and those results can be viewed in Appendix B.

After reviewing the data in Figures 5. 1 – 10 and Appendix B it can be concluded that the total bed depth has a significant impact on the estimated final moisture content of the pellets regardless of the value of the drying coefficient. Other factors that will impact the drying of pellets include the amount of product and air flowing through the cooler and initial pellet temperature. These conclusions were supported by Maier (1988).

After studying the information in Figures 5. 1 – 10 and Appendix B, this research will assume a drying coefficient of 1.6 for livestock feed pellets. The main factors that will fluctuate in an operating OP><FLO cooler are the ambient conditions and the initial pellet moisture content and temperature (Hensley, 2006). A drying coefficient value of 1.6 will allow the model to estimate a final product moisture content that is consistent

with the 7 – 8% range that is provided by the data in Appendix A for the given ranges of initial temperature and moisture values of product and air.

It should also be noted that Maier (1988) concluded from experimental data collected by Biagi (1986) that the diffusivity of feed pellets is approximately three times that of corn. This conclusion supports the use of a drying coefficient of 1.6 which is approximately three times the value of the drying coefficient proposed by Pabis and Henderson (1961) for corn of 0.54.

Using an appropriate value for the drying coefficient the model will estimate a final moisture content consistent with the data provided by Bliss Industries. However, Bliss Industries reports a final product temperature within 10 ^{o}F of the ambient air temperature for all of their OP><FLO coolers. In Figure 5. 11, it can be seen that the estimated value for final product temperature and ambient temperature difference is more than 10 ^{o}F. However, by adjusting the airflow, as a client will in the field, the difference in ambient and final product temperature can be adjusted. This can be seen in Figure 5. 12.

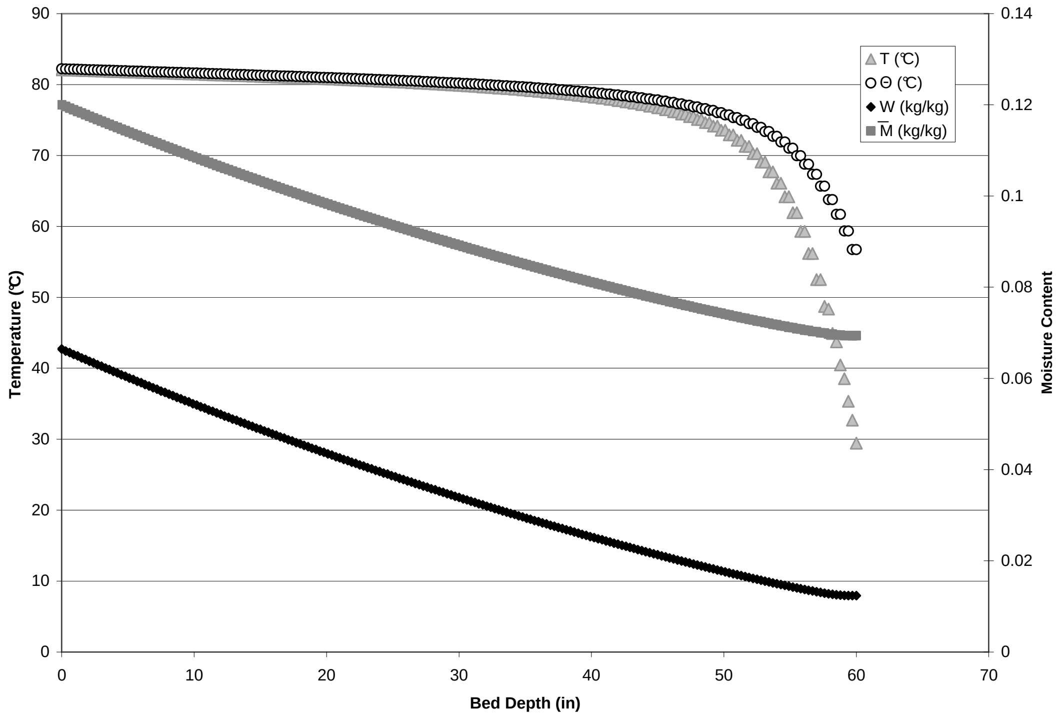

Figure 5. 11 Estimated cooler profiles using data from Table A – 2, an ambient temperature of 85 ^{o}F (29.4 ^{o}C), an initial relative humidity of 49%, and a total airflow rate of 6000 CFM

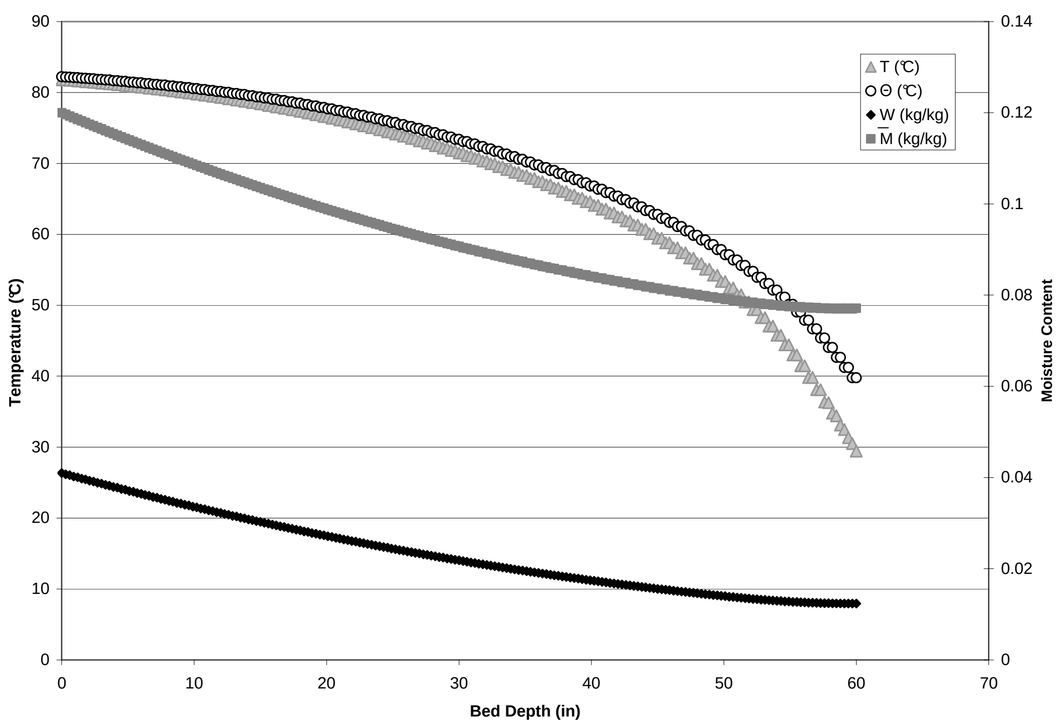

Figure 5. 12 Estimated cooler profiles using data from Table A – 2, an ambient temperature of 85 ^{o}F (29.4 ^{o}C), an initial relative humidity of 49%, and a total airflow rate of 9700 CFM

5.3) Validating the Model

As a validation process, the model was used to estimate the temperature and moisture profiles for the data in Table A – 3. The model estimated a final moisture content of 5 – 6% for location 3, lower than the reported 7 – 8% final moisture content. The information in Table A – 3 was then compared to the other information provided in Appendix A. A comparison of the information in Table A – 2 and A – 3 reveals that both coolers are used for similar product streams (15 tons per hour of ¾” pellets), but a larger cooler was selected for Location 3. Location 3 had a listed relative humidity of 32% and is more arid than Location 2 with a relative humidity of 49%. After a discussion with Bliss Industries personnel, a possible reason was identified for the low final moisture content estimation: the cooler in Location 3 may have been oversized. This can be supported by the fact that Bliss Industries literature indicates that a model of these dimensions could process an average of about 35 tons per hour of product (Bliss Industries Inc., 1999). There are several reasons why an oversized cooler may have been selected for this location. A few of them include: a client with plans to increase production in the future, a more appropriately sized cooler may not have been compatible with the client’s other pelletizing equipment, or an appropriately sized cooler may not have been immediately available (Edens, 2008). However, it is unclear why this particular unit was selected for Location 3, but with the use of the model developed in this research, Bliss Industries may not install oversized OP><FLO coolers in the future.

6) Conclusions

The goal of this research was to develop a tool that would assist Bliss Industries personnel in determining the appropriate size of a counter flow style, OP><FLO livestock feed pellet cooler. The result of this research is a computer model that will provide an estimate of the moisture and temperature profiles inside a counter flow feed pellet cooler given: cooler diameter, cooler bed depth, initial pellet temperature, ambient air temperature, initial pellet moisture content, ambient relative humidity, pellet flow rate, air flow rate, pellet diameter, average pellet length, pellet density, and bulk density. The model will allow Bliss Industries to estimate how an OP><FLO cooler will perform under varying operating and ambient conditions. They will then be able to use these estimates to aid in the selection of on an appropriate cooler size for a given client and location.

The model was designed to run in Microsoft Excel and uses VBA for custom functions and macros. The model is compatible with all versions of Excel that are currently available (Excel 2007 through Excel XP). Therefore, the model will be easily accessible and usable by Bliss Industries without purchase of specialized software. A portion of the code used in the model can be seen in Appendix C, but the portion of the code that designed to facilitate the iterative loop will not be published to protect the interests of Bliss Industries Inc.

For this research, only a limited amount of data was available to calibrate and test the model. Much of the data originally provided by Bliss Industries is for OP><FLO coolers that are used to dry and cool wood pellets. Only three of the provided information sets were for livestock feed pellets. Data from two of those locations, Table A – 1 and Table A – 2, was used to calibrate the model. This left only one data set, Table A – 3, to validate the model, and the model indicates that the cooler described in Table A – 3 may be oversized. Additional data should be collected to further validate the model.

This model should be used as one of many tools that Bliss Industries personnel can use to determine appropriate size for an OP><FLO cooler. The model does provide an estimate of the moisture content and temperature of feed pellets and air in an OP><FLO cooler. The data provided by Bliss Industries does support the estimations provided by the model for final moisture content of the pellets, but the estimated final temperature values are higher than the values reported by Bliss Industries. However, the model will provide an indication of how variations in product size, product flow, air flow, cooler size, bed depth, ambient conditions, and properties of the product upon entry will affect the performance of an OP><FLO cooler.

7) Recommendations

The author recommends that future research in this area should include:

1) Additional data on operating OP><FLO coolers to further validate the model.
2) An investigation of the model’s ability to accurately describe the cooling and drying of wood pellets in an OP><FLO cooler.
3) An in depth investigation to determine the most appropriate expressions for the drying rate, Equation 4. 4, and moisture equilibrium content, Equation 4. 18, for livestock feed pellets and wood pellets.
4) An investigation to determine an expression for the most appropriate number of finite differences, n_s, necessary for the model to describe any OP><FLO cooler.

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Appendix A

Data provided by Bliss Industries describing three OP><FLO coolers currently in use:

Table A – 1: Location 1	
10 - 12%	Product Moisture Content Entering Cooler
7 - 8 %	Product Moisture Content Exiting Cooler
150 - 180 F	Product Temperature Entering Cooler
129 inches	Cooler Diameter
60 inches	Bed Depth
0 - 120 F	Ambient Temperature
92%	Ambient Relative Humidity
17500 CFM	Airflow in Cooler
50 tons per hour	Product Flow in Cooler
11/64 inches	Product Diameter
40 lb/ft^3	Product Bulk Density

Table A – 2: Location 2	
10 - 12%	Product Moisture Content Entering Cooler
7 - 8 %	Product Moisture Content Exiting Cooler
180 F	Product Temperature Entering Cooler
86 inches	Cooler Diameter
60 inches	Bed Depth
0 - 120 F	Ambient Temperature
49%	Ambient Relative Humidity
6000 CFM	Airflow in Cooler
15 tons per hour	Product Flow in Cooler
3/4 inches	Product Diameter
40 lb/ft^3	Product Bulk Density

Table A – 3: Location 3	
10 - 12%	Product Moisture Content Entering Cooler
7 - 8 %	Product Moisture Content Exiting Cooler
180 - 190 F	Product Temperature Entering Cooler
103 inches	Cooler Diameter
60 inches	Bed Depth
0 - 120 F	Ambient Temperature
32%	Ambient Relative Humidity
7200 CFM	Airflow in Cooler
15 tons per hour	Product Flow in Cooler
3/4 inches	Product Diameter
40 lb/ft^3	Product Bulk Density

Appendix B

The following figures represent a sensitivity analysis conducted on the OP><FLO cooler in Location 2 using data provided in Table A-2. Unless otherwise specified in the legend of the figure, values used for the boundary conditions are: $T(L_{bed}) = 50\ ^{o}F$, $W(L_{bed}) = 0.003684$ (which yields a relative humidity of 49% at 50 ^{o}F), $\overline{M}(0) = 12\%$ and $\Theta(0) = 180\ ^{o}F$.

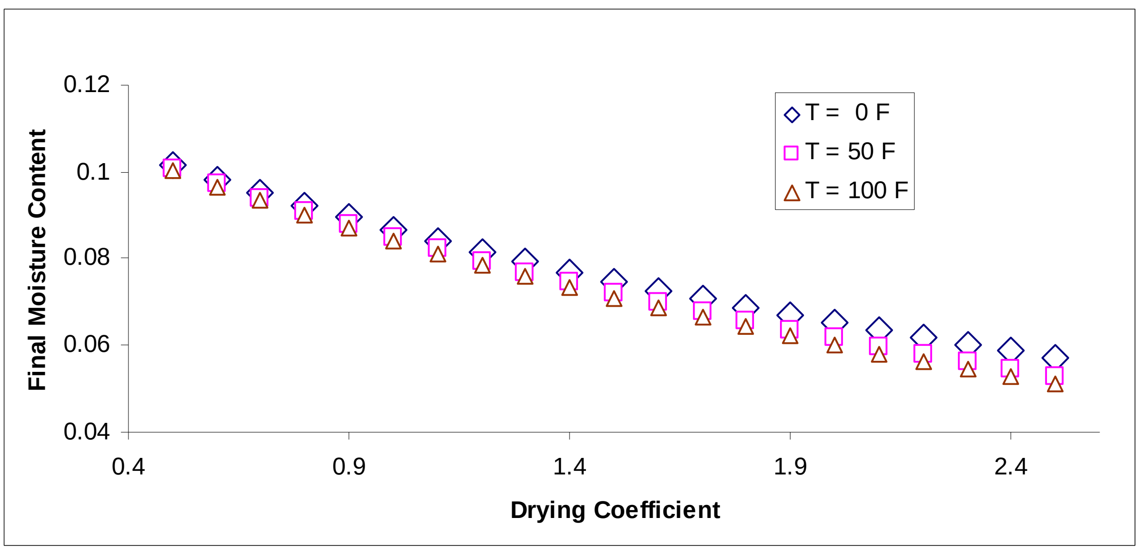


Figure B - 1

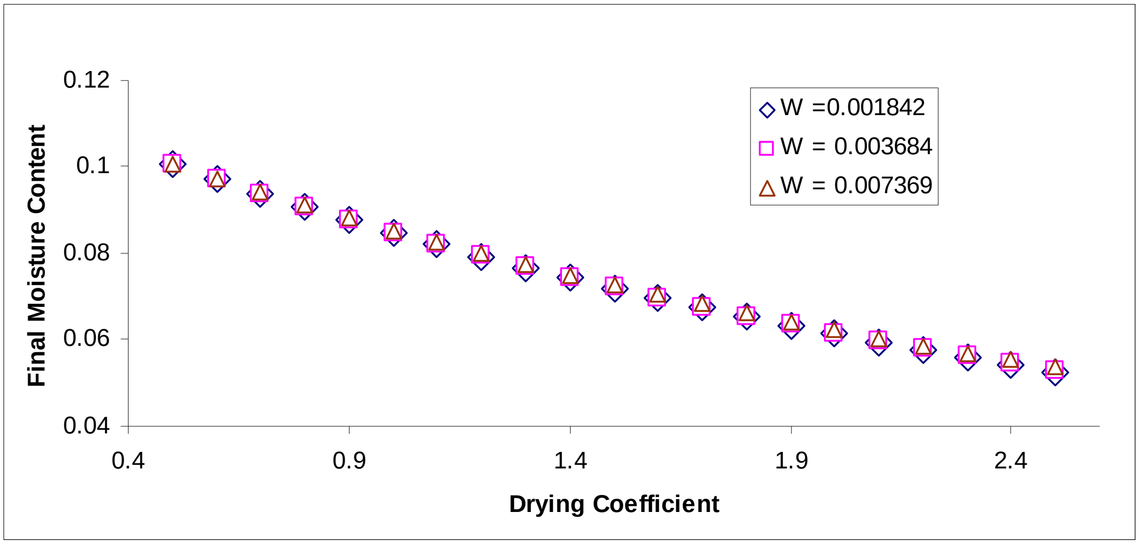


Figure B - 2

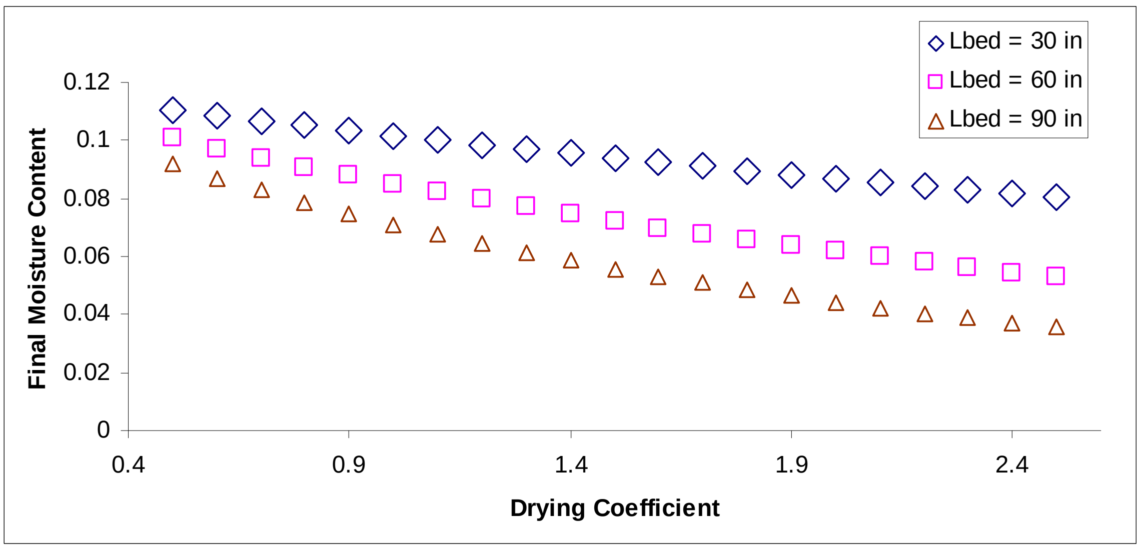


Figure B - 3

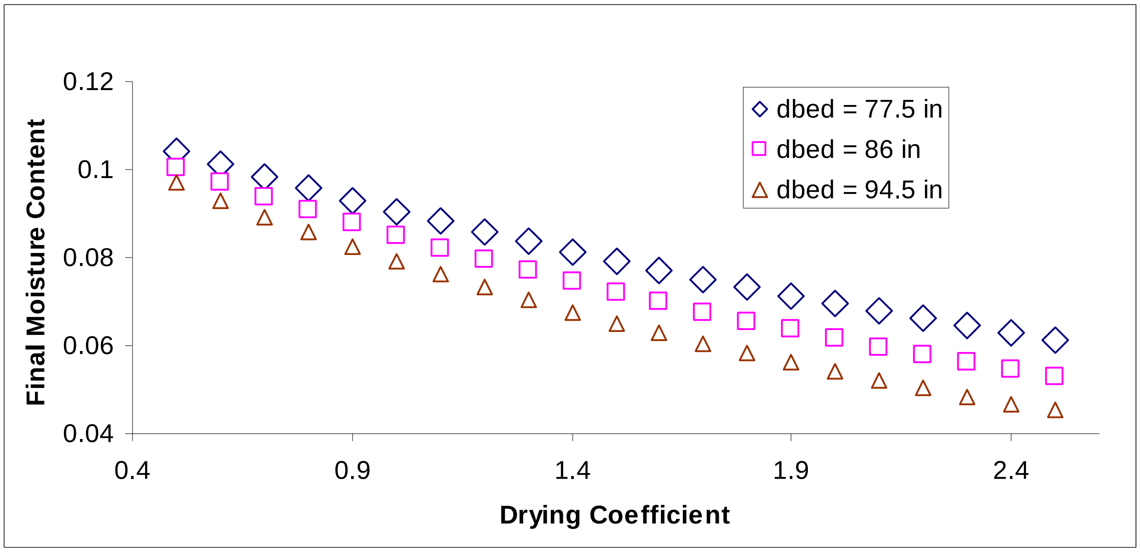


Figure B - 4

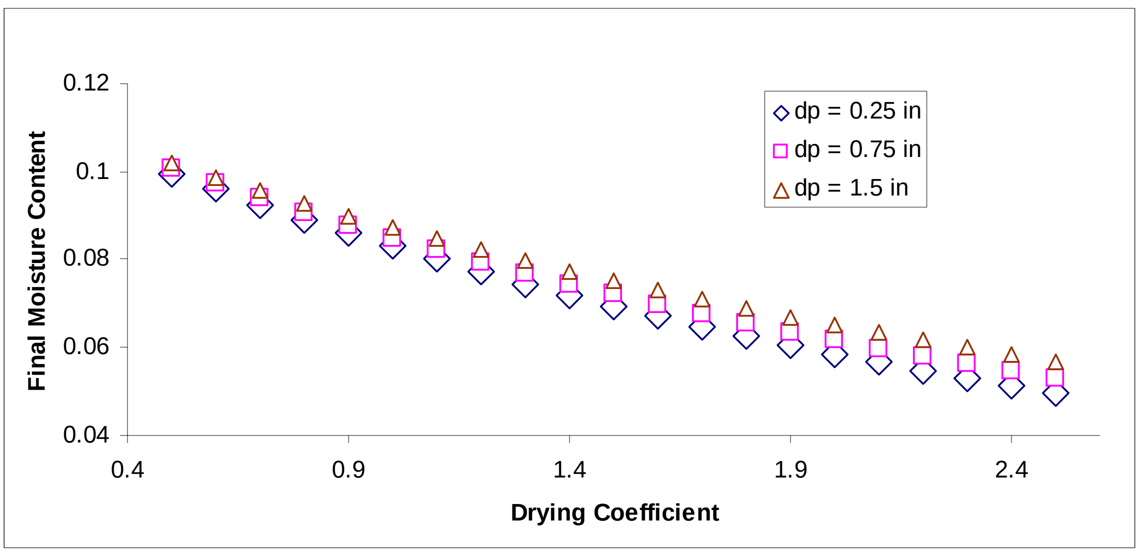


Figure B - 5

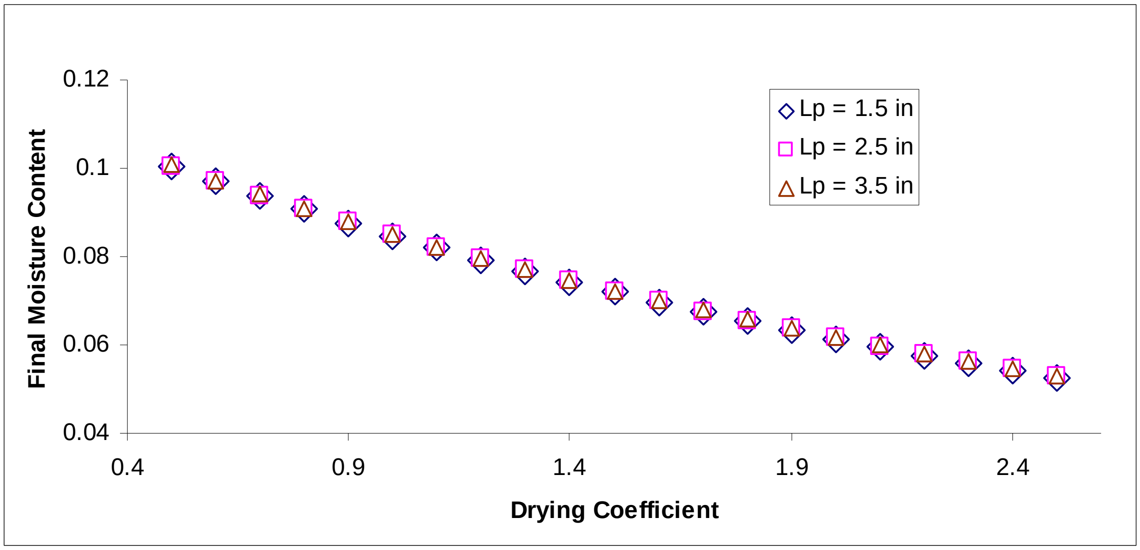


Figure B - 6

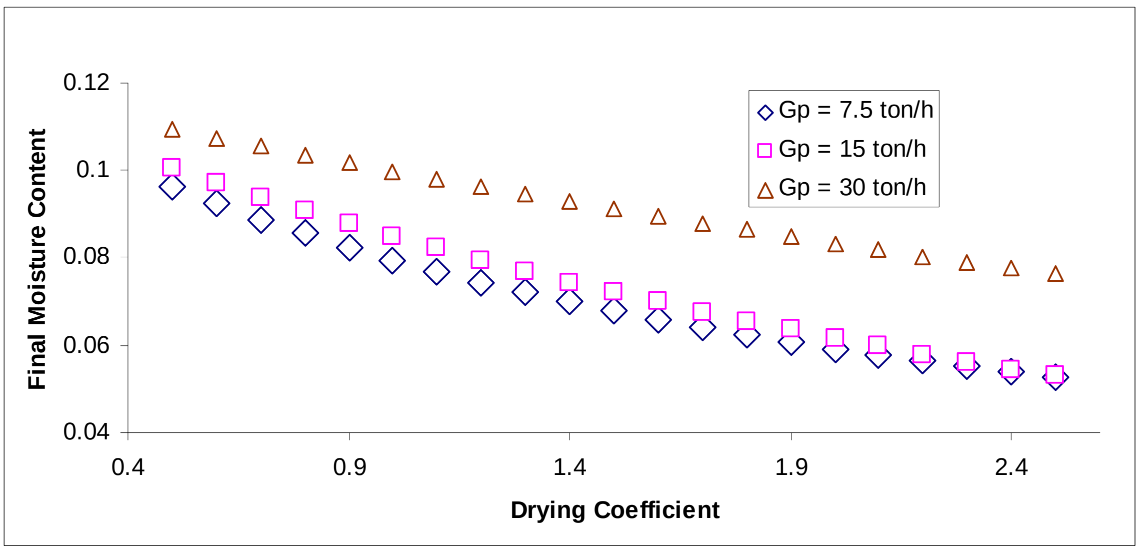


Figure B - 7

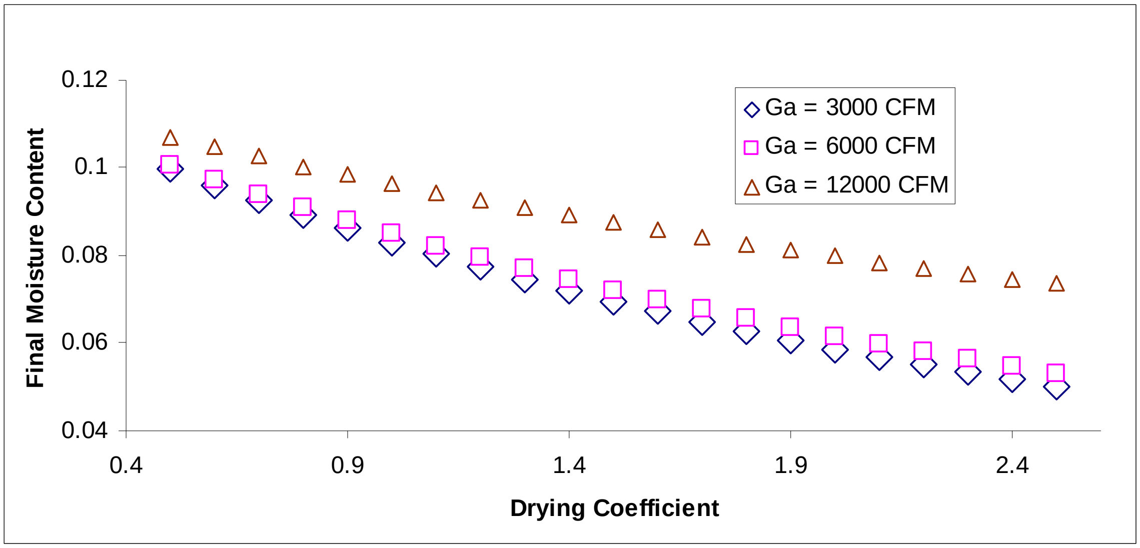


Figure B - 8

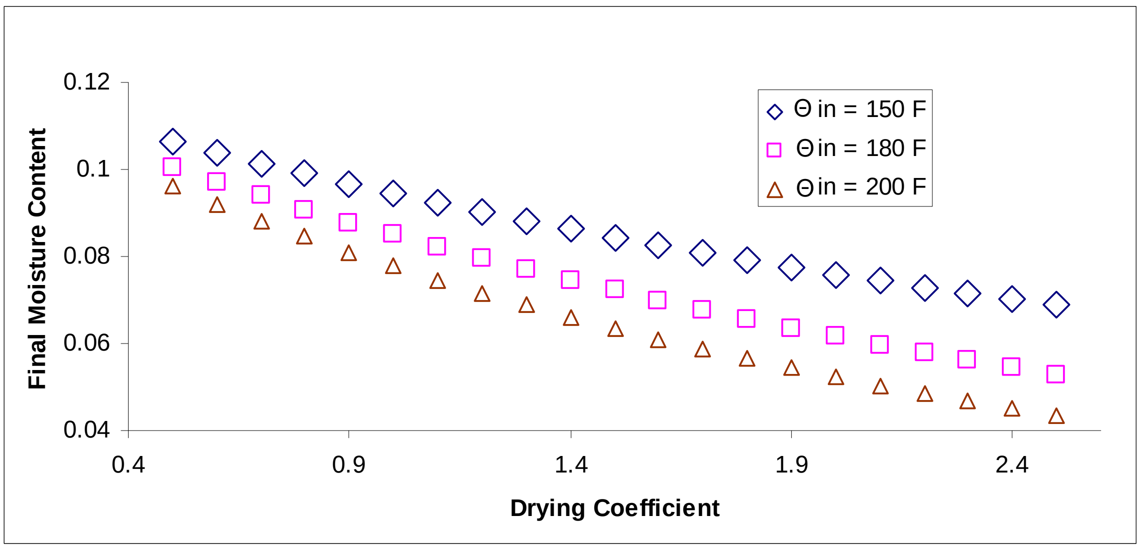
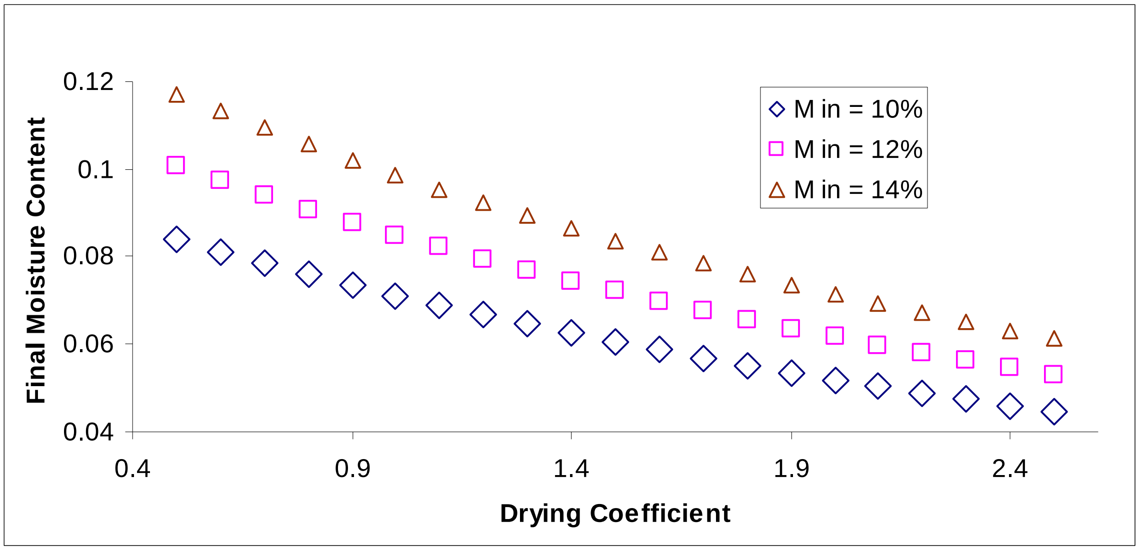


Figure B - 9



Final Moisture Content
0.12
0.1
0.08
0.06
0.04
0.4
0.9
1.4
1.9
2.4
Drying Coefficient
M in = 10%
M in = 12%
M in = 14%

Figure B - 10

Appendix C

This section contains a portion of the VBA code used in the model. Again a portion of the source code will not be published to protect the interests of Bliss Industries Inc.

Note: Lines starting with a “ ' ” symbol are text comments.

```
'vba doesn’t include a natural log function so here it is
Function Ln(x)
Ln = Log(x) / Log(2.718282)
End Function
```

```
'relative humidity function
'dry bulb temp in K
'W as decimal
'Patm in Pa
Function rh(tempk, W, Patm)

Dim Ps As Double
Dim Pv As Double
Dim A As Double
Dim B As Double
Dim C As Double
Dim d As Double
Dim E As Double
Dim F As Double
Dim G As Double
Dim R As Double
Dim Rv As Double
Dim T As Variant

If tempk > 530 Then tempk = 530
T = tempk
```

```
A = -27405.526
B = 97.5413
C = -0.146244
d = 0.000126
E = -0.0000000485
F = 4.34903
G = 0.00394
R = 22105649.25
Rv = 461.915

Ps = R * Exp((A + B * T + C * T ^ 2 + d * T ^ 3 + E * T ^ 4) / (F * T - G * T ^ 2))
Pv = (Patm * W * Rv) / (287 + W * Rv)
If Ps = 0 Then Ps = 1E-200
If (Pv / Ps) > 0 Then
   If (Pv / Ps) < 1 Then
      rh = Pv / Ps
   Else: rh = 0.999
   End If
Else: rh = 0.001
End If
End Function
```

```
'absolute humidity function
'dry bulb temp in K
'rh as decimal
'Patm in Pa
Function W(tempk, rh, Patm)

Dim Ps As Double
Dim Pv As Double
Dim A As Double
Dim B As Double
Dim C As Double
Dim d As Double
Dim E As Double
Dim F As Double
Dim G As Double
Dim R As Double
Dim Rv As Double
Dim T As Variant
```

```
If tempk > 530 Then tempk = 530
T = tempk
A = -27405.526
B = 97.5413
C = -0.146244
d = 0.000126
E = -0.0000000485
F = 4.34903
G = 0.00394
R = 22105649.25
Rv = 461.915

Ps = R * Exp((A + B * T + C * T ^ 2 + d * T ^ 3 + E * T ^ 4) / (F * T - G * T ^ 2))
W = ((rh / 100) * Ps * 287) / (Patm * Rv - (287 + Rv))
End Function
```

```
'convective transfer coefficient
'Ga=kg/h/m^2 d=pellet diameter m Ca=kJ/kgK T = temperature C

Function hprime(Ga, Ca, d, T)
Dim x As Variant

x = 0.2755 * Ca * Ga * (Ga * d / (0.06175 + 0.000165 * T)) ^ -0.34
x = 3.6 * x
'3600s/h and 1kJ/1000J
hprime = x
End Function
```

```
'specific surface area m^-1
'ro=pellet radius m l=average pellet length m  void= bulk/pellet density
Function sarea(ro, l, void)
sarea = (1 - void) * 2 * (ro + l) / (ro * l)
End Function
'latent heat of vaporization kJ/kg
'T in C and M as decimal
Function hfg(T, m)
hfg = (2542.1 - 2.384 * T) * (1 + 1.2925 * Exp(-16.961 * m))
End Function
```

```
'specific heat of pellets kJ/kgK
Function cp(m)
cp = 1.465 + 3.559 * m
End Function
```

```
Function meq(T, rh)
Dim dum As Double
'error prevention
If T < -24.6 Then T = -24.59
dum = 0.375 - 0.0668 * Ln(-1.98 * (T + 24.6) * Ln(rh))
'dum = 0.375 - 0.1 * Ln(-1.98 * (T + 24.6) * Ln(rh))

If dum > 1 Then
   meq = 1
Else:
   If dum < 0 Then
      meq = 0
   Else: meq = dum
   End If
End If

End Function
```

```
'basic numerical integrator
'currently uses euler method
Function grate(y1, x1, x2, dy1)
Dim dum As Double
dum = y1 + (x2 - x1) * dy1
grate = dum
End Function
```

```
'a more advanced numerical integrator
'uses ymax and ymin to keep numerical integrator reasonable
'uses grate() if dy0 is invalid
Function grateb(y0, y1, x0, x1, x2, dy0, dy1, dy2, ymax, ymin)
Dim dum As Double
```

```
' the next statement can be removed to use Simpson's method of integration if desired
dy0 = "a"

If IsNumeric(dy0) = False Then
    dum = grate(y1, x1, x2, dy1)
    Else: dum = y0 + ((x2 - x0) * (dy0 + 4 * dy1 + dy2) / 6)
End If

If dum < ymin Then dum = ymin
If dum > ymax Then dum = ymax
grateb = dum
End Function
```

VITA

Steven Littleton Fowler

Candidate for the Degree of

Master of Science

Thesis: OPTIMAL SIZING OF A COUNTERFLOW COOLER FOR FEED PELLETS

Major Field: Biosystems Engineering

Biographical:

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The author was born and raised in Oklahoma. The author is passionate about agricultural engineering, teaching, and music

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The author has worked in multiple facets of the beef industry including: breeding, raising, feeding, managing, and meat processing.
The author also has four years of teaching experience in higher education

Professional Memberships:
American Society of Agricultural and Biological Engineers
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Name: Steven Littleton Fowler   Date of Degree: July 2008

Institution: Oklahoma State University   Location: Stillwater, OK

Title of Study: OPTIMAL SIZING OF A COUNTERFLOW COOLER FOR FEED PELLETS

Pages in Study: 61   Candidate for the Degree of Master of Science

Major Field: Biosystems Engineering

Scope and Method of Study: The goal of this research is to develop a tool to assist in the selection of an appropriately sized counter flow cooler for feed pellets. Of primary concern is the OP><FLO cooler manufactured and sold by Bliss Industries Inc. A computer model was developed to estimate the temperature and moisture content of the feed pellets and cooling air throughout a working cooler, and calibrated using data from operational OP><FLO coolers.

Findings and Conclusions: A stable model was developed in a Microsoft Excel workbook containing functions and macros written in VBA. This workbook was provided to Bliss Industries as a tool for selecting an appropriate size for an OP><FLO cooler. The model provides reasonable estimates of final moisture content of feed pellets, and an estimate of how a cooler operates under varying conditions. Additional data may be needed to further validate the model.

Advisor's Approval Timothy Bowser