Steam generation, control, and quality for feed manufacturing

BY CARLOS A. CAMPABADAL, PH.D. AND DIRK E. MAIER, PH.D., P.E.

REVIEWED AND EDITED BY ADAM FAHRENHOLZ, CHARLES STARK, AND CASSANDRA JONES

Feed processing refers to the treatment of a feed prior to its consumption by animals. Processing may consist of a few steps such as grinding and mixing, or a series of steps including grinding, mixing, conditioning, extruding, pelleting, dehydration, and cooling. The central process in most feed mills is the pelleting operation. A mash feed is prepared from a mixture of ingredients, such as grains, protein source, minerals, vitamins and drugs, according to a specified formulation. In most U.S. feed mills the mash feed is pelleted in a roller-and-die press (McEllhiney, 1994). Before entering the press the feed is conditioned with steam, and sometimes molasses and/or fat are added to increase its energy content, lubricity, and pelletability. Temperature increase is furthered in the die due to frictional heating as the pellet is extruded. The pellets are cooled (and dried) with ambient air immediately following the pelleting operation.

Problems with the pelleting operation in many commercial feed mills are often caused by an ineffective conditioning process. Effective conditioning depends on a properly designed, maintained and operated steam supply system. The purpose of this chapter is to discuss steam generation, control and quality, and to illustrate the effect of steam system performance (or lack thereof) on mash conditioning and pelleting.

Little peer-reviewed literature appears to exist on the subject of steam conditioning of a feed mash. Skoch et al. (1981) investigated the effect of steam conditioning on the pelleting process. Dry pelleting of a mash was compared to steam conditioning a mash to 149°F (65°C) and 176°F (80°C), respectively, before pelleting. Pellet durability and fines results showed that steam improved pellet quality. Dry pelleting caused more starch damage in the feed than steam-conditioned pelleting. Although steam conditioning increased the total energy required for pelleting, it allowed for increased production rates and improved pellet quality of the finished feed.

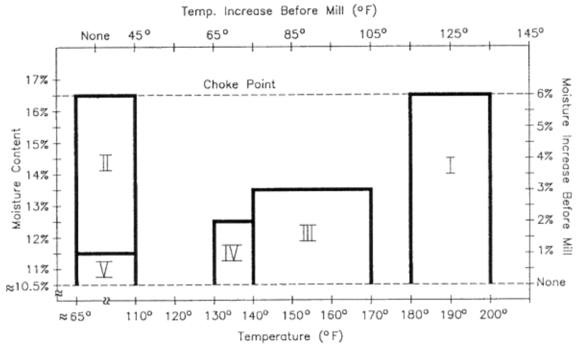
Much of the existing literature on steam conditioning of a feed mash has been published in trade journals of the feed processing industry, such as Winowiski (1985), Bode (1986), Winowiski (1988), and in a number of handbooks and manuals, such as MacBain (1968), Leaver (1982), Anon. (1984), Wetzel (1991), and McEllhiney (1994). The amount of steam that can be added to a mash depends largely on the feed ingredients and on its initial moisture content (Winowiski, 1985). Five categories of feed formulations are generally distinguished (MacBain, 1968; Anon. 1984): (1) high starch feeds for poultry and hogs containing 50-80% starch from cereal grains or tapioca; (2) heat-sensitive high starch feeds containing 5-25% dry milk powder, sugar and/or whey; (3) high natural protein supplements and concentrates containing 25-45% protein; (4) high fiber feeds for complete dairy rations containing 12-16% protein; and (5) high urea (i.e., 6-30% of formulation) and high molasses (i.e., 5-20% of formulation) feeds.

Conditioning and Pelleting Requirements

Pellet quality is primarily established in the conditioner rather than in the pellet die. A summary of the conditioning and pelleting requirements for the five feed categories is given in **Figure 8-1**. In four of the five categories the addition of moisture is needed, while in three of the five categories heat and moisture (i.e., from steam) are both needed to produce a quality feed pellet.

The high starch feeds (Category I) can be conditioned above 180°F (80°C) with steam to increase the mash moisture content by up to 6 percentage points. Due to steam conditioning, the starch pregelatinizes and becomes a natural binding agent as the pellet is extruded from the die. Heat sensitive feed rations (Category Il) need to be maintained below 110°F (45°C) to prevent carmelization of the sugars in the conditioner and pellet die. Since no or little heat can be added, thinner dies must be used to prevent excessive frictional heating. Since the starch cannot be pre-gelatinized, fat or other binding agents may be added to improve pelletability. High protein rations (Category III) require a mash temperature up to 170°F (75°C). However, no or little steam can be condensed, since the protein absorbs only up to 3 percentage points of moisture.

Figure 8-1. Conditioning temperature and moisture content requirements of the five pelleted feed categories (I = high starch; II = heat sensitive high starch; III = high natural protein; IV = high fiber; V = high urea/molasses). Adapted from MacBain, 1968.



(adapted from MacBain 1968)

The temperature rise in the mash has to be accomplished mostly by frictional heating in the die, and pellet durability by adding a binding agent. High-fiber dairy feeds (Category IV) can only be pelleted with little steam addition, since the fiber and protein absorb only up to 2 percentage points of moisture. Thick dies have to be used to raise the mash temperature up to 140°F (60°C) and to allow sufficient compression to produce a good pellet. Feeds with high urea and molasses contents (Category V) can be conditioned with no or little steam, since the urea may dissolve in the condensed moisture. Pelleting is difficult and may require additional binding agents.

Steam System

Steam is an important feed manufacturing input but is often poorly understood and often mismanaged. Steam generation and use is a major cost for most feed manufacturing facilities. Given current energy costs, attention should be paid to optimizing the operation of the steam system and the feed mash conditioning process.

Steam Properties

In order to optimize the steam conditioning of a feed mash, the basic thermodynamic properties and behavior of steam in the feed processing system must be understood.

When water begins to boil, it has reached the boiling point of saturated water, at which it can take no more energy without changing into vapor (steam). At sea level and under atmospheric conditions the boiling point of water is 100°C (212°F). However, the actual boiling point of saturated water depends not only on elevation but also on whether water is boiled in an open system (i.e., under atmospheric conditions) or in a closed system (i.e., in a boiler). In closed systems, the boiling point is referred to in terms of saturation temperature, which increases as the pressure increases. Transfer of more energy into saturated water at the saturation temperature results in a change of water into saturated steam. If the pressure remains constant, the steam temperature remains at the saturation temperature. Saturation temperature of steam at any operating pressure is available from so-called steam tables. Saturated steam temperatures for a range of operating pressures typically found in steam systems of feed mills are summarized in **Table 8-1**.

Table 8-1. Saturated steam temperatures for a range of operating pressures typically found in steam systems in feed mills

Gauge Pressure, Pg		Absolute Pressure, P_a		Steam Temperature	
psig	kPa	psia	kPa	°F	°C
0	0	14.7	101.4	212.0	100.0
20.3	140.0	35.0	241.3	259.3	126.3
30.3	208.9	45.0	310.3	274.4	134.7
40.3	277.9	55.0	379.2	287.1	141.7
50.3	346.8	65.0	448.2	298.0	147.8
60.3	415.8	75.0	517.1	307.6	153.1
70.3	484.7	85.0	586.1	316.3	157.9
80.3	553.7	95.0	655.0	324.1	162.3
90.3	662.6	105.0	724.0	331.4	166.3
100.3	691.6	115.0	792.9	337.9	169.9
110.3	760.5	125.0	861.9	344.3	173.5
120.3	829.5	135.0	930.8	350.2	176.8

Gauge Pressure (P_g; psig) is the steam pressure as indicated on a pressure gauge installed on a steam supply pipe. It excludes atmospheric pressure (P_{atm}), which is 14.7 pounds per square inch (psi). Absolute Pressure (P_a; psia) quantifies the true force per unit area exerted by steam on the pipes and walls of the steam system. It includes atmospheric pressure. Therefore,

$$P_a = P_g + P_{atm}$$

As water and steam are heated, they absorb energy. The total absorbed heat energy consists of sensible heat, latent heat, and super heat. Sensible heat, or heat of the liquid, is the heat required to raise the temperature of a unit mass of liquid water to the saturation temperature (boiling point). Latent heat, or heat of the vapor, is the heat required to convert a unit mass of liquid water at the saturation temperature to dry steam of the same temperature. Super heat is the heat required to raise the temperature of a unit mass of dry steam at the saturation temperature to any higher temperature. Therefore, the total heat contained in steam at any time is the sum of the sensible heat, latent heat and super heat (**Figure 8-2**).

Another steam property to define is its specific volume (v). It is defined as the amount of volumetric space (m3; ft3) occupied by one pound of steam. Given that steam vapor occupies a much greater volume for a given mass than liquid water, specific volume has to be taken into consideration when designing steam supply piping and the associated condensate return system.

Figure 8-2. Heat content of steam vs. temperature

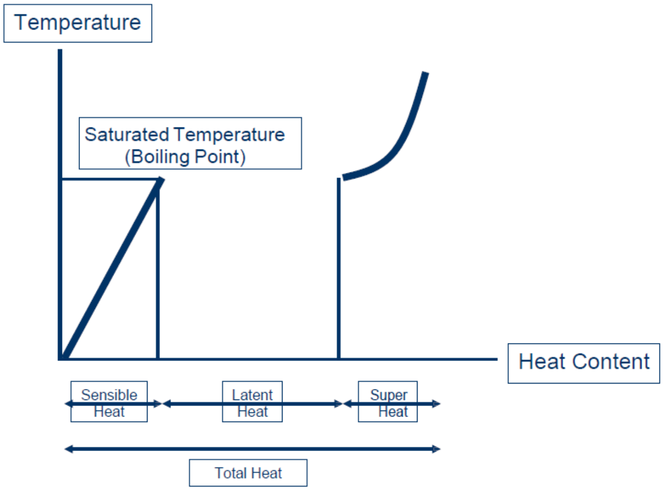
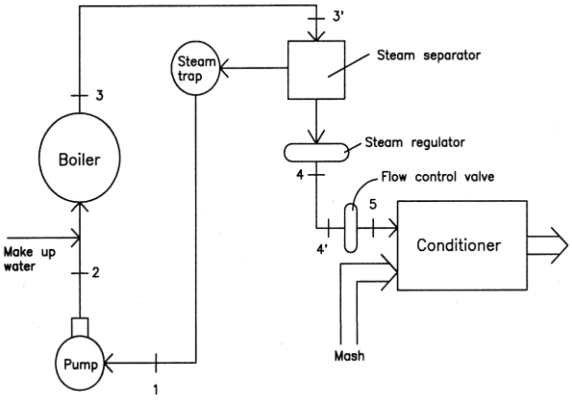


Figure 8-3 is a schematic of a simplified steam system, which consists of steam supply, steam regulation, and conditioner. Steam is generated in the boiler at a given pressure. As heat is added to the water, its temperature increases until the water reaches the saturation point at which it can no longer exist as a liquid.

Figure 8-3. Schematic of a simplified steam system supplying steam to a feed mash conditioner.

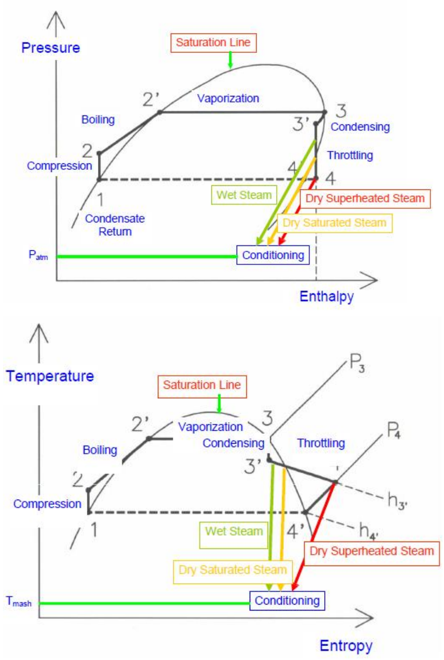


Note the numbers 3' and 4' refer to changes in the quality of steam as it travels without system units.

Beyond that point, additional heat added to the water causes some of the water to boil off as steam, which is piped to the feed conditioner. This evaporation requires a huge amount of energy per unit weight of water vaporized. It also transfers that energy to the steam to be used to increase the temperature and moisture content of the mash in the conditioner.

Steam quality is controlled with steam traps, separators, and regulators placed along the steam pipes. The proper placement of each component is critical to the efficiency of the system. A valve operated either manually or automatically controls the steam flow into the feed mash conditioner. Condensate is collected along various points of the steam pipe; collection is especially critical before the conditioner. The condensate is returned to the boiler via a pump. The steam quality at various points in the system can be analyzed in terms of its thermodynamic properties such as temperature, pressure, enthalpy, and entropy (Wark, 1983). **Figures 8-4** summarizes the temperature-entropy and pressure-enthalpy relationships for the simplified system presented in **Figure 8-3**, respectively.

Figure 8-4. Idealized thermodynamic steam pressure (P) vs. enthalpy (h) diagram with steam state points for a basis feed mill system.

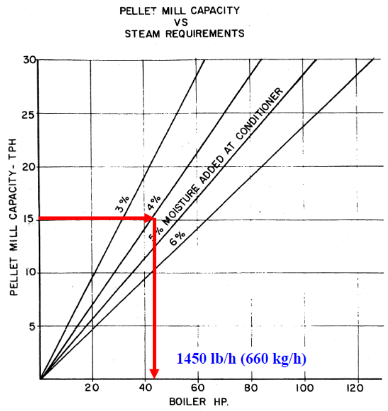


Condensate (1) returns from the steam trap as a saturated liquid. During pumping it is slightly compressed (2). The condensate is mixed with make-up water before entering the boiler. The feed water is heated to its boiling point (2'). Steam exits the boiler as a saturated vapor (3). As it travels along the pipe, energy is lost and condensate forms (3') before reaching the steam regulator. The condensate and any suspended solids are subsequently separated out and returned to the boiler (1). The regulator acts like a throttle and reduces the steam pressure at constant enthalpy. After the regulator (4) the steam thermodynamically is a superheated vapor. As soon as the superheated steam enters the conditioner, the steam pressure is reduced to atmospheric, and the steam condenses into the mash. This raises the temperature and moisture content of the mash. The amounts of heat and moisture added are completely dependent on the thermodynamic steam properties.

Steam Supply

An adequate supply of high-quality steam is necessary to have an efficient pelleting operation. A properly sized steam supply accounts for steam quantity, pressure, and quality. The amount of steam flow per hour needed from a boiler is directly related to the amount of moisture to be added to the mash, and the pellet mill capacity (**Figure 8-5**) (Leaver, 1982). For example, if 4 percentage points of moisture are to be added to a mash at a pellet mill capacity of 15-ton per hour (TPH) the boiler needs to supply about 1450 lb of steam per hour.

Figure 8-5. Pellet mill capacity as a function of steam supply and moisture added during mash conditioning. Adapted from McEllhiney, 1994.



The amount of steam required can also be calculated based on the heat energy required to raise the mash temperature. Every material has a characteristic specific heat (cp). Water has a specific heat of 1 BTU/lb./°F, which is defined as the amount of heat energy needed to raise the temperature of one pound of water by one degree Fahrenheit. Most grains and feed ingredients have a specific heat of 0.45 BTU/lb./°F, which implies that it only takes 0.45 BTU to raise the temperature of one pound of grain by one degree Fahrenheit.

This is difficult in concept, but the examples to follow should help provide clarity.

Example: How much steam (lb./h; kg/h) at 30 psig is required to condition 20,000 lb./h (10 T/h) of maize-based mash from 21°C (70°F) to 85°C (185°F) prior to pelleting?

Step 1 - Determine the heat energy required:

Heat (BTU/h) = M x cp x (Tf – Ti)

= 20,000 lb./h x 0.45 BTU/lb.°F x (185°F – 70°F) = 1,035,000 BTU/h

Step 2 – Determine the heat content of the steam from steam tables assuming saturated steam at 30 psig, which yields:

Latent heat = 929.1 BTU/lb. Sensible heat = 243.1 BTU/lb.

Step 3 – Account for the sensible heat content in the conditioned mash:

Sensible heat of water at 0 psig and 185°F is 153 BTU/lb

Note: When conditioned to 185°F, the water in the mash at 0 psig (atmospheric conditions) contains 153 BTU/lb in sensible heat energy.

Step 4 – Calculate the amount of steam energy condensed into the mash:

Steam energy (BTU/lb) = latent heat + sensible heat difference

= 929.1 BTU/lb + (243.1 BTU/lb – 153.0 BTU/lb)

= 1,019.2 BTU/lb of steam energy condensed

Step 5 – Calculate the amount of steam required:

Steam (lb/h) = Heat required / Steam condensed

= 1,035,000 BTU/h / 1,019.2 BTU/lb = 1,015.5 lb/h

Example: What is the final moisture content of the conditioned maize-based mash into the pellet mill if the initial moisture content was 13% wet basis?

Step 1 - Determine initial water content:

Water (lb.) = 20,000 lb. x 0.13 = 2,600 lb.

Step 2 – Determine the dry matter content of the feed mash:

Dry matter (lb.) = 20,000 lb. total – 2,600 lb. water
= 17,400 lb. dry matter

Step 3 – Determine the final moisture content of the feed mash:

Final moisture content = (Initial Water Content + Steam Condensation)/(Dry Matter + All Water)

= [(2,600 lb. + 1,015.5 lb.) / (17,400 lb. + 2,600 lb. + 1,015.5 lb.)] × 100%
= 17.2% moisture content (w.b.)

Steam Boiler

When steam is generated, pure water vapor is discharged from the boiler. Since water contains solids, the concentration of dissolved and suspended solids increases in the remaining boiler water as steam evaporates. To maintain optimum steam generation and boiler efficiency, a maximum allowable concentration limit for each solid component in the boiler water exists. To prevent exceeding these limits, boiler water is withdrawn and discarded, while feed water is added to dilute the solids concentration. This process is known as boiler blowdown (or bleedoff).

Boiler blowdown is either intermittent or continuous (Murphy, 1994). If the blowdown is intermittent, the boiler water is allowed to concentrate until the maximum level is reached. A valve is opened for a short time (e.g., open the valve for 3 s, close it for 3 s, open it again for 3 s, then close it again), while boiler water is withdrawn and feedwater is added. If no chemical analysis of the water is used as a guide, blowdown should occur at least once every 24 h. The boiler water is then allowed to reconcentrate. If the blowdown is continuous, a regulating valve removes a small but steady stream of boiler water in order to maintain a constant solids concentration.

One measure to determine adequate blowdown is the concentration of total dissolved solids (TDS) (**Table 8-2**). It is the sum of all particles dissolved in the boiler water. The maximum limit recommended to provide an adequate steam supply in boilers operating at up to 300 psig (2,069 kPa) is 3,500 mg of TDS per liter of boiler water (or parts per million, ppm) (Murphy, 1994). If the TDS is too high, the boiler walls will build-up scales, and solids may be carried over into the steam. As little as 1/8" of scale deposits can reduce boiler efficiency by 18% (Anon, 1988); while carry-over causes corrosion of steam pipes, traps, regulators and valves.

Table 8-2. Recommended boiler water control limits for total dissolved solids (TDS) in drum-type boilers. Adapted from Murphy, 1994

Softened (non-deionized) feed water						
psi	150	300	600	900	1,200	1,500
TDS (mg/L)	4,000	3,500	3,000	2,000	500	30
High purity (deionized) feed water						
psi	< 600	900	1,200	1,500	1,800	2,400
TDS (mg/L)	3,000 to 4,000	500	300	200	100	50

If the TDS is too low, too much make-up water and too little condensate enters the boiler. This reduces the steam production capacity of the system, since the available energy is needed to raise the feed water temperature from a lower initial temperature to the boiling point. In addition, excess water is consumed and water treatment chemicals are wasted.

Steam Piping

Steam supply from the boiler to the mash conditioner also requires properly sized piping. Supply piping should be sized so that steam velocity is about 100 ft/s (30 m/s) (McEllhiney, 1994). A steam trap should be installed at every low point and major directional change in the piping system. All piping including valves should be insulated in order to reduce heat loss. The final pressure reducing valve should be no closer than 15 ft. (4.5 m) from the conditioner use point.

Example: What pipe diameter is needed between a boiler and regulator, and between a regulator and conditioner given a mass steam flow of 400 kg/h (880 lb/h), boiler steam pressure of 100 psia, and regulated steam pressure of 30 psia?

Step 1 - Determine the steam properties:

Assuming 100 psia steam is saturated vapor, then T = 164°C (328°F); v = 0.2761 m3/kg (4.4325 ft3/lb.)
Assuming 30 psia steam is superheated, then T = 147°C (296°F); v = 0.9176 m3/kg (14.7306 ft3/lb.)

Step 2 – Calculate the supply line diameter based on the fact that mass steam flow multiplied by specific volume (v) of the steam yields volumetric steam flow, which when divided by the recommended design steam velocity yields cross-sectional area of the pipe:

$$(400\ \text{kg/h} \times 0.2761\ \text{m}^3/\text{kg})/(30\ \text{m/s} \times 3600\ \text{s/h}) = 0.001023\ \text{m}^2$$

The cross-sectional area (A) of the pipe is defined as $A = (\pi d^2)/4$, which can be solved as follows:

$$d^2 = 4\ (0.001023\ \text{m}^2)\ /\ 3.141, \text{ or } d = 3.6\ \text{cm}\ (1.4\ \text{in})$$

Thus, a supply line diameter of 1.5 inches is needed from the boiler to the steam pressure regulator.

Step 3 – Calculate the line diameter between the regulator and conditioner:

$$(400 \text{ kg/h} \times 0.9176 \text{ m}^3\text{/kg}) / (20 \text{ m/s} \times 3600 \text{ s/h}) = 0.005098 \text{ m}^2$$

$$d^2 = 4\ (0.005098 \text{ m2}) / 3.141, \text{ or } d = 8.1 \text{ cm } (3.1 \text{ in})$$

Thus, a steam line diameter of 3 inches is needed from the steam pressure regulator to the conditioner.

Example: How much heat is lost through the surface of a conditioner of 5 ft. in diameter and 12 ft. tall that is 1/8” thick and not insulated? The thermal conductivity of steel is 312 BTU-in/ft2/h/°F

Equation to calculate heat loss due to conduction is:

$$q = [A \times \{T_2 - T_1\}] / [(1/h_{ci}) + (d/k) + (1/h_{co})]$$

Where q = heat loss due to conduction, A = area of the conditioner = 2π (d/2), T_2 = temperature inside vessel, T_1 = temperature outside vessel, h_{ci} = conductance coefficient for condensing steam (5,000 BTU/ft2/h/°F), d = material thickness, k = material thermal conductivity, h_{co} = conductance coefficient for air on surface (1.65 BTU/ft2/h/°F),
For A = 188.5 ft^2, T_2 = 210°F and T_1 = 60°F, d = 0.125 in., the heat loss is:

$$q = [(188.5 \text{ ft}^2) \times (210°\text{F} - 60°\text{F})] / [(1/5000) + (0.125/312) + (1/1.65)]$$

$$q = 46{,}581 \text{ BTU/h}$$

Example: How much heat is lost through the surface of the same steam chest when insulated with one inch of glass wool with a thermal conductivity of 0.3 BTU-in/ft2/hr/°F?

$$q = [(188.5 \text{ ft}^2) \times (210°\text{F} - 60°\text{F})] / [(1/5000) + (0.125/312) + (1/0.3) + (1/1.65)]$$

$$q = 7{,}176 \text{ BTU/h}$$

Thus, adding insulation reduced the heat loss by 23,405 BTU/ h (46,581 BTU/h – 7,176 BTU/h) and eliminated a waste of about 29 ft^3 of gas per hour assuming a heat content of 800 BTU per ft^3 of gas.

Steam Regulation

The steam supply includes a regulator that controls the steam pressure before the conditioner. The steam pressure from the boiler modulates between a high and a low setting to maintain an average desired operating pressure. Without a steam regulator the pressure at the flow control valve would modulate up and down also. This would cause unsteady temperatures in the conditioner, and uncontrolled moisture addition. Strainers, separators, and traps are needed to provide high quality steam before the conditioner. The removal of condensate is especially critical before the steam enters the conditioner. The flow control valve regulates the amount of steam into the conditioner (but not its quality).

Steam Quality

Steam quality is critical, yet much confusion appears to exist among feed mill managers with respect to its thermodynamic behavior. Steam quality (QS) is defined as the percentage of steam in the water phase. It is calculated by dividing the mass of steam (m_s) by the sum of the mass of steam plus mass of water (m_w):

$$Q_S = m_s / (m_s + m_w) \times 100$$

Steam produced at a given boiler pressure enters the steam pipe at its saturation vapor temperature (see Table 1). As the saturated steam vapor travels along the insulated pipe, the steam cools off, and moisture condenses out. The condensing steam loses its saturated quality and turns into a liquid-vapor mixture ($Q_S < 100\%$) that carries actual water droplets along ("wet" steam). The total heat energy of "wet" steam consists of sensible heat plus latent heat only. If “wet” steam is allowed into the conditioner, it may not have enough energy to properly heat and add moisture to the feed mash. When saturated steam vapor cools, moisture condenses out. In this case, the energy transfer from the steam to the mash would be primarily in terms of latent heating. If during condensation a sufficient temperature rise of the mash is not achieved, it may condense too much moisture, which can only partially be absorbed by the mash. This may lead to plugging of the pellet mill, or the production of poor pellets.

Though actual water droplets in the steam liquid-vapor mixture can be removed with steam separators and steam traps, the steam quality before the conditioner can only be returned to a saturated vapor state by reducing its pressure. The pressure is reduced by regulating the boiler pressure from its range of 75 - 160 psig (517-1,103 kPa) to 20 - 35 psig (138-241 kPa) before the conditioner (Leaver, 1982; Anon, 1984). This pressure reduction turns the steam liquid-vapor mixture into superheated steam (Q_S = 100%). For example, the saturation temperature at 100 psig (690 kPA) is 338°F (170°C), while it is only 275°F (135°C) at 30 psig (209 kPa) (see **Table 8-1**). Thus, throttling the boiler pressure before the conditioner turns high pressure "wet" steam into low pressure "dry" steam. The superheated steam contains sensible, latent and super heat.

When superheated steam vapor cools, steam becomes saturated first during which sensible heating of the mash occurs. This raises the mash temperature without moisture addition. Subsequently, latent heating of the mash increases the mash temperature further while adding moisture due to steam condensation.

Feed Mash Conditioner

A pellet mill consists of a (a) variable speed feeder unit, (b) conditioning chamber, (c) die-and-roller assembly, and (d) electric motor. The variable speed feeder unit is generally a screw conveyor and controlled with a variable frequency drive (VFD). The purpose of the feeder is to provide a uniform flow of mash into the conditioner. The feed quality, pellet durability, and power, requirements of the pellet mill are significantly influenced by the effectiveness of the conditioning process. Short-term conditioning generally occurs in a mixer mounted on top of the pellet press.

The flow-through mixer, containing bulk fixed and adjustable paddles, is equipped with steam manifolds and liquid injection ports. The mash and steam enter the chamber at the same end and flow concurrently through the length of the conditioner. In the chamber steam and liquids, such as molasses and fat, are thoroughly mixed with the feed mash. The shaft speed varies from 90 to 500 rpm depending on the feed being processed and the retention time that is needed. The pressure in the conditioner is atmospheric. Most research suggests that both pellet quality and throughput are optimized when mash retention time in short-term conditioners are in the range of 30 to 90 seconds (Behnke, 2006).

To keep track of the conditioning process, it is important to measure the temperature of the mash both upon entering and leaving the conditioner. For example, if the initial mash temperature is 68°F (20°C) and the final mash temperature is 158°F (70°C), the temperature increase is 90°F (50°C). As a rule of thumb, about 1 percentage points of moisture are added for every 25°F (14°C) of mash heating (Anon, 1984). Thus, the moisture increase of the mash during the conditioning process in this example would be about 5 percentage points (i.e., 5 x 1% = 5%). The addition of too much moisture to the feed mash (due to excess steam condensation) causes the rolls of the pellet mill to slip on the die surface; while insufficient moisture in the mash causes dry and brittle pellets. The addition of too much heat can cause denaturation of feed ingredients, which reduces the feed efficiency in animals; while too little heat causes significant frictional heating in the die, which reduces the pellet mill capacity and shortens die life.

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Dr. Carlos Campabadal is the Program Specialist for Grain Storage, Quality and Processing, U.S. Grain Grading and Export Systems, and Feed Manufacturing for the International Grains Program at Kansas State University. Dr. Dirk Maier is the head of the Department of Grain Science and Industry and Director of the International Grains Program at Kansas State University.

This content was edited and reviewed by Dr. Adam Fahrenholz, Assistant Professor of Feed Milling at North Carolina State University, Dr. Charles Stark, Jim and Carol Brown Associate Professor of Feed Technology at Kansas State University, and Dr. Cassandra Jones, Assistant Professor of Feed Technology at Kansas State University.