EFFECT OF FEED PROCESSING ON BROILER PERFORMANCE

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Introduction

It is well recognized that feed represents the most significant cost of broiler production. Most production costs estimates range from 60-70% as being feed costs. Certainly, the major portion of feed costs is for the ingredients used. However, the cost of feed processing represents a significant portion of feed costs and likely gives the greatest opportunity for influencing broiler performance beyond nutritional adequacy.

"Feed processing" and the costs associated with processing include a wide range of unit operations including receiving, grinding, proportioning, mixing, pelleting, loadout, and delivery. Nearly every one of these operations can have either a negative or positive influence on subsequent animal performance and can certainly influence the profitability of a poultry production company.

The rate of gain for broilers has increased substantially during the last few decades. In 1960, a commercial broiler chicken attained a 2.2 Kg market weight by 12 weeks of age. Today's broilers attain the same market weight in just 6 weeks (Havenstein et al., 1994). A similar trend has been noted for turkeys (Ferket, 2001). This remarkable improvement can be mainly attributed to improved genetics, however, tremendous improvements in nutrition have made it possible to take advantage of the genetic changes. Furthermore, our understanding of feed processing and feed delivery has allowed the economical implementation of many of the innovations in nutrition.

This paper will focus on three of the unit operations mentioned above: grinding, mixing, and pelleting. These operations are likely to have the greatest influence on broiler performance and feed quality and are dealt with, at least to some extent, in the scientific literature. Because grinding likely has a greater influence on the pelleting operation rather than on bird performance, these two topics will be addressed together later in the paper.

Early Nutrition and Enteric Development

Because the first few days after hatch now represent a greater percentage of a broiler's life span than any time in history, it is critical that the bird be given every opportunity to get off to a good start. During those few days of "adjustment", chicks are making the metabolic and

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physiological transition from having the egg supply all required nutrients to having nutrients supplied by compounded feed. During this transition, dietary carbohydrates and amino acids are not well utilized because of limits in digestion and absorption. In most cases chicks are in a negative nutritional status and utilize critical body resources (i.e., muscle tissue) to survive. As a result, chicks are more susceptible to disease, body weight loss, and environmental stress than would be desired. Losses of 2 to 5% or more during the critical post hatch period are not uncommon. Additionally, many survivors exhibit stunted growth, inefficient growth, reduced disease resistance, and poor meat yield (Ferket and Uni, 2002). The earliest possible development of the intestine, the primary nutrient supply organ, is critical in getting hatchlings off to a good start.

Feed Intake Initiation

To survive and be as productive as possible, chicks must initiate food intake, digestion, and nutrient assimilation within the first 1 to 4 days following hatch, the sooner the better. The organs involved in digestion, the pancreas, liver, and small intestine, develop rapidly following hatch (Vieira and Moran, 1998). Other scientists have proposed that the rate and degree of development of digestive capacity is dependent on the chicks nutritional status at hatch and the early and rapid exposure of dietary components to the gastrointestinal system and enteric mucosa.

Several studies have been initiated to investigate *In Ovo* feeding as a way to accelerate enteric development (Ferket and Uni, 2002; Al-Murrani, 1982; Ohta et al., 1999; Gore and Qureshi, 1997). While these studies have shown promise, the lack of practical technology for *In Ovo* feeding has prevented the adoption of such practice. A U.S. and world patent has now been filed (Uni and Ferket, 2001) and is under review that addresses some of the technical hurdles of *In Ovo* feeding, however, wide adoption of the technology is years into the future. It is, therefore, imperative that we address issues related to feeding newly hatched chicks using conventional practices.

Mixing Operations and Nutrient Uniformity

Mixing is an operation basic to feed manufacturing and, in fact, is the one operation necessary to define a feed mill. When ingredients are combined to be fed as a complete diet, they must undergo a mixing process and, intuitively, nutrient uniformity in a complete diet is necessary to maximize nutrient utilization. To optimize growth, production, and health, animals should receive a balanced diet that supplies nutrients and feed additives at the desired concentrations. Beumer (1991) cited uniformity as one of the most important quality aspects in feed production. Ensminger et al. (1990) stated that because baby chicks consume only a few grams of feed each day, it is necessary to have all essential nutrients at the proper level in a very small meal. However, despite an extensive review of the literature, little quantitative data were found documenting the effect of inadequate diet mixing on subsequent animal performance.

Because it is not practical to assay each nutrient for its uniformity throughout a batch of mixed feed, tests have been developed that use either an indigenous nutrient (e.g., chloride or sodium ion) or an added marker to evaluate uniformity (Eisenberg, 1992). Ideally, the chosen

marker will be contributed by only one ingredient in the formulation; thus its uniformity distribution would indicate the degree of adequate mixing. Once random samples, collected throughout the batch of feed, have been analyzed, a coefficient of variation (CV) is determined. A CV of 10% has become the accepted degree of variation separating uniform from non-uniform mixes (Beumer, 1991; Wicker and Poole, 1991; Duncan, 1973) This value includes variation from sampling procedures, assay variability, randomness, as well as uniformity of the mix.

It is common practice to assay for the chloride ion from salt because the procedure is rapid, accurate, and inexpensive. A rapid test for sodium, using a specific ion electrode, is also available. Finally, the distribution of iron particles, dyed with either red or blue food coloring, can be used for evaluating mixer performance. There have been numerous other tracers proposed for mixer-uniformity testing, however, most are either too expensive on a per-assay basis (e.g., animal drugs) or the assay lacks sufficient precision to be of any value (e.g., some drugs, vitamins, and the like). In all cases, multiple samples are taken throughout the batch of feed, and statistical analyses are used to calculate a CV as the measurement of diet uniformity.

McCoy et al. (1994) conducted two experiments to determine the effects of dietary non-uniformity, caused by inadequate mixing, on the performance of broiler chicks. In both experiments, a common diet was mixed for different times to represent poor, intermediate, and adequate uniformities. Methods of uniformity analysis had quadratic responses (P < .001), with diet variability decreasing as the mixing treatment was increased from poor to intermediate and a negligible reduction was noted as the mixing time was increased from intermediate to adequate. In the first feeding study (a 24-day growth study), average daily gain, average daily feed intake, bone strength and ash, and carcass CP, fat, and ash were not affected by mixing time (P > .10). However, there was a 3.5% increase (linear, P < .09) in the gain:feed ratio as the mixing treatment was increased from poor to adequate. In the second experiment (a 28-day growth assay), quadratic responses were observed for average daily gain (P < .04) and gain:feed ratio (P < .07), increasing as the mixing treatment was increased from poor to intermediate, with no further increase as the mixing treatment was increased from intermediate to adequate. A linear increase (P < .08) in average daily feed intake was observed as diet uniformity increased. Mortality was not affected by treatment (P > .20). Birds were fed a common finishing diet to determine if compensatory growth occurred. Finishing phase average daily gain was not affected by treatment (P > .30), indicating that compensatory gain did not occur for chicks previously fed the poorly mixed diet. However, a linear decrease (P < .007) in finishing phase gain:feed ratio resulted from increased diet uniformity in the growing phase. These experiments indicate that diet uniformity can have a dramatic influence on broiler chick performance. However, the results indicate that, depending on the uniformity test used, CV's of up to 20% (twice the current industry recommendation) may be adequate for maximum growth performance in broiler chicks.

Although insufficient mixing time is often implicated as a source of variation in complete feeds (Pfost et al., 1974; McEllhiney and Olentine, 1982; Wilcox and Balding, 1986; Wicker and Poole, 1991;), numerous other factors have may have influence. Filling the mixer beyond rated capacity is a common source of variation (Wilcox and Balding, 1986; Wicker and Poole, 1991). Other factors include: worn, altered, or broken equipment (Wilcox and Balding, 1986; Wicker and Poole, 1991); improper mixer adjustment (McEllhiney and Olentine, 1982; Wilcox and Balding, 1986); poor mixer design (Wilcox and Balding, 1986); incompatibility of physical

characteristics of the ingredients being mixed (McEllhiney and Olentine, 1982; Wicker and Poole, 1991); improper sequencing; residual ingredient build-up in the mixer; leaking discharge gates and leaking liquidation addition systems (Wicker and Poole, 1991); variations in the composition or quality of ingredients; weighing or proportioning errors; and post-mix segregation (Pfost et al., 1974).

Pelleting and Other Hydrothermal Processes

The pelleting process is defined as "the agglomeration (process of molding into a mass) of small particles into larger particles by the means of a mechanical process in combination with moisture, heat, and pressure" (Falk, 1985). The process has not undergone major technological changes in the past fifty years. Since the introduction of the pelleting process, technology development has been primarily centered around improving pellet quality while maintaining an acceptable throughput. Processing research has centered on changing diet formulation, the conditioning process, and die design.

Improving pellet quality has always been important to the feed industry as manufacturers strive to produce quality feeds. However, within the integrated poultry and swine industries, the issue of desirable pellet quality has been based on growth performance rather than customer expectations. Commercial integrated feed manufacturers need the ability to identify and control the factors that affect pellet quality. Refining the process requires identification and manipulation of the factors that have the greatest influence on pellet quality.

Justification for Pelleting Poultry Feeds

Pelleting tends to improve animal performance and feed conversion. The improvements in performance have been attributed to (Behnke, 1994):
1. Decreased feed wastage
2. Reduced selective feeding
3. Decreased ingredient segregation
4. Less time and energy expended for prehension
5. Destruction of pathogenic organisms
6. Thermal modification of starch and protein
7. Improved palatability

Historically, research has concentrated primarily on the benefits of feeding pellets versus meal. Pellet quality has become more important in the swine and poultry industries as integrators continue to expand and recognize the value of feeding quality pellets.

Poultry – broilers

Pelleted broiler diets improve growth performance and feed conversion (Table 1). Hussar and Robblee (1962) reported reground pellets did not affect early bird performance. However, as the birds matured, those fed whole pellets had better growth and feed conversion rates compared with those fed reground pellets. This would suggest that feed form had some influence on performance. Hull et al. (1968) reported birds fed pelleted diets had a 5% better

feed conversion, but regrinding the pellets resulted in a lower feed conversion than the meal diet. A field study conducted by Scheidler (1991) indicated birds fed 75% whole pellets as compared to 25% whole pellets showed improved feed conversion (F/G 2.08 vs. 213).

Poultry – turkeys

Turkeys appear to be sensitive to pellet quality and fines. Several studies indicate pellet fines decrease turkey performance (Table 2). Proudfoot and Hulan (1982) reported pelleted diets improved feed conversions. However, as pellet fines increased from 0% to 60%, performance decreased. Moran (1989) showed a decrease in growth and performance when reground pellets were fed. Salmon (1985) reported no difference in bird performance when high quality pellets were fed.

The physical form may have a stimulatory effect in the digestive tract that improves nutrient utilization of the pellet. Lower feed conversion is primarily a result of increased feed consumption or feed disappearance associated with poor quality pellets. Feed wastage and spoilage due to poor feeder management is often a primary contributing factor in feed disappearance and, consequently, decreased feed efficiency.

Table 1. Effects of pellets on broiler performance.

Reference	Meal		Pellet		
	ADG, g	F/G	ADG, g	F/G	Comment
Hussar and Robblee (1962)	18.8	2.17	23.6	1.98	Pellets
			21.2	2.00	Reground pellets
Hull (1968)	18.9	1.56	19.3	1.48	Pellets
			18.3	1.61	Reground pellets
Runnels et al. (1976)	42	2.14	47.0	2.10	Pellets (unsifted)
			44.9	2.11	Pellets (sifted)
			44.5	2.12	Crumbles
			44.7	2.12	½ Pellets & ½ Crumbles
Proudfoot and Hulan (1982)					
Experiment 1	34.0	2.10	33.6	2.09	100% fines
			35.3	2.02	45% fines
			35.5	2.02	35% fines
			35.6	2.03	25% fines
			35.8	2.01	15% fines
			36.5	2.04	5% fines
			36.4	2.01	0% fines
Experiment 2	39.2	2.11	38.7	2.11	100% fines
			39.3	2.06	80% fines
			40.5	2.06	60% fines
			40.9	2.05	40% fines
			41.6	2.04	0% fines
Choi et al. (1986)	35.1	2.69	39.3	2.67	
Scheidler (1991)	—	—	43.3	2.08	25% fines
			42.2	2.13	75% fines

Table 2. Effects of pellets on turkey performance.

Reference	Mash ADG, g	F/G	Pellets ADG, g	F/G	Comments
Proudfoot and Hulan (1982)	60.3	2.50	62.1	2.31	0% fines
			61.8	2.35	7.5% fines
			62.7	2.37	15% fines
			61.8	2.37	30% fines
			61.4	2.40	60% fines
Salmon (1985)					
Added fat	Mash		Pellets		PDI, %[1]
0%	53.8	2.09	58.2	2.09	97.3
3%	58.5	2.02	61.4	1.96	93.0
6%	61.4	1.99	61.8	1.98	89.7
9%	62.1	1.93	63.1	1.99	84.4
			Pellets + binder		
0%			59.0	2.10	96.2
3%			61.0	2.02	94.9
6%			61.2	2.01	93.0
9%			62.3	1.92	84.2
Moran (1989)	138.0	3.92	148.1	3.30	Pellets
			135.8	3.88	Reground pellets
Waibel et al. (1992)	97.3	2.94	102.6	2.87	

[1]Mechanical

Pelleting Broiler Feeds – Modern Perspective

It is difficult to review contemporary literature concerning the effects of pelleting on bird performance. Few studies have been conducted with sufficient feed processing data to support their hypotheses. For example, were the percent fines and pellets between variables examined or was the pellet quality data reported? Two different diets with the fines removed but having differing pellet durability values can result in different performances.

The risk associated with pathogens passing from feed to growing birds is small but does exit. This is a risk factor which has the potential to be extremely costly; however, this is not factored into feed manufacturing practices by the poultry industry. Clearly we have ways to improve the hygienic quality of feed using different types of manufacturing methods, but we must be willing to absorb additional feed manufacturing costs as well as make basic changes in the way feed is processed, handled, and transferred to the farm.

Commercial poultry have certain behavioral, physiological, and even anatomical traits that may require consideration when manufacturing feed. It is also possible that certain feed processing techniques will affect the bioavailability of some nutrients as well as impact the nutritional requirement of the bird. It has been recognized for many years that providing feed to

poultry in the form of pellets could enhance the economics of production by improving feed conversion and growth rates. For this reason, feed for meat birds is processed into pellets or crumbles.

A survey of various literature sources indicates that pelleting results in improvements in feed conversion from 0 to 12 percent. Because the cost of feed is a substantial portion of producing meat, even small increases in feed conversion can increase economic returns. The cost to mix and manufacture feed must also be considered. These costs must not exceed the performance gains observed in the production of the birds.

Over the years, the basic manufacturing process for pelleting feed has remained virtually the same. At the same time, great changes have occurred in the meat bird industry. Producers no longer purchase feed from feed mills, instead feed manufacturing exists as a part of an integrated, highly efficient production system. Thus, any emphasis on feed quality, a task originally undertaken by independent feed mills, has declined since feed is made "in-house". Nutritionists now know the biological value of feed ingredients and the nutrient requirements of all poultry to the finest degree. Geneticists have improved the growth rate, body size, yield, etc. to levels once thought unattainable. However, even though it is well recognized that high quality manufactured feed will directly impact growth and feed conversion, the importance of feed quality has decreased priority.

During the past few years, a renewed interest by equipment manufacturers has resulted in significant changes in the way feed can be manipulated. The feed mill will have more flexibility to change processing parameters, which in turn could affect the nutrient profile of the feed. The purpose of this review is to the examine implications of poorly manufactured feed on production and what changes are on the horizon.

Crumble Quality and Early Growth Performance

Several studies previously mentioned document the value of the pelleting process to broiler performance. It is becoming clear that pellet quality can influence growth and feed efficiency.

However, few studies have focused on crumble quality and size and their effect on the transitional chick and post-hatch performance. A study was conducted at Kansas State University to investigate the relationship of crumble size and early (0-3 wk) growth performance in broiler chicks (Wilson 2001).

In this study, the same diet was fed as a coarse crumble (~4.0 mm), a medium crumble (-4.0 to +1.5 mm), and fine crumble (-1.5 mm). Over the entire study there were no differences in body weight gain between the coarse and medium size crumbles but both outperformed the fine crumble (777 gm vs 738). A similar result was noted in feed efficiency (0.750 vs 0.725 F/G). It is obvious that something as simple as crumble size can dramatically influence performance.

Defining Feed Quality

Feed quality is generally defined using the *pellet durability index* (PDI) (ASAE, 1997). This is a simple test in which the pelleted feed is tumbled in a specially designed box for a defined period of time that stimulates the transfer and handling of feed (Fairfield, 1994). The ratio of fines after tumbling to whole pellets at the start is the PDI. Thus, feed with a higher PDI means that the manufactured pellets will more likely remain intact prior to feeding. Feed mills should use this method as a simple measure of pellet quality. Unfortunately, almost all of the previous literature reported in poultry publications focuses on the number of fines and pellets by weight, not the PDI. This makes it difficult, if not impossible, to interpret much of the available

data on poultry feed quality. For example, a diet screened to contain 100% pellets may only contain "soft" pellets which easily break apart during the feeding process, an observation that we have made in our research trials (Wilson and Beyer, 1998) at K-State.

Many feed pellets are damaged by loading, storage, augering, and transferring to feed pans. Manipulation of the feed results in reduced pellet numbers, and in some cases, seriously reduces the total percentage of pellets that ultimately reach the feed pans. Because automated feed transfer and handling systems are necessary, it would seem that the best remedy for this situation is to increase the PDI of the feed using a different manufacturing process. It is important to reiterate that the PDI is a better measure of feed quality than the total number of pellets.

Pelleting and Management Considerations

Certain behavioral and anatomical traits of poultry must be considered during feeding. Pelleting reduces feed waste on the farm and this is due partially to avian anatomy. Without teeth and with the need to use gravity to consume feed, broilers and turkeys cannot easily grasp food. Feed with uneven particle size may increase waste since the smaller particles easily fall from the bird's mouth. To fill the crop, a bird consuming fines or mash must spend more time standing to consume food. This decreases feed conversion since more energy must be expended to feed. Even feeder height is important, since setting above or below optimal will influence the amount of feed wasted. Indeed, work at Kansas State has shown that feeder height may need to be lower than recommended if the feed quality is poor. Today's birds are young and heavy and thus are able to stand for shorter time periods. Of course, there are other practical reasons for pelleting feed which include a reduction in dustiness, improved handling characteristics, increased physical density, and decreased stratification, among others.

Selection for increased body weight at a younger age has no doubt influenced basic anatomical and physiological traits. For example, the anatomical changes in the bird due to increased growth rate and size means that the oral cavity of birds has changed slightly. At first this may seem trivial, but even this small change may influence feed spillage and feeding time.

It is also known that the anatomy of the digestible system is affected by feed particle size, which could impact nutrient absorption (Choi et al., 1986). This is especially important considering that the digestive system of broilers and turkeys selected for rapid growth is less mature as the birds are pushed to market weight faster. Research is limited on the proper pellet sizes required by broilers and turkeys, and this may need to be addressed as feed manufacturing changes are made. We may have missed the importance of pellet length and size since current manufacturing methods often result in soft feed which may degrade in an experiment or on a farm. It is likely that a refinement of pellet size to age or body weight can be optimized to improve performance.

Because birds have a keen sense of sight, feed particle size is also of importance. Studies indicate that birds desire feed in a larger size than mash. If provided a diet with equal portions of pellets and fines, the birds will consume the pelleted feed first (Scheidler, 1991). Poorly manufactured feed with excess fines results in some of the birds consuming only pellets, leaving the smaller fines for less aggressive birds. Because pellet quality affects the rate of growth, the presence of fines in a feed can affect flock uniformity and impact processing.

If fines are fed to poultry, a loss in feed conversion and rate of gain is observed (Blakely et al., 1963; Brewer and Ferket, 1989; Moran, 1989; Waibel et al., 1992). Almost as a rule of thumb, it would appear that older data indicates that with each additional 10% fines, a loss of one conversion point will result. This has also been noted in recent broiler trials.

New Manufacturing Considerations

Because of the incidence of food borne pathogens, the desire to eliminate contaminated feed as a source of these bacteria may soon impact how poultry feed is manufactured. In the farm-to-table effort to reduce the incidence of food borne pathogens, sources of possible contaminants such as certain feed ingredients will be closely scrutinized (Pomeroy et al., 1989).

A great deal of interest has developed recently in the concept of producing pathogen free feeds for breeders (Muirhead, 1999a; Orchard, 2000). In this instance, the focus has been on producing breeder stock that is salmonella-free to meet import restrictions in international markets. Pathogen concerns are not limited to the international markets as U.S. domestic clients are demanding pathogen free breeder chicks as well.

The facility identified in the article cited above was designed and built and is operated to provide the highest degree of bio-security possible. All personnel must shower in. Feed not meeting strict processing parameters is reprocessed. Delivery trucks never enter the farm and all trucks are company owned. While these measures seem extreme, this may be a glimpse of the future for broiler production in general.

The availability of new feed processing equipment that improves pellet quality and thus bird performance is also receiving attention. Fortunately, as we improve pellet quality by utilizing new equipment, feed hygiene will improve. This may also affect the way we currently use pellet binders and other additives to improve feed quality (Salmon, 1985).

Interest in alternative feed manufacturing methods has increased. These methods include the use of expanders, compactors, pressurized pelleting, etc. Interest in expanders in the U.S. has recently increased, although they have been in use in Europe for some time (Vest, 1996). An expander is a device somewhat similar to an extruder yet requires less energy and maintenance input. Briefly, the feed passes through a conditioning chamber and passes a thin gap between a cone shaped device and the chamber. The width of the gap and thus the mechanical pressure that is exerted on the feed is maintained by an adjustable hydraulic system. As feed passes the gap, a rise in temperature due to friction force occurs. Thus the feed not only undergoes a short-term temperature increase, but the feed particles have also experienced a shear force. Exposure to high temperature occurs for a short time so that destruction of heat sensitive nutrients appears to be minimal under normal conditions. Presumably, these factors may lead to an improvement in bioavailability of previously hard to digest feed components, while decreasing the microbial content of the feed (Peisker, 1994; Armstrong, 1993; Fancher et al., 1996).

Conditioning feed while under pressure is another method under consideration (Pelleting Concepts International, 1998). The increase in pressure allows the physical nature of steam to change thus increasing the temperature of steam to greater than 212°F. This increases the gelatinization potential and presumably lowers the cost of processing. Work at K-State has shown that this type of manufacturing greatly increases pellet quality (Wilson et al., 1999a).

Wenger Manufacturing Inc. (1998) has recently introduced a new piece of equipment that greatly increases gelatinization and thus feed quality. Work has shown that feed manufactured by this method increases bird performance (Wilson et al., 1999b). Because the cost of feed is so important to the cost of production, it is likely that alternative feed manufacturing methods will be considered for producing poultry feed.

Nutritional Considerations in Pelleting

Although nutritionists have precisely defined the nutrient requirements for poultry, little work has focused on the effect of feed form on nutrient requirements. Long ago, Jensen et al.

(1965) determined that feed in pellet form increased the requirement for lysine in growing turkeys compared to when the turkeys were fed similar diets in mash form, especially when formulated at marginal levels. Because pelleting increased the productive energy of the diet, the authors speculated that more lysine was required since the requirement of some nutrients is related to the level of other nutrients available to the bird. If the average increase in feed conversion due to pelleting is near 10%, for example, then the theoretical requirement for lysine for growing turkeys would be 1.43% compared to mash at 1.3% normally used.

Somewhat troubling is the fact that many tables of nutrient bioavailabilities are based on feed in mash form that has not been processed. Thus, the performance of birds in the field fed poorly manufactured feed may differ from those fed diets with high pellet quality.

The nutritional considerations for adding an expander or other type of exotic feed manufacturing equipment to the feed mill are numerous. On the practical side, an expander will allow the use of more feed ingredients that reduce PDIs while eliminating the need for additives that improve pellet durability. Some producers add fat post-pellet, however, an expander will allow for more fat to be added at the mixer, eliminating the need to spray fat on the outside of the pellet.

Annular gap expanders produce high quality feed with greatly increased PDIs (Wilson and Beyer, 1997). This is attributed to increased gelatinization of starch granules, which serves as glue to hold the feed particles together. However, little evidence suggests that increased starch gelatinization improves digestibility in poultry. According to Peisker (1994), expanders increase starch gelatinization, increase fat stability, increase metabolizable energy, decrease microbial contamination, and increase the soluble fiber. Fancher et al. (1996) reported improved growth and feed conversion in male turkeys fed expanded diets compared to diets that were only pelleted. Data from our laboratory indicate that these parameters are improved by 5-10% when expanded diets are compared to conventionally pelleted rations in broiler trials. Some nutritionists were concerned that expanders could destroy certain heat sensitive nutrients, but work has shown that this is not much of a concern (Coelho, 1994).

Smith et al. (1995) found that there was no difference in true metabolizable energy due to expansion, although expansion improved feed conversion. This is similar to data reported for pelleted rations and is understandable, if the energy gained by pelleting is due to productive energy gain rather than an increase in metabolizable energy. However, it would seem that the use of shear force by an expander would allow increased nutrients to be accessible which were previously bound within cellular material. Work in our laboratory has shown that increased amino acid bioavailability may occur when corn or soybean meal is expanded under different cone pressures. Increasing cone pressure led to a general increase in TME, as availability, protein solubility, and increased starch gelatinization (Wilson and Beyer, 1997). However, these products were processed separately, and further data is required to determine if an interaction of nutrients from different sources occurs in the gelatinization phase. The interaction of protein, starch, and fat particles will likely be interactive when under pressure or at high temperature.

Moisture Control and Pelleting
Moisture addition at the mixer has been shown to increase pellet durability and decrease pellet mill energy consumption for corn-soybean meal diets; however, the effect of this process on animal performance has not been tested (Fairchild and Greer, 1999). From a feed manufacturing standpoint, the objective of pelleting is to produce a high quality product with minimum production expense (Mommer and Ballantyne, 1991). Fairchild and Greer (1999) have demonstrated that increasing the moisture content of mash feed at the mixer subsequently

decreased pellet mill energy consumption and increased pellet durability. The increase in pellet durability alone should economically improve broiler production.

Recent studies at Kansas State University (Moritz et al., 2000) indicate that adding moisture at the mixer to a pelleted corn-soybean meal diet resulted in a significant increase in broiler feed efficiency (FE) when feed intake was equalized on a nutrient density basis. They concluded that increased FE resulted from improved nutrient availability, or feeding advantages associated with improved pellet quality or a combination of these two. Studies are currently underway to better determine the effect of moisture addition, pre-pellet, on nutrient requirements and availability.

Factors Affecting Pellet Quality

If it is accepted that pellet quality (or, more accurately, percentage pellets at the feeder) does influence broiler growth and performance, a discussion on the factors that affect pellet quality is appropriate. 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 may 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.

Studies have been conducted to evaluate 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 (at about 13%) as compared to corn (at about 9%). This conclusion is consistent 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) indicated may control 20% of a pellet's quality. Decreasing particle size from a coarse to a fine 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 (ASAE, 1997) as determined by the tumbling can method.

Mash Moisture - Steam

Some 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; 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 or mixer and serves to soften feed particles and lubricate the mash as it moves through the diet.

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 controlled 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 these experiments 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, 1999b).

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.
        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 by changing shaft speed. Adjusting pick angles changes the forward motion and elevation of product as it is conveyed through the conditioner. This angle adjustment, however, can be time consuming as the conditioner must be shut down and locked out before the operator can access the picks inside of the conditioner. In addition, these angles 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 motor on the conditioner. In addition to slowing down the conditioner RPM, this adjustment will affect the amount of elevating motion that a product undergoes as it passes through the conditioner.
        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 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 the degree of pitch, or conditioner design, affected pellet quality. Pellet durability of mash conditioned using the parallel pitch averaged 5 percentage 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 spoiling 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. As moisture soaks into the particles, they become softer, and moisture has been found to act as a lubricant to reduce friction between the pellet 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 rate by 100 gives the percent steam quality. As steam is transferred from the boiler to its use location, it loses some of its 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 3 to show how they compare.

Table 3. **Properties of 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, condensation and heat transfer in the conditioner only occurs at atmospheric pressure. This means that the temperature of steam must first be reduced to around 100° C before any condensation or 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 3 shows that there is less than an 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 quality and mill performance. MacBain (1966) presented 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 stated 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) agree 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 efficiency 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 than 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.

Summary

As can be noted from the above discussion, feed processing has a dramatic influence on broiler performance. It is apparent that new developments in processing and the understanding of how feed manufacturing practices influence performance have been neglected relative to genetic improvement in broilers and even to the understanding of nutrient requirements. However, all are important.

Processes such as expanding, compacting, and pressure pelleting usually result in improved feed performance. Whether or not the cost can be justified is nearly a local issue and depends upon the costs of ingredients, energy, labor, and capital. It may well be that something like feed hygiene will begin to dictate decisions concerning which feed processing technologies to adopt. There is little doubt that food safety will be the main issue for the next several decades. All feed manufacturers must accept the fact that we are part of the food industry, and we must conduct our business accordingly.

It was the aim of this paper to clarify how some of the various feed processes can interact to influence the performance of broilers. Only by optimizing each process can we hope to optimize broiler performance.

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