THE INFLUENCE OF INITIAL MOISTURE, RETENTION TIME, AND STEAM QUALITY IN TWO CONDITIONERS ON THE PELLETING PROCESS

by

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ABSTRACT

Pelleting of animal feed occurs extensively throughout the feed manufacturing industry. Steam conditioning plays an important role in any pelleting system, yet there is little research available to help understand this process. The overall objective of this research is to gain an understanding of what actually occurs during the mash conditioning process by examining the effects of mash moisture, retention time, and steam quality in two conditioners on the pelleting process and pellet quality.

This experiment was conducted with a split-plot treatment structure within a CPM and Bliss conditioner. Mash moisture served as the whole plot treatment. Retention time (short and long), and steam quality (70, 80, 90, and 100%) made up the sub-plot treatments. Combinations of sub-plot treatments were completely randomized within the two mash moistures (12% and 14%). Three replications of all above combinations were completed. Data collection included moisture contents, pellet durabilities, energy consumption, and steam flow.

The results of this study indicated that pellet quality, energy consumption, and steam flow were significantly related to mash moisture, retention time, and steam quality. The optimal operating performance was achieved through several combinations of treatments. For example, a short retention time combined with 14% mash moisture and using 70% steam quality produces high quality pellets at the lowest kWh/t. In contrast, a long retention time provided nearly equal quality pellets and energy consumption in combination with 12% mash moisture. It is important, however, to keep in mind that these results were obtained using a constant conditioned mash temperature of 82.2°C.

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INTRODUCTION

Conditioning of mash feed has a significant impact on pelleting which is one of the most capital intensive cost centers in a feed mill. Since its introduction to the feed industry, research has been done on pelleting to gain a better understanding of its physical and nutritional benefits. Despite this, conditioning of mash feed is often overlooked and remains an area where additional research is needed so that this process can be better understood, and thus optimized.

There are several factors that influence the conditioning process: feed and ingredient characteristics, conditioner design, retention time, and steam properties. Though these factors can be identified, how they directly affect pellet quality and production is not well understood. Gaining an understanding of how these elements affect conditioning will allow for optimal efficiency in the pelleting process and improved pellet quality.

The overall objective of this research is to develop a better understanding of what actually occurs during the mash conditioning process. This will be accomplished by examining the effects of mash moisture, retention time, and steam quality in two conditioners on pellet quality and production. Observing the effects on the mash of manipulating these variables will provide insight to what actually happens in the conditioner.

LITERATURE REVIEW

Pelleting was introduced to the U.S. feed industry in the late 1920's (Schoeff, 1994). Today, the pelleting process is widely used because of the physical and nutritional benefits it provides. The physical benefits include improved ease of handling, less ingredient segregation, less wasted feed, and increased bulk density. Nutritional benefits have been measured through animal feeding trials. Stark (1994) conducted experiments demonstrating that feed containing a high quality pellet resulted in greater efficiency of gain than feed containing 30% fines. This may explain why feed manufacturers place pellet quality as a high priority. It is also an area in which the industry is continually trying to make improvements.

Conditioning

The importance of steam conditioning was quantified by Skoch et al (1981) in an experiment comparing dry pelleting with pelleting using steam conditioning. The results of this study indicated that steam conditioning improved pellet durability and production rates, and decreased the amount of fines generated and energy consumption. From this, it was concluded that steam acted as a lubricant to reduce friction during pelleting.

Mash entering the conditioner may be comprised of a wide variety of ingredients that make up the diet formulation. The nutritional as well as physical properties of this mash have an effect on conditioning and eventual pellet quality. According to Reimer (1992), pellet quality is proportionally dependent on the following factors: 40% diet formulation, 20% particle size, 20% conditioning, 15% die specifications, and 5% cooling and drying. If this is correct, 60% of the factors that affect a pellet's quality are determined before the mash enters the conditioner. This increases to 80% after conditioning, but before mash has even entered the die chamber of a pellet mill.

There has been some research conducted looking at the effects of the first two of these variables, diet formulation and particle size, on pellet quality. Studies by Stevens (1987) and Winowiski (1998) have compared pellet durabilities of diets containing corn with those where some or all of the corn was replaced with wheat. In both instances, pellet durability was higher for the diets containing wheat. It can be reasoned that this is due to the higher crude protein content of wheat (≅13%) as compared to corn (≅9%). This ties in with a study conducted by Briggs et al (1999) which found that increasing the protein content in a poultry diet from 16.3% to 21% increased the average pellet durability from 75.8 to 88.8.

Particle size is the second factor that Reimer (1992) proposed affected 20% of a pellet's quality. Decreasing particle size from a coarse to a find grind exposes more surface area per unit volume for absorption of condensing steam. MacBain (1966) indicated that a variation in particle size produces a better pellet than a homogeneous particle size. Work by Stevens (1987) in pelleting corn or wheat based diets, however, found that particle size had no effect on pellet durability index (PDI) as determined by the tumbling can method.

Mash Moisture

Those involved in the feed industry may argue that the moisture of mash entering the conditioner should fall under the category of diet formulation. Water may be physically removed or added to ingredients in a diet in order to alter its moisture. There are, however, two types of moisture; bound moisture and added moisture (MacBain, 1966 and Leaver, 1988). Bound moisture is that which is contained within an ingredient, and is not easily removed. Added moisture is that which is added at the conditioner and serves to soften feed particles or lubricate the mash as it moves through the die.

The initial moisture of mash entering the conditioner is thought to dictate the amount of steam that can be added to the mash. Leaver (1988) indicates that typically no more than 6% moisture can be added at the conditioner. Thus, large variations in initial mash moisture will be reflected in the moisture of hot mash. This may cause varying pellet mill performance if the characteristics of steam added to the mash are not adjusted as the moisture changes. Experiments recently conducted at Kansas State University have compared the effects of mash moisture contents between 12% and 15% on pellet quality. The results of this experiment show that there is a high correlation between cold mash moisture and PDI (Greer and Fairchild, 1999). Adjustment of mash moisture to 14% produced the highest quality pellet with the most efficient pellet mill operating conditions (Muirhead, 1999).

Retention Time and Conditioner Design

Retention time refers to the amount of time that mash feed spends in the conditioner. Thus, it is a measure of the duration of exposure mash has to steam for heat and moisture absorption. A conditioner operates as a continuous system in which mash is constantly entering and exiting. Flow through a conditioner, however, cannot be characterized as simple plug-flow since the mash experiences some axial and longitudinal mixing. Therefore, retention time may better be characterized as a residence time distribution (RTD) function (van Zuilichem et al, 1997). This is a mathematical relationship describing the dwell time of components within the conditioner with respect to time (van Zuilichem et al, 1997).

Retention time is affected by conditioner design including physical dimensions and operating parameters. The design and dimensions of conditioners vary in diameter, length, type of picks, number and placement of picks, pick angles, steam inlet location, presence or absence of baffles, and baffle placement. Changing any of these physical parameters will affect conditioner retention time.

Within an existing conditioner, the most common ways to manipulate retention time are by adjusting pick angles or changing shaft speed. Adjusting pick angles changes the forward motion and tossing of product as it is conveyed through the conditioner. This angle adjustment, however, can be time consuming as the conditioner must be powered down and locked out before the operator can access the picks inside of the conditioner. In addition, the pick angle is not easily measured, and the location in relation to the shaft is, at best, an estimate. Increasing or decreasing shaft speed as a means of manipulating retention time requires that there be a variable speed drive on the conditioner. In addition to slowing down the conditioner RPM, this adjustment will affect the amount of tossing motion that a product undergoes as it passes through the conditioner.

Briggs et al (1999) used the first of these methods, pick angle adjustment, to look at the effect of retention time on pellet quality. One conditioner was used in the experiment, and the angles of the picks were changed to give two different retention times. A standard setting was used in which all mixing picks were set at about a 45° forward angle. The second setting was a parallel pitch where all picks were set parallel to the conditioner shaft, except for the first and last. Average retention time was estimated at five seconds for the standard pitch, and fifteen seconds for the parallel pitch design.

The results of this study indicated that degree of pitch, or conditioner design, affected pellet quality. Pellet durability of mash conditioned using the parallel pitch averaged 5 points higher than pellets produced with the standard pitch. This improved durability can be explained by the longer retention time achieved with the parallel pitch. Conditioner design and retention time remains an area where additional research is needed so that benefits of different designs, dimensions, and operating parameters can be understood and used to the feed manufacturers benefit.

Steam Properties

High levels of heat and moisture are needed to achieve proper pelleting of grain-based diets that are high in starch (MacBain, 1966). Because of its unique thermodynamic properties that allow for the transfer of heat and moisture simultaneously, steam conditioning has presented itself as one of the most important factors in pelleting.

According to Reimer and Beggs (1993), the purpose of heat in conditioning is to gelatinize the starch portion of the feed. Other benefits of heat are to destroy pathogens and other microorganisms, and to promote drying of pellets in the cooler. Smallman (1996) explains that the moisture contribution from steam forms a cohesive bridge between particles and has a profound effect on pelleting. This moisture soaks into materials to soften them, and has been found to act as a lubricant to reduce friction between the mash and the walls of the die (Skoch et al, 1981). To optimize the conditioning process, the proper balance of heat and moisture must be obtained. Steam has the ability to provide this combination, however, it exhibits a wide variety of properties that must be understood and correctly utilized to produce high quality pellets.

Steam may exist in three different conditions: saturated, superheated, or subcooled. The American Society of Mechanical Engineers has published steam tables (ASME, 1967) that list the thermophysical properties of steam for each of these conditions. These tables include the relationship between pressure, temperature, specific volume, enthalpy, and entropy. For saturated steam, the relationship between temperature and pressure is unique. If pressure is held constant, adding heat above the saturation temperature will produce superheated steam. Likewise, at a constant pressure, cooling water below the saturation temperature creates subcooled water. "Under superheated or subcooled conditions, fluid properties, such as enthalpy, entropy and volume per unit mass, are unique functions of temperature and pressure. However, at saturated conditions where mixtures of steam and water coexist, the situation is more complex and requires an additional parameter for definition" (Stultz and Kitto, 1992).

The additional parameter referred to here is steam quality, or the percentage of steam that is in the vapor phase. Steam quality is calculated as the mass of steam divided by the mass of steam and water (Stultz and Kitto, 1992). Multiplying this by 100 gives the percent steam quality. As steam is transferred from the boiler to its location of use, it will lose some energy. Therefore, final steam quality at the conditioner depends upon "energy put into the steam at the boiler, heat losses, and water addition or removal in the steam system" (Reimer and Beggs, 1993). Steam characteristics, along with the steam quality and flow, dictate the amount of heat and moisture that is added to mash at the conditioner.

There has been a lot of discussion concerning the use of high pressure versus low pressure steam for conditioning. The properties of low (138 KPa or 20 psig) and high (552 KPa 80 psig) pressure steam are compared in Table 1 to show how they compare.

Table 1. Thermodynamic properties of low (20 psig) and high (80 psig) pressure saturated steam.

Pressure	138 kPa (20 psig)	552 kPa (80 psig)
Temperature	126 °C (259 °F)	162 °C (324 °F)
Specific Volume	.75 m^3/kg (11.9 ft^3/lb)	.29 m^3/kg (4.67 ft^3/lb)
Sensible Heat, h_f	529.3 kJ/kg (227 BTU/lb)	684.3 kJ/kg (294 BTU/lb)
Latent Heat, h_{fg}	2185.4 kJ/kg (939 BTU/lb)	2075.96 kJ/kg (881 BTU/lb)
Total Heat, h_g	2714.7 kJ/kg (1166 BTU/lb)	2760.3 kJ/kg (1185 BTU/lb)

The temperature of 552 kPa steam is 36 °C (65 °F) higher than the temperature of 138 kPa steam. Regardless of the steam pressure in the line, in an atmospheric conditioner condensation and heat transfer only occurs at atmospheric pressure. This means that the temperature of steam in the conditioner must first be reduced to around 100 °C before any condensation including moisture and heat transfer occurs.

The specific volumes of 138 and 552 kPa steam are also quite different. In handling similar quantities of these steams, a larger steam pipe is necessary to handle the low pressure steam because of its increased volume. This explains why steam is often transferred from the boiler to its location of use at a high pressure and then regulated down to a lower pressure.

Enthalpy refers to the heat or energy that steam has available in kJ/kg. This energy is broken down in the steam table as sensible heat, latent heat, and total heat. Sensible heat is the energy required to heat one kilogram of water from 0 °C to the boiling point at the corresponding temperature and pressure. Latent heat, or heat of vaporization, is the energy needed to convert this kilogram of boiling water into one kilogram of steam. Table 1 shows that there is less than a 2% difference in the total energy of the high and low pressure steam.

Though the thermodynamic properties of saturated steam at a given temperature and pressure are known, the debate still continues as to what pressure gives the best pellet quality and mill performance. MacBain (1966) presents data to show that low pressure steam produces a higher quality pellet with greater capacity on high-starch formulations. This is in contrast to Leaver (1988) who states that use of high pressure steam is more advantageous than the use of low pressure steam. Yet others, such as Thomson (1968), believe that the total energy of high and low pressure steam are similar enough that it does not make much difference as to which is used.

Stevens (1987) completed a study comparing the use of steam at 138 and 552 kPa (20 and 80 psig) to condition mash to 65°C (149°F). A swine diet consisting of primarily 72.4% corn or wheat was used in the study. Results indicated no significant differences in production rate, mill efficiency, pellet quality, percent fines, or moisture addition at the conditioner for the two diets at these pressures. Research by Briggs et al (1999) agreed with these results in a study also comparing the effects of 138 and 552 kPa (20 and 80 psig) steam on poultry diets.

A review of the literature indicates a general agreement that high quality steam is necessary for efficiently producing a durable pellet (MacBain, 1966; Skoch et al, 1981; Stark, 1990; Maier and Gardecki, 1993). Despite this, there is no published data examining the effects of steam quality on pellet durability or pellet production. Wet steam, or that which has a quality less than 100%, is known to contain less energy then saturated steam. Therefore, using wet steam requires a larger quantity be added to reach the conditioning temperature. Taking this a step further, it can be reasoned that moisture addition to the mash should increase as steam quality decreases. "Steam quality directly affects the maximum obtainable feed temperature because of moisture limits" (Reimer and Beggs, 1993). If the pellet mill reaches a choke point before the conditioning temperature is obtained, adjustments must be made. This is an area where additional research is needed.

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INTRODUCTION

Conditioner Design

Smallman (1996) defines conditioning as "the injection of steam into meal to raise temperature and moisture levels, and then a controlled agitation and retention time within the conditioner to allow optimum absorption of liquid by the meal particles." Though this process is universal to feed manufacturers, the equipment suppliers of short-term, atmospheric conditioners all have products that vary somewhat in design. The reason for the various conditioner designs may be due to the fact that the development of conditioners and conditioning came about through empirical methods without an understanding of the basic engineering principles involved in optimal conditioning (Bouvier, 1996).

Conditioners used in the feed industry contain many physical differences. These differences may include, but are not limited to, diameter, length, type of picks, number and placement of picks, pick angles, steam inlet location, presence or absence of baffles, and baffle placement. Changing any of these physical parameters will affect the flow of feed through the conditioner, and, ultimately, conditioner retention time. Retention time refers to the amount of time that mash feed spends in the conditioner. Thus, it is a measure of the duration of exposure mash has to steam for heat and moisture absorption.

A study by Briggs et al (1999) used pick angle adjustment to look at the effect of varying conditioner design, and thus retention time, on pellet quality. One conditioner with a constant shaft speed was used in the experiment, and the pitches of the picks were changed to give the two different designs. A standard setting was used in which all picks were set at about a 45° forward angle. The second setting was a parallel pitch where all picks were set parallel to the conditioner shaft, except for the first and last. Average retention time was estimated at five and fifteen seconds for these two conditioner designs. The results of this study indicated that conditioner design affected pellet quality as determined by the tumbling can method. Pellet durability of mash conditioned using the parallel pitch averaged five points higher than pellets produced with the standard pitch.

Mash Moisture

Until recently, the moisture of mash entering the conditioner has been a variable that many thought was not an important factor in producing a quality pellet. After mixing a batch of feed, operators typically send the mash to the pelleting bins without any consideration given to the mash or what its moisture is. This tendency is partially due to the fact that many believe mash moisture is difficult to both measure and control. Others argue that steam adds a sufficient amount of moisture to the mash in the conditioner to get it to a level where a quality pellet can be produced. The unfortunate result of not monitoring moisture leaves feed manufacturers at the mercy of ingredient suppliers to dictate their mash moisture year-round. This can cause varying pellet mill performance and pellet quality throughout the year because it is common for the moisture of commodities, particularly grain, to fluctuate as supplies vary from new crop to stored grains, and even between geographical regions.

Upon completing a survey of several commercial feed mills experiencing pellet quality problems, Gardecki (1996) randomly selected 21 pelleting systems to determine how much moisture was being added at the conditioner. For this study, a sample of dry mash was taken at the mixer, and a sample of hot mash was taken at the conditioner outlet. The moisture content of the samples analyzed by Gardecki (1996) averaged 11.9% for dry mash and 14.5% for hot conditioned mash. He reasoned that adding water to the mash in the mixer would help solve pellet quality problems. He believed if the moisture content at the conditioner outlet was increased to 17.5-18% a more durable pellet could be produced.

Recently, research has been conducted to specifically determine the significance mash moisture has on pellet quality and production. One such study compared the effects of mash moisture contents between 12% and 15% on pellet durability (Greer and Fairchild, 1999). For this research, a sensor was flush-mounted in the mixer to electronically measure the moisture of each batch of feed. Water was then added at the mixer to adjust moisture content to the desired level. The results of this study indicated that there is a high correlation ($r = 0.97$) between cold mash moisture and PDI (Greer and Fairchild, 1999). Moisture added at the conditioner from condensation of steam introduced greater variability to the moisture as shown in the lesser correlation ($r = 0.86$) between hot mash moisture and PDI. Adjustment of mash moisture to 14% at the mixer produced the highest quality pellet with the most efficient pellet mill operating conditions (Muirhead, 1999).

Retention Time

Retention time refers to the amount of time that mash feed spends in the conditioner. Thus, it is a measure of the duration of exposure mash has to steam for heat and moisture absorption. A conditioner operates as a continuous system in which mash is constantly entering and exiting. Flow through the conditioner, however, can not be characterized as simple plug-flow since the mash experiences some axial and longitudinal mixing. Therefore, retention time may better be characterized as a residence time distribution (RTD) function (van Zuilichem et al, 1997). This is a mathematical relationship describing the dwell time of components within the conditioner with respect to time (van Zuilichem et al, 1997). The mean of the RTD is often taken as the average retention time.

There is published material available in the extrusion industry that outlines the significance of the RTD. According to Bouvier (1996), the RTD is important for two reasons. First, it shows flow of product through the conditioner with respect to time which is an indicator of the amount of mixing that is taking place. This is important because it reveals the shortest amount of time that some particles are spending in the conditioner. Second, since the RTD is an indicator of the amount of mixing that is taking place in the conditioner, it allows one to determine how much mash/steam contact is taking place. He goes on to state that "good axial mixing allows an efficient application of fluid/particle contact in the preconditioner. But, it also means a wide dispersion of the residence time, and thus the existence of low residence times."

Within the feed industry there has been little published material detailing a method for measuring residence time distribution. Smallman (1996) described one such method in which ferrous trace powder is inserted into the feed throat of the conditioner while samples are taken at the outlet over timed intervals. Using magnetism, the trace material is separated from the samples. Plotting time vs. particle count for these samples gives a graph, the peak of which represents average retention time. Bouvier (1995) explains a similar method used in extrusion for finding RTD using a "physical or non reactive tracer." Either a step or pulse of the selected tracer is injected into the feed throat of the conditioner. Samples are taken at the outlet end and their concentration is determined and plotted as a function of time. The inflection point in the resulting curve is taken as average retention time (Bouvier, 1995).

Within an existing conditioner, the most common ways to manipulate retention time are by adjusting pick angles or changing shaft speed. Adjusting pick angles changes the tossing and forward motion of product as it is conveyed through the conditioner. This angle adjustment, however, can be time consuming as the conditioner must be powered down and locked out before the operator can access the picks inside of the conditioner. In addition, these angles or pitches are not easily measured, and their location in relation to the shaft is, at best, an estimate. Increasing or decreasing shaft speed as a means of manipulating retention time requires that there be a variable speed drive on the conditioner. Bouvier (1996) notes that RTD dispersion is significantly affected by shaft speed. A conditioner will exhibit nearly plug flow behavior at low shaft speeds, and increase to a nearly complete mixed flow behavior at elevated shaft speeds (Bouvier, 1996).

A study done by Briggs et al (1999) used the first of these methods, pick angle adjustment, to look at the effect of retention time on pellet quality. One conditioner with a constant shaft speed was used in the experiment, and the pitches of the picks were changed to give two different retention times. A standard setting was used in which all mixing picks were set at about a 45° forward angle. The second pitch was a parallel pitch where all picks were set parallel to the conditioner shaft, except for the first and last. Average retention time was estimated at five seconds for the standard pitch, and fifteen seconds for the parallel pitch design.

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Steam Quality

Within the feed industry, there is a general consensus that high levels of heat and moisture are needed to achieve proper pelleting of grain-based diets that are high in starch (MacBain, 1966). Because of its unique thermodynamic properties that allow for the transfer of heat and moisture simultaneously, steam conditioning has presented itself as one of the most important factors in pelleting.

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Steam may exist in three different conditions: saturated, superheated, or subcooled. The American Society of Mechanical Engineers has published steam tables (ASME, 1967) that list the thermophysical properties of steam for each of these conditions. These tables include the relationship between pressure, temperature, specific volume, enthalpy, and entropy. For saturated steam, the relationship between temperature and pressure is unique. If pressure is held constant, adding heat above the saturation temperature will produce superheated steam. Likewise, at a constant pressure, cooling water below the saturation temperature creates subcooled water. "Under superheated or subcooled conditions, fluid properties, such as enthalpy, entropy and volume per unit mass, are unique functions of temperature and pressure. However, at saturated conditions where mixtures of steam and water coexist, the situation is more complex and requires an additional parameter for definition" (Stultz and Kitto, 1992).

The additional parameter referred to here is steam quality, or the percentage of steam that is in the vapor phase. Steam quality is calculated as the mass of steam divided by the mass of steam and water (Stultz and Kitto, 1992). Multiplying this by 100 gives the percent steam quality. It is important at this point to distinguish between steam quality and steam purity, which are often confused. "Steam purity refers to matter other than water in steam" (ASME, 1970). Percent steam purity, therefore, is the percentage of steam (vapor) that is free from foreign materials or particulate. These impurities may get into the steam supply from boiler "burping", or by other means. Most impurities can not be transformed into vapor so they are typically present in a condensate form, hence the confusion with steam quality.

According to Stultz and Kitto (1992), the most common ways to test for steam quality and steam purity are by sodium tracer, electrical conductivity, throttling calorimeter, and gravimetricly. A throttling calorimeter is the only method available for directly measuring steam quality. The other three methods listed above measure the solids content, or purity, of steam. The ASME (1970) describes each of these methods in detail in Performance Test Code 19.11, Water and Steam in the Power Cycle (Purity and Quality, Leak Detection and Measurement).

The throttling calorimeter measures steam quality using a sample of steam taken from a special sampling nozzle inserted into the line. This sample passes through an orifice that allows reduction to atmospheric pressure in the body of the calorimeter. The enthalpy of the steam sample taken from the line should equal the enthalpy of the steam throttled to atmospheric pressure in the calorimeter. Due to this pressure drop, moisture that enters the calorimeter will flash to steam (within the range of the calorimeter at the given pressure) and the excess energy creates superheated steam. This superheat temperature is read on a thermometer that is inserted into the body of the calorimeter (Leighton, 1998; and ASME, 1970). Steam quality is calculated based on the superheat temperature obtained in the calorimeter and steam properties in the line.

"The accuracy of the throttling calorimeter generally exceeds the accuracy of sampling" (ASME, 1970). Sampling is complicated by the irregular distribution of moisture in steam as it flows through the line (ASME, 1970). It is also important that an isokinetic sample of steam be supplied to the calorimeter for proper quality determination. The American Society for Testing and Materials (ASTM) has outlined guidelines for sampling nozzles including their location and design in ASTM method D 1066, Standard Practice for Sampling Steam (ASTM, 1990).

Final steam quality at the conditioner depends upon "energy put into the steam at the boiler, heat losses, and water addition or removal in the steam system" (Reimer and Beggs, 1993). Steam characteristics, along with the steam quality and flow, dictate the amount of heat and moisture that is added to mash at the conditioner. A review of the literature indicates a general agreement that high quality steam is necessary for producing a durable pellet (MacBain, 1966; Skoch et al, 1981; Stark, 1990; Maier and Gardecki, 1993;). Despite this, there is no published data examining the effects of steam quality on pellet durability or pellet production. Wet steam, or that which has a quality less than 100%, is known to contain less energy then saturated steam. Therefore, using wet steam requires a larger quantity of steam be added to reach the conditioning temperature. Taking this a step further, it can be reasoned that moisture addition to the mash should increase as steam quality decreases. "Steam quality directly affects the maximum obtainable feed temperature because of moisture limits" (Reimer and Beggs, 1993). If the pellet mill reaches a choke point before the conditioning temperature is obtained, adjustments must be made.

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MATERIALS AND METHODS

The feed mill in the Kansas State University Grain Science Department was used for this research. Table 1 shows the swine finishing ration used for the investigations. Whole (No. 2 yellow) corn was ground through a 30 Hp Jacobson hammermill (Model P-240, Jacobson Mfg. Co., Minneapolis, MN) using a 3.175 mm (1/8") screen to produce the ground corn. All other ingredients were used in the form in which they were received.

After batching, ingredients in the feed formulation were mixed with a horizontal, double-ribbon batch mixer. This mixer is equipped with a flush-mounted, Grain Prep Auto Delivery System (batch version, AgriChem, Inc., Ham Lake, MN) that has the capability to electronically measure moisture content of feed in the mixer and adjust it to a desired level by adding water automatically. Each batch size was 294.8 kg (650 pounds) and underwent a 120 s dry mix followed by a 180 s wet mix. Wet mix additions included both water and soybean oil. The amount of water to be added was calculated by the Grain Prep system based upon the measured moisture content of the batch, and the target moisture level. After addition of the wet ingredients, the Grain Prep system again measured moisture content. The two mash moistures used for this study were 12% and 14%. After adjusting moisture content, these batches of mash were then transferred to the pelleting system.

CPM and Bliss Conditioners

Steam was used to condition mash prior to pelleting using either a CPM (California Pellet Mill Co., Crawfordsville, IN) or Bliss (Bliss Ind., Ponca City, OK) short-term, atmospheric conditioner. Figures 1 and 2 show the drawings of these conditioners including their physical dimensions. As the figures show, there are some distinct differences between the two conditioners. First, the Bliss conditioner is longer with a length of 48 inches as compared to the CPM with a length of only 36 inches. Another main difference is the presence of baffle plates in the Bliss conditioner. Figures 3 and 4 show the pick settings for each of the conditioners. Figure 3 illustrates the location of the two baffle plates that are present in the Bliss conditioner. These baffles extend from the top of the conditioner down almost to the center shaft. The Bliss conditioner contains a total of 30 picks, including 10 single and 10 double picks. The CPM conditioner contains only 12 single picks. The CPM conditioner was used for the first half of experimentation. This conditioner was then removed and replaced with the Bliss conditioner to conduct the second half of the research.

Retention Time Measurement

Two retention times were used for this study and they were differentiated as short and long for each of the conditioners. For experimentation, retention time was adjusted by changing the RPM on the variable speed drive (shaft speed) of the conditioner. Retention time was previously determined at various shaft speeds by injecting a tracer into the feed throat of the conditioner and determining its concentration in samples collected over timed intervals at the conditioner outlet. Chromic oxide and salt were used as tracers with ground corn serving as the medium. For RTD testing, feeder speed was held constant at 20 RPM which equates to approximately two tons per hour of throughput, a typical load for the pellet mill. Both feeder and conditioner RPM were measured with a handheld tachometer.

To begin RTD testing, a pulse-input consisting of 15 g of chromic oxide and 45 g of salt was dropped into the conditioner feed throat as timing began. All material coming out of the conditioner was collected in numbered containers over three second intervals for approximately one minute. The material in each container was mixed by hand prior to sampling. These samples were then analyzed separately for their color intensity and salt concentration. Color analysis was performed on a Minolta chroma meter (Model CR-310, Ramsey, NJ) to obtain the values for L, a, and b. Quantab chloride titrators (Environmental Test Systems, Elkhart, IN) were used to determine the chloride ion (salt) concentration in the sample.

Table 2 shows the data collected during RTD testing using both chromic oxide and salt in the CPM conditioner at two different tip speeds. For the chromic oxide tracer, plotting average time versus 1/L gives a RTD as shown in Figure 5. For salt, plotting average time versus chloride ion concentration also gives the RTD shown in Figure 6. The peaks of these curves are taken as the average retention time, and are quite similar for the two methods as shown by the graphs. Variations in the distributions obtained for these two tracers may be explained by their difference in particle size and bulk density. Data collected for

RTD testing using the Bliss conditioner is listed in Table 3. The corresponding graphs showing the RTD for the chromic oxide and salt tracers are located in Figures 7 and 8.

In order to keep the retention time variable as consistent as possible, an effort was made to obtain a RTD with similar peaks for the two conditioners. Therefore, the short retention time variable consisted of a CPM conditioner shaft speed of 160 RPM, or tip speed of 586 feet per minute (fpm) based on a 14 inch diameter. Short retention time for the Bliss conditioner consisted of a shaft speed of 300 RPM, or tip speed of 942 fpm based on a 12 inch diameter. For the long retention time, the CPM and Bliss conditioners were operated at 80 and 150 RPM shaft speed, respectively, giving tip speeds of 293 and 471 feet per minute.

RTD analysis was completed without the addition of steam to the conditioner. There is no published material available discussing the effects of steam and/or other moisture addition on the residence time distribution. Therefore, the difference between the RTD as determined and the actual RTD during mash conditioning with steam injection is unknown.

Steam Quality Measurement

Before experimentation could begin, a method had to be developed to allow manipulation and measurement of steam quality. It was assumed that the steam coming into the feed mill had an initial quality near 100% because of traps and separators located in the main line. Therefore, to create lower quality steam, either water could be injected into the line, or a heat exchanger used to remove energy from the steam. It was decided that a heat exchanger be used for steam quality manipulation using tap water. If the initial quality of steam in the line was known, the water flow and temperature differential of water going through the heat exchanger could be used to calculate steam quality. Adjustments could then be made in water flow to get a target steam quality.

Next came the issue of determining a method for measuring initial steam quality in the line. The first attempt made at measuring steam quality involved using an insulated bucket filled with water. With this method, steam was run into a bucket containing cool water of a known initial temperature and weight. The increase in weight and temperature from the steam was determined. Using this information and the properties of steam in the line, a calculation was used to determine quality. After several attempts, it was determined that this method was not only inaccurate, but also inconsistent.

Further research indicated that a throttling calorimeter is one of the only direct methods available for measuring steam quality. This device uses special sampling nozzles to supply the calorimeter with a quantity of steam. This sample is then throttled through an orifice to atmospheric pressure. The enthalpy of the high pressure steam in the line should be equal to the enthalpy of the same steam at atmospheric pressure in the calorimeter. At the lower pressure, energy equal to the difference in these two enthalpies is available to flash any condensate into steam and create superheat. This superheat temperature is indicated on a thermometer in the body of the calorimeter and used to calculate steam quality.

Upon determination of these methods, the steam lines in the KSU feed mill used for pelleting were modified for this experiment. Figure 9 shows the design of the new steam system. This system was designed with the capability to manipulate and measure steam quality, in addition to measuring steam flow. Three steam systems commonly seen in the feed industry are installed in parallel and can be used independently to supply steam to the conditioner. These designs include a conventional, manual (standard) steam system, steam system with TLV Cospect valve (COS-16, TLV Co., Charlotte, NC), and a Bliss steam system with TLV COSR-16 valve and purifier (Model PI-2008-T, Bliss Ind., Ponca City, OK). A heat exchanger is included in the main line to facilitate steam quality manipulation. Flexible hoses are used on the unit so that it can be operated with water either in parallel or counter flow. The design and dimensions of the heat exchanger are shown in Figure 10. The steam system contains three locations where temperature and pressure readings can be taken. There are also three sampling ports where a calorimeter can be used to measure steam quality.

The primary steam supply to the conditioner was held at approximately 172.5 kPa (25 psig) with a corresponding temperature of 131.7 °C (269 °F) using the standard steam line. Four different steam qualities were used in this research; 70, 80, 90, and 100%. For the lower quality steam (70, 80, and 90%), water flowing in parallel across the heat exchanger was used to remove energy and create the lower quality. Appendix A shows the calculations used for this determination which is based on the water flow and temperature differential in the heat exchanger.

For high quality steam (≅100%), an Ellison throttling steam calorimeter (900 Series, Cal Research, Inc., Ransomville, NY) was used to determine quality. This device pulls a sample out of the steam line and superheats it by reduction to atmospheric pressure to determine the amount of moisture present.

Calculations for the throttling calorimeter are also shown in Appendix A. For all investigations, the standard steam system was used with the steam traps closed. This was necessary to insure that steam quality was not altered as it flowed through the line. Steam flow was determined for each run with a Honeywell Vortex (SVM 3000 PLUS, Honeywell Inc., Fort Washington, PA) steam flow meter.

Pelleting of individual batches was done with a CPM (Master HD, Model 10-21) pellet mill with a 30 Hp variable speed die drive. The 31.75 mm thick die with a 3.97 mm hole diameter (5/32" X 1 1/4") was warmed prior to data collection, and die speed was constant at 163.7 m/min (537 ft/min). Motor load was held constant at about 15 Amps, and steam was added until the hot mash temperature reached 82.2 °C (180 °F). Hot pellets coming off the die were cooled through a double-pass horizontal cooler using ambient air. Fines were screened from the whole pellets, with each being collected and weighed separately.

Data collection did not begin until the steam and pellet mill had stabilized at the conditioning temperature and pre-determined operating parameters. Pellets were diverted into a vertical cooler during the start-up and shut down period. Once data collection began, samples of hot mash and hot pellets were placed into sealed sampling bags. These samples were emerged in a solution of dry ice (CO_2) and windshield washer fluid (freezing point –28.8 °C) to facilitate rapid cooling. The revolutions per minute (RPM) of the feeder and conditioner were measured with a handheld tachometer and noted. Hot mash and hot pellet temperatures were recorded at the pellet mill. Hot pellet temperature was determined by filling an insulated container with hot pellets and putting a probe thermometer into them. After approximately three minutes the hot pellet temperature was read. Production rate was determined by dividing the total weight of whole pellets by the data collection time. The percent fines were calculated as the weight of fines divided by the weight of whole pellets and fines. A recording volt-ammeter was used to determine electrical energy consumption and specific energy consumption. Samples of mixed mash were taken prior to data collection as mash was being transferred to the pelleting bin. Samples of cool pellets were taken at the bagger.

Data from the steam system that were recorded included temperature at two locations, pressure at three locations, and steam flow. In the runs using high quality steam (≅100%), superheat temperature in the calorimeter was recorded. If a lower quality steam was being used, the water flow and inlet and outlet temperatures at the heat exchanger were noted. Steam quality was calculated using this information as outlined in Appendix A. Steam conductivity, total dissolved solids (TDS), and pH was measured each day of experimentation with a handheld Ultrameter (Model 6P, Myron L Co., Carlsbad, CA).

The mixed feed had an average particle size (Dgw) of 656.6 microns with a standard deviation (Sgw) of 2.04 as determined by ASAE (1997a) methods. ASAE Standard S269.4 (ASAE, 1997b) was used to determine pellet durability (PDI). The pellets used for durability testing were collected at the mill and placed in a batch sample cooler for approximately 15 minutes. For each batch, four durability tests were completed. Two of these were standard PDI's and two were modified PDI's where five, ½" NC nuts were added to the tumbling can to simulate handling in the durability test. Moisture of mixed mash, hot conditioned mash, hot pellets, and cool pellets was determined by drying for 1 hr at 130 °C using an air oven (AACC, 1995). Starch gelatinization of hot mash and hot pellets was determined with an enzymatic method presented by Xiong et al (1990).

This experiment was conducted with a split-plot treatment structure within a Bliss and CPM conditioner. Mash moisture served as the whole plot treatment with retention time and steam quality making up the sub-plot treatments. Retention time (short and long), and steam quality (70, 80, 90, and 100%) made up the sub-plot treatments. Combinations of sub-plot treatments were completely randomized within the two mash moistures (12% and 14%). Three replications of all above combinations were completed.

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Table 1. Swine finishing formula used for all experimentation

Ingredient	Internat'l Feed No.	Percent
Ground Corn	4-02-861	73.8
Soybean Meal	5-04-604	20.7
Soybean Oil	4-05-077	3
Limestone	6-02-632	1
Monocalcium Phosphate	6-01-082	.7
Salt	6-04-152	.35
L-Lysine	5-08-022	.16
Vitamin Premix[1]		.15
Trace Mineral Premix[2]		.15
L Threonine	5-08-092	.048

[1]Guaranteed Analysis Per Pound of Premix; Vitamin A minimum 2,000,000 I units, Vitamin D3 minimum 300,000 I units, Vitamin E minimum 8,000 I units, Vitamin B12 minimum 6 mg, Menadione (Vitamin K) minimum 800 mg, Riboflavin minimum 1,500 mg, D-Pantothenic Acid minimum 5,200 mg, Niacin minimum 9,000 mg, Choline minimum 30,000 mg.

[2]Guaranteed Analysis Per Pound of Premix; Iron (Fe) minimum 11.01%, Zinc (Zn) minimum 11.01%, Manganese (Mn) minimum 2.64%, Copper (Cu) minimum 1.10%, Iodine (I) minimum .02%, Selenium minimum .02%.

Table 2. Data from retention time (RTD) measurement testing using chromic oxide and salt as tracers in a CPM Conditioner

Long RTD Tip Speed – 293 feet per minute				
Time, t	Ave. T	CrO	CrO	Salt
(sec)	(sec)	L	1/L	(Cl)
0	0	80.6	0.01241	0.06
1-3	2	81.04	0.01234	0.005
4-6	5	80.24	0.01246	0.06
7-9	8	79.57	0.01257	0.065
10-12	11	79.21	0.01262	0.13
13-15	14	77.84	0.01285	0.22
16-18	17	77.46	0.01291	0.33
19-21	20	75.62	0.01322	0.39
22-24	23	76.54	0.01307	0.43
25-27	26	77.3	0.01294	0.22
28-30	29	77.41	0.01292	0.16
31-33	32	77.92	0.01283	0.16
34-36	35	77.97	0.01283	0.16
37-39	38	78.74	0.0127	0.18
40-42	41	78.73	0.0127	0.09
43-45	44	79.3	0.01261	0.11

Short RTD Tip Speed – 586 feet per minute				
Time, t	Ave. t	CrO	CrO	Salt
(sec)	(sec)	L	1/L	(Cl)
0	0	79.48	0.01258	0.09
1-3	2	78.75	0.0127	0.125
4-6	5	73.57	0.01359	0.41
7-9	8	74.35	0.01345	0.32
10-12	11	75.49	0.01325	0.375
13-15	14	75.27	0.01329	0.24
16-18	17	76.83	0.01302	0.23
19-21	20	77.4	0.01292	0.16
22-24	23	77.97	0.01283	0.15
25-27	26	78.23	0.01278	0.19
28-30	29	78.04	0.01281	0.1
31-33	32	79	0.01266	0.18
34-36	35	78.93	0.01267	0.125
37-39	38	79.41	0.01259	0.09

Table 3. Data from retention time (RTD) measurement testing using chromic oxide and salt as tracers in a Bliss conditioner

Long RTD Tip Speed – 471 feet per minute				
Time, t (sec)	**Ave. T (sec)**	**CrO L**	**CrO 1/L**	**Salt (Cl)**
0	0	75.45	.01325	.06
1-3	2	75.96	.01316	.06
4-6	5	76.55	.01306	.06
7-9	8	78.13	.0128	.095
10-12	11	76.2	.01312	.15
13-15	14	75.29	.01328	.25
16-18	17	74	.01351	.28
19-21	20	73.77	.01356	.37
22-24	23	74.3	.01346	.34
25-27	26	75.64	.01322	.25
28-30	29	76.56	.01306	.31
31-33	32	76.31	.0131	.21
34-36	35	77.67	.01287	.17
37-39	38	78.17	.01279	.14

Short RTD Tip Speed – 942 feet per minute				
Time, t (sec)	**Ave. t (sec)**	**CrO L**	**CrO 1/L**	**Salt (Cl)**
0	0	72.63	.0138	.196
1-3	2	78.24	.0128	.28
4-6	5	71.94	.0139	1.099
7-9	8	72.46	.0138	1.043
10-12	11	74.26	.0135	.63
13-15	14	75.88	.0132	.5495
16-18	17	77.99	.0128	.406
19-21	20	78.93	.0127	.2485
22-24	23	79.47	.0126	.238
25-27	26	79.12	.0126	.161
28-30	29	80.61	.0124	.1575
31-33	32	79.63	.0126	.14
34-36	35	80.68	.0124	.133
37-39	38	80.63	.0124	.133

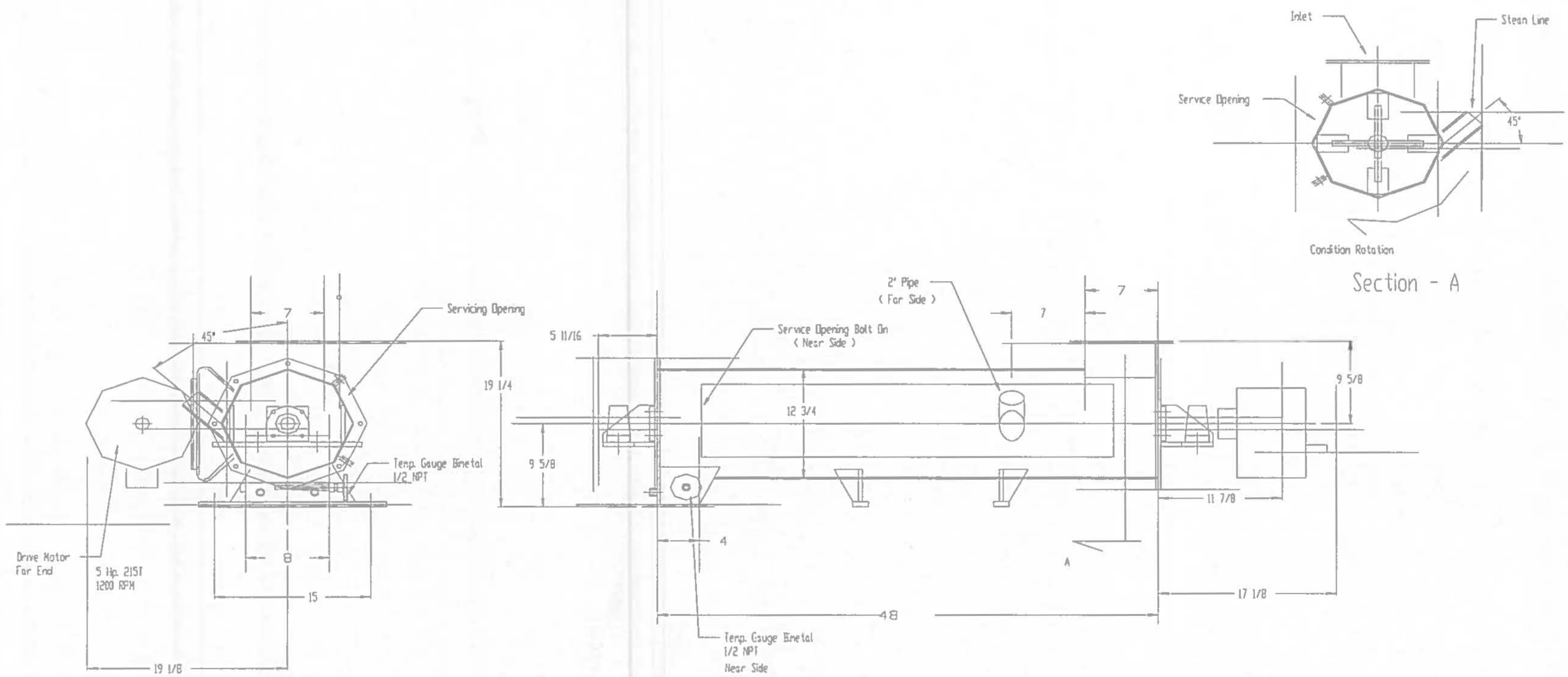

Figure 1. Bliss Conditioner
(Reprinted With Permission From Bliss Industries)

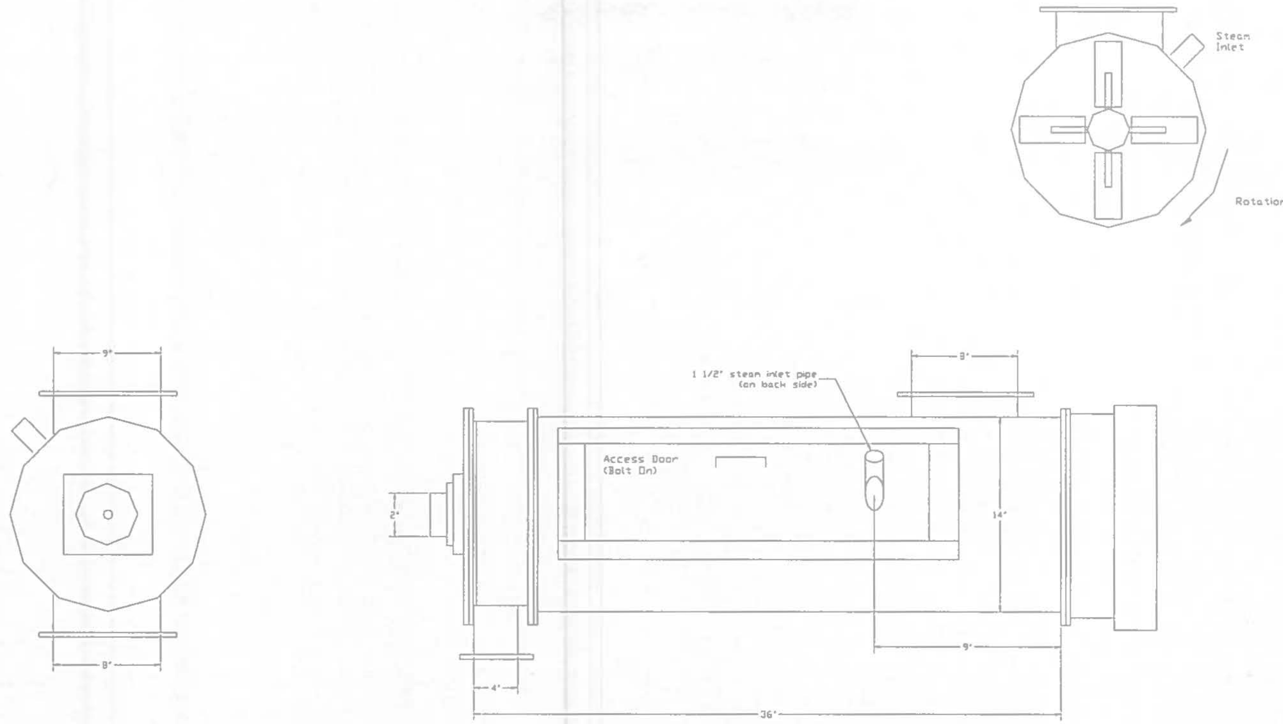

Figure 2. CPM Conditioner

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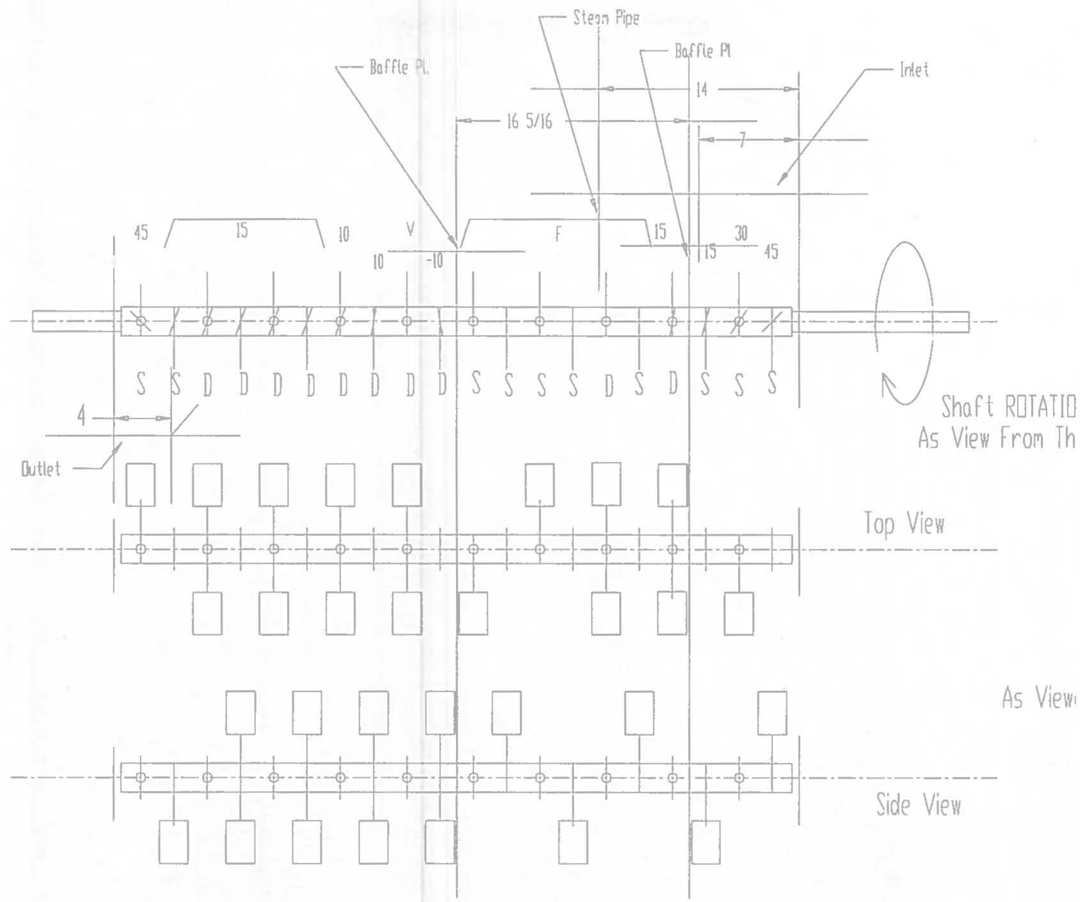

Figure 3. Bliss Conditioner Pick Setting
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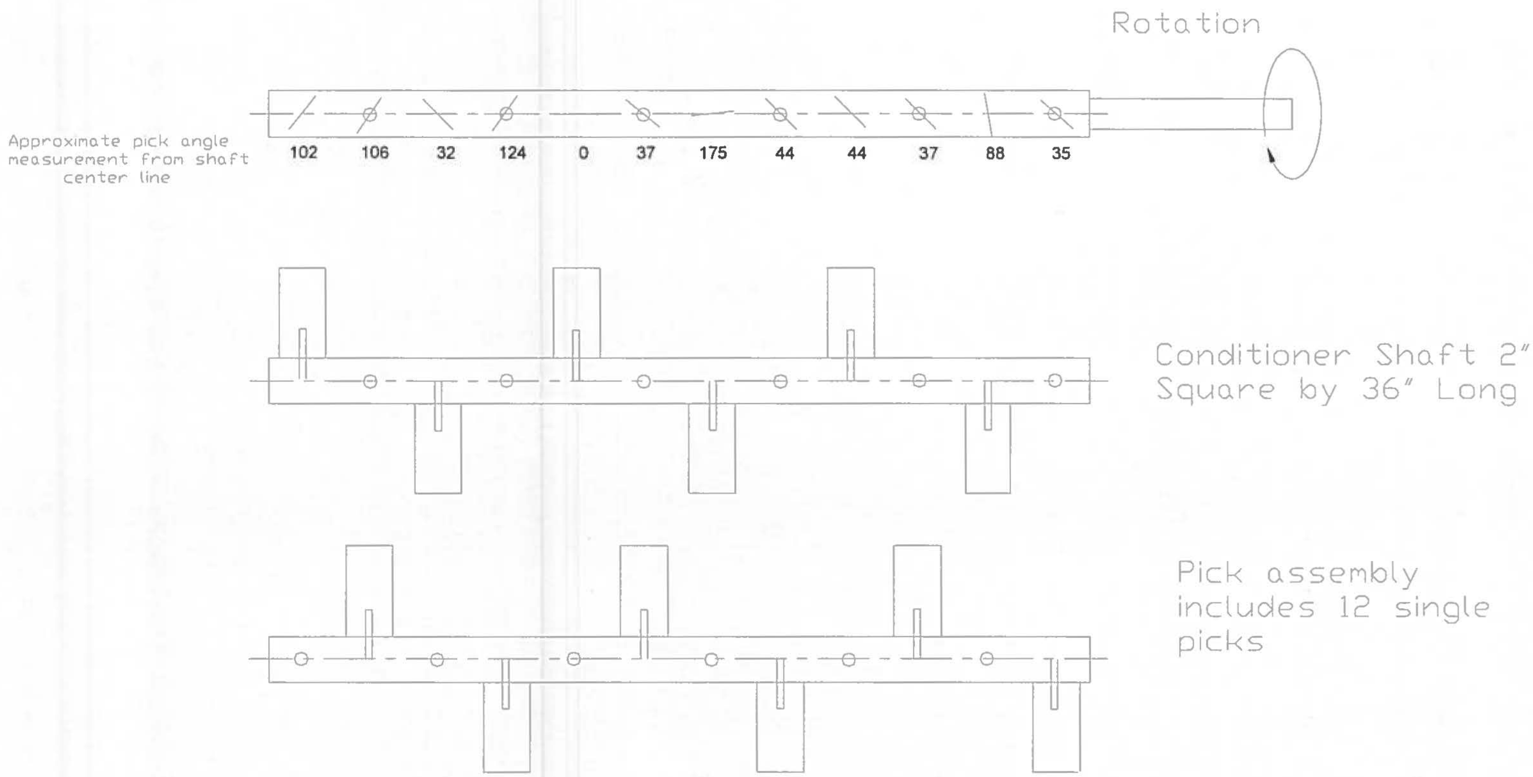


Figure 4. CPM Conditioner Pick Setting

Figure 5. Residence time distribution (RTD) plot using chromic oxide as a tracer in a CPM conditioner

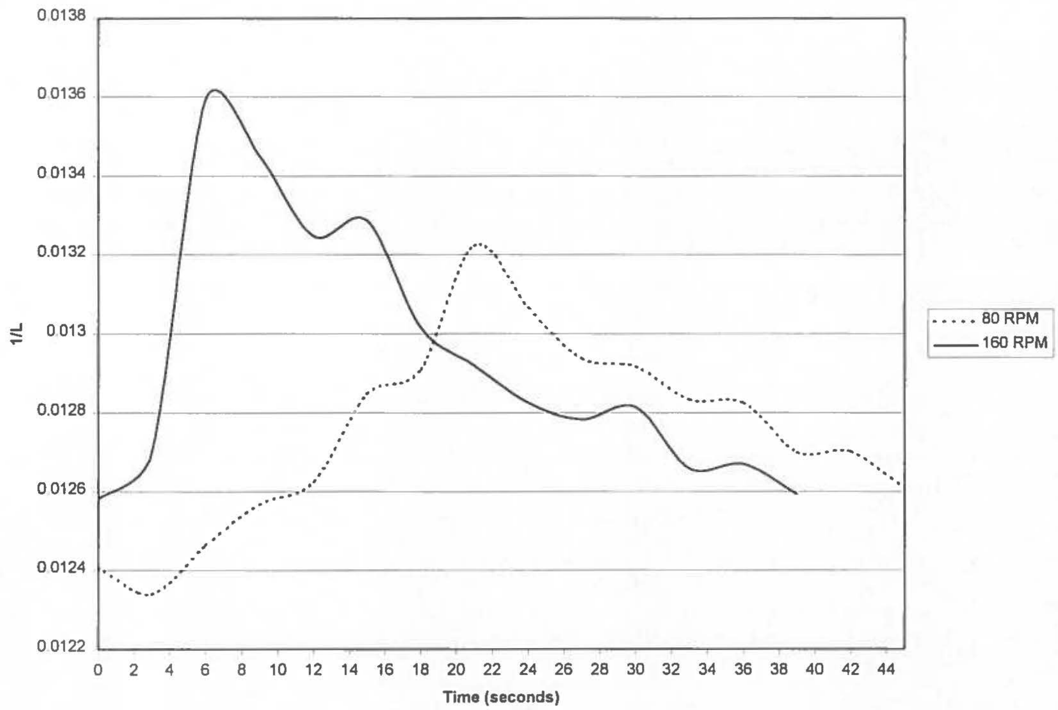


Figure 6. Residence time distribution (RTD) plot using salt as a tracer in a CPM conditioner

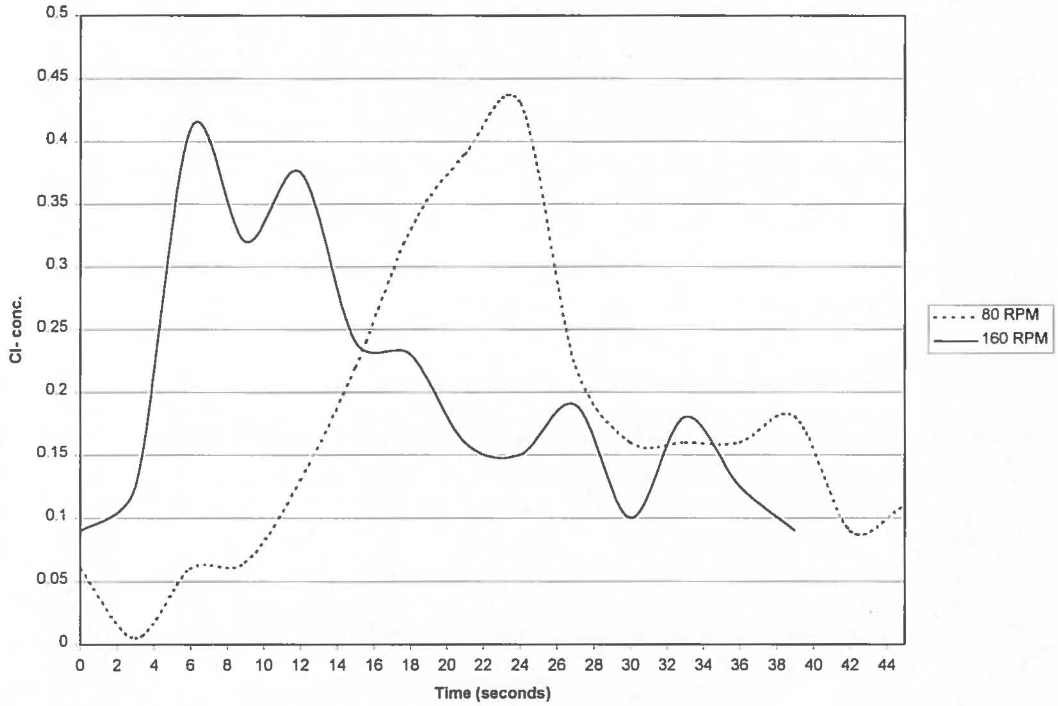


Figure 7. Residence time distribution (RTD) plot using chromic oxide as a tracer in a Bliss conditioner

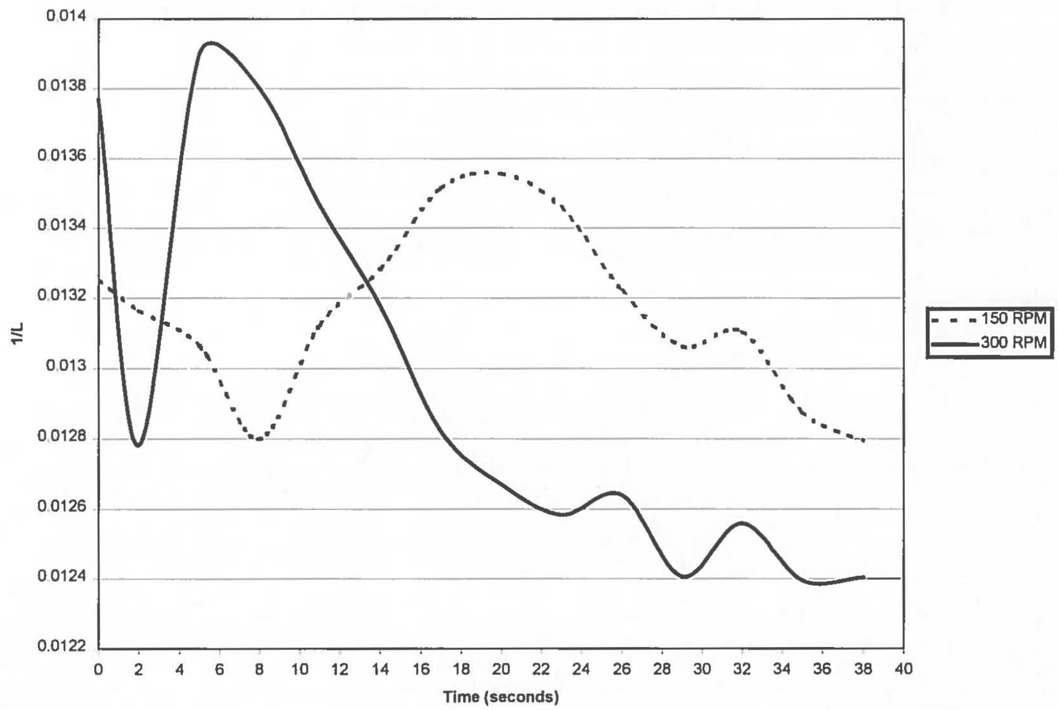


Figure 8. Residence time distribution (RTD) plot using salt as a tracer in a Bliss conditioner

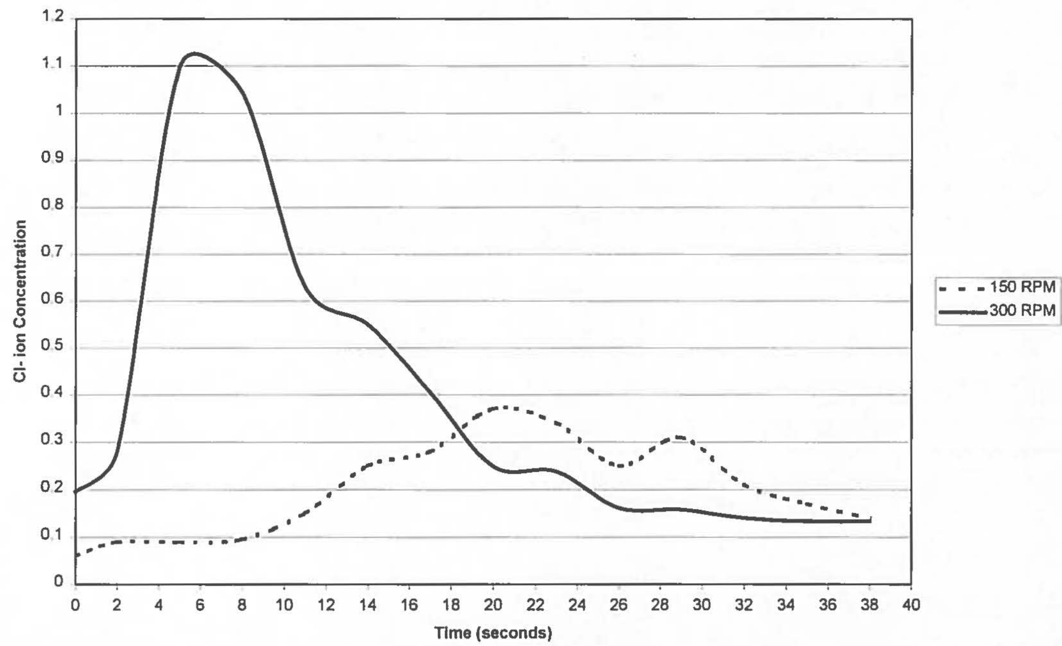
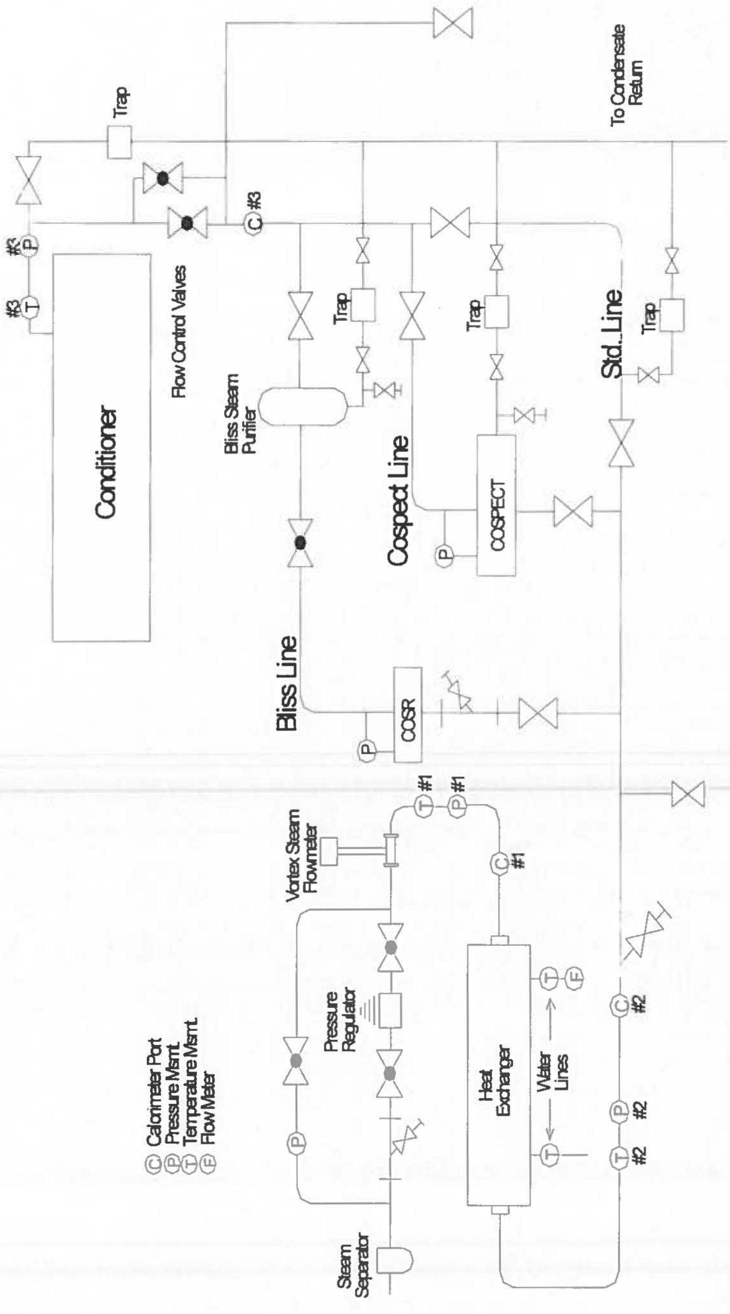


Figure 9. New steam system design



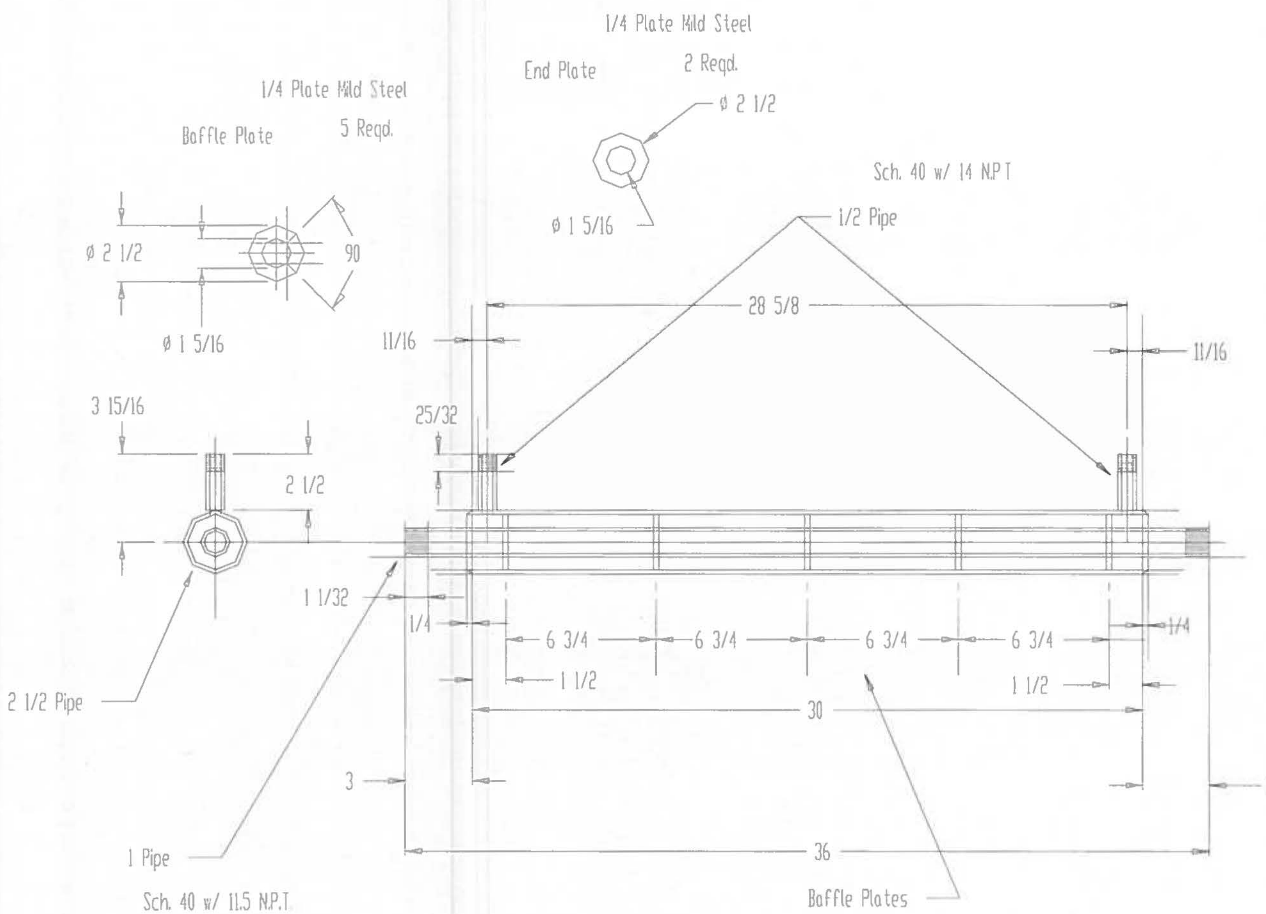


Figure 10. Heat Exchanger

RESULTS AND DISCUSSION

The significance (p-values) of main effects and interactions for each of the response variables using the CPM conditioner are listed in Table 1, and similar data for the Bliss conditioner in Table 2. For the CPM conditioner, mash moisture displayed a significant effect on all response variables except energy consumption. Retention time significantly influenced PDI and steam flow, while the variables energy consumption, steam flow, and hot mash moisture responded significantly to steam quality. The moisture x retention time interaction was significant for pellet gelatinization and energy consumption with p-values less than .01. The moisture x steam quality interaction was significant for pellet gelatinization and steam flow, and the retention time x steam quality interaction was significant for all response variables except pellet gelatinization. The three-way interaction (moisture x retention time x steam quality) was significant for standard and modified PDI and hot mash moisture.

For the Bliss conditioner, mash moisture, retention time, and steam quality exerted a significant influence on most response variables; exceptions include steam flow response to mash moisture and percent fines, and energy consumption response to retention time. The two-way interaction of mash moisture x retention time showed a difference only for energy consumption. The moisture x steam quality interaction was significant for standard and modified PDI, percent fines, energy consumption, and hot mash moisture. The retention time x steam quality interaction showed differences for all response variables except the three indices of pellet quality; standard and modified PDI and percent fines. The three-way interaction was significant for hot mash moisture content.

Standard PDI, energy consumption at the pellet mill, and steam flow are discussed below for each of the conditioners. These variables were chosen because they represent the three main items of interest; pellet quality, pellet mill performance, and steam line usage.

Standard PDI

CPM Conditioner

The affect of mash moisture content and steam quality on standard PDI differed for long and short retention times in the CPM conditioner (Figure 1). Optimum pellet quality (90% PDI) was achieved using 14% mash moisture with the following combination of effects: 1) 70% steam quality with a short retention time, and 2) 80% steam quality with a long retention time. The temperature of mash exiting the conditioner was held constant at 82.2°C. Therefore, these results indicate that the optimum steam quality by retention time combination (for 14% mash moisture) was related to conditioned mash moisture content. The opposite trend was evident with the lowest quality pellet (lowest PDI) being produced using 12% mash moisture with a short retention time and 100% steam quality. This combination produces hot conditioned mash with the lowest moisture content.

Previous research by Greer and Fairchild (1999) explored the effect of adding water in the mixer to create mash moisture contents between 12% and 15%. The results of their experiment showed a positive relationship between mash moisture in the mixer and PDI. This research indicates that a 14% mash moisture content enables feed manufacturers to adjust steam quality and retention time to maximize pellet quality.

A long retention time provides mash adequate time and exposure for moisture absorption. As a result, there was no significant decrease in PDI with increased steam quality using the 14% moisture mash in the long retention time. Conditioned mash characteristics are improved with a long retention time because more time is available for the steam to condense on mash particles in the conditioner and be absorbed. This allows moisture in both the liquid and vapor forms time to condense on particles and begin to penetrate them. For the short retention time, Figure 1 shows that standard PDI decreased as steam quality increased. The short retention time does not provide enough time for moisture in the vapor form to completely condense on particles and penetrate them.

Lower quality steam contains less energy, so a greater amount is required to achieve the conditioning temperature. Low quality steam also contains more moisture that is in the form of condensate initially as it enters the conditioner. Steam that is in the vapor phase must reduce its temperature to approximately 212°F and give up its latent heat before condensing to a liquid. The low quality steam already contains free water that is absorbed by mash particles and begins to penetrate them giving more effective conditioning, and, therefore, improved pellet durability. The steam quality that will provide optimal conditioning, therefore, depends on the cold mash moisture content. If initial mash moisture going into the conditioner is low, high quality steam will not provide the mash enough free moisture to produce a durable pellet as compared to lower quality steam that contains free moisture.

Bliss Conditioner

For the Bliss conditioner, optimal pellet quality (PDI) was optimized using 14% mash moisture and 80% steam quality (Figure 2). This response is similar to that shown with the CPM conditioner long retention time treatment, however, the Bliss PDI is approximately 5 points lower. For 90% and 100% quality steam, less moisture was available which has a negative impact on pellet durability. For the 70% quality steam, mash has surpassed its optimal moisture and the overly wet mash produced a pellet with a slightly lower standard PDI, possibly because of pelleting problems.

Standard PDI shows an inverse relationship to steam quality for 12% mash moisture (Figure 2). As steam quality was reduced from 100% down to 70%, more steam was required to achieve the conditioning temperature because lower quality steam contains less energy. This means that with a greater steam quality less moisture is available to condense on the mash as it passes through the conditioner. Looking at Figure 2, there is a nearly linear reduction in Standard PDI for the 12% mash moisture as steam quality increases. This decrease in durability is attributed to the decreasing steam flow provided to the conditioner to achieve conditioning temperature.

Correlation Between Pellet Quality Indices

There is a strong, positive correlation between standard and modified PDI and a moderate and strong, negative correlation between percent fines and standard PDI for the Bliss and CPM conditioners, respectively (Tables 3 and 4). Pellet gelatinization was negatively correlated with PDI for the CPM (not significant) and Bliss (moderately significant) conditioners. The effects of steam quality, mash moisture, and retention time on these response variables are present in Figures 3 through 7. In view of the moderate to strong correlation between standard PDI and other pellet quality indices, no further discussion of these indices are present below.

Energy Consumption

CPM Conditioner

As mash moisture increased from 12% to 14% for the long retention time, energy consumption at the pellet mill increased (Figure 8). The opposite response was evident with a short retention time. The 12% moisture mash was able to utilize long retention time to absorb the condensing steam and allow it to begin penetrating the mash. In addition, moisture coated the surface of mash particles and acted as a lubricant. The 14% mash had a higher initial moisture, thereby giving it a somewhat reduced capacity for moisture absorption. The long retention time coupled with this moisture caused the mash to be overly wet. If mash is too wet it cannot effectively be forced through the die and will, therefore, cause plugging or slippage between the rolls and die that increases the required energy consumption. A short retention time limits the duration of exposure between mash particles and moisture in the conditioner. The combination of 12% moisture mash and a short retention time results in mash that is too dry for optimal pelleting resulting in an increase in the energy required for pelleting. The 14% mash moisture and short retention time resulted in the lowest kWh/t combination, though not significantly different from the 12% mash moisture x long retention time combination.

The interaction between steam quality and retention time on energy consumption is presented in Figure 9. The highest kWh/t occurred for the long retention time at 80% steam quality and for the short retention time at 90% steam quality. These peaks distort the energy utilization trend observed for each retention x steam quality interaction. For the short retention time, kWh/t increased as steam quality increased. Lower quality steam contains less energy, so more flow to the conditioner is required to achieve the conditioning temperature. This increased flow at the lower qualities means more moisture is available which reduces energy consumption at the pellet mill. For the long retention time, energy consumption was not significant between the steam qualities 70%, 90%, and 100%.

Bliss Conditioner

For the Bliss conditioner, the greatest energy consumption at the pellet mill occurred with 100% quality steam and 12% mash moisture (Figure 10). For the 12% moisture mash, as steam quality increased, energy consumption also increased. Lower quality steam contains less energy so more flow is required in the conditioner. This increase in flow also increases mash moisture content which improves the ease of pelleting. For the 14% moisture mash, reaction to steam quality is not as obvious. The lowest amount of energy consumption is shown with 90% quality steam. Increasing or decreasing steam quality from 90% provided less than optimal conditions due to the resulting changes in moisture content.

For the retention time x steam quality interaction, the lowest kWh/t occurred using the 70% quality steam and a short retention time (Figure 11). As steam quality was increased to 100% for the short retention time, energy consumption also increased. This trend is due to the energy differences (and corresponding moistures) amongst the four steam qualities shown. A long retention time provides adequate time for condensation and penetration of moisture into the mash. This is evident by the reaction of energy consumption to steam quality for a long retention time. Steam quality extremes (70% and 100%) exhibited slightly greater energy requirements. This is due to the mash being either slightly wetter than optimal (70% steam) or drier than optimal with the 100% quality steam.

Energy consumption for the retention time x mash moisture interaction is present in Figure 12. As mash moisture increased from 12% to 14%, energy consumption moved inversely. This effect is slightly more dramatic for the short retention time as shown by the greater difference in energy between the two mash moistures.

Steam Flow

CPM Conditioner

Steam flow to the conditioner reacted similarly for both mash moistures over all combinations of steam quality (Figure 13). There is, however, a distinct difference between steam flow with 100% quality steam for the mash moistures. The flow required to heat 12% moisture mash to the conditioning temperature is significantly less than that of the 14% mash. Greatest flow to the conditioner occurs for both moistures using 80% steam quality. Basic thermodynamic principles indicate that as steam quality is increased, steam flow should increase because of the reduced energy content of the steam. This trend is present for all incremental quality changes except from 70% to 80%. The reason for this is unknown.

When comparing retention times, steam flow generally increased when using lower quality steam (Figure 14). For the short retention time, each incremental quality increase, decreased the amount of steam flow needed to achieve 82.2°C. The long retention time, followed a similar trend except for the 70% quality steam which caused a decrease in flow and explains the steam quality x mash moisture interaction for the CPM conditioner.

Bliss Conditioner

Steam flow to the Bliss conditioner exhibited expected decreases with increasing steam quality (Figure 15). Reductions in flow were similar when increasing quality from 70% to 80% to 90% with a short retention time. The steam flow decrease was less dramatic between 90% and 100% quality steam. For the long retention time, steam flow was not significantly different between 70%, 80%, and 90% steam quality. The 100% quality steam, however, showed a greater reduction in steam flow due to its greater energy content.

Correlations

CPM Conditioner

Standard PDI showed significant correlations for modified PDI, percent fines, mash moisture, and steam flow. The correlation between mash moisture content and PDI was moderate (r=.537). Similar correlations were found in previous research by Greer and Fairchild (1999), and reflect the significance of moisture content in producing a durable pellet. Steam flow rather weakly correlated to PDI, however, this is a positive correlation. Increased steam flow, therefore, improves pellet quality by providing additional moisture to the mash.

Significant correlations ($P<.05$) are exhibited between pellet mill energy consumption and percent fines. Steam flow to the conditioner was significant for standard and modified PDI, pellet gelatinization, and steam quality. The correlation between PDI and steam flow is moderately strong, and indicates that increased steam flow improves pellet durability. Pellet gelatinization has a significant, negative correlation to steam flow. Increased steam flow provides moisture that lubricates mash and reduces the friction in the die that causes pellet gelatinization. There is a strong, negative correlation between steam quality and steam flow to the conditioner. This follows thermodynamic principles because lower quality steam contains less energy and, therefore, increases flow to achieve the desired conditioned mash temperature.

Bliss Conditioner

Mash moisture shows a strong, positive correlation and energy consumption exhibits a strong, negative correlation with standard PDI (Figure 4). The r-value for correlation between steam quality and standard PDI was negative at $r=-.341$. This is a moderately strong correlation resulting from energy differences in steam quality. Steam flow should present the opposite reaction as steam quality. This is true and the strong correlation coefficient between standard PDI and steam flow is $r=.476$.

Energy consumption also shows significant correlations for all response variables with p-values for each of these relationships being than .01. In addition, the signs for the correlation coefficients (r-values) react in an expected manner.

Correlations between steam flow and all response variables are significant ($p<.05$). The relationship (positive or negative correlation coefficients) between the response variables and steam flow are similar to those for standard PDI. The signs on the correlation coefficients are also opposite of those of corresponding variables for energy consumption. As steam flow to the conditioner increases, more moisture is added which improves pellet durability (PDI). This increased moisture also reduces energy consumption, and, therefore, explains the relationships described above.

Conclusions

Response variables were significantly related to mash moisture, retention time, and steam quality. The optimal operating performance was achieved through several combinations of treatments. For example, a short retention time combined with 14% mash moisture and using 70% steam quality produces high quality pellets at the lowest kWh/t. In contrast, a long retention time provided nearly equal quality pellets and energy consumption in combination with 12% mash moisture. It is important, however, to keep in mind that these results were obtained using a constant conditioned mash temperature of 82.2°C.

The interaction of these variables suggests feed mill managers can pursue several strategies to optimize the pelleting process. The use of a steam flow meter can greatly assist this process. Knowledge of the mash moisture content, conditioner retention time, and approximate steam quality permits feed manufacturers to predict the optimal steam flow setting. Alternatively, controlling mash moisture content in the mixer also enables the mill operator to optimize the pelleting process. As feed manufacturers continue to experience competitive pressure to reduce cost while maximizing quality, the information presented in this study provides insight into how to control this important cost center.

Table 1. Significance (p-values) for fixed effects on pellet quality, energy consumption, steam flow, and mash moisture with a CPM conditioner

	Standard PDI	Modified PDI	Percent Fines	Pellet Gelatinization	Energy Consumption	Steam Flow	Hot Mash Moisture
Mash Moisture	<.01	<.01	.01	<.01	.99	.04	<.01
Retention Time	<.01	<.01	.09	.51	.84	.04	.69
Steam Quality	.06	.08	.38	.22	.01	<.01	.02
Moisture x Ret. Time	.54	.23	.28	<.01	<.01	.56	.21
Moisture x Steam Quality	.26	.40	.17	.03	.14	.04	.07
Ret. Time x Steam Quality	<.01	<.01	.04	.39	.01	<.01	.27
Moisture x Ret. Time x Steam Quality	.03	.01	.78	.43	.77	.19	<.01

Table 2. Significance (p-values) for fixed effects on pellet quality, energy consumption, steam flow, and mash moisture with a Bliss conditioner

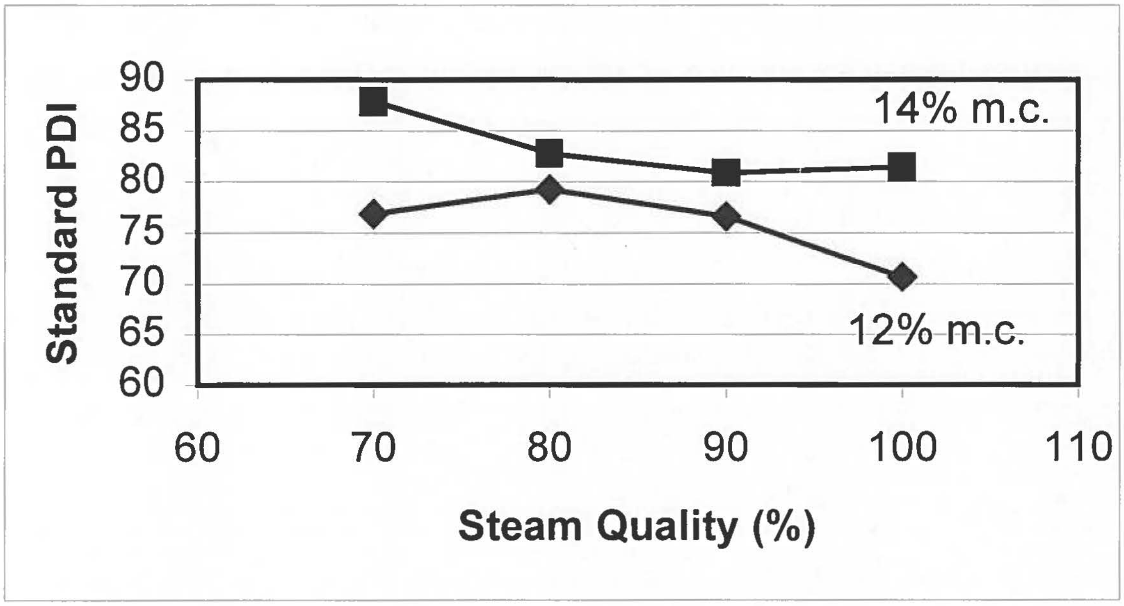
	Standard PDI	Modified PDI	Percent Fines	Pellet Gelatinization	Energy Consumption	Steam Flow	Hot Mash Moisture
Mash Moisture	<.01	<.01	<.01	<.01	<.01	.16	<.01
Retention Time	<.01	<.01	.85	<.01	.34	.04	<.01
Steam Quality	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Moisture x Ret. Time	.65	.22	.90	.87	<.01	.09	.44
Moisture x Steam Quality	<.01	.02	<.01	.51	<.01	.43	<.01
Ret. Time x Steam Quality	.39	.38	.16	<.01	<.01	<.01	<.01
Moisture x Ret. Time x Steam Quality	.55	.36	.05	.61	.21	.06	.01

Table 3. Correlation coefficients and their significance (p-values) for standard PDI, energy consumption, and steam flow with a CPM conditioner

	Standard PDI		Energy Consumption		Steam Flow	
	r-value	p-value	r-value	p-value	r-value	p-value
Standard PDI	--	--	.07	.47	.27	<.01
Modified PDI	.99	<.01	.05	.59	.25	.01
Percent Fines	-.66	<.01	.34	<.01	-.09	.35
Mash Moisture (%)	.54	<.01	.08	.39	.08	.41
Pellet Gelatinization (%)	-.09	.34	.11	.25	-.24	<.01
Energy Consumption (kWh/ton)	.07	.47	--	--	-.04	.68
Steam Quality (%)	-.12	.19	.08	.40	-.49	<.01
Steam Flow (lb/hr)	.27	<.01	-.04	.68	--	--

Table 4. Correlation coefficients and their significance (p-values) for standard PDI, energy consumption, and steam flow with a Bliss conditioner

	Standard PDI		Energy Consumption		Steam Flow	
	r-value	p-value	r-value	p-value	r-value	p-value
Standard PDI	--	--	-.58	<.01	.48	<.01
Modified PDI	.99	<.01	-.56	<.01	.51	<.01
Percent Fines	-.82	<.01	.51	<.01	-.46	<.01
Mash Moisture (%)	.60	<.01	-.60	<.01	.21	.03
Pellet Gelatinization (%)	-.38	<.01	.57	<.01	-.27	<.01
Energy Consumption (kWh/ton)	-.58	<.01	--	--	-.46	<.01
Steam Quality (%)	-.34	<.01	.25	<.01	-.50	<.01
Steam Flow (lb/hr)	.48	<.01	-.46	<.01	--	--



Short Retention Time

Long Retention Time

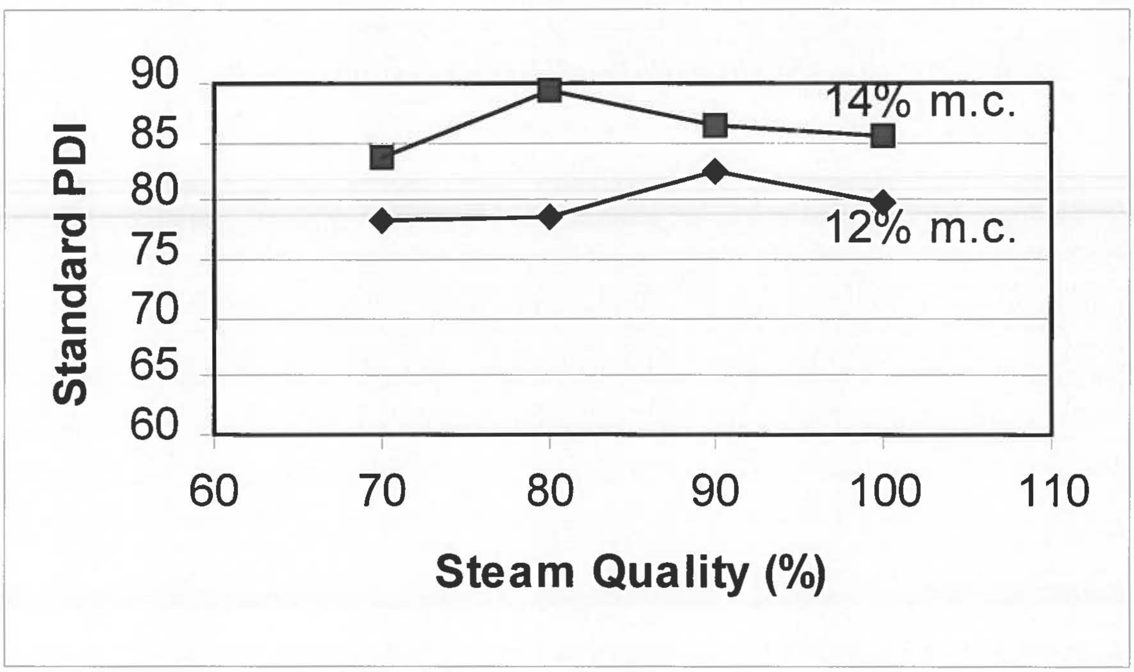


Figure 1. Standard pellet durability index (PDI) in response to steam quality and mash moisture content (m.c.) at short and long retention times for a CPM conditioner

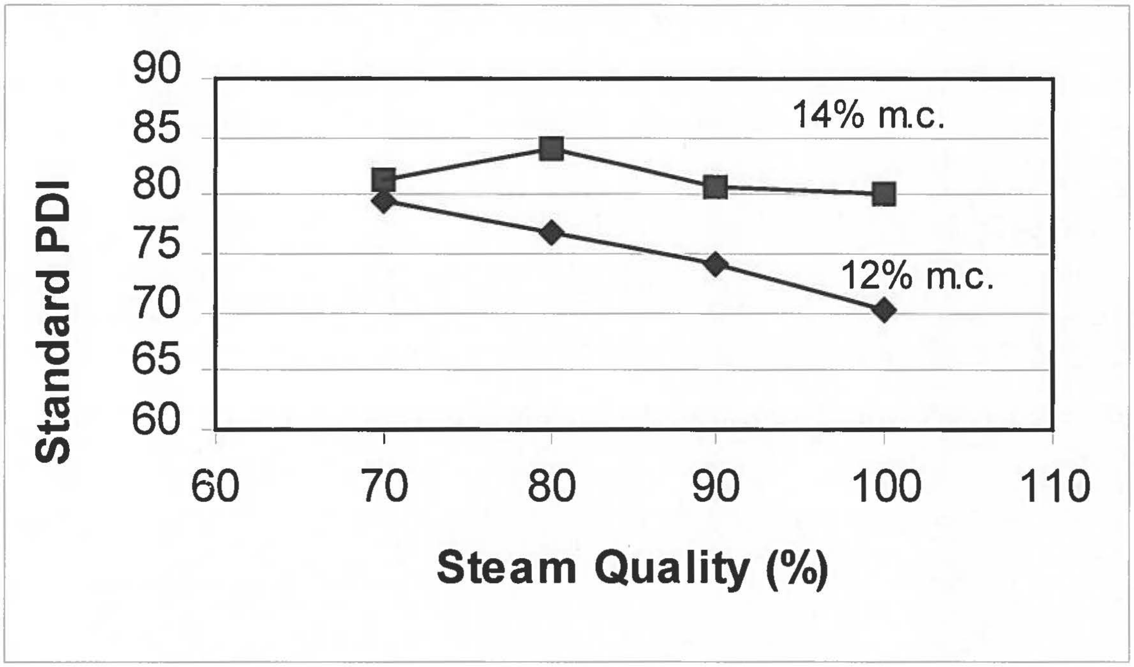


Figure 2. Standard pellet durability index (PDI) in response to steam quality and mash moisture content (m.c.) for a Bliss conditioner

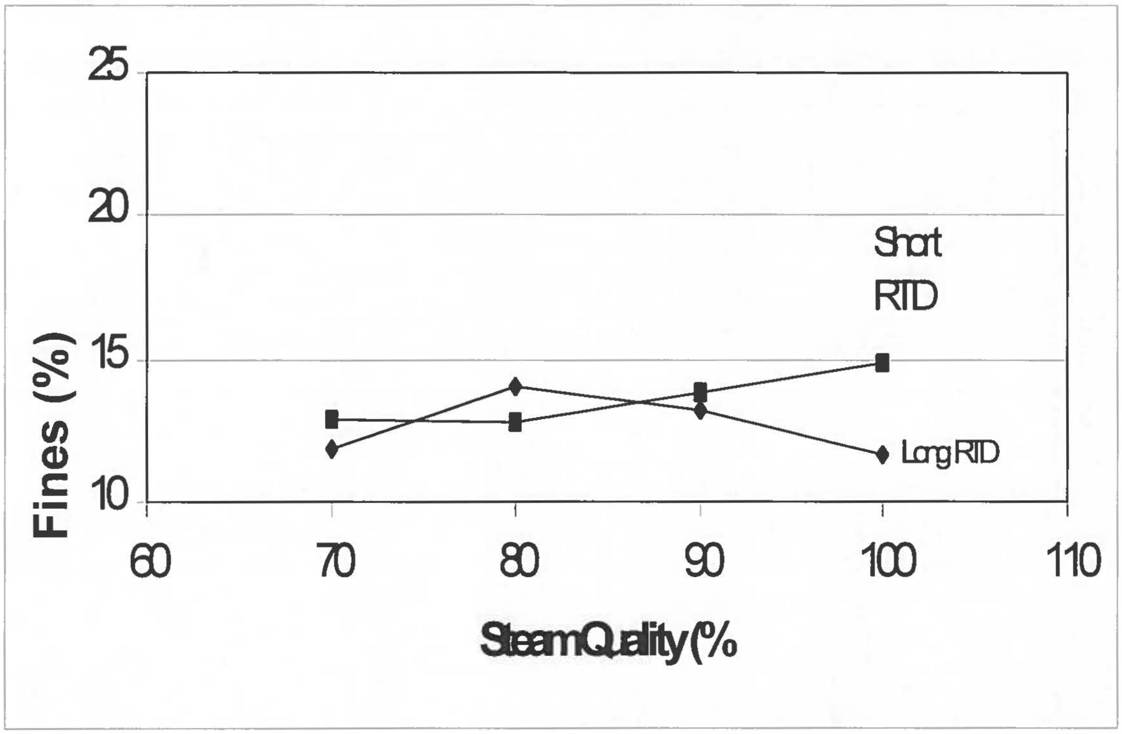


Figure 3. Percent fines in response to steam quality and conditioner retention time (RTD) for a CPM conditioner

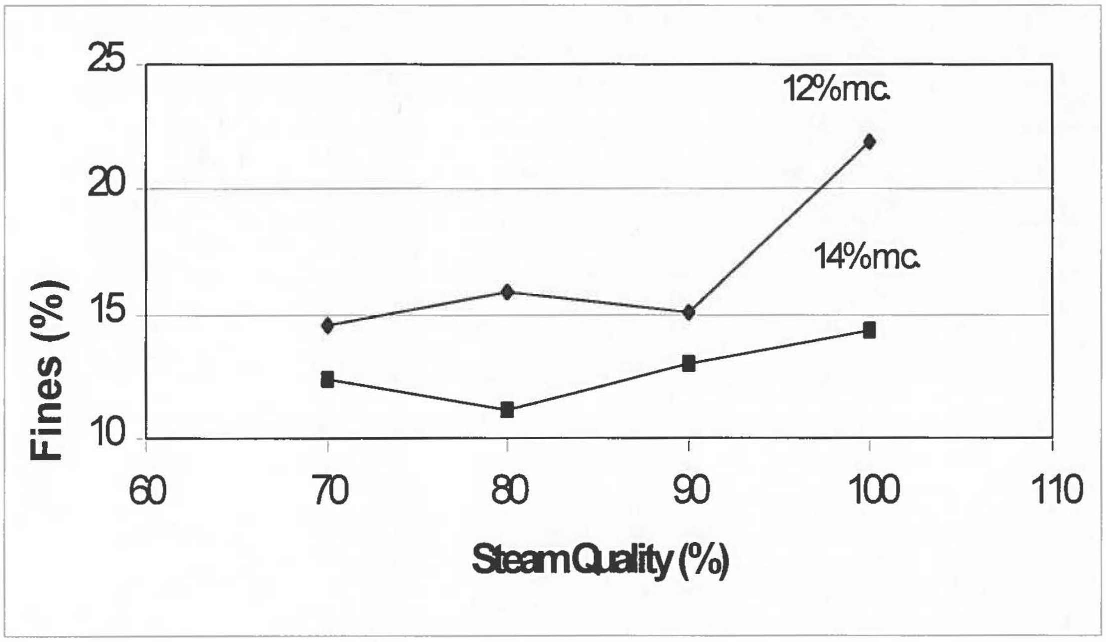


Figure 4. Percent fines in response to steam quality and mash moisture content (m.c.) for a Bliss conditioner

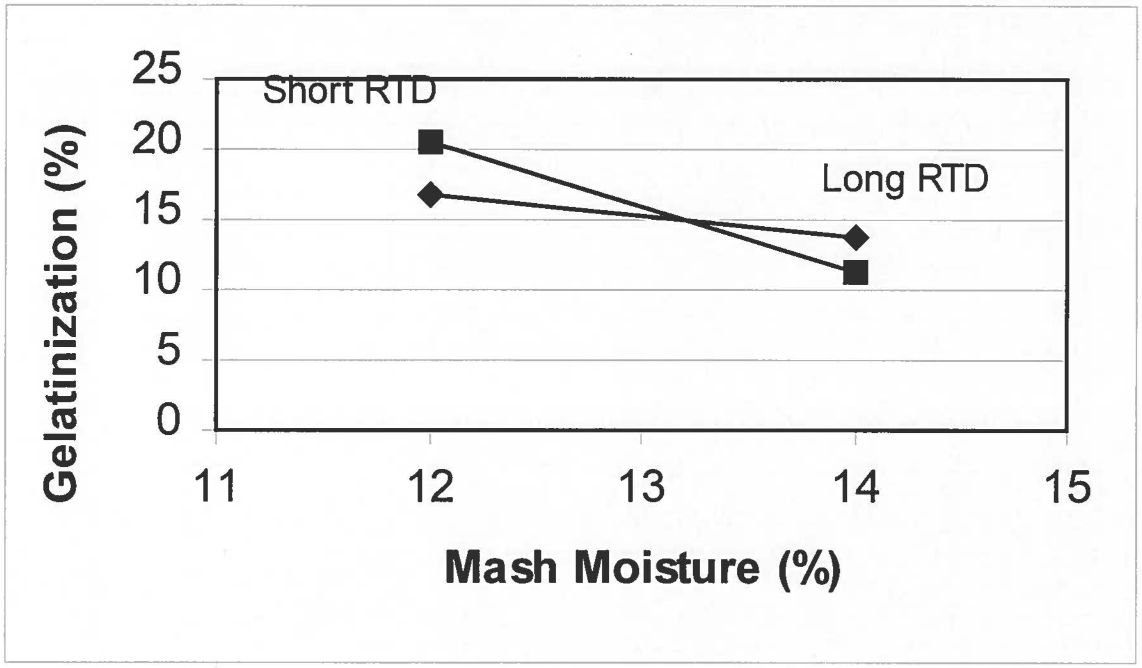


Figure 5. Pellet gelatinization (%) in response to mash moisture content (m.c.) and conditioner retention time (RTD) for a CPM conditioner

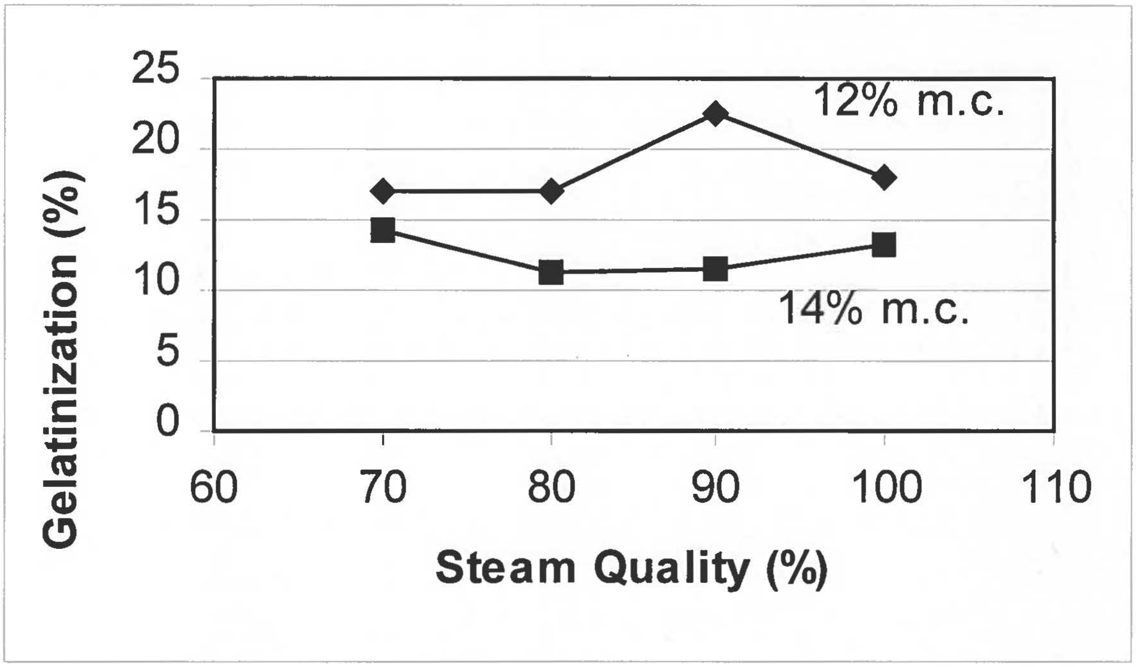


Figure 6. Pellet gelatinization (%) in response to steam quality and mash moisture content (m.c.) for a CPM conditioner

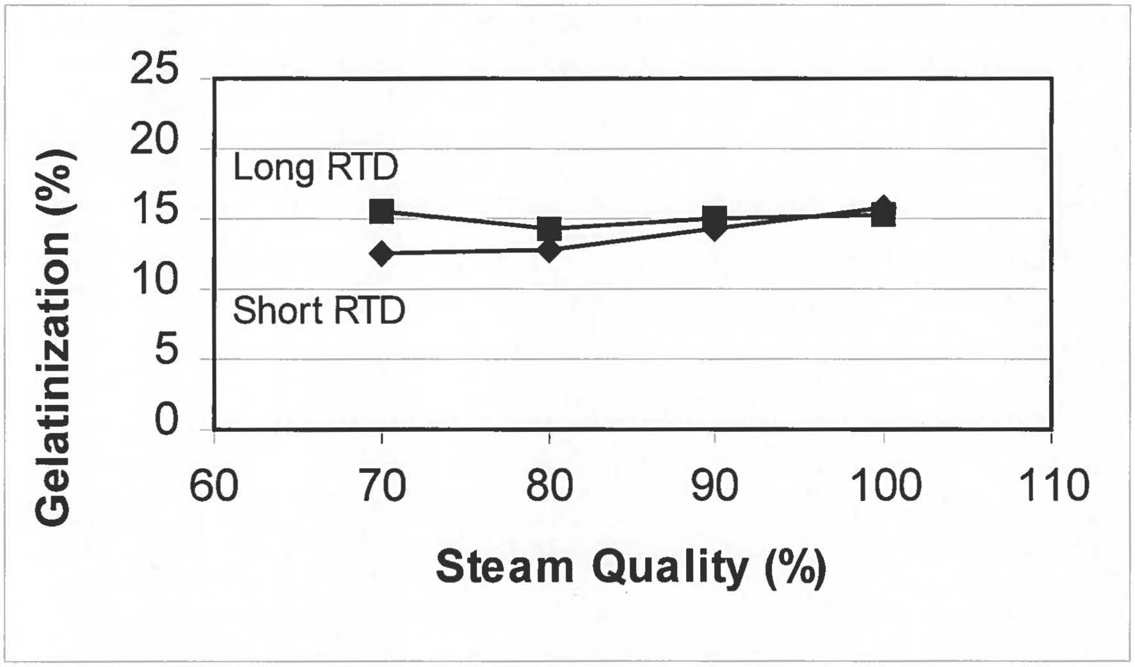


Figure 7. Pellet gelatinization (%) in response to steam quality and conditioner retention time (RTD) for a Bliss conditioner

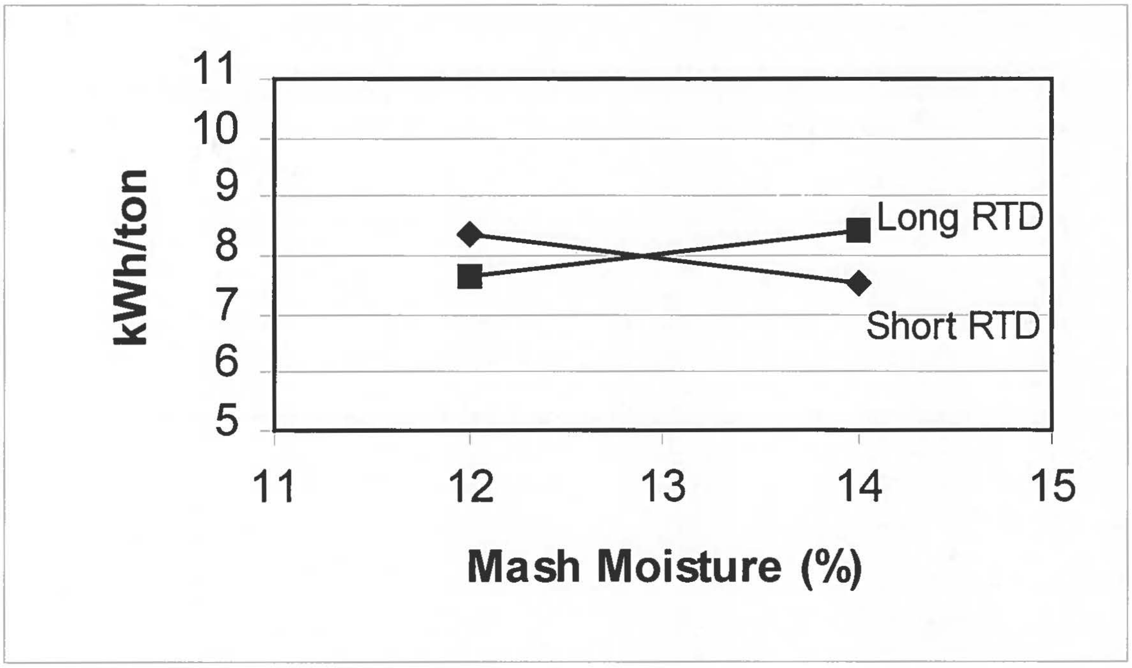


Figure 8. Pellet mill energy consumption (kWh/t) in response to mash moisture content (m.c.) and conditioner retention time (RTD) for a CPM conditioner

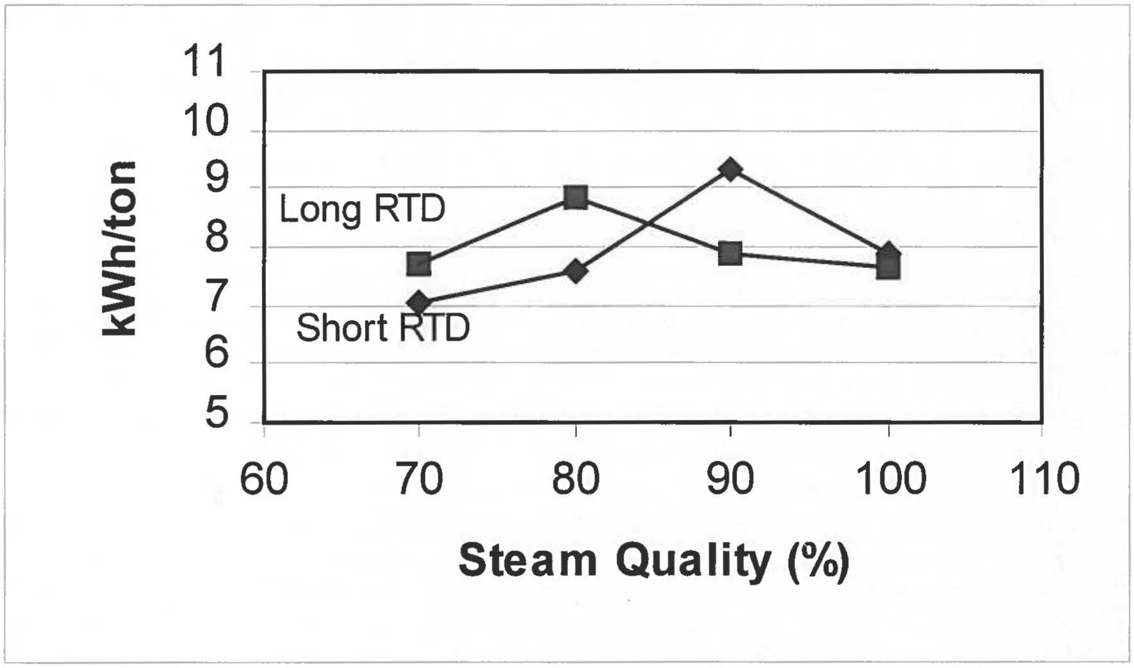


Figure 9. Pellet mill energy consumption (kWh/t) in response to conditioner retention time (RTD) and steam quality for a CPM conditioner

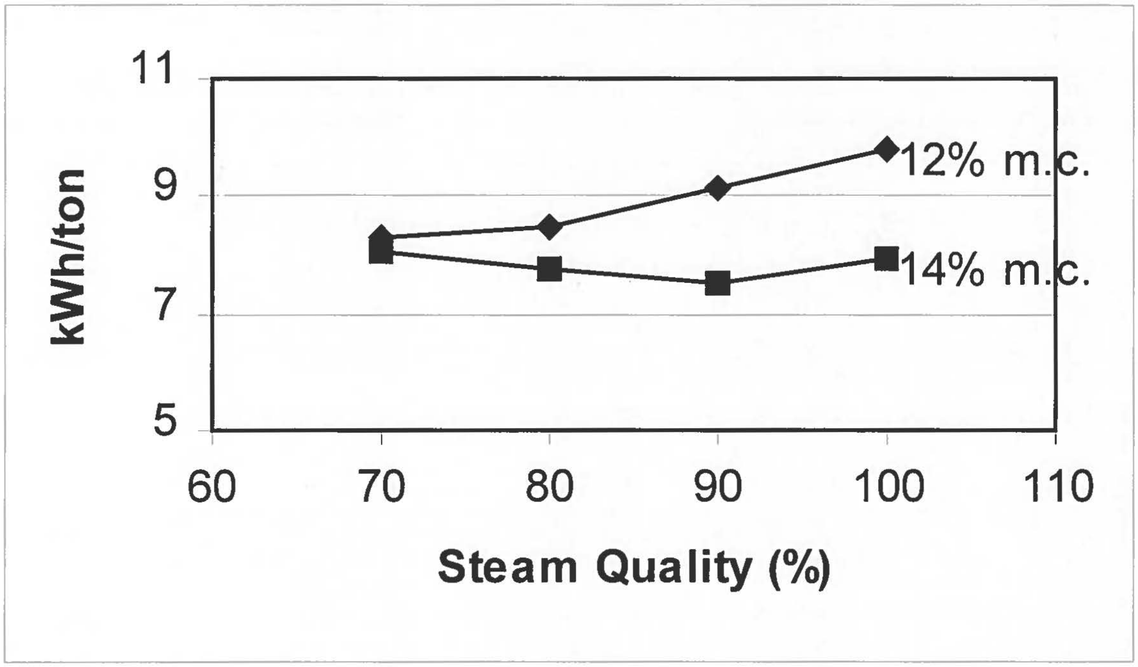


Figure 10. Pellet mill energy consumption (kWh/t) in response to mash moisture content (m.c.) and steam quality for a Bliss conditioner

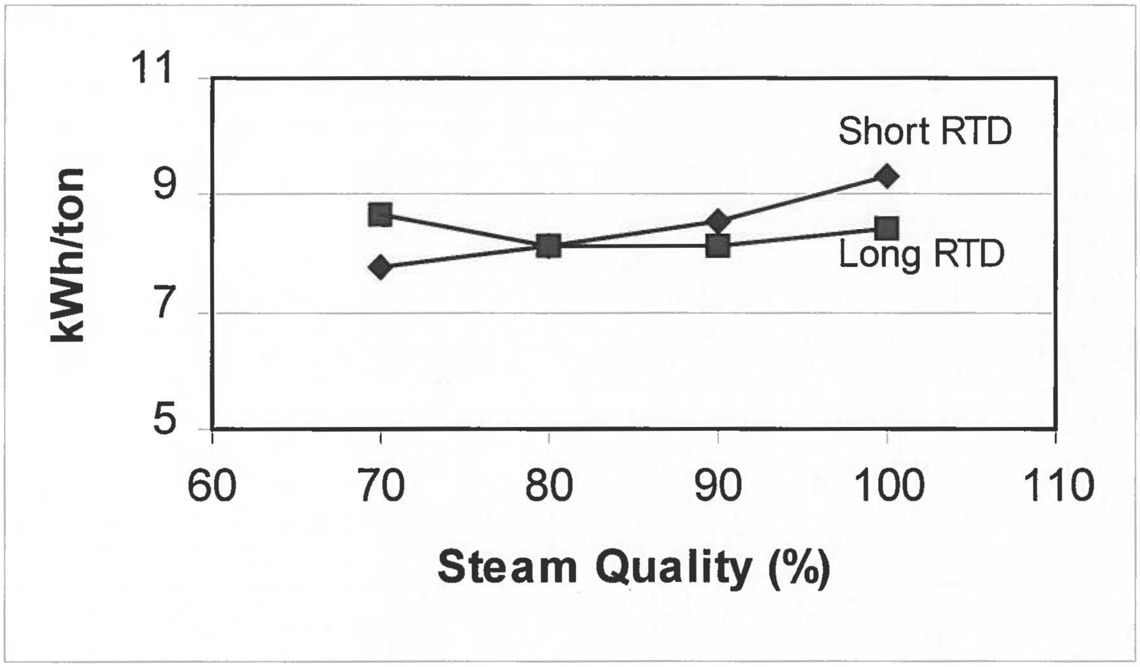


Figure 11. Pellet mill energy consumption (kWh/t) in response to conditioner retention time (RTD) and steam quality for a Bliss conditioner

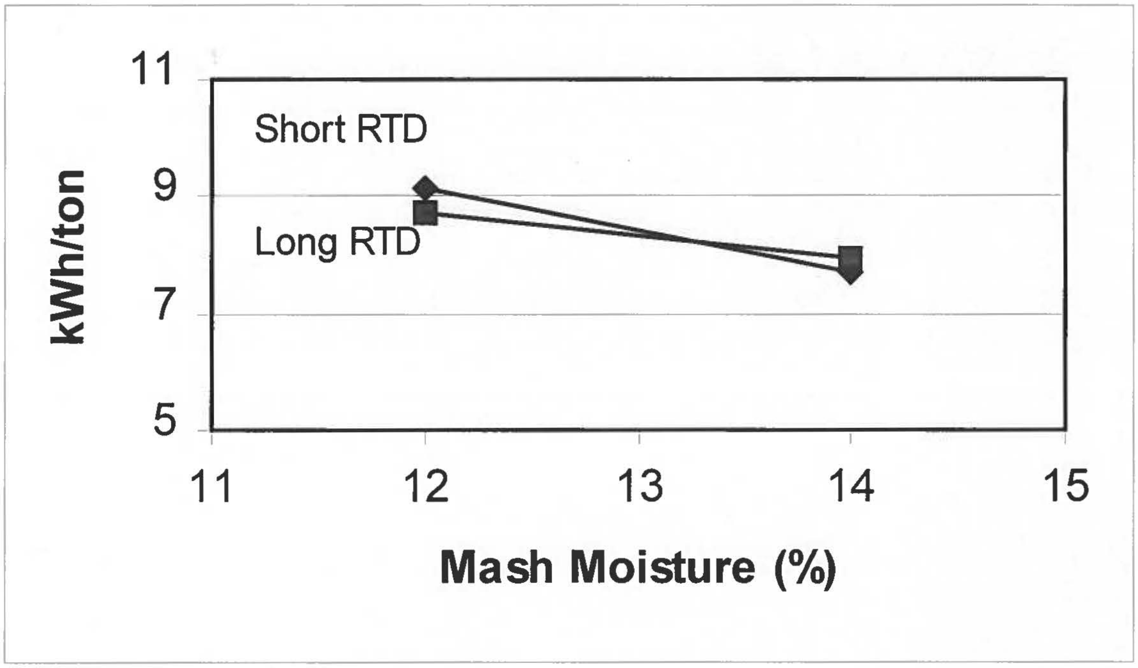


Figure 12. Pellet mill energy consumption (kWh/t) in response to mash moisture content (m.c.) and conditioner retention time (RTD) for a Bliss conditioner

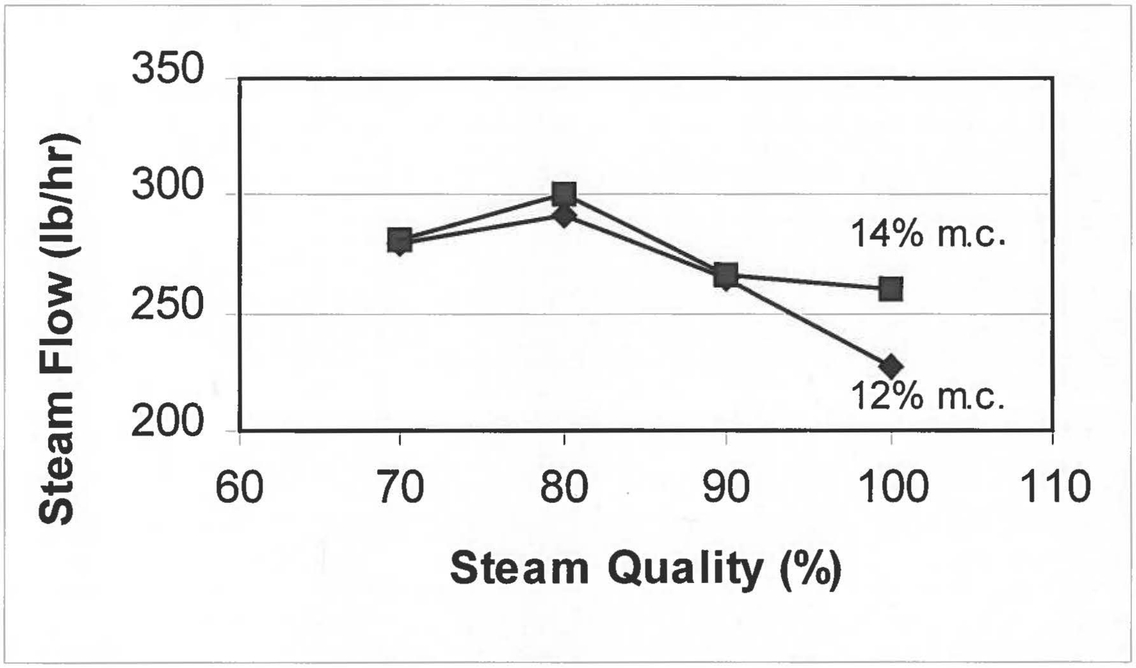


Figure 13. Steam flow (lb/hr) to the conditioner in response to mash moisture content (m.c.) and steam quality for a CPM conditioner

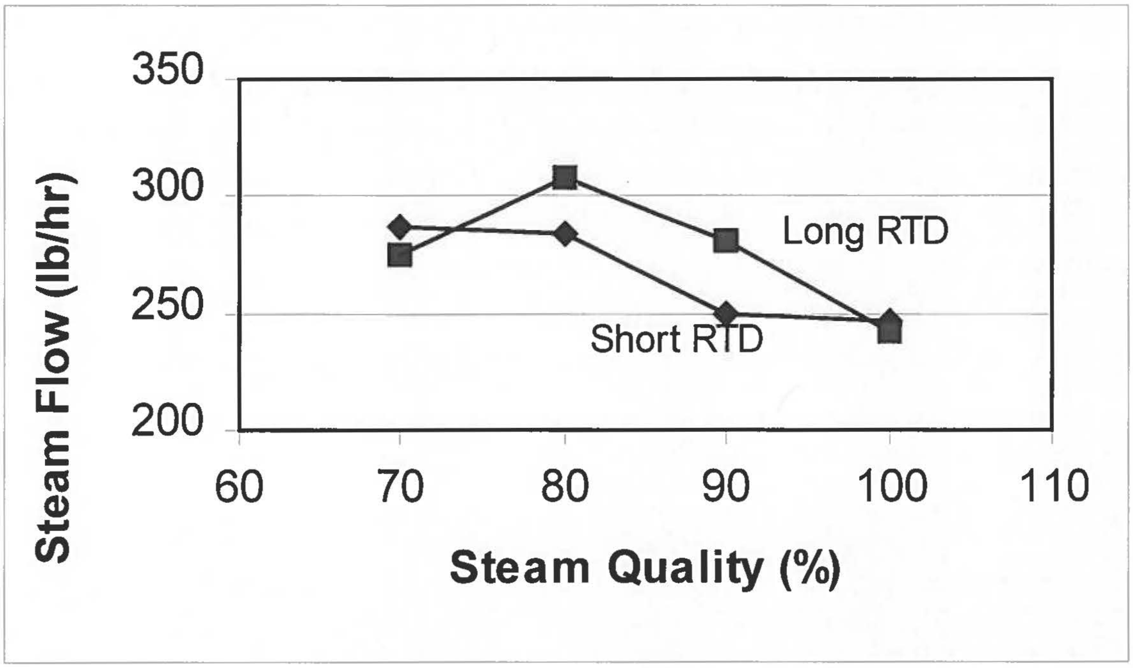


Figure 14. Steam flow (lb/hr) to the conditioner in response to conditioner retention time (RTD) and steam quality for a CPM conditioner

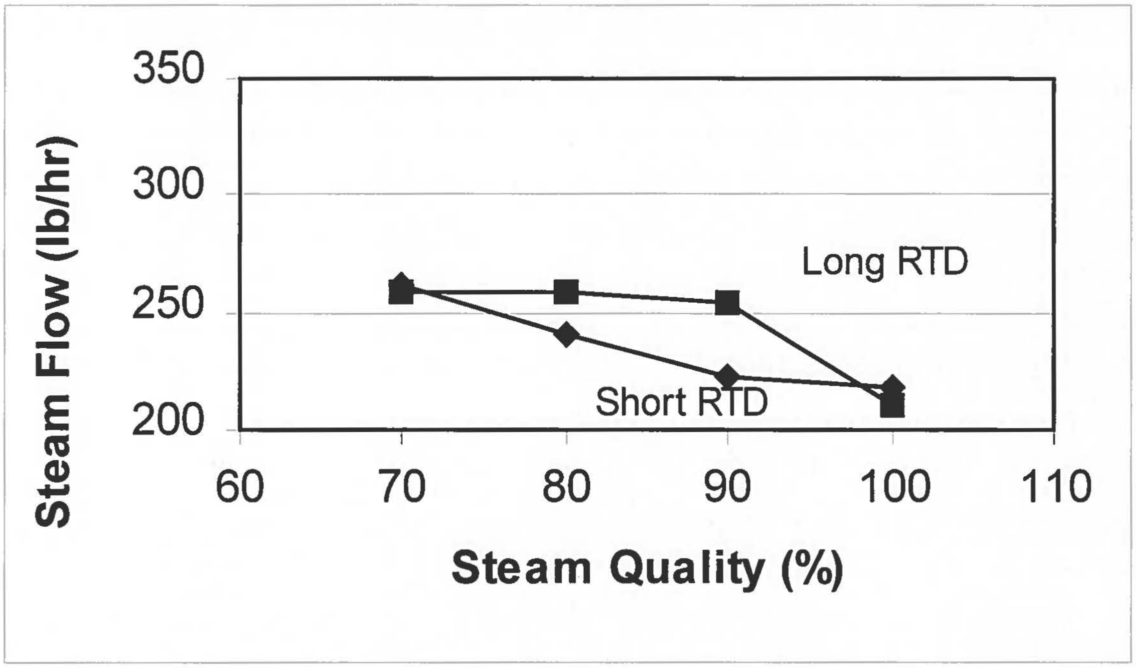


Figure 15. Steam flow (lb/hr) to the conditioner in response to conditioner retention time (RTD) and steam quality for a Bliss conditioner

Appendix A. Calculations for Steam Quality

Steam Quality Calculations Using Heat Exchanger

Assume steam is flowing through the line at 236 lb/hr with a temperature of 265°F and a pressure of 24 psig. Initial quality is assumed to be 98%.

Steam has the following enthalpies at 24 psig:

Sensible Heat (h_f) = 233 Btu/lb

Latent Heat (h_{fg}) = 934 Btu/lb

Total Heat (h_g) = 1167 Btu/lb

Based upon a steam quality of 98%, the actual total heat (h_g) of the steam will be:

$h_g = h_f + (h_{fg} * \text{quality}) = \text{Btu/lb}$

$h_g = 233 + (934 * .98) = 1148.32$ Btu/lb

The total energy of the steam running through the line is then:

E_{Steam} = Steam Flow (lb/hr) * Total Heat (Btu/lb) = Btu/hr

E_{Steam} = 236 lb/hr * 1148.32 Btu/lb = 271,003.52

Assume water is running in-parallel through the heat exchanger at a rate of 400 lb/hr. The initial temperature of the water is 70 °F, and water is leaving the heat exchanger at 155 °F. Specific heat of water (c) is 1 Btu/lb-°F

Energy removed with the heat exchanger is calculated as:

E_{water} = m (lb/hr) * c (Btu/lb-°F) * Delta T (°F)

E_{water} = 400 lb/hr * 1 Btu/lb-°F * (155-70) °F = 34,000 Btu/hr

The energy remaining in the steam and final steam quality are then calculated as follows:

$E_{final} = E_{Steam} - E_{water}$ = Btu/hr

E_{final} = 271,003.52 Btu/hr – 34,000 Btu/hr = 237,003.52 Btu/hr

$$\text{Quality} = \frac{(E_{final}\text{ (Btu/hr)} \div \text{Steam Flow (lb/hr)}) - h_f\text{ (Btu/lb)}}{h_{fg}\text{ (Btu/lb)}} * 100 = \%$$

$$\text{Quality} = \frac{(237{,}003.52\text{ Btu/hr} \div 236\text{ lb/hr}) - 233\text{ Btu/lb}}{934\text{ Btu/lb}} * 100 = 82.6\%$$

Appendix A. Calculations for Steam Quality

Steam Quality Calculations Using Throttling Calorimeter

When using a throttling calorimeter, the following formula is used to calculate quality.

$$m = \frac{100 * [(H - h) - K(T - t)]}{L}$$

$$SQ = 100 - m$$

m = percentage of moisture
H = total heat (Btu) of steam at line pressure at saturated condition
h = total heat (Btu) of steam at calorimeter pressure at saturated condition
K = specific heat of superheated steam
T = temperature of superheat in calorimeter
t = temperature due to the pressure in the calorimeter
L = latent heat in the steam line

Appendix B. Results for all response variables over three replications using 12% mash moisture with two retention times in a CPM conditioner

Retention Time	Steam Quality	Std. PDI	Mod PDI	Fines (%)	Hot Pellet Gelat. (%)	Energy Consumption (kWh/t)	Steam Flow (lb/hr)	Hot Mash (% m.c.)
Rep1								
Short	70%	68.6	53.6	18.60%	7.90%	8.4	280.1	15.00%
Short	80%	80.4	73.9	14.00%	15.60%	7.4	327.4	15.90%
Short	90%	67.2	52.5	20.00%	17.60%	8.6	280.97	15.00%
Short	100%	64.5	47.8	18.60%	15.10%	8.5	252.78	15.20%
Long	70%	84.1	78	11.10%	6.40%	6.7	266.67	16.80%
Long	80%	71.7	62.1	17.80%	9.80%	8.2	314.8	15.40%
Long	90%	82.4	75.9	12.90%	14.10%	7.3	336.3	15.80%
Long	100%	78.7	73.2	13.00%	11.80%	7.7	220.3	15.60%
Rep 2								
Short	70%	79.5	74	12.00%	24.80%	7.8	289.81	16.50%
Short	80%	80.1	72.8	12.50%	19.90%	7.5	280.2	17.10%
Short	90%	84.9	79.5	7.00%	24.80%	11.7	222.2	16.60%
Short	100%	76.7	67.6	14.10%	25.10%	8.5	210.33	16.50%
Long	70%	81	75.3	11.00%	20.60%	8.3	291.99	17.00%
Long	80%	85.6	82.1	11.90%	15.40%	7.5	284.16	16.20%
Long	90%	81	74.9	11.60%	25.10%	7.5	296.83	16.40%
Long	100%	80.7	76	12.70%	16.60%	7.6	199.19	16.60%
Rep 3								
Short	70%	82.4	76.4	11.50%	28.30%	7.6	282.23	17.00%
Short	80%	77.2	71.5	16.70%	25.70%	8.2	252.13	16.50%
Short	90%	77.6	68.9	15.00%	26.30%	8.1	221.32	16.20%
Short	100%	70.8	60.2	18.60%	14.90%	8.2	217.76	15.00%
Long	70%	71.4	62.9	15.30%	24.80%	8	264.11	15.40%
Long	80%	77	68.3	15.10%	5.30%	7.1	280.4	16.80%
Long	90%	84.4	79.3	14.60%	27.10%	7.7	229.41	16.30%
Long	100%	80.3	75	12.10%	24.90%	7.5	263.43	17.00%

Appendix C. Results for all response variables over three replications using 14% mash moisture with two retention times in a CPM conditioner

Retention Time	Steam Quality	Std. PDI	Mod PDI	Fines (%)	Hot Pellet Gelat. (%)	Energy Consumption (kWh/t)	Steam Flow (lb/hr)	Hot Mash (% m.c.)
Rep 1								
Short	70%	82.8	78	13.10%	11.70%	7	305.43	18.60%
Short	80%	80.7	71.9	10.00%	7.40%	5.6	293.84	18.50%
Short	90%	89.1	86.4	13.20%	9.20%	12.6	276.92	18.50%
Short	100%	78.5	71.3	11.80%	14.70%	6.6	314.72	18.20%
Long	70%	87.3	83	8.30%	19.10%	6.8	262.13	18.10%
Long	80%	89.9	87.3	11.90%	5.90%	7.4	328.51	18.20%
Long	90%	83.5	78.4	11.50%	15.80%	6	269.04	18.70%
Long	100%	89.5	86.2	9.20%	17.10%	7.8	285.97	18.60%
Rep 2								
Short	70%	90.6	88.2	15.20%	15.50%	9.5	266.99	18.70%
Short	80%	81.4	75.2	12.30%	11.60%	7.3	248.14	18.50%
Short	90%	70.9	60.2	16.60%	7.20%	7.6	245.63	18.80%
Short	100%	82.3	77.2	15.70%	12.20%	8.3	245.03	18.10%
Long	70%	77.4	69.7	14.10%	10.00%	9	271.88	18.50%
Long	80%	85.3	81	10.30%	20.30%	7.2	277.16	18.60%
Long	90%	89.4	86.2	18.60%	13.20%	11.9	285.78	17.60%
Long	100%	83.2	76	13.00%	10.90%	7.5	240.03	18.10%
Rep 3								
Short	70%	90.2	88.1	7.10%	9.70%	7.8	295.4	18.40%
Short	80%	86.3	81.8	11.30%	13.70%	9.6	302.43	17.40%
Short	90%	82.5	76.4	11.10%	12.60%	7.4	251.59	15.00%
Short	100%	83.6	77.5	10.20%	11.00%	7.3	234.24	16.90%
Long	70%	92.7	90	12.20%	16.80%	10.8	331.93	18.40%
Long	80%	86.8	82.1	14.40%	11.40%	12.1	303.54	17.80%
Long	90%	86.4	82.4	10.00%	11.40%	6.9	266.99	17.40%
Long	100%	83.5	78.3	9.90%	13.40%	7.7	241.71	18.40%

Appendix D. Results for all response variables over three replications using 12% mash moisture with two retention times in a Bliss conditioner

Retention Time	Steam Quality	Std. PDI	Mod PDI	Fines (%)	Hot Pellet Gelat. (%)	Energy Consumption (kWh/t)	Steam Flow (lb/hr)	Hot Mash (% m.c.)
Rep1								
Short	70%	80.9	75.5	14.90%	14.20%	8.9	257.9	15.20%
Short	80%	70.4	61.7	16.00%	14.70%	9.4	229.13	15.40%
Short	90%	72.5	63.6	14.70%	14.90%	10.1	189.81	15.00%
Short	100%	57.1	42.2	30.30%	18.50%	9.8	207.01	14.80%
Long	70%	81.8	76.1	13.70%	19.10%	8.7	217.26	16.30%
Long	80%	76	69.3	16.50%	16.10%	8.7	236.79	15.20%
Long	90%	74.9	66.2	18.60%	17.70%	8.5	260.09	15.40%
Long	100%	70.7	62.5	20.70%	18.20%	9.4	218.06	14.20%
Rep 2								
Short	70%	79	70.9	18.50%	13.60%	7.8	258.85	16.20%
Short	80%	75	66.6	16.90%	14.90%	8.1	254.82	16.00%
Short	90%	74.1	66.5	14.00%	19.30%	9.4	220.37	15.70%
Short	100%	74.3	64.2	13.30%	17.60%	9.7	184.63	14.80%
Long	70%	80.9	74.7	13.10%	15.90%	8.6	258.16	17.80%
Long	80%	76.9	70	19.10%	17.70%	8.6	251.33	16.10%
Long	90%	73.6	64.1	18.00%	17.00%	9.3	244.25	15.00%
Long	100%	65.3	54.3	30.30%	16.00%	9.8	175.13	15.20%
Rep 3								
Short	70%	72	59.2	16.30%	11.20%	7.8	268.25	17.00%
Short	80%	79.2	72.1	15.30%	12.90%	7.8	219.09	16.40%
Short	90%	72.5	62.5	14.00%	13.00%	9	247.8	15.60%
Short	100%	76.8	65.5	16.70%	15.50%	11.9	196.95	16.00%
Long	70%	83.2	79.1	10.70%	14.80%	8.1	268.52	16.80%
Long	80%	83.1	78.1	11.40%	14.00%	8.2	286.28	17.90%
Long	90%	76.8	69.5	11.10%	12.40%	8.4	276.85	16.00%
Long	100%	77	68.2	19.90%	14.40%	8.3	250.23	15.00%

Appendix E. Results for all response variables over three replications using 14% mash moisture with two retention times in a Bliss conditioner

Retention Time	Steam Quality	Std. PDI	Mod PDI	Fines (%)	Hot Pellet Gelat. (%)	Energy Consumption (kWh/t)	Steam Flow (lb/hr)	Hot Mash (% m.c.)
<u>Rep1</u>								
Short	70%	75.2	65.4	14.00%	11.20%	7.8	244.76	18.90%
Short	80%	77.6	69.4	14.10%	13.80%	8.7	237.86	18.00%
Short	90%	84.7	80.7	12.80%	13.20%	8	206.67	17.30%
Short	100%	75.7	65.6	18.30%	14.40%	8.6	261.02	17.50%
Long	70%	78.6	70.6	16.00%	16.60%	9.7	243.52	17.30%
Long	80%	89.4	85.5	10.80%	14.20%	7.9	271.62	17.10%
Long	90%	80.8	73.8	14.40%	17.40%	8.2	199.03	17.40%
Long	100%	78.8	64.2	18.90%	15.70%	7.8	180.91	18.00%
<u>Rep 2</u>								
Short	70%	88.6	85.6	9.80%	14.30%	6.9	287.04	19.40%
Short	80%	83.4	77.4	10.50%	10.10%	7.4	263.36	17.60%
Short	90%	78.7	68.7	12.50%	11.60%	7	240.27	17.90%
Short	100%	83.9	77.7	11.90%	14.10%	7.8	216.2	17.30%
Long	70%	87.5	82.6	9.30%	13.80%	8.8	312.6	17.90%
Long	80%	87.8	83.1	9.10%	10.40%	8.1	247.2	17.30%
Long	90%	84.6	80.2	11.20%	14.60%	6.6	307.26	17.70%
Long	100%	84.1	78.6	11.00%	15.90%	7.3	255.52	17.30%
<u>Rep 3</u>								
Short	70%	79.5	73.4	11.10%	10.10%	7.2	256.65	18.00%
Short	80%	82.1	74.4	11.40%	10.10%	7.2	238.5	18.40%
Short	90%	75.5	68.1	13.30%	13.80%	7.7	227.67	16.20%
Short	100%	80	72.7	12.30%	14.40%	8.3	241.02	17.10%
Long	70%	78.9	72.5	14.00%	13.00%	7.9	248.53	17.30%
Long	80%	83.5	75.7	10.80%	12.70%	7.2	257.7	17.80%
Long	90%	80.1	70.6	13.50%	10.60%	7.7	234.39	17.30%
Long	100%	78.9	71.2	13.50%	10.60%	8	179.7	17.50%