INFLUENCE OF FEED PROCESSING ON THE PERFORMANCE, NUTRIENT UTILISATION AND GUT DEVELOPMENT OF POULTRY AND FEED QUALITY

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Abstract

The first two experiments of this thesis investigated the effects of conditioning temperature in relation to grain type (maize, wheat and sorghum) on the performance, nutrient utilisation and digestive tract development of broiler starters. The third experiment examined the influence of feed form (mash vs. pellet) and conditioning temperature in broiler starters fed wheat-based diets. The effects of improved pellet quality from the addition of a pellet binder or/and moisture to a wheat-based diet, and the effects of pellet diameter and pellet length on the quality of pellets and, performance, nutrient utilisation and digestive tract development of broilers were studied in fourth and fifth experiments, respectively.

In the first experiment discussed in Chapter 4, increasing conditioning temperatures decreased the weight gain and feed intake of broilers fed wheat-based diets, whereas birds fed maize-based diets conditioned at 60 and 90 ℃ had higher weight gain and feed intake than those fed the diet conditioned at 75 ℃. Increasing conditioning temperatures increased the feed per gain in both grain-type diets. Pellet durability index (PDI) improved with increasing conditioning temperatures in wheat-based diets, but was unaffected in maize-based diets. In wheat-based diets, increasing conditioning temperatures decreased the ileal digestibility of nitrogen (N) and starch. Ileal N digestibility of maize-based diets conditioned at 60 and 90 ℃ was higher than at 75 ℃. Starch digestibility was unaffected by conditioning temperature in maize-based diets. No effect of conditioning temperature was found for the apparent metabolisable energy (AME).

Data reported in Chapter 5 showed that birds fed maize- and sorghum-based diets conditioned at 60 ℃ had a similar weight gain to those fed diets conditioned at 90 ℃ and higher than those fed diets conditioned at 75 ℃. In both grain-type diets, birds fed diets conditioned at 60 and 90 ℃ tended to have higher feed intake than those fed diets conditioned at 75 ℃. Conditioning temperature had no effect on the feed per gain. Increasing conditioning temperatures caused gradual improvements in the PDI of maize-based diets, while the improvement was marked in the sorghum-based diet conditioned at 90 ℃. In both grain-type diets, pellet hardness increased with increasing conditioning temperatures, particularly at 90 ℃. In maize-based diets, ileal N digestibility was poorer at 75 ℃ compared with 60 and 90 ℃ whereas ileal starch digestibility was unaffected by conditioning temperature and AME was higher at 75 ℃

compared with 60 and 90 ℃. For sorghum-based diets, increasing conditioning temperatures resulted in linear reductions in the ileal N and starch digestibility and AME.

Data reported in Chapter 6 showed that in mash diets, increasing conditioning temperatures above 60 ℃ had negative effects on weight gain, feed per gain and nutrient utilisation of broiler starters. But the deterioration in performance parameters caused by conditioning at higher temperatures was restored when steam-conditioned mash diets were pelleted. Pellet durability and hardness increased with increasing conditioning temperatures.

Data reported in Chapter 7 showed that the negative effect of higher conditioning temperature on weight gain, and to some extent feed intake, of broilers is not limited to the starter period (d 1 to 21), but can also be carried over the whole growth period (d 1 to 35). This study also illustrated possibilities for high quality pellets to be manufactured by the addition of pellet binder or/and moisture to a mash diet without the need for high conditioning temperatures.

The final experiment (Chapter 8) demonstrated that increasing the pellet length from 3- to 6-mm during the grower period (d 10 to 21) positively influenced the weight gain and feed per gain of broilers. While the weight gain response disappeared as the birds grew older, improvements in feed per gain was maintained over the finisher (d 22 to 42) and whole grow-out (d 10 to 42) periods in 4.76-mm diameter pellets. This study also showed that using a small diameter die hole and longer pellet length may have an additive effect on pellet quality, and provide opportunities to produce high quality pellets under low conditioning temperatures.

The major finding of this thesis research was that the balance between the negative effect of high conditioning temperatures on nutrient availability and the positive effect on pellet quality is relevant in determining the broiler performance. The probability and magnitude of these two counteracting effects determine the performance of broilers. Another important finding was that the pre-conditioning addition of moisture and the use of small diameter die hole and longer pellet length can effectively address pellet quality concerns at low conditioning temperatures.

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Publications

Studies completed during candidature, some of which are reported in this thesis have been presented in the following communications:

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Abdollahi, M.R., Ravindran, V., Wester, T.J., Ravindran, G. and Thomas, D.V. (2010) Influence of conditioning temperature on performance, apparent metabolisable energy, ileal digestibility of starch and nitrogen and the quality of pellets, in broiler starters fed maize- and sorghum-based diets. Animal Feed Science and Technology 162: 106-115.

Abdollahi, M.R., Ravindran, V., Wester, T.J., Ravindran, G. and Thomas, D.V. (2010) Influence of conditioning temperature on the performance, nutrient utilisation and digestive tract development of broilers fed on maize- and wheat-based diets. British Poultry Science 51: 648-657.

Conference proceedings:

Abdollahi, M.R., Thomas, D.V., Wester, T.J., Ravindran, G. and Ravindran, V. (2011) Effects of a commercial pellet binder and moisture addition on pellet quality and, the performance and nutrient utilisation of broilers. Proceedings of the Australian Poultry Science Symposium 22: 61-64. Sydney, Australia.

Abdollahi, M.R., Wester, T.J., Thomas, D.V., Ravindran, G. and Ravindran, V. (2011) Influence of feed form and conditioning temperature on the performance and nutrient utilisation of broiler starters fed wheat-based diet. Proceedings of the Australian Poultry Science Symposium 22: 209-212. Sydney, Australia.

Ravindran, V., Amerah, A.M. and Abdollahi, M.R. (2010) Influence of particle size, feed form and pelleting temperature on broiler performance. Proceedings of 4th International Broiler Nutritionists' Conference, Poultry Beyond 2015, Pages 177-187. Convention Centre, Christchurch, New Zealand.

Abdollahi, M.R., Ravindran, G., Wester, T.J., Thomas, D.V. and Ravindran, V. (2010) Influence of conditioning temperature and feed form on the nutrient utilisation and the performance of broilers fed wheat-based diets. Proceedings of the Massey Technical Update Conference, Volume 12, Pages 67-76. Monogastric Research Centre, Massey University, Palmerston North, New Zealand.

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Abdollahi, M.R., Ravindran, V., Thomas, D.V. and Amerah, A. M. (2008) Effect of pelleting temperature on broilers performance and pellet quality. Proceedings of the Massey Technical Update Conference, Volume 10, Pages 113-118. Monogastric Research Centre, Massey University, Palmerston North, New Zealand.

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List of Abbreviations

ADE	Apparent digestible energy
AME	Apparent metabolisable energy
AMEn	Nitrogen-corrected apparent metabolisable energy
ANOVA	Analysis of variance
BTU	British thermal units
cPs	Centipoise
d	Days
DDGS	Distiller's dried grains with solubles
DM	Dry matter
DSC	Differential scanning calorimetry
g	Gram
GE	Gross energy
GIT	Gastrointestinal tract
GLM	General linear model
GS	Gelatinised starch
h	Hours
HT/ST	High-temperature/Short-time
IU	International unit
KJ	Kilo joule
kPa	Kilo Pascal
mg	Milligram
MJ	Mega joule
mm	Millimetre
N	Nitrogen
NE	Net energy
NRC	National research council
NSP	Non-starch polysaccharide
PD	Pellet diameter
PDI	Pellet durability index
PL	Pellet length
psig	Pound-force per square inch gauge
RDS	Rapidly digestible starch
RS	Resistant starch
SDS	Slowly digestible starch
SEM	Standard error of mean
Ti	Titanium
TMEn	Nitrogen-corrected true metabolisable energy
U	Unit
UV	Ultra violet

CHAPTER 1

General introduction

Feed is the greatest cost item in broiler production representing 60 to 70% of the total production cost. The cost of ingredients accounts for a major portion of the feed cost, but feed processing also significantly increases the cost of feed (Behnke and Beyer, 2002). However, feed processing provides an opportunity to improve broiler performance (Behnke and Beyer, 2002). Therefore, a major emerging area for research in poultry nutrition is the preparation of feeds before ingestion to increase the value of the feed (Peisker, 2006). There are many possible strategies to improve feed processing techniques; however, the cost of each strategy must be carefully weighed against achievable performance improvements in the target animal (Behnke, 1996).

The technology of poultry feed processing involves a wide range of thermal treatments including extrusion, expansion, conditioning and pelleting. Although pelleting represents the greatest energy expenditure in the feed manufacturing process, when the cost-benefit is considered, pelleting is cost effective and the most widely used thermal processing method. The main aim of pelleting is to agglomerate smaller feed particles by the use of mechanical pressure, moisture and heat (Peisker, 2006). A major step in the pelleting process is conditioning of mash prior to pelleting (Skoch *et al*., 1981), which is generally accomplished by adding steam to the mash feed to be pelleted.

Offering feed to poultry in pellet form enhances the economics of production by improving feed efficiency and growth performance in broilers (Behnke and Beyer, 2002). These improvements are attributed to decreased feed wastage, higher bulk and nutrient density, no selective feeding, decreased time and energy spent for eating, decreased ingredient segregation, destruction of feed-borne pathogens, thermal modification of starch and protein, improved palatability and inactivation of enzyme inhibitors (Behnke, 1994; Jensen, 2000; Peisker, 2006).

Pelleting may result in poor broiler performance if the appropriate temperature is not used during steam-conditioning. Loss of lysine and arginine due to Maillard complexing with sugars, retrogradation of starch into enzyme-resistant starch which causes loss of available energy, increased viscosity due to solubilisation of non-starch

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polysaccharides (NSP) and loss of heat-labile vitamins, exogenous enzymes and crystalline amino acids, are some of the known negative effects of high conditioning temperatures (Creswell and Bedford, 2006).

Despite the practical importance, studies examining the effects of conditioning temperature on nutrient digestibility, broiler performance and gut measurements are limited. Consequently, more research is warranted to further elucidate the influence of conditioning temperature on nutritional and physical quality of feed, and bird performance.

This thesis consists of nine chapters. The first two chapters present the framework for the experimental research, with Chapter 1 giving a general introduction to the thesis. Chapter 2 reviews the principles of feed processing technology and the research conducted into the pelleting process and its effects on feed components. Chapter 2 also highlights the various issues relating to the effect of pelleting process on bird performance and provides a brief discussion on some possible manipulations to manufacture high physical quality pellets. The general methods employed in the experimental work reported in this thesis are described in Chapter 3. Chapters 4 through 8 present the experimental work of this thesis. Each chapter includes an abstract, introduction, materials and methods, results, discussion and conclusions. The objectives of the experiments conducted in this thesis include,

1. To investigate the influence of conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed maize- and wheat-based diets (Chapter 4).

2. To investigate the influence of conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed maize- and sorghum-based diets (Chapter 5).

3. To investigate the influence of feed form and conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed wheat-based diets (Chapter 6).

4. To investigate the effect of improved pellet quality from the addition of a pellet binder or/and moisture to a wheat-based diet conditioned at different temperatures on performance and nutrient utilisation of broilers (Chapter 7).

5. To investigate the influence of pellet diameter and length on the quality of pellets and, performance, nutrient utilisation and digestive tract development of broilers fed wheat-based diets (Chapter 8).

Chapter 9 is a general discussion of the experimental results. This chapter addresses the major findings and draws some conclusions from the data generated.

CHAPTER 2

Review of Literature

2.1.   Feed processing technology

2.1.1.   Introduction

Feed processing involves any treatment which animal feed undergoes prior to consumption (Maier and Bakker-Arkema, 1992). Feed processing has witnessed substantial improvements, from a hand scoop shovel as the basic mixing tool (Schoeff *et al*., 2005) to various processing operations which are currently performed utilising modern feed technology (Deyoe, 1976). The widely used processing operations in feed manufacturing plants are: receiving the raw materials, grinding or particle size reduction, proportioning or batching, mixing, heating or thermal treatment, packaging, warehousing and loading. Each of these operations can have either a positive or negative impact on feed quality and will influence the animal performance (Behnke and Beyer, 2002). The aim of this section is to provide an overview of the common feed processing operations with particular emphasis on thermal treatments, especially the pelleting process.

2.1.2.   Receipt of the raw materials

This process includes the actual receiving of feed ingredients at the receiving area and placing the ingredients at their destinations (McCarty, 2005). It also encompasses the scheduling, weighing and sampling of ingredients, unloading the ingredients into receiving system, cleaning and scalping the grains to remove undesired materials, quality-control analyses and making claims relating to weight and quality of materials received (Rempe, 1985; McCarty, 2005).

Ingredients received in the feed manufacturing plants can be classified in one of the following groups (McCarty, 2005):

I.   Unprocessed grains such as maize, wheat, barley and any other grains. This group usually accounts for a large portion of the received ingredients and requires further processing prior to being included to the feed.

II.   Pellets and processed ingredients in bulk such as alfalfa and gluten feed. These ingredients also need further processing before inclusion to the feed.

III.   Soft bulk ingredients such as flour milling co-products and protein meals.

IV.   Fluffy and light-density products such as whole cotton seed or cotton seed hulls.

V.   Heavy materials such as inorganic phosphates, limestone, oyster shell and salt.

VI.   Liquid ingredients such as molasses, oils and choline chloride.

VII.   Micro-ingredients which make up a very small portion of incoming ingredients.

2.1.3.   Grinding (Particle size reduction)

The majority of feed ingredients, particularly the coarse cereal grains, require some degree of grinding prior to mixing into a diet (Koch, 1996). Grinding or particle size reduction modifies the physical characteristics of ingredients to increase surface area for higher nutrient digestion, improve blending ability and homogeneity of the mixed feed, decrease segregation and mixing problems, and facilitate further processes such as extrusion or pelleting (Behnke, 1996; Koch, 1996). In broiler industry wherein the majority of the feed is pelleted, the particle size reduction is the second greatest energy cost after that of pelleting (Reece *et al*., 1985).

The initial particle size reduction of cereal grains begins by disrupting the hard outer protective layer of the seed (hull), exposing the interior (Figure 2.1; Koch, 1996).
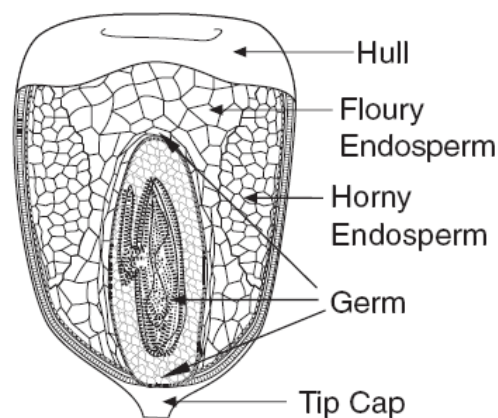
Figure 2.1. Maize kernel (Source: Koch, 1996)

Particle size reduction enhances access of nutritional components such as starch and protein to digestive enzymes through increasing the number of particles and the surface area per unit volume (Koch, 1996; Goodband *et al.*, 2002). However, excessive size reduction increases energy input and cost and may result in dust problems, feed bridging and unnecessary wear on mechanical equipments (Koch, 1996; Goodband *et al.*, 2002).

The most common pieces of equipment used to reduce the particle size of the feed ingredients are hammer and roller mills (Figure 2.2). In hammer mills, particle size reduction is accomplished by impacting slow moving ingredients, such as cereal grain, with a set of hammers moving at high speed. Hammer mills generally produce spherical shaped particles with a polished surface. The size distribution of particles produced in a hammer mill varies widely around the geometric mean, with some large- and many small-sized particles (Koch, 1996). In roller mills, size reduction is accomplished through a compression force between the rotating roll pairs, and produces more uniform particle size distribution with a low proportion of fine materials. The shape of the particles produced is more irregular, cubic and rectangular (Koch, 1996).
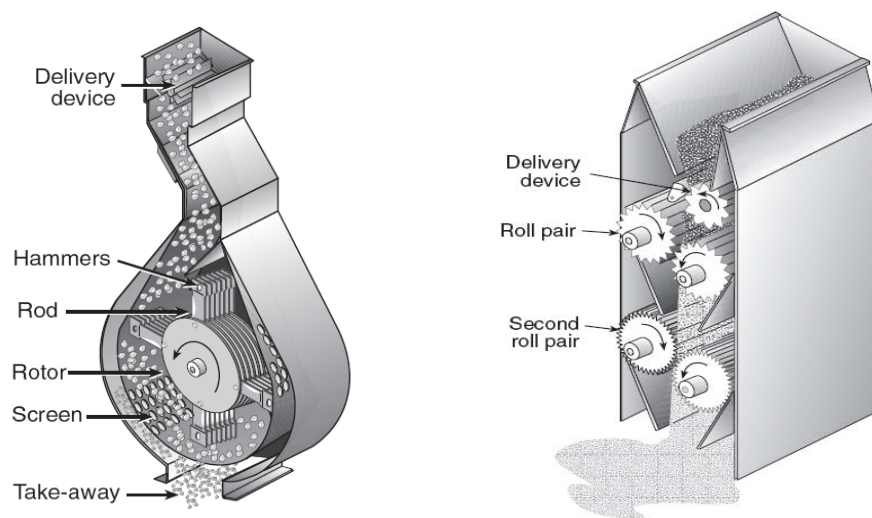
Figure 2.2. Hammer mill and roller mill (Source: Koch, 1996)

2.1.4.   Proportioning and Mixing

Proportioning and mixing are considered as the most important steps in the feed manufacturing process and involve the funnel through which all ingredients of specific amounts must pass to be blended to make a premix, supplement, or complete feed (Fairchild and Moorehead, 2005). Proportioning can be accomplished using two basic methods, namely, cyclical (batch) and continuous. In a cyclical or batching system ingredients are individually weighed into batches, whereas continuous system involves concurrently and continuously adding of the ingredients (Fairchild and Moorehead, 2005).

To achieve a homogeneous mixture of proportioned ingredients, proper mixing of the ingredients is required (Martin, 2005). Since nutrient uniformity in a complete balanced feed is essential to optimise nutrient utilisation and animal performance (Behnke and Beyer, 2002), mixing is thought to be one of the most critical operations in feed manufacturing (Behnke, 1996; Behnke and Beyer, 2002). Problems in providing a homogeneous mixture of ingredients through inappropriate mixing can lead to poor animal performance (Behnke, 1996).

Continuous and batch mixing systems can be used to combine feed ingredients, but batch systems are preferred by most feed manufacturers (Martin, 2005). Batch systems proportion the ingredients according to a specific formula and mix them in discreet batches (Martin, 2005). Ribbon mixers, paddle mixers, twin-shaft mixers and drum mixers are different types of mixers used in batch mixing systems (Martin, 2005).

2.1.5.   Thermal treatments

2.1.5.1.   Extrusion cooking

Extrusion is a shaping operation which is accomplished by forcing a plastic or dough-like material through a die (Riaz, 2000). Extrusion was first commercially used in the 1920's and 1930's to produce pasta from wheat flour (Jones *et al*., 1995). Extrusion may include a number of functions such as agglomeration, degassing and dehydration of ingredients, starch gelatinisation, protein denaturation, grinding, mixing, homogenisation, pasteurisation and sterilisation, expansion, shaping, shearing, texture alteration and thermal cooking (Riaz, 2000). Since extrusion is a high-temperature/short-time (HT/ST) thermal treatment, it minimises nutrients degradation while has the ability to inactivate enzyme inhibitors,

destroy pathogenic microorganisms and improve starch (by gelatinising) and protein (by denaturing) digestibility (Riaz, 2000).

Jones *et al.* (1995) reported that broilers fed crumbled, extruded starter diets gained more weight than birds fed crumbled, pelleted diets. However, when diets were not crumbled (i.e. grower and finisher diets), birds fed extruded diets had body weights lower than those fed pelleted diets. As extruded diets weighed less per unit volume than pelleted diets, they suggested that the reduced density of extruded diets may account for the reduced body weights observed. They observed some protein and amino acid destruction due to extrusion process and suggested that extruded diets should be formulated at slightly higher nutrient density to compensate for the loss of nutrient availability. Due to the very high capital investment costs, extrusion has not been used commonly in commercial poultry feed production (Jones *et al.*, 1995).

2.1.5.2. Expansion (Thermal pressure conditioning)

Expansion describes the formation of puffed and low-density materials from a hot and gelatinised mass of starch which is forced under pressure through a restricted opening into the atmosphere (Camire *et al*., 1990). During the expansion process, which is referred to as a HT/ST process, mash temperatures as high as 126.7 ℃ can be reached by the transfer of mechanical energy to thermal energy (Fancher *et al*., 1996). Expanders can be mounted directly after the mixer and before the pelleter; in this case, the need for a pelleter is becoming obsolete (Armstrong, 1993).

Expanders increase starch gelatinisation, soluble fibre, fat stability and metabolisable energy due to more available fat and starch and decrease feed pathogens (Armstrong, 1993; Peisker, 1994). Expanders also increase the flexibility of diet formulation and allow the use of high dietary levels of feed ingredients, such as oil, molasses and milling by-products, which normally reduce pellet quality while eliminating the need for binders to improve pellet quality (Armstrong, 1993; Fancher *et al*., 1996).

2.1.5.3. Pelleting process

Pellets are defined as "agglomeration of individual ground ingredients, or mixture of such ingredients, commonly used for animal feeds" (Anonymous, 1985; ASAE, 1997). Thus, the pelleting process may be defined as "the agglomeration of small particles into larger

particles by the means of a mechanical process in combination with moisture, heat, and pressure" (Falk, 1985).

Over the years, the pelleting process has evolved from an art to a science (Falk, 1985), and become an integral process to the modern feed manufacturing technology due to the fact that the cost of pelleting is offset by improved animal performance (Behnke, 1996).

A typical flow diagram of the pelleting process is shown in Figure 2.3 (Fairfield *et al.*, 2005). The general process involves passing a feed mash from the mash bin into the feeder and conditioner. After steam injection to the feed inside the conditioner, the conditioned mash flows into the pelleting chamber. Pellets are formed by passing the hot mash through a metal die and sent to the cooler. As the hot pellets pass through the cooler, they are cooled by air movement from a fan. Fines entrained in the cooler are separated in a collector and returned to the pellet chamber to be reprocessed. Cool and dry pellets are discharged from the cooler and pass around or through the crumbler, depending on the product being manufactured. The product is screened and undesired crumbles or pellets are returned to the pellet mill for reprocessing. Acceptable product goes to the finished feed bins (Fairfield *et al.*, 2005).
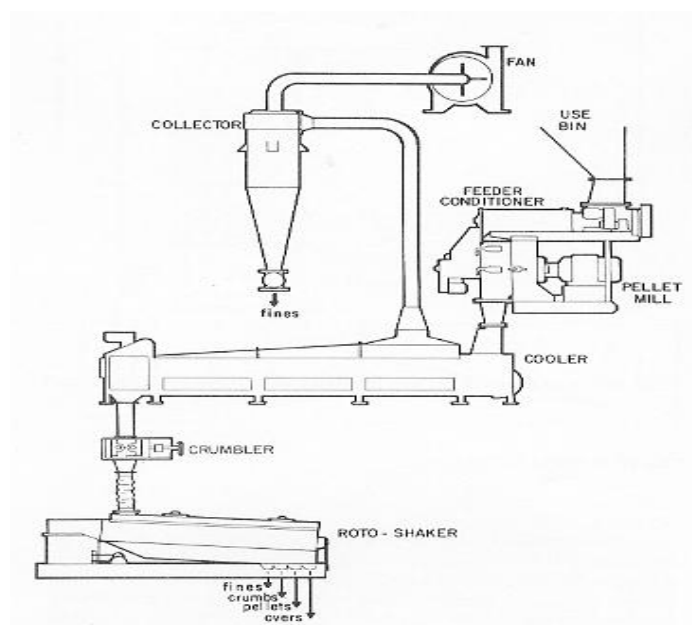
Figure 2.3. Typical flow diagram for pelleting system (Source: Fairfield *et al.*, 2005)

I.   Steam conditioning

Steam-conditioning of mash prior to pelleting is a major step in the pelleting process (Skoch *et al*., 1981), which is generally accomplished by adding steam to the mash feed to be pelleted. To optimise the conditioning process, the proper balance of heat and moisture must be obtained (Wellin, 1976; Smallman, 1996). Steam has the ability to provide the proper balance of heat and moisture and, because it is relatively inexpensive, easy to introduce and easy to control, it has presented itself as an important component in pelleting process (Wellin, 1976; Behnke and Beyer, 2002).

It is generally assumed that at 0 ℃ water contains no heat energy (enthalpy). The specific enthalpy of water is approximately 4.19 kJ per kg per ℃ (kJ/kg ℃). This means that to raise the temperature of 1 kg of water by 1 ℃, 4.19 kJ, and from 0 to 100 ℃, $100 \times 4.19 = 419$ kJ will be needed, which the latter refers to the enthalpy of water at 100 ℃ (the heat content). When water is cooled down from 100 ℃ to 0 ℃, 419 kJ will be released (or an equivalent of the temperature difference $\times$ 4.19 kJ). At atmospheric pressure (100 kPa), when the water temperature reaches 100 ℃, the heat being added will no longer increase its temperature, because the water will evaporate into steam. This change of state requires a considerable input of heat energy (enthalpy) of evaporation. To change water of 100 ℃ into steam of 100 ℃, the enthalpy of evaporation is 2257 kJ/kg. So the heat content of steam or enthalpy of steam (at atmospheric pressure) is equal to the enthalpy of water plus the enthalpy of evaporation or $419 + 2257 = 2676$ kJ/kg. This emphasises the considerable amount of heat contained in steam, which is why steam is such a useful heating medium (Smith, 2003).

The objective of heat injection during conditioning is to improve binding characteristics through gelatinisation of starch (Wellin, 1976; Reimer and Beggs, 1993; Smallman, 1996) and the plasticising of proteins (Smallman, 1996). From the feed physical quality point of view, these chemical changes produce sticky and clinging substances which bond to the less reactive materials and hold the mass together (Smallman, 1996). Other benefits of heat are to eliminate feed-borne pathogens and to promote drying of pellets in the cooler (Reimer and Beggs, 1993). Injected moisture associated with the steam has a profound effect on pelleting and is required for starch gelatinisation and to form a cohesive bridge between feed particles (Smallman, 1996). Moisture also soaks into absorbent raw

materials, softening them so they readily mould into shape (Smallman, 1996). Moreover, due to the lubricative effect of moisture, it can reduce the frictional force generated between the feed and die holes (Reimer and Beggs, 1993; Smallman, 1996).

According to Skoch *et al*. (1981), additional energy used for steam-conditioning may be justified by the advantages which it offers to the feed processing. They reported that steam-conditioning at 65 and 78 ℃ increased the pellet production rate by 250 and 275%, respectively, above dry-conditioning (21 ℃). The production rates were 655, 1636 and 1800 kg/h for dry, 65 and 78 ℃ treatments, respectively. Pellet durability index (PDI) was also improved by steam-conditioning (90.6 and 93.8% in steam-conditioning at 65 and 78 ℃, respectively, compared to 69.5% in dry-conditioning).

To have an efficient pelleting operation, an adequate supply of high quality steam is imperative (Cutlip *et al*., 2008). Dozier (2003) defined steam quality as "the amount of vapour divided by the mixture of free water and vapour". He speculated that high quality steam, 97% vapour, increases conditioning temperature by 13.9 ℃ for every 10 g/kg moisture added through the steam. However, low quality steam, 80% vapour, may only provide 11.1 ℃ rises in temperature for the same amount of moisture addition.

II. Pelleting

Pellets can be manufactured in different shapes and sizes. The piece of equipment that is responsible for the various forms of pellets is the die (Ziggers, 2003). After steam-conditioning, the mash feed needs to be agglomerated. The pelleting process involves forcing the softened feed ingredients through a set of holes in a metal die by pressure exerted by the pellet rollers (Wellin, 1976; Ziggers, 2003). Pellet die holes may be round or square, tapered or non-tapered and can have diameters ranging from 1 mm to over 20 mm depending on the material to be pelleted or the animal species to be fed (Ziggers, 2003). As the pellet die rotates, feed is pressed between the die liner wall and a set of roller(s). Pellets with desired lengths are cut off by an assembly of knives mounted on the inside of the die casting (Ziggers, 2003).

III. Cooling

Pellets leave the mill at temperatures as high as 88 ℃ and as much as 150-170 g/kg moisture. The temperature must be reduced to about 8 ℃ above ambient temperature and

the moisture to 100-120 g/kg (Robinson, 1976). A stream of ambient air passed through the bed of hot pellets removes heat and moisture from the pellets (Robinson, 1976). Assuming the ambient air has a lower temperature than the pellets and is not saturated with moisture, the air will reduce the temperature and evaporate the excess moisture (Wellin, 1976).

IV.   Pellet crumbling

Since producing pellets through dies with very small holes is not economical, larger pellets are produced and then processed through a pellet crumbler to reduce pellet size (Wellin, 1976). A pellet crumbler is a roller mill which has two cast-hardened rolls that are corrugated (Fairfield *et al*., 2005). Pellet crumbler is used to break pellets into smaller particles, for special feeding applications, by a shearing action between the fast and slow rolls (Figure 2.4; Fairfield *et al*., 2005).
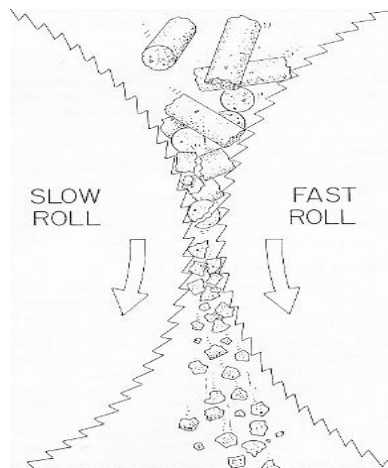
Figure 2.4. Side view of pellet crumbler rolls (Source: Fairfield *et al*., 2005)

V.   Pellet screening

Cooled pellets or crumbles are usually screened prior to packaging to remove particles with undesired size (Fairfield *et al*., 2005). Figure 2.5 shows a pellet screener with two screens. The overs (oversized particles) and the fines represent particles that need to be reprocessed. The mid-cut pellets are considered, in this example, as acceptable product (Fairfield *et al*., 2005).
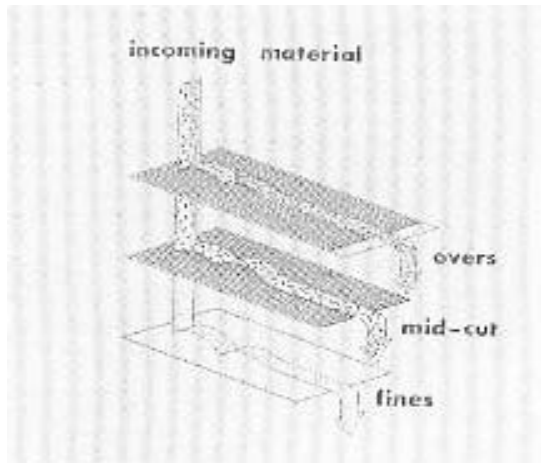
Figure 2.5. Pellet screener (Source: Fairfield *et al*., 2005)

2.1.6. Packaging, Warehousing and Loading

The packaging process includes weighing the complete feed to the each bag, closing the bag, tagging, coding and palletising the bag and moving the bagged feed to the warehouse storage (Williamson, 2005). The warehousing and loading operations begin with the transportation of the complete packed feed from the packaging line to the warehouse or the final transportation vehicle, and end as the vehicles are loaded, closed and sealed (Yoder, 2005).

2.1.7. Conclusions

- Ever-increasing cost of feed ingredients underlines the need for continuous improvements in feed processing technology to improve the feeding value and to reduce feed costs.
- To achieve the benefits which feed processing technology can offer to the broiler industry, the importance of each processing step and possible improvements must be carefully examined.

2.2. Effect of pelleting process on feed components

2.2.1. Introduction

Most of the operations in the compound feed manufacturing process impact on the nutritive value of the complete feed. The nutritive effect is exerted mainly through nutrient digestibility and energy utilisation (Peisker, 2006).

It has been observed that pelleting may cause the formation of starch that is not susceptible to enzymatic hydrolysis (resistant starch). Losses of heat-labile vitamins, exogenous enzymes and crystalline amino acids, loss of lysine due to Maillard complexing with sugars and perhaps formation of indigestible starch-protein and starch-lipid complexes are other known negative effects of severe pelleting process. In the case of diets based on viscous cereals (wheat and barley), increased feed viscosity due to greater solubilisation of fibre may occur at higher conditioning temperatures. This impedes nutrient absorption in the small intestine and also increases the amount of substrate available for bacterial growth in the hind gut (Creswell and Bedford, 2006).

2.2.2. Starch

Starch in cereals is the most abundant energy source (70 to 80% of most cereal grains) for most domestic animals (Rooney and Pflugfelder, 1986; Svihus *et al*., 2005). Starch occurs naturally as water-insoluble granules (Parker and Ring, 2001) and has unique chemical and physical characteristics, in addition to a good nutritional quality (Di Paola *et al*., 2003). Starch is a glucan composed of two main polysaccharides, amylose and amylopectin. Both polysaccharides are based on chains of 1→4 linked α-D-glucose but whereas amylose is essentially linear, amylopectin is highly branched containing on average one branch point which is 1→4→6 linked for every 20-25 straight chain residues (Rooney and Pflugfelder, 1986; Parker and Ring, 2001; Svihus *et al*., 2005). While amylopectin represents up to 70-80% of normal starches, amylose comprises the balance 20 to 30% (Rooney and Pflugfelder, 1986).

2.2.2.1. Starch gelatinisation

Starch granules are water-insoluble but swell if heated in an aqueous medium. Initially, the swelling is reversible, but when a certain temperature is reached, the swelling becomes irreversible and the structure of the granule is altered significantly. The process is called "gelatinisation" and the temperature at which gelatinisation occurs is referred to as "gelatinisation temperature". At this temperature, material from the granule diffuses into the water (Lund, 1984). The polysaccharide molecules inside native starch granules are inaccessible to high molecular weight enzymes. Gelatinisation opens the granule's structure and these enzymes can enter the starch granules (Seib, 1971), markedly increasing susceptibility for amylolytic degradation (Rooney and Pflugfelder, 1986).

Di Paola *et al.* (2003) investigated the changes in the morphology of granules throughout the gelatinisation range. In this study, aqueous maize starch suspensions were treated to different temperatures, ranging from 25 ℃ (control without gelatinisation) to 85 ℃ to obtain different degrees of gelatinisation. The native maize starch granules had a characteristic form and size, showing birefringence when observed under polarised light microscopy (Figure 2.6.a, control). From 55 ℃ onwards, an increase in the size of some granules was observed (Figure 2.6.b), and above 55 ℃, loss of birefringence of some granules (Figure 2.6.c), loss of integrity and granular disruption (Figures 2.6.d and 2.6.e) was observed.
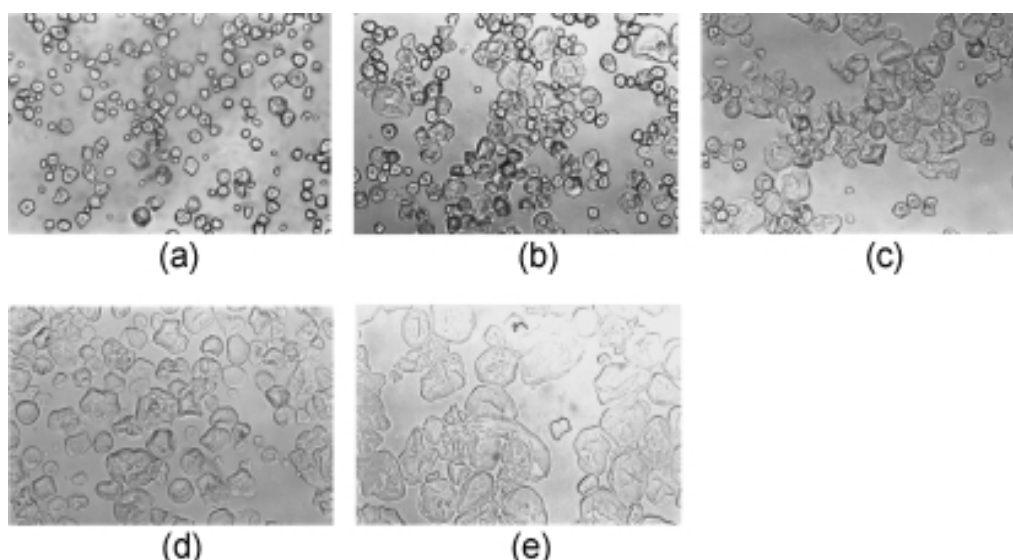
Figure 2.6. Changes in the morphology of maize starch granules at different temperatures
(a) 25 ℃; (b) 60 ℃; (c) 65 ℃; (d) 67 ℃; (e) 85 ℃ (Source: Di Paola *et al.*, 2003)

Presence of water is a prerequisite to initiate starch gelatinisation (Camire *et al.*, 1990; Thomas *et al.*, 1998); however, mechanical processes like grinding, crushing, and milling also cause gelatinisation to a certain extent (Camire *et al.*, 1990). According to Eliasson and Gudmundsson (1996), starch gelatinisation occurs at temperatures ranging from 45 to 90 ℃, depending on starch source and moisture content. At excess water content, most starches will gelatinise at a temperature between 50 and 70 ℃ (Donald, 2001). On the other hand, with limited water contents (below approximately 400 g/kg; Donald, 2001) the gelatinisation temperature will increase (Camire *et al.*, 1990; Donald, 2001; Parker and Ring, 2001) and be inversely related to water content (Donald, 2001). It has also been known that during the gelatinisation process, those starch granules which are gelatinised first reduce the amount of water available for gelatinisation of other granules (Liu *et al.*, 1991).

Lund (1984) postulated that a water to starch ratio of 0.3:1 is generally needed for gelatinisation and for complete starch gelatinisation, a ratio of about 1.5:1 would be required. Since only around 30 g/kg moisture is added to the feed during the steam-conditioning process, water is considered as a limiting factor to fully gelatinise starch (Thomas *et al.*, 1998).

According to Lund (1984), starches from different cereals have different gelatinisation characteristics. Wheat starch has a low gelatinisation temperature (52-65 ℃, differential scanning calorimetry [DSC] method) and the temperature is higher for maize (65-70.6 ℃, DSC method). Furthermore, gelatinisation heat depends on starch source. Gelatinisation heat of wheat starch (10.05 joules/g) is lower than maize (13.82 joules/g). This means for every gram of wheat and maize starch to be gelatinised, 10.05 and 13.82 joules of heat are required, respectively (Lund, 1984). Taylor and Dewar (2001) reported that the temperature at which sorghum starch is gelatinised (68-78 ℃) exceeds that of maize (62-72 ℃), implying that sorghum-based diets may need higher conditioning temperatures than maize-based diets. High-amylose content cereals are more resistant to gelatinisation during processing than those with normal and high amylopectin cereals (Svihus *et al.*, 2005).

Research data on starch gelatinisation caused by steam-conditioning and pelleting are inconsistent. According to Pfost (1971), a small portion (10 to 20%) of starch is

gelatinised during conventional pelleting process. This gelatinisation may occur during steam-conditioning but probably occurs as feed is pressed between the pellet roller and the die. Heffner and Pfost (1973) pelleted a layer diet after steam-conditioning at 80 ℃ and reported increased gelatinisation values, and while some occurred in the conditioner chamber, most was caused by the pellet die. Skoch *et al*. (1981; 1983a,b) compared dry- and steam-conditioning, and reported more starch damage during dry-pelleting than steam-pelleting.

Stevens (1987) correlated the temperature rise at the pellet die to the extent of starch gelatinisation. He investigated the effect of conditioning temperatures of 23, 43, 63 and 80 ℃ on the degree of starch gelatinisation in 100% maize diets and showed that, in the outer portion (2 mm thick) of the pellet, the greatest amount of gelatinisation (58.3%) was observed when the diet was dry-pelleted (at 23 ℃ conditioning temperature) and the least extent of gelatinisation (25.9%) occurred when the diet was steam-conditioned at 80 ℃ prior to pelleting. He also reported that increasing the conditioning temperature from 23 to 80 ℃ decreased gelatinisation degree of whole pellets from 41.9 to 28%. The higher extent of gelatinisation in the outer portion of the pellet compared to the whole pellet (58.3 vs. 41.9%) when the diet was dry-pelleted (23 ℃) indicated that frictional heat and mechanical shear generated next to the surface of the die hole was responsible for a substantial amount of gelatinisation. At 80 ℃, starch gelatinisation was uniform throughout the entire pellet. A tendency for higher extent of starch gelatinisation on the surface of pellets has also been reported by Zimonja *et al*. (2008).

Recent research has shown a low extent of starch gelatinisation in pelleted diets (Moritz *et al*., 2002; 2003; Svihus *et al*., 2004; Zimonja *et al*., 2007; 2008), due primarily to the limited amount of moisture and moderate temperature applied during conventional pelleting process (Zimonja *et al*., 2007). However, majority of gelatinisation occurs as the feed passes through pelleting chamber, and not during conditioning, most likely due to mechanical shearing generated in the pellet die (Pfost, 1971; Heffner and Pfost, 1973; Zimonja *et al*., 2008).

Moritz *et al*. (2001; 2002) reported that increasing the water to starch ratio in a maize-soy broiler diet prior to pelleting significantly increased starch gelatinisation. In one study (Moritz *et al*., 2002), adding 50 g/kg moisture to the diet increased starch

gelatinisation from 15.8 to 29.6% in an NRC-recommended diet and from 5.5 to 12.2% in a modified diet (5% increase in all nutrients compared with initial diet). In contrast, Moritz *et al*. (2003) reported that moisture addition to a maize-soy broiler diet, independent of dietary energy density, decreased the extent of starch gelatinisation in the pellets. Gelatinised starch content in the NRC-recommended diet decreased from 18.4% (control diet without moisture addition) to 10.6 and 6.1% due to addition of 25 and 50 g/kg water, respectively. Starch gelatinisation reduction in the modified low-energy diet (5% less than NRC-recommendations) was observed from 24.5% (control diet without moisture addition) to 18.1 and 14.6% due to addition of 25 and 50 g/kg water, respectively. It was suggested that lubricating effects of added moisture could decrease the die hole frictional heat, and reduced the gelatinisation extent.

2.2.2.2. Starch retrogradation

According to Englyst *et al*. (1992), starch may be categorised into three groups based on *in vitro* starch digestion. First are rapidly digestible starches (RDS) which include gelatinised starch for instance by cooking. Slowly digestible starches (SDS), which include native starch granules from many cereals, are the second category and finally resistant starches (RS) that are resistant to digestion. The resistant starch category is considered to encompass three subcategories, namely, RS1, RS2 and RS3 (Brown, 1996). The first category (RS1) refers to inaccessible starch granules in whole or partially ground starch-containing ingredients. The action of digestive enzymes can be delayed or even prevented by the particle size or composition of these ingredients. The second category of resistant starch (RS2) includes native starch granules in which the degree of resistance appears to be related to the granule structure and its susceptibility to gelatinisation. The third category of resistant starch (RS3) reflects retrograded starch during processing.

Upon cooling a gelatinised starch-water mixture to room temperature, crystallisation, commonly defined as starch retrogradation, is favoured (Parker and Ring, 2001). Retrogradation is the reassociation of starch molecules separated during gelatinisation. This phenomenon may be viewed as the opposite of gelatinisation and may decrease digestibility of starch (Rooney and Pflugfelder, 1986). It has been suggested by Asp *et al*. (1987) that as indigestible starch fractions (RS) behave physiologically like NSP;

they should be included in the dietary fibre component. According to Zimonja *et al*. (2008), insoluble fibre is composed of cellulose and other insoluble NSP, lignin, resistant starch, tannin and cutins.

Eerlingen *et al*. (1994) observed a level of 420 g/kg resistant starch in waxy maize starch after storing for 24 h at 6 ºC followed by 29 d at 40 ºC. They also showed a reduction in the starch susceptibility to pancreatic α-amylase and amyloglucosidase by increasing the retrogradation extent.

2.2.3. Protein

Proteins are heat-sensitive structures (Peisker, 1994). Upon exposure to moist heat the physical structure of the proteins usually changes, causing substantial alterations in reactivity, functional and nutritional properties (Voragen *et al*., 1995).

2.2.3.1. Protein denaturation

Camire *et al*. (1990) defined protein denaturation as any changes in the conformation of a protein which do not involve the breaking of peptide bonds. Most proteins undergo structural unfolding followed by aggregation when exposed to moist heat or shear. Unfolding is usually a reversible process and if the thermo-mechanical treatment is stopped before aggregation begins, the protein can return to its native conformation. If more heat or shear is added, non-covalent interactions which contribute to the stabilisation of the three-dimensional structure (secondary, tertiary and quaternary structures) of proteins will be broken, resulting in irreversible protein denaturation. If thermo-mechanical treatment continues, covalent bonds such as disulphide bonds will also break (Voragen *et al*., 1995). While temperature, moisture content and shear forces are considered as the main factors influencing the denaturation process, residence time, pH and the presence of other components like lipids and carbohydrates are, to a lesser extent, of importance (Voragen *et al*., 1995). Since feed processing involves a combination of shear, heat, residence time and water, it may result to partial denaturation of the proteins in the feed (Thomas *et al*., 1998), by which their solubility generally decreases and their digestibility increases (Voragen *et al*., 1995). In general, heating improves the digestibility of proteins by inactivating enzyme inhibitors and denaturing the protein which may expose new sites for enzyme attack

(Camire *et al*., 1990). Upon cooling, proteins reassociate and bonds can be established between the different particles (Thomas *et al*., 1998). Wood (1987) suggested that binding properties of wheat, which are due to hydration and partial denaturation of the protein (gluten) fraction during feed processing, may positively affect physical quality of pellet feeds.

2.2.3.2. Maillard reaction

Feed processing may result in the so-called Maillard reaction, in which many feed constituents can participate (Thomas *et al*., 1998). High temperatures and low moisture contents used in thermo-mechanical treatments are known to favour the Maillard reaction (Voragen *et al*., 1995). In the presence of water and heat, free aldehyde groups from reducing sugars, such as glucose, fructose, lactose, or maltose, and free amino groups from amino acids, the epsilon-amino group of lysine in particular, may combine to form melanoides that darken the product and also increase viscosity (Voragen *et al*., 1995; Thomas *et al*., 1998). This reaction, known as nonenzymatic browning, has important nutritional and functional consequences (Camire *et al*., 1990). This is positive for pellet-binding; however, Maillard products may impair nutritional value of the feed due to reduced utilisation of proteins and perhaps carbohydrates (Pickford, 1992; Hendriks *et al*., 1994; Thomas *et al*., 1998). Since lysine is the limiting amino acid for protein quality in cereals, the loss of available lysine from these ingredients is of major consequence. Starch and non-reducing sugars such as sucrose may be hydrolysed during processing, especially extrusion, to form reducing sugars and result in lysine loss (Camire *et al*., 1990).

Hussar and Robblee (1962) reported that pelleting to a maximum temperature of 72 ºC had no effect on the lysine content in wheat, oats and barley grains. It was suggested that the temperature to which feed is subjected during pelleting at 72 ºC is probably insufficient to damage the lysine.

2.2.4. Non-starch polysaccharides (NSP)

The cell wall of cereals is comprised primarily of complex carbohydrates, known as non-starch polysaccharides, which exhibit some anti-nutritive characteristics (Choct and Annison, 1992). It is known that a proportion of NSP is of high molecular weight, which

dissolves in the intestinal tract, leading to an increase in the viscosity of the gut contents (Silversides and Bedford, 1999; Bedford, 2002). A relatively higher intestinal viscosity has a number of negative effects on the nutritive value of poultry diets. These effects include reduced rate of feed passage (reduced feed intake), litter quality problems, increased water consumption, increased proliferation of bacteria in the gastrointestinal tract (GIT) and changes in the GIT environment (Choct and Annison, 1992; Silversides and Bedford, 1999; Bedford, 2002).

Cowieson *et al*. (2005b) reported a significantly higher dietary viscosity for pelleted wheat-based diet than that of the mash diet when no xylanase was added, whereas the addition of xylanase reduced the viscosity to that of the mash diet. The increases in viscosity from mash to pellet diets conditioned at 80, 85 and 90 ºC were 53, 116 and 121%, respectively, for the starter diet and 57, 83 and 76%, respectively, for the finisher diet. Increased diet viscosity was attributed to an increased release of NSP. They also suggested that the negative effect of conditioning temperature on viscosity is primarily responsible for the poorer performance of birds fed on high-temperature conditioned diets. Their conclusion was supported by the fact that the addition of exogenous xylanase markedly improved the performance of birds fed diets with higher viscosity, but failed to improve the performance of those fed the diet that was pelleted at the lowest temperature and had the lowest viscosity. These results are in agreement with those of Samarasinghe *et al*. (2000) who reported higher dietary viscosity due to high conditioning temperatures (75 and 90 ºC) during pelleting a barley-maize-soy diet compared to 60 ºC. Although, supplemental enzyme reduced the dietary viscosity at all three temperatures, its effect was greater at higher temperatures (11, 14 and 17% reduction in viscosity of the diets conditioned at 60, 75 and 90 ºC, respectively). Enzyme addition increased the weight gain of broilers by 11.1% at 90 ºC, but had no effect at low temperatures.

Creswell and Bedford (2006) reported an increased diet viscosity following increasing the conditioning temperature. In their study, viscosity of the diet was increased from 6.5 cPs at 65 ºC to 7.0, 8.5, 9.3 and 15.2 cPs at conditioning temperatures of 75, 85, 95 and 105 ºC, respectively, due likely to xylan solubilisation and starch gelatinisation.

It has been shown that heating of diets can increase intestinal viscosity presumably due to increased solubility of NSP (Nissinen, 1994; Silversides and Bedford 1999) as well

as the destruction of endogenous enzymes of cereals (Silversides and Bedford 1999; Cowieson *et al*., 2005b). Zimonja *et al*. (2008) observed a dramatic increase in digesta viscosity of broilers when diets were steam-pelleted at 90 ºC. Increased viscosity was associated with increased water content and stickiness of excreta.

Viscosity is a composite of soluble carbohydrate concentration and more importantly the degree of polymerisation or the molecular weight of carbohydrate (Izydorczyk and Biliaderis, 1992; Cowieson *et al*., 2005b). The viscosity of a solution can be extremely high, even if the solution contains a low concentration of soluble polysaccharides, if the soluble polysaccharides are of a sufficiently high molecular weight (Cowieson *et al*., 2005b). Izydorczyk and Biliaderis (1992) indicated that the molecular weight of wheat arabinoxylans is an important determinant of their physical properties in an aqueous environment. In their study, high molecular weight arabinoxylans exhibited a great potential to form cross-linked hydrogels with large water-holding capacity. As increasing conditioning temperature can destroy the activity of diet endogenous (Silversides and Bedford 1999; Cowieson *et al*., 2005b) and microbial enzymes (Cowieson *et al*., 2005b) which degrade xylan (Silversides and Bedford 1999; Cowieson *et al*., 2005b), thus contributes to an increase in molecular weight (i.e. less depolymerisation of carbohydrates). Therefore, it is possible to have increased viscosity in diets conditioned at higher temperatures regardless of soluble carbohydrate concentration.

2.2.5. Energy

Energy value of a feed can be expressed in several ways. Gross energy (GE) is the energy released as heat when a substance is completely oxidised to carbon dioxide and water (NRC, 1994). The GE of a feed is not necessarily all available to the bird. A portion of feed energy is undigested and voided in the faeces. The GE of the feed consumed minus the GE of the faeces is apparent digestible energy (ADE) (Sibbald, 1980; NRC, 1994). Birds excrete faeces and urine together and it is difficult to separate the faecal energy. Metabolisable energy (ME) represents the GE of the feed minus the GE of the excreta (faeces + urine). On the other hand, digestion and nutrient metabolism produce heat, known as heat increment, which has no value to the bird except in cold environments. Net energy (NE) is ME minus the energy lost as the heat increment (Sibbald, 1980; NRC, 1994). Net

energy may include the energy used for maintenance only or for maintenance and production (NRC, 1994).

Sibbald and Wolynetz (1989) reported no significant difference in nitrogen-corrected true metabolisable energy (TMEn) of a diet in mash or steam-pelleted form (14.34 vs. 14.40 MJ/kg). Cutlip *et al*. (2008) reported that TMEn did not differ among dietary treatments (unconditioned mash, conditioned with different conditioning temperatures and steam pressures, and reground pellet) when tested with the adult rooster model. These results are congruent to past research (Hussar and Robblee, 1962) demonstrating that pelleting does not influence apparent metabolisable energy (AME) and energy retention of the feed. Conversely, Svihus *et al*. (2004) reported that pelleting increased the AME of diets from 11.6 to 11.8 MJ/kg. However, the increase in AME was not reflected in a higher starch digestibility. Increased metabolisable energy content of broiler diets due to pelleting has been also reported by Farrell *et al*. (1983) and Kilburn and Edwards (2001). In contrast to these studies, Amerah *et al*. (2007b) reported negative effect of pelleting on nitrogen-corrected apparent metabolisable energy (AMEn). In their study, pelleting reduced the AMEn of a wheat-based diet from 12.5 to 11.8 MJ/kg.

One of the effects of pelleting on feed efficiency is reduction in feed energy used for maintenance and, therefore, improved productive energy (Nir *et al*., 1994). Productive energy is an estimation of the MJ per unit of feed actually used for lipid and protein synthesis (Reddy *et al*., 1962). Reddy *et al*. (1961) observed that chickens fed pellets spent approximately 4% of their time in the ingestion of feed compared with 15% for mash-fed birds. By determining productive energy content, they also noted that pellet diet contained more productive energy than mash diet. Reddy *et al*. (1962) showed that the pelleted diet yielded approximately 30% more productive energy than the mash diet (9.84 joules/g for pellets and 7.54 joules/g for mash). It has been reported that increasing diet density through the pelleting process did not significantly affect the ME content of the diet, but markedly increased productive energy (Jensen, 2000). Reduced maintenance energy expenditure would allow for an increase in productive energy value of the diet, thus providing more calories for protein and lipid synthesis in growing birds (Greenwood and Beyer, 2003). A recent study by Latshaw and Moritz (2009) showed that heat increment and the energy from each unit of feed that was utilised as product were affected by feed form. Broilers fed

pellets had lower heat increment and utilised more of the feed energy for productive purposes than those fed mash.

2.2.6.　　Destruction of feed ingredients cell wall

The aleurone layer of cell walls in cereals encapsulates significant amounts of nutritive components (Saunders *et al*., 1969). The effect of steam-pelleting on aleurone cells of wheat bran has been studied by Saunders *et al*. (1969). After feeding wheat bran to chickens, microscopic examination of the excreta showed a number of undigested aleurone cells (Figure 2.7). The proportion of empty aleurone cells (utilised contents) was significantly greater in the pellet diets than mash diets. Also, the level of non-utilised (residual) protein by the chickens decreased as the proportion of empty cells increased, with pellet diets always having the lowest residual protein.
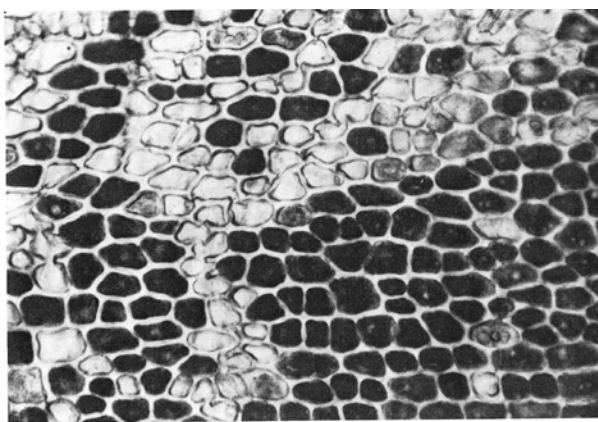
Figure 2.7. Aleurone cells present in the excreta

Dark cells, non-utilised contents; white (empty) cells, utilised contents

(Source: Saunders *et al*., 1969)

In this study, some cell walls were broken as a result of the physical stress of pelleting. None of the walls of the intact cells appear to have been damaged, but all the empty cells show evidence of breakage (Figure 2.8). It was evident that the cell wall breakage provided greater accessibility of cellular contents to digestive enzymes since, without exception, where breakages occur, the contents have been utilised.
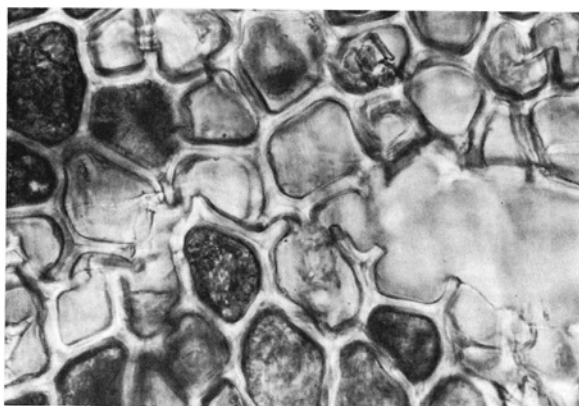
Figure 2.8. Cell wall breakage in aleurone cells present in the excreta (Source: Saunders *et al*., 1969)

2.2.7.   **Enzymes**

The stability of added feed enzymes to the pelleting process is a major concern of feed manufacturers, because pelleting can significantly reduce the safety margins incorporated into the feed formulation (Inborr and Bedford, 1994; Silversides and Bedford, 1999). Enzymes need to be biologically active when reaching the gastrointestinal tract to be able to act on the substrates. Due to their chemical and physical nature, enzymes are susceptible to inactivation by various external factors such as high temperatures, pH and proteolysis (Nissinen, 1994; Spring *et al*., 1996). High temperatures during the steam-conditioning will inactive enzymes commonly added to poultry diets (Jensen, 2000).

Inborr and Bedford (1994) found significant inactivation of β-glucanase, enzyme applied to improve the feed value of barley, at a conditioning temperature of 95 ºC. According to their study, conditioning at 75 ºC for 30 seconds reducedβ -glucanase activity compared with control mash diet to 66% of initial activity, whereas 15 minutes conditioning at 75 ºC reduced recovery to 49%. At 85 ºC with 30 seconds and 15 minutes conditioning, the recoveries were 56 and 31%, and at 95 ºC, these were 16 and 11%, respectively. These results suggest that partial enzyme inactivation takes place during pelleting. The magnitude of the inactivation depends on the pelleting conditions, with higher temperatures and longer retention times during steam-conditioning increasing inactivation. According to Eeckhout *et al*. (1995), most of the inactivation of added feed

enzymes occurs during steam-conditioning, when the diet is heated with steam, rather than during extrusion of the pellets.

Spring *et al*. (1996) studied the stability of cellulase, pentosanase, and bacterial and fungal amylase in a barley-wheat-soy diet following pelleting at 60, 70, 80, 90 and 100 ℃ (temperature was measured at the die outlet). Cellulase, pentosanase and fungal amylase were stable up to pelleting temperatures of 80 ℃ but lost more than 90% of their activity when pelleted at 90 ℃. Bacterial amylase was more stable, with 40% activity lost after pelleting at 100 ℃.

Silversides and Bedford (1999) reported that endogenous xylanase activity in wheat-based diet was largely destroyed by heating above 80 ℃ for 55 seconds and above 75 ℃ for 140 seconds. They also reported that xylanase activity in diets supplemented with enzyme before pelleting declined in a linear manner with increasing conditioning temperatures.

Samarasinghe *et al*. (2000) studied the activity of cellulase enzyme in a barley-maize-soy diet conditioned at 60, 75 and 90 ℃ and reported that the enzyme activity was unaffected at 60 and 75 ℃, but reduced by 73% at 90 ℃. It was concluded that conditioning temperatures as high as 90 ℃ drastically reduce cellulase activity. Conversely, Bedford *et al*. (2003) measured relative efficacy of a thermotolerant variant of an E. coli derived phytase in wheat-based pellet diets conditioned at 65, 75 or 85 ℃ and reported that the enzyme maintained its efficacy at all conditioning temperatures.

Cowieson *et al*. (2005a) reported an enzyme activity recovery of xylanase, amylase and protease above 80% of expected values in maize-soy diets pelleted at 70 and 85 ℃. Cowieson *et al*. (2005b) reported that the amount of soluble xylan decreased with increasing pelleting temperature for diets without and with added xylanase. Mash diets often contain endogenous and microbial enzymes which may cause increased degradation of xylan and a decreasing effect as pelleting temperatures increased (Cowieson *et al*., 2005b). Endogenous xylanase activity in the unsupplemented mash diet was between 155 and 236 U/kg, whereas the unsupplemented pelleted diet had an activity of below 100 U/kg. Also, pelleting the diet supplemented with xylanase had a negative effect on xylanase activity, especially in the diets pelleted at 85 and 90 ℃.

Silversides and Bedford (1999) showed that steam-conditioning of diets with no xylanase supplementation increased intestinal viscosity presumably due to the increased solubility of NSP exacerbated by destruction of endogenous enzymes in the diet. In diets supplemented with xylanase, intestinal viscosity was relatively low even at higher conditioning temperatures.

Although post-pelleting application of liquid form of exogenous enzymes can overcome the problem of inactivation, this approach can be costly and may result in lack of homogenous distribution of enzymes in the diet (Nissinen, 1994; Silversides and Bedford, 1999; Amerah *et al.*, 2011). Enzyme activity can also be protected from the heat, moisture and high pressures associated with pelleting by using granulated enzyme preparations coated with hydrophobic compounds (Nissinen, 1994; Silversides and Bedford, 1999; Amerah *et al.*, 2011). Despite these possibilities, many enzymes are mixed in the diet as a dry powder prior to pelleting because of simplicity, better homogeneity and storage stability (Nissinen, 1994; Silversides and Bedford, 1999).

2.2.8. Vitamins and Minerals

Vitamins are sensitive compounds which can be destroyed by oxygen, moisture, heat and other factors. In mash diets, the moisture content of the diet is mainly responsible for the stability of vitamins. During pelleting process, a combination of heat, moisture and pressure is applied which can be detrimental to a number of vitamins (Gadient, 1986). It has been clearly indicated that steam humidity is more destructive to vitamin A stability than heat (Gadient, 1986).

Pelleting can affect naturally occurring vitamins in feed ingredients as well as the commercial vitamins added to the feed. However, added vitamins often can be protected either chemically with an antioxidant or physically with a coating that is frequently a gelatine-based matrix (Gadient, 1986). Cutlip *et al.* (2008) added vitamin A in the form of retinyl acetate in gelatine-lactose coat with antioxidant (BHT) to a basal diet at 7200 IU/kg of feed to accommodate losses sustained during pelleting. Analysis of the pelleted diets for vitamin A demonstrated slight oxidative damage during pelleting. Despite efforts to increase the stability of commercial vitamins, pelleting remains a potentially aggressive

process. Therefore, pelleting conditions should be carefully controlled to minimise losses of vitamins (Gadient, 1986).

Although minerals represent only a minor portion of a poultry diet, they play a major role in nutrition. Kirkpinar and Basmacioglu (2006) found that feeding a maize-soy diet pelleted at three different temperatures (65, 75 and 85 ºC) had no effect on ash, Ca, P, Na, K, Mg, Zn, Fe, Mn and Cu contents of tibia of broiler chickens. No effect of pelleting temperatures on Ca content in the serum was observed. However, P content in the serum was increased by feeding the diet pelleted at 65 ºC compared to the other treatments.

2.2.9.   Enzyme inhibitors

Proteinaceous enzyme inhibitors have been found in many plants (Granum, 1979). Trypsin and alpha-amylase inhibitors are the most important inhibitors in poultry feed ingredients.

2.2.9.1.   Trypsin inhibitors

Trypsin inhibitors, mostly present in legume seeds, bind with trypsin and form an inhibitor-trypsin complex that prevents pancreatic enzyme from cleaving the carboxyl linkages of lysine and arginine (Camire *et al*., 1990). However, trypsin inhibitors are thermo-labile and can be inactivated by heat treatments.

2.2.9.2.   Alpha-Amylase inhibitors

The presence of alpha-amylase inhibitors has been shown in wheat, rye, triticale and sorghum, but not in rice, barley and maize (Saunders, 1975). Granum (1979) reported high alpha-amylase inhibitor activity in wheat flour (590 U/g) and whole wheat flour (351 U/g). Lang *et al*. (1974) demonstrated that inclusion of alpha-amylase inhibitors (20, 40 and 80 g/kg of the diet) isolated from wheat flour, into a starch-containing diet significantly reduced starch availability. However, starch availability was restored when the activity of the inhibitors was destroyed by autoclaving. Inhibition of chicken pancreas alpha-amylase by inhibitors isolated from wheat and its milling fractions has been reported by Saunders (1975). He also measured the content of alpha-amylase inhibitors in three wheat brans before and after steam-pelleting and reported considerably higher content of inhibitors in unpelleted compared to the pelleted brans. He concluded that it is likely that steam-

pelleting not only enhanced the amylolytic susceptibility of starch by gelatinisation, but it also partially destroyed the alpha-amylase inhibitors.

2.2.10. Effect of pelleting on feed particle size

According to Svihus (2010), whilst pelleting moulds mash diets to macro-particles in the form of pellets, it simultaneously reduces the size of the micro-particles that constitute the intact pellet. Svihus *et al*. (2004) wet sieved diets before and after pelleting and showed that the amount of coarse particles diminished and the amount of fine particles increased as a consequence of pelleting. In their study, hammer milled wheat-based broiler mash diets had between 40 to 50% particles smaller than 0.2 mm before pelleting, which increased to between 50 to 60% after pelleting. In agreement, Amerah *et al*. (2007b) reported that pelleting reduced the relative proportion of particles > 1 mm and increased the proportion of fine particles < 0.075 mm in coarse diets. These findings are in accordance with the results of Engberg *et al*. (2002) who reported that pelleting considerably reduced feed particle size and equalised the differences between the coarsely and finely ground pellets. In their study, due to pelleting, the fraction of feed particles with a size of over 1 mm reduced from 262 to 149 g/kg in the coarsely ground diet, and from 209 to 135 g/kg in the finely ground diet. Reduction in particle size due to pelleting has also been reported by Péron *et al*. (2005).

Svihus *et al*. (2004) speculated that, during pelleting, the large particles are particularly prone to grinding due to the narrow gap between the pellet rollers and the pellet die, and this may explain why the pelleting process tends to even out differences in particle distribution. Moreover, it is also possible that frictional force inside the die hole can further grind the coarse particles to the smaller particles.

2.2.11. Conclusions

- Because pelleting is widely used in broiler feed manufacture and can have a large physical and chemical impact on feed components, the pelleting process offers the greatest opportunity in feed processing technology to improve production profits.

- Optimal processing is required to maximise the nutritional value of feed. Under-processing may be associated with incomplete inactivation of anti-nutritional factors, insufficient starch gelatinisation and inadequate protein denaturation, whereas over-processing can result in the formation of resistant starch and Maillard reaction products, and inactivation of supplemental enzymes and vitamins.

- Further investigations on the relationship between each component of the pelleting process, pellet quality, nutrient availability and bird performance are required.

2.3. Pelleting and bird performance

2.3.1. Introduction

Bird performance is improved by pellet feeding. The improvements in performance have been attributed to a number of factors (Behnke, 1994; Behnke and Beyer, 2002; Peisker, 2006):

Decreased feed wastage: Pelleting reduces feed wastage by birds. Conglomeration of heterogeneous feed particles into a discrete pellet prevents small feed particles falling easily from the bird's mouth (Behnke and Beyer, 2002). Pelleting also prevents birds from selecting larger particles from mash feed and the messy sorting which may cause feed to be pushed out of feeders and increase feed wastage. In addition, less feed is wasted in the drinkers when broilers and turkeys are fed pellets (Jensen, 2000).

Decreased time and energy spent for eating: Pellet-fed birds spend less time and energy consuming feed and obtain more nutrients per every unit of expended energy than those fed mash diets (Scheideler, 1991; Jones *et al*., 1995). In a study by Jensen *et al*. (1962), mash-fed chickens (21-28 d) spent 14.3% of a 12-hour period eating versus only 4.7% with pellet-fed chickens. They observed a similar trend with greater difference for poults (38-45 d), with those fed mash using 18.8% of the 12-hour day eating while poults fed pellets used only 2.2%. Nir *et al*. (1994) also found that pellet-fed chickens (28-40 d) were less active and spent less time (about one third) consuming feed compared to mash-fed birds.

Reduced selective feeding: Even a homogenised and balanced mash diet may fail to meet the nutritional requirements of the birds if they pick out only the large particles (Armstrong, 1993). Scheideler (1991) observed that in a diet containing pellets and fines, birds consumed the pellets first. By preventing sorting, pelleting ensures that birds receive the complete diet and, thus a balanced level of nutrients (Falk, 1985).

Decreased ingredient segregation: Agglomeration of particles during pelleting process keeps ingredients including segregate ones, such as limestone, fixed within the pellet (Greenwood and Beyer, 2003).

Improved feed intake: Feed intake is the major factor driving body weight gain and this is a primary motivation for pelleting broiler diets. According to Peisker (1994), pelleting is associated with increased feed intake, simply due to the reduction of fine particles.

Other benefits: In addition, pelleting allows a wide variety of ingredients to be included in the diet (Behnke, 1996). Pelleting increases the bulk density of mash feed (approximately 400 kg/m^3) to a pellet with bulk density of 500-600 kg/m^3 (Ziggers, 2003); which allows for more efficient transportation (Behnke, 1994; Jensen, 2000; Greenwood and Beyer, 2003). Pelleting also enhances flow properties that allow for good conveying by screw augers, as well as improved discharge behaviour from feed bins due to reduced bridging compared to mash (Behnke, 1994; Jensen, 2000; Greenwood and Beyer, 2003). Decreased feed dustiness is another positive aspect of pelleting (Behnke, 1994; Nir *et al*., 1994).

2.3.2.   Effect of physical form and quality of feed on broiler performance

It is generally accepted that pelleting enhances the economics of production by improving growth and feed efficiency in broilers (Behnke and Beyer, 2002). Bolton (1960) reported that pelleting improved weight gain and feed efficiency, but digestibility of nutrients was not affected. Hussar and Robblee (1962) reported that re-ground pellets did not affect early bird (7-14 d) performance. However, as the birds grew older (28-49 d), those fed whole pellets had better weight gain and feed efficiency compared to those fed re-ground pellets.

Generally, weight gain and feed efficiency of birds fed re-ground pellets were superior to those fed mash. Conversely, Plavnik *et al*. (1997) reported that performance of birds fed the re-ground pellets was either not different or inferior to that of the mash. Growth and feed efficiency improved only when feeding whole actual pellets.

Proudfoot and Sefton (1978) reported a 150 gram (g) decrease in the final (49 d) body weight of male broilers fed pelleted diets containing 45% fines compared to those fed pelleted diets containing no fines (1810 vs. 1960 g). Overall performance was similar among birds fed unprocessed mash diets and those fed diets containing 100% fines (reground pellets with equivalent levels of energy, protein, fat and fibre). Several other studies (Reddy *et al*., 1962; Hull *et al*., 1968; Moran, 1989) have also shown that a greater response was obtained by feeding actual pellets compared to re-ground pellets.

Parsons *et al*. (2006) compared two different pellet textures, namely, soft (1,662 g of pellet breaking force) and hard (1,856 g of pellet breaking force) and reported that broilers fed hard pellets had improved nitrogen (N) and lysine retention, TMEn, weight gain and feed efficiency compared to those fed soft pellets. They speculated that pellet texture and particle size may have similar effects on broilers.

Recent research has shown significant negative effects of poor feed form on body weight and feed efficiency of broilers fed maize- (Cutlip *et al*., 2008; Kenny, 2008; Corzo *et al*., 2011) and wheat-based diets (Kenny, 2008). Cutlip *et al*. (2008) showed that broilers fed a maize-soy pelleted diet had a 433 g greater final body weight (39 d) and a decreased feed per gain (10 points) compared to those fed the same diet as unprocessed mash.

Kenny (2008) compared a good quality wheat-based pelleted diet (starter crumble and grower pellet) with diets containing 50 and 100% mix of fines. The fines were created by roller-grinding the control crumbles and pellets to less than 0.5 mm particle size. The results showed that feeding diets containing 50 and 100% fines reduced the body weight by 7 and 20%, respectively, compared to the control. Another trial, evaluating similar treatments in maize-based diets, revealed the similar effect on performance. The 50 and 100% fines reduced the body weight by 4.5 and 19%, respectively. Feed per gain also deteriorated by 2.2 and 6.1% in the 50 and 100% fines, respectively.

Corzo *et al*. (2011) evaluated the effects of a non-conditioned mash diet and diets with 32 and 64% intact pellets, all based on maize, on broiler performance. At 28 and 42 d

of age, birds fed either pellet-containing diet had similar body weight and feed intake but higher than those fed the non-conditioned mash diet. The lowest feed per gain was observed in birds fed the diet with 64% pellets. These birds also showed the highest efficiency in terms of feed cost associated with producing 1 kg of body weight, carcass weight, breast meat, drumsticks and thighs. These studies highlight the opportunity to improve broiler performance through manipulation of feed form.

2.3.3. Effect of conditioning temperature on broiler performance

Steam injected into the conditioner chamber elevates the temperature of the mash diet prior to entering the pellet die (Creswell and Bedford, 2006). Pelleting temperature generally refers to the temperature of the mash diet at the outlet of the conditioner (Creswell and Bedford, 2006). Some effect of pelleting on bird performance depends on the conditioning temperature used. Moderate thermal treatment of broiler diets appears to improve their nutritional value, which may be attributed to gelatinisation and increased enzyme susceptibility of starch granules, degradation of heat-labile anti-nutrients, destruction of cell walls and improved availability of nutrients (Pickford, 1992; Silversides and Bedford, 1999; Cutlip *et al*., 2008). On the other hand, high temperatures can destroy heat-labile vitamins, enzymes and amino acids, reduce the availability of starch by formation of RS and lower the availability of lysine through Maillard reaction (Pickford, 1992; Silversides and Bedford, 1999). Furthermore, increasing conditioning temperatures above 80 ℃ can also increase the viscosity of broiler diets based on viscous grains, suggesting the release of previously encapsulated NSP (Cowieson *et al*., 2005b). Diets containing high levels of starch (500-800 g/kg) have been suggested to be more amenable to higher conditioning temperatures (above 82 ℃) than diets high in protein or fibre (Maier and Gardecki, 1993). Pelleting may result in poor broiler performance if the appropriate temperature is not used during conditioning. It has been shown that high conditioning temperatures are associated with poor broiler performance, in terms of weight gain, feed per gain and mortality (Creswell and Bedford, 2006; Kenny and Flemming, 2006). Specifically, it appears that conditioning temperatures over 85 ℃ should be avoided (Creswell and Bedford, 2006).

Nir *et al*. (1994) reported increased weight gain in broilers fed sorghum-based diets steam-pelleted once at 60 ℃ compared to those fed mash diets. Weight gain of birds fed

diets steam-pelleted twice at 60 ℃ was significantly lower compared to those fed diets steam-pelleted once. Feed intake of birds fed twice steam-pelleted diets was similar to those fed the mash diet, while feed intake was higher in birds fed once steam-pelleted diets. It was concluded that twice steam-pelleting at 60 ℃ reduced the beneficial effect of pelleting.

Silversides and Bedford (1999) demonstrated that moderate conditioning temperatures (80 to 85 ℃) resulted in the best broiler performance, but that increasing conditioning temperature above 85 ℃ impaired performance. Samarasinghe *et al*. (2000) found that conditioning temperatures as high as 90 ℃ reduced energy and N utilisation, and broiler performance. In their study, while birds consumed 6% more feed and gained 9% more weight when conditioning temperature was increased from 60 to 75 ℃, further increasing conditioning temperature to 90 ℃ resulted in lower feed intake and weight gain. High conditioning temperature also reduced ME and N utilisation by 3.2 and 4%, respectively.

In a study reported by Bedford *et al*. (2003), the negative effects of higher temperature in wheat-based diets were evident once pelleting temperature (temperatures measured as pellets exit the pellet die) exceeded 65 ℃. In this trial, there was a significant linear, negative effect of temperature on both weight gain and feed per gain, with -75 g of gain and 4.0 points in feed per gain for every 10 ℃ increase in pellet die temperature.

Cowieson *et al*. (2005b) showed that increasing conditioning temperatures from 80 to 90 ℃ reduced weight gain and resulted in higher feed per gain (2.03 vs. 1.94) in broilers. They concluded that performance of broilers fed wheat-based diets can be compromised at conditioning temperatures above 80 ℃.

Kirkpinar and Basmacioglu (2006) showed that pelleting a maize-soy diet at 65 ℃ resulted in higher weight gain compared to the basal mash diet and diets pelleted at 75 and 85 ℃. Increasing pelleting temperature to 75 and 85 ℃ resulted in a significant reduction in weight gain of broilers to an extent that birds fed diets pelleted at 85 ℃ had weight gains similar to those fed the basal mash diet.

Bedford (cited in Creswell and Bedford, 2006) reported a significant reduction in weight gain and increase in feed per gain of broilers fed maize-based diets with pelleting temperature at 93 ℃ compared to 85 ℃. Raastad and Skrede (cited in Creswell and Bedford, 2006) reported lower body weights when the conditioning temperature increased

from 69 to 86 ºC. Feed per gain was not influenced by conditioning at 69 or 78 ºC, but deteriorated as conditioning temperature increased from 78 to 86 ºC, especially during the initial 1-21 d feeding period. The AME content of diets pelleted at 86 ºC was 3% lower than those pelleted at 69 ºC. Conversely, Cutlip *et al*. (2008) demonstrated decreased feed intake, similar weight gain and decreased feed per gain for broilers fed diets pelleted at 93.3 ºC compared to those fed diets pelleted at 82.2 ºC. Feeding high temperature pelleted diets resulted in a 20-point decrease in feed per gain.

2.3.4.   Effect of feed form on nutrient requirements of broilers

Nutrient requirements of broilers are usually determined based on unprocessed mash diets (Behnke and Beyer, 2002). Given that broilers are mostly fed pelleted diets, these requirements need to be re-evaluated for the effect of feed form.

According to McKinney and Teeter (2004), dietary energy level of a diet with good pellet quality may be reduced without compromising growth response due to the fact that productive energy value of pelleting is mediated by bird energy expenditure. They reported that pelleting contributed 0.78 MJ MEn/kg of diet at 100% pellet quality (no fines), with this value decreasing with increasing proportions of fines to pellets, but still contributing 0.32 MJ/kg for 20% pellets.

Jensen *et al*. (1965) reported that pelleting increased protein and lysine requirements for growing turkeys compared to similar diets in mash form. When diets were formulated at critical levels of lysine or protein, pelleting accentuated the deficiency. They suggested that when diets are fed in pellet form, productive energy is increased and the protein and lysine requirements are increased as a proportion of the diet. Due to the known effects of lysine on partitioning for energy deposition and protein retention, dietary lysine concentration could be of particular concern (Batterham *et al*., 1990). An imbalance between dietary energy level and lysine concentration can occur if extra available calories for growth due to pelleting are neglected (Greenwood *et al*., 2004).

Greenwood *et al*. (2004) reported that increasing lysine concentrations from 8.5 to 10.5 g/kg resulted in a linear increase in weight gain of pellet-fed birds, while no growth response was observed in mash-fed birds at digestible lysine levels higher than 8.5 g/kg. Greenwood *et al*. (2003) suggested that pellet-fed birds require 1.3 and 0.9 g/kg more

digestible lysine than mash-fed birds for optimal weight gain and feed efficiency, respectively, from 16 to 30 d (8.7 and 9.0 g/kg for the mash-fed birds compared to 10.0 and 9.9 g/kg for the pellet-fed birds). Using dose-response analysis, they illustrated that feed form affects the estimated lysine needs of broilers. Jensen (2000) suggested that to match the lysine intake (per g of body weight) of a mash diet with 10.0 g/kg lysine, a pelleted diet with 10.8 g/kg lysine concentration is needed.

According to Greenwood and Beyer (2003), total sulphur amino acids requirements of the birds are not influenced by feed form to the extent that was observed with lysine. If it is accepted that nutrient requirements of broilers per unit of feed in a pelleted diet are higher than in a diet in mash form, application of amino acid recommendations determined through feeding purified, semi-purified, dose-response or mash diets to an industry situation where good pellet quality exists, may result in broiler suboptimal performance due to underestimation of the bird's amino acid needs (Greenwood and Beyer, 2003; Greenwood *et al*., 2004).

2.3.5.   Effect of pellet feeding on nutrient digestibility

Since starch is partially gelatinised by the pelleting process (in the conditioner and at the pellet die), which increases its availability for enzymatic degradation, starch digestibility may be expected to be increased in pelleted diets. However, the conventional pelleting process has been shown to gelatinise only small amounts of starch (Pfost, 1971; Skoch 1981; 1983a,b; Moritz *et al*., 2002; 2003; Svihus *et al*., 2004; Zimonja *et al*., 2007; 2008) and this effect on starch digestion may be of modest importance (Svihus *et al*., 2004; Zimonja *et al*., 2008). Svihus (2001), in a review of literature on starch digestibility, revealed that high starch digestibility usually coincides with mash feeding, whereas low starch digestibility is associated with feeding cold-pelleted diets. He studied starch digestibility of cold-pelleted diets containing high levels of wheat (four varieties) and reported an average apparent ileal starch digestibility coefficient of less than 0.83 in all four wheat varieties. It was suggested that starch digestibility of wheat diets is negatively correlated to feed intake (Svihus, 2001). Due to a significant increase in starch digestibility when a wheat diet was diluted with cellulose, Svihus and Hetland (2001) speculated that an overload of wheat starch in the small intestine is the major cause of low starch digestibility,

not a high feed intake *per se*. According to Zimonja *et al*. (2007), amylose-lipid complex formation during feed processing can also reduce starch digestibility. They reported a greater extent of amylose-lipid complex formation in pelleted diets than expanded diets.

While the effect of pelleting on starch digestibility in wheat is well documented (Svihus, 2001; Svihus and Hetland, 2001), research regarding the effect of pelleting on protein and fat digestibility in wheat and other grains are scant. Duodu *et al*. (2002) reported that cooking (10 min at approximately 95 ℃) reduced *in vitro* protein digestibility of sorghum, but not maize. The poorer protein digestibility of cooked sorghum was explained by formation of enzyme-resistant disulphide-bonded oligomeric proteins that occur to a greater extent in sorghum than in maize. They also suggested pericarp components, germ, endosperm cell walls, and gelatinised starch as possible factors limiting protein digestibility in sorghum. Bryden *et al*. (2009) suggested that steam-pelleting of sorghum-based diets at temperatures above 90 ℃ may provide sufficient 'moist-heat' to induce disulphide linkages in kafirin and compromise protein and starch digestibility in sorghum.

2.3.6.   Effect of pelleting on digestive tract development and morphology

Choi *et al*. (1986) reported that feeding crumble diets to broilers during the starter period resulted in decreased gizzard weight at 28 d of age. Feeding pelleted diet during the finisher period (28-56 d) also reduced weights of the digestive tract and gizzard compared to those fed the mash diet. These results demonstrated that birds do not fully develop their digestive tract when highly processed feeds are offered. Munt *et al*. (1995) also reported a greater gizzard weight in broilers fed mash diets compared to pellet-fed birds.

Nir *et al*. (1994) reported that pelleting reduced the relative weight of the gizzard, as well as length of jejunum and ileum. Nir *et al*. (1995) reported that pelleting reduced proventriculus weight and that of its contents at 21 d of age, but not at 40 d. Pelleting also reduced gizzard weight and that of its contents at 21 and 40 d of age. Pelleting was accompanied by a reduction of weight and contents of GIT, and pancreas weight at 21, but not at 40 d of age.

Preston *et al*. (2000) indicated that birds fed a diet containing whole wheat (basal diet pelleted and then mixed with 333 g/kg whole wheat) had approximately 50% greater

relative gizzard weights compared to those fed a cold-pelleted diet at 42 d of age. The increase in gizzard weight appeared to be due to a more developed muscular wall. The improvements observed in AME content and feed efficiency with whole wheat feeding in this study was attributed, in part, to more extensive grinding of feed within the gizzard.

A study conducted by Engberg *et al.* (2002) showed that pellet-fed birds had lower gizzard and pancreas weights than mash-fed birds. They also reported higher pancreatic activities for amylase, lipase, and chymotrypsin in mash-fed birds compared to pellet-fed birds. Agah and Norollahi (2008) reported lower relative pancreas weight (at 42 d of age) in broilers fed pelleted diets compared to those fed mash diets.

Amerah *et al.* (2007b) reported that relative empty weight of gut segments were greater in birds fed wheat-based mash diets than those fed pelleted diets. In their study, the improvement in bird performance with pelleting was accompanied by a decrease in the relative length of all segments of the intestinal tract. Their study also showed that offering pelleted diets to broiler starters lowered the relative gizzard weight and contents compared to feeding mash diets. Mirghelenj and Golian (2009) reported heavier gizzard and caeca in mash-fed broilers compared to pellet- or crumble-pellet-fed birds. Relative weights of crop, proventriculus and small intestine were unaffected by physical form of the feed.

Numerous studies have reported greater gizzard development in birds fed coarsely ground diets (Nir *et al.*, 1994; Hetland and Svihus, 2001; Engberg *et al.*, 2002). According to Svihus (2010), the increase in size of the gizzard is a logical consequence of an increased need for particle size reduction, as the increased grinding activity of the gizzard increases the size of the gizzard muscles. A mash diet, in particular one that is coarsely ground, tends to remain longer in the gizzard, thus increasing the mechanical stimulation of this organ (Nir *et al.*, 1994; Carre, 2000; Hetland and Svihus, 2001; Engberg *et al.*, 2002). It has been suggested that pelleting decreases the grinding requirement of the gizzard so that its function is reduced to that of a transit organ (Amerah *et al.*, 2007b).

Nutrient digestibility and bird performance will be impaired if gizzard is not well-developed (Gonzalez-Alvarado *et al.*, 2008). A large and well-developed gizzard is associated with developed gizzard muscles (Preston *et al.*, 2000; Svihus, 2010), increased grinding activity (Nir *et al.*, 1994; Amerah *et al.*, 2007a,b; Svihus, 2010), increased pancreatic enzyme secretion through increased release of cholecystokinin (Svihus, 2010),

and improved GIT motility (Ferket, 2000; Gonzalez-Alvarado *et al*., 2008), resulting in improved nutrient digestion and energy utilisation (Carre, 2000). Garcia *et al*. (2007) reported an increase in gizzard/intestine weight ratio was accompanied by an increase in AMEn values. They suggested that this ratio was an efficient means for predicting variations in AMEn responses observed with xylanase and antibiotic supplementation.

It has also been suggested that an active and more developed gizzard can regulate feed intake and prevents overconsumption of feed by birds (Svihus, 2010). Increased retention time in the gizzard as a consequence of increased gizzard volume may increase nutrient digestibility through providing more time for the secretion of hydrochloric acid (Gonzalez-Alvarado *et al*., 2008; Svihus, 2010) and possibly pepsin (Svihus, 2010), and by increasing intestinal refluxes that serve to re-expose the digesta to pepsin (Gonzalez-Alvarado *et al*., 2008). Increased retention time may also potentially improve efficacy of exogenous enzymes (Svihus, 2010) through facilitating the mixing of the feed with added enzymes (Gonzalez-Alvarado *et al*., 2008).

Amerah *et al*. (2007b) also reported greater mucosal extent, villus height and crypt depth in both duodenum and jejunum in pellet-fed birds compared to mash-fed birds. This finding was considered as a general response of the digestive and absorptive capacity of the proximal small intestine to the greater load of nutrients caused by pellet feeding.

2.3.7. Conclusions

- Although pelleting enhances the growth responses in broilers, there is no consensus regarding the factors contributing to this improvement. Investigations, comparing intact pellets with re-ground pellets, to examine the relative importance of intact pellets *per se* and chemical changes during pelleting are limited.

- Since probable chemical changes in pellets caused by pellet die can be carried over even after grinding the pellets, further research are warranted to differentiate the effects of conditioning process from pelleting process.

- Despite its practical importance, optimal conditioning temperature remains a debatable pelleting variable. High conditioning temperatures may compromise nutrient digestibility and broiler performance. On the other hand, high

conditioning temperatures are required to produce sanitised and good quality pellets.

2.4. Physical pellet quality

Physical pellet quality is defined as the ability of pellet to withstand fragmentation and abrasion during mechanical and pneumatic handling (bagging, storage, transport and manipulation by birds) without breaking up; and to reach feeders without generating a high proportion of fines (Cramer *et al*., 2003; Löwe, 2005; Amerah *et al*., 2007a).

2.4.1. Physical pellet quality parameters

Attrition of pellets is by two phenomena, namely, fragmentation and abrasion. Fragmentation involves "the fracture of pellets into smaller particles and fines at the fracture area," while abrasion involves "the fracture on the edges or surface-unevenesses of particles" (Thomas and van der Poel, 1996). Physical quality of pellets can be evaluated using pellet durability and pellet hardness parameters.

2.4.1.1. Pellet durability

Pellets are exposed to abrasion from the time they are manufactured to the time they are ingested by the birds, resulting in fines in the feed. The pellet durability test determines the proportion of intact pellets remaining in manufactured pellets prone to attrition stresses due to mechanical or pneumatic agitation (Thomas and van der Poel, 1996). Higher pellet durability means that pellets will more likely remain intact until the time of feeding (Behnke and Beyer, 2002).

Pellet quality is generally defined using the pellet durability index (ASAE, 1997). Several instruments are available for the determination of pellet durability. Pellet durability can be determined using the Pfost tumbling can device. According to the procedure of Pfost (1963), durability is measured by inducing fines through an abrasing action of pellets shearing over each other and over the wall of the drum. To do a pellet durability test, first the pellet samples to be tested are sieved on the appropriate sieve to remove fines. Then the sample of sieved pellets is tumbled in the tumbling can device for a defined period of time (Thomas and van der Poel, 1996). After tumbling, samples are subsequently sieved and the amount of pellets not passing the sieve is determined. Pellet durability index is then

calculated as the ratio of intact pellets after tumbling to whole pellets at the start (Pfost, 1963; Winowiski, 1998; Behnke and Beyer, 2002).

The 'Holmen' pellet tester (pneumatic resistance test) is another device for measuring pellet durability (Thomas and van der Poel, 1996; Winowiski, 1998). To do the test, a 100 g sieved sample of pellets is introduced in a stream of air. For a standard time (30 to 120 seconds), the air and pellets are circulated through right-angled bends, impinging repeatedly on hard surfaces. After the test cycle, the sample is sieved again using a sieve with an opening of approximately 80% of the pellet diameter (Thomas and van der Poel, 1996). Pellet durability index is expressed as the ratio of the pellets not passing through the sieve after test to whole pellets at the start. Holmen pellet tester is widely used in feed mills to measure the durability of pellets.

The third pellet durability testing device is called the LignoTester. In this method, a 100 g sample of pellets is rapidly circulated in an air stream around a perforated test chamber for a defined period of time. Fines are removed continuously through the perforations as they are generated. After the test, the weight of remaining pellets gives an immediate reading of PDI (Winowiski, 1998).

2.4.1.2. Pellet hardness

A test for hardness is important to avoid pellet breakdown due to pressure in bulk bins (Major, 1984). Hardness is determined by using equipment which measures the force necessary to crush a pellet. The most common device used in industry to test pellet hardness is the 'Kahl' device. In the Kahl device, a pellet is inserted between two bars, and by increasing static pressure applied by means of a spring, the force needed to fragment the pellet is determined (Thomas and van der Poel, 1996). Other generally applied test devices for pellet hardness are: Schleuniger test apparatus, Pendulum test device, Instron device, Kramer shear press (Thomas and van der Poel, 1996) and Texture Analyser (Svihus *et al*., 2004).

2.4.2. Possible manipulations to manufacture high physical quality pellets

Feeding pelleted diets is not enough to ensure good performance of broilers. The physical quality of pellets must also be taken into account (Briggs *et al*., 1999). The importance of physical quality of pellets in improving growth responses is well recognised in the broiler

industry (Reddy *et al*., 1962; Hull *et al*., 1968; Proudfoot and Sefton, 1978; Moran, 1989; Moritz *et al*., 2001; Behnke and Beyer, 2002; Moritz *et al*., 2003; Parsons *et al*., 2006; Cutlip *et al*., 2008; Hott *et al*., 2008; Kenny, 2008; Corzo *et al*., 2011). Moreover, feed is too expensive to waste; so pellet quality has an economic value (Löwe, 2005).

To create high physical quality pellets, a better understanding of factors affecting pellet quality is necessary. According to Reimer (Cited in Behnke, 2001), pellet quality depends proportionally on the following factors: 40% feed formulation, 20% feed particle size, 20% steam-conditioning, 15% pellet die specification, and 5% cooling and drying. A number of strategies can be employed, alone or in combination, to manufacture high physical quality pellets (Moritz and Lilly, 2010).

2.4.2.1.   Manipulating diet formulation

Feed ingredients incorporated into the diet influence the pellet quality in different ways (Löwe, 2005). Stevens (1987) compared pellet durability of diets containing 724 g/kg wheat or maize after conditioning at 65 ℃. Wheat-based pellets were more durable (90.3-91%) than those based on maize (57.5-57.6%). Winowiski (1988) increased the proportion of wheat (from 0 to 600 g/kg) in diets by directly displacing maize without balancing the nutrients, and reported an improved PDI from 32 (68% fines) to 73 (27% fines). Higher crude protein content of wheat (about 130 g/kg) as compared to maize (about 90 g/kg) was accounted for the higher pellet durability of wheat diets. These results are consistent with a study conducted by Briggs *et al*. (1999) which found that increasing the protein content from 163 to 210 g/kg increased the average pellet durability from 75.8 to 88.8%. This is due likely to the formation of hydrogen bonds between the hydrophilic portion of the protein and water molecules provided from the injected steam (Maier and Briggs, 2000). Wheat also has a higher dough-forming capability than maize due to higher levels of gluten proteins and pentosan/hexosan hemicelluloses that serve as good pellet binders (Jensen, 2000).

Buchanan and Moritz (2009) reported an improved pellet quality when 50 g/kg of either soy protein isolate, as pure source of protein, or cellulose, as pure source of fibre, was included at the expense of maize in a maize-soy broiler diet. Better pellet quality due to cellulose inclusion was attributed to the ability of cellulose to absorb water.

Zimonja and Svihus (2009) studied the effect of inclusion of 200 g pure wheat starch/kg to the diets with equal amounts of oat hulls, rapeseed and fish meal which were cold-pelleted or steam-pelleted. In both processing conditions, starch-containing diets showed lower PDI compared to non-starch diets. Although replacing native wheat starch with pre-gelatinised wheat starch improved pellet quality within starch-containing diets, pellet durability was still inferior to non-starch diets. Better binding properties of non-starch diets were attributed to their higher protein content. In agreement with this finding, Wood (1987) reported that improvements in pellet durability due to inclusion of raw (not denatured) soy protein were greater than those from inclusion of pre-gelatinised tapioca starch.

Zimonja *et al*. (2008) observed superior durability and higher breaking resistance for pellets based on oats compared with wheat. Higher gelatinised starch content in oats diets compared with wheat diets may partially account for the better pellet quality in oat-based diets. They also reported a significant increase in pellet durability when fine oat hulls were included in wheat-based diets, but not in diets based on oats. In contrast, inclusion of 20 and 40 g/kg oat hulls has been shown to negatively affect PDI (Buchanan and Moritz, 2009). It has also been reported that replacing maize with sorghum compromised pellet quality (Behnke, 1994).

Briggs *et al*. (1999) revealed a negative effect of increasing oil content from 29 to 75 g/kg on pellet quality. However, an oil content of about 56 g/kg and protein content of about 200 g/kg did not diminish pellet quality. Due to lubricating effects, fat can reduce friction force generated in the die holes and result in lower pellet quality. Moreover, high level of dietary fat inclusion can partially coat the feed particles, making a barrier to steam penetration of the feed particles, preventing starch gelatinisation and development of binding adhesions (Löwe, 2005).

When formulating broiler diets, consideration should be given to the potential negative effects of feed ingredients on pellet quality. High inclusion of some ingredients in diets may not be feasible if they are detrimental to pellet quality even though they may be good and cost-effective sources of nutrients. For instance, the caloric value attributable to added fat can be discounted or even eliminated due to reduction in pellet quality associated with fat inclusion (McKinney and Teeter, 2004). However, a study by Gehring *et al*.

(2009b) suggested that dietary fat inclusion can protect heat-labile nutrients and exogenous enzymes by decreasing the frictional heat in the die holes. Another example of this type of ingredient impact on pellet quality is provided by distiller's dried grains with solubles (DDGS), the main by-product of ethanol production from maize. This ingredient, which has recently received more attention in commercial poultry diets, needs to be treated carefully when is included in broiler diets. Recent work by Loar II *et al.* (2010) showed that dietary inclusion of DDGS into broiler diets adversely affected the quality of pellets. A negative effect of conventional DDGS on PDI in broiler diets has also been reported by Srinivasan *et al.* (2009). Although the choice of feed ingredients impacts on pellet quality, due to the fact that least-cost diet formulation is the primary concern of the poultry nutritionists as well as the use of concepts such as ideal protein in feed formulations which eliminates the need for high dietary protein levels, achieving high quality pellets through manipulating diet formulation has become relatively difficult.

2.4.2.2. Use of binding agents

A binding agent can be as simple as added water at the mixer or a commercial pellet binder (Moritz and Lilly, 2010). Increased pellet durability gained through increasing the moisture content of the feed is well documented (Fairchild and Greer, 1999; Moritz *et al.*, 2001; 2002; 2003; Lundblad *et al.*, 2009). Both heating and the presence of water are prerequisites for starch gelatinisation (Kim *et al.*, 2000; Parker and Ring, 2001; Svihus *et al.*, 2005), but it is the presence of water which allows linear and cyclic molecules of ruptured starch granules to hydrate and become sticky (Hasting and Higgs, 1978).

Moritz *et al.* (2003) reported that water addition (25 and 50 g/kg) to a maize-based broiler diet decreased starch gelatinisation while increasing the pellet durability. Previous studies (Pfost, 1971; Heffner and Pfost, 1973; Skoch *et al.*, 1981; 1983a,b; Stevens, 1987) have shown that frictional heat generated in die holes has a marked effect on starch gelatinisation. Therefore, it seems plausible that lubricating effects of added moisture could decrease the frictional heat generated inside the die holes, thus decreasing the degree of starch gelatinisation (Moritz *et al.*, 2003). One explanation for the higher pellet quality of moisture-containing diets despite a decreased starch gelatinisation extent may be that in a normal conditioning process, the moisture, injected as steam, is held largely on the surface

of the starch-containing feed particles rather than permeating the starch granules (Smith, 1959); but water addition at the mixer provides better moisture permeation to the starch granules and this will result in a lower but more uniform starch gelatinisation through the entire pellet. According to Moritz *et al*. (2003), a small amount of gelatinisation evenly distributed throughout the pellet may be more effective in agglomerating of feed particles than high amounts of localised gelatinisation. Another possible explanation is that while starch gelatinisation favours pellet quality it is not the main factor determining pellet quality. Bernardin and Kasarda (1973) showed rapid change of the wheat endosperm matrix protein into long, sticky protein fibrils upon exposure to moisture. These hydrated protein fibrils spread out from the mass of endosperm with starch granules and suspended particulates adhering to their surface. These fibrils were suggested to be the structural elements forming the cohesive matrix of dough.

Recent work by Lundblad *et al*. (2009) also showed a significant increase in PDI of barley- and maize-based diets with water addition. In contrast, Hott *et al*. (2008) reported no effect of moisture addition on PDI of broiler diets manufactured at a pilot feed milling facility. This was attributed to the high PDI of the control diet, which did not leave much space for improvement.

Hemmingsen *et al*. (2008) studied water adsorption of some ingredients (barley, wheat, dehulled oats, soybean meal and rapeseed meal) following exposure to moist air at 80 ℃ or water in the liquid state (20 and 80 ℃), and reported that starchy ingredients (barley, wheat and dehulled oats) showed greatest water adsorption in liquid water at 80 ℃ and low water adsorption in moist air at the same temperature. The protein-rich ingredients (soybean meal and rapeseed meal) showed the highest water adsorption in moist air at 80 ℃. It was speculated that the effect of ingredient composition on pellet quality seems to be determined by the water adsorption pattern of the feed ingredients. As commercially manufactured pelleted diets generally contain several ingredients, they suggested that a combination of steam and water should be used to optimise the effect of conditioning during the pelleting process.

Positive effects of lignin pellet binders (calcium lignosulphonate) on pellet quality of turkey and layer diets have been studied by Pfost (1964). Acar *et al*. (1991) reported a 56% improvement in the amount of intact pellets by adding calcium lignosulphonate

(CaLs) to a maize-soy broiler diet. Recent research by Gehring *et al*. (2009a) demonstrated that fish muscle proteins, incorporated at less than 50 g/kg of the diet, will provide pellet binding benefits.

2.4.2.3.   Decreasing grain particle size

Coarsely-ground particles are believed to compromise the pellet quality, although there is no objective evidence to support this claim (Amerah *et al*., 2007b). Thomas *et al*. (1998) postulated that coarse grade particles result in weak points, facilitating breakage of the pellet and thus decreasing pellet quality. Smaller feed particle size through fine grinding increases surface area, provides more contact points with adjoining particles, leads to faster penetration of heat and moisture to the core of particles, and results in better binding characteristics and higher quality pellets (Behnke, 2001; Dozier, 2003; Löwe, 2005; Moritz and Lilly, 2010).

Published data on the effect of feed particle size on pellet quality are contradictory (Reece *et al*., 1986; Stevens, 1987; Angulo *et al*., 1996; Thomas *et al*., 1998; Dozier, 2003; Svihus *et al*., 2004; Amerah *et al*., 2007b). Reece *et al*. (1986) observed that coarsely ground maize particles produced more durable pellets than those made from fine particles. In contrast, Angulo *et al*. (1996) showed that increasing the grinder screen size from 3 to 6 mm markedly decreased the durability of pellets. It was also suggested that particle size is more important than the presence of binder in determining pellet durability.

Stevens (1987) reported no difference in pellet durability values from different particle sizes of maize; however, the coarse particles resulted in lower durability when wheat was used in the formula. Dozier (2003) suggested that to achieve adequate pellet quality for broilers a maize particle size of 650-700 microns is required.

Svihus *et al*. (2004) observed a slight reduction in pellet durability of a wheat-based diet made from coarse particles compared to those from fine particles. This finding was attributed to more weak spots as well as lower gelatinised starch content in the pellets made from coarsely ground wheat. Amerah *et al*. (2007b) observed no difference between PDI of pellets made from diets based on medium- (3 mm screen size) and coarsely-ground (7 mm screen size) wheat. Zimonja *et al*. (2008) reported that addition of finely ground oat hulls improved pellet durability while no such effect was observed for coarse oat hulls.

2.4.2.4. Manipulation of steam-conditioning process

Steam-conditioning has more impact on pellet quality than any other feed manufacturing process (Dozier, 2003).

I. Steam pressure

The most commonly used values for steam pressure in steam-delivery system range from 138 (20 psig) to 552 kPa (80 psig) which are generally referred to as low and high pressures (Cutlip *et al*., 2008). Briggs *et al*. (1999) studied the effect of steam pressure on pellet quality and found that pellet durability was not influenced by steam pressures of 138 and 552 kPa. Similar results were observed by Stevens (1987) who reported that steam pressures of 138 and 552 kPa during steam-conditioning at 65 ºC had no effect on PDI with either the maize- or wheat-based diets.

Cutlip *et al*. (2008) reported that high pressure conditioning (552 kPa) increased pellet durability compared to low pressure conditioning (138 kPa). However, pellet quality differences obtained with variations in steam pressure were not as dramatic as those associated with variations in steam-conditioning temperature. Increasing steam pressure from 138 to 552 kPa increased PDI only by a 0.5 percentage point.

The reason for the lack of effect of steam pressure may lie in the thermodynamic properties of steam (Briggs *et al*., 1999; Maier and Briggs, 2000). According to Briggs *et al*. (1999) and Maier and Briggs (2000), assuming that the steam enters the conditioner as saturated vapour (100% quality), there is only a 2.3% difference between the enthalpies of steam at 138 (1156.4 BTU) and 552 kPa (1183.6 BTU). A BTU (British Thermal Units) is "the quantity of heat required to raise the temperature of one pound of water by 1 ºF" (Dozier, 2003). Enthalpy represents steam energy that can be transferred to the mash to raise the temperature. Briggs *et al*. (1999) and Maier and Briggs (2000) recommended that feed mills should apply steam pressure between 138 and 552 kPa, such as 241 (35 psig) to 276 kPa (40 psig). Often, low pressure (138 kPa) steam cannot adequately separate the condensate collecting in the steam pipes, causing excessive water in the mash, which may lead to plugging of the pellet mill. Running high steam pressures, 552 kPa, is not economically acceptable due to high input energy required by the boiler (Briggs *et al*., 1999; Maier and Briggs, 2000).

II. Conditioning temperature

In a conventional pelleting process, increasing conditioning temperature can be performed by increasing steam flow rate. More steam means more heat and moisture, the two primary perquisites needed for feed particle adhesion, thus improving pellet quality. Skoch *et al.* (1981) reported that pellet durability was improved by steam-conditioning (90.6 and 93.8% in steam-conditioning at 65 and 78 ℃, respectively) compared to 69.5% in dry-conditioning. Spring *et al.* (1996) pelleted a barley-wheat-soy diet at 60, 70, 80, 90 and 100 ℃ and found that increasing pelleting temperatures increased pellet hardness with marked improvements at 90 ℃ (123%) and 100 ℃ (210%), compared to 60 ℃. This finding is in agreement with an earlier study by Pfost (1964), which demonstrated a positive effect of increasing conditioning temperature on pellet durability of turkey and layer diets. Raastad and Skrede (cited in Creswell and Bedford, 2006) reported that physical quality of the pellets (durability and hardness) was improved by increasing conditioning temperature from 69 to 78 and 86 ℃. Cutlip *et al.* (2008) reported that increasing conditioning temperature from 82.2 ℃ to 93.3 ℃ increased PDI by 4.0 percentage points. Although increasing the conditioning temperature improves the pellet quality, it should be noted that high heat and moisture applied during steam-conditioning may induce chemical changes which may be detrimental to nutrient availability and may reduce or completely negate the benefits of pelleting (Moritz and Lilly, 2010).

III. Retention time

The objective of steam-conditioning is to fully plasticise the feed particles and eliminate any dry core. This is accomplished by performing three unit operations: heating, hydrating, and mixing (Plattner, 2002). While heating and moisture addition are critical to pellet quality, good mixing is needed to bring the surface of the feed particles into contact with the added steam (Plattner, 2002). Longer retention time allows the moisture penetration (hydration) and heat transfer to be more uniform (Plattner, 2002). Increasing the residence time of the mash inside the steam conditioner, which may be accomplished by adjusting the mixer paddle configuration, slowing the rotational speed of the mixing paddle shaft, or using longer conditioners, improves pellet quality (Maier and Briggs, 2000). Briggs *et al.* (1999) showed that increasing the residence time of the mash inside the steam conditioner

by changing mixing paddle pitch resulted in an average 4.5 percentage point increase in PDI.

It has been suggested that as the hydration time of the feed particles is much longer than the time required to heat them, retention time of the feed inside the conditioner should be based on the time required for adequate hydration, not the time for adequate heating (Plattner, 2002).

2.4.2.5. Manipulating pellet press settings

I. Changing die specification

The effectiveness of frictional force generated inside the die hole during pelleting process on starch gelatinisation is well documented (Pfost, 1971; Heffner and Pfost, 1973; Skoch *et al.*, 1981; 1983a,b; Stevens, 1987). Longer die channels, through using thicker die, increase the frictional forces and the probability that binding will take place between the feed particles, so that pellet quality is improved (Löwe, 2005; Moritz and Lilly, 2010). The same effect can be reached if pellet dies with a small-hole diameter are used (Löwe, 2005). A recent study (Miladinovic and Svihus, 2010) demonstrated higher PDI due to the use of a greater die thickness (60 mm compared to 50 mm) while maintaining the same die-hole diameter (3.5 mm). Pfost (1964) showed a significant effect of increasing die thickness on pellet durability of non-fat supplemented diets, but not diets containing high levels of added fat. According to Heffner and Pfost (1973) there is a relationship between die hole diameter, starch gelatinisation and pellet durability. Reducing the die hole diameter can produce more gelatinised starch and more durable pellets. Cerrate *et al.* (2009) reported better pellet quality (determined as a percentage of retained pellets after shaking on a 2-mm screen sieve) in the diet pelleted using 1.59-mm diameter die hole compared to that of 3.17-mm diameter die hole (96 vs. 83%). A strong positive effect of decreased die hole diameter (from 5 mm to 3 mm) on PDI in maize-soy and maize-barley-soy diets has also been reported by Miladinovic and Svihus (2010). Stevens (1987) reported higher degree of gelatinisation in the outer portion of the pellet compared to the whole pellet. He suggested that heat and mechanical shear generated next to the surface of the die hole caused a substantial degree of the gelatinisation. Therefore, it is plausible that using dies with small

diameter holes enhances frictional forces and provides more frictional heat and gelatinisation to the core of the pellet.

II. Changing the gap between the pellet roller and pellet die

According to Miladinovic and Svihus (2010), in the gap between the pellet roller(s) and die wall, a layer of feed material with a specific thickness is formed. This layer of feed material and its thickness influence the formation and compaction of the material inside the die hole by roller/die frictional force. They showed that increasing the distance between roller and die from 0.1 mm to 2 mm, increased PDI which was more pronounced when feeder rate was reduced by 50%. Larger roller/die gap provides higher pressure on the material that enters the die hole as well as material in the hole, resulting in better compacting particles into the intact pellets and elevating physical pellet quality (Miladinovic and Svihus, 2010).

III. Increasing the gap between pellet die and knives (increasing pellet length)

The most sensitive part of the pellet is the surface of the break resulting from cutting the pressed and extruded feed into cylindrical pieces (Löwe, 2005; Miladinovic and Svihus, 2010). The number of these sensitive breaks depends on the pellet length. Short pellets yield a higher number per mass than longer pellets which means more possibilities to create abrasion and fines (Löwe, 2005). Wood (1987) reported a linear relationship (r = 0.89) between pellet length and durability, and observed that the variability in pellet length decreased with increasing durability. Pellet length is not usually considered when pellet quality is defined by durability and percentage of fines, but high quality pellets may be of longer length than pellets of lesser quality (Cutlip *et al*., 2008).

2.4.2.6. Decreasing production rate

According to Moritz and Lilly (2010), the primary reason for the production of poor quality pellets in many feed mills is that they usually operate above their intended capacity to meet the need for a high volume of feed to be manufactured within a given amount of time. Slower through-put allows for greater retention of feed inside the conditioner and the pellet die, resulting in an increased thermo-mechanical nutrient interaction and feed particle adhesion (Moritz and Lilly, 2010).

2.4.2.7. Manipulating cooling and drying system

When pellets leave the pellet mill, they are hot (65-85 ºC), moist (up to 170 g/kg moisture) and soft (Ziggers, 2004). Pellets that are not properly cooled can have a reduced quality due to stresses in the pellet between the (cooled) outer layer and the (still) warmer core (Thomas and van der Poel, 1996).

Cooling time is critical to manufacture high physical quality pellets. Up to a certain level, relative cool air takes up moisture and heat from the pellets during the cooling process. In a steady state, the same amount of moisture (and latent heat) is transported through capillaries from the core to the surface. If the pellets are cooled too quickly, more water and heat will be removed from the pellet surface than can be delivered by the capillaries; a brittle outer layer emerges with physical properties differing from those of the inner part, which is still warm, moist and viscous (Thomas and van der Poel, 1996; Ziggers, 2004). These differences in physical properties create stresses in the pellet which may cause the outer layer to crack (Thomas and van der Poel, 1996). These cracks will lead to higher abrasion and formation of fines (Thomas and van der Poel, 1996; Ziggers, 2004). Cooling for a long period favours pellet abrasion, because the pellets become too dry (Ziggers, 2004). It should also be noted that small pellets lose heat and moisture more quickly than large pellets (Ziggers, 2004). To ensure good storage quality, pellets should retain moisture content of not less than 140 g/kg (Ziggers, 2004).

2.4.3. Conclusions

-   The major aim of feed technology, from the nutritional point of view, is moulding a balanced mash diet to high physical quality pellets which are highly digestible.
-   There are several possible solutions which can be employed to increase the physical quality of the pellets. Potential negative effects of these solutions on nutrient availability, however, need careful consideration.

CHAPTER 3

General Materials and Methods

All experimental procedures described in this thesis were approved by the Massey University Animal Ethics Committee and complied with the New Zealand Revised Code of Ethical Conduct for the Use of Live Animals for Research, Testing and Teaching (Anonymous, 2008).

3.1. Birds and Housing

Day-old male broilers (Ross 308) were obtained from a commercial hatchery, individually weighed and assigned to the cages (eight birds per cage) in electrically heated battery brooders so that the average total bird weight per cage was similar. The birds were transferred to grower cages on d 12 and were maintained on the same diets until d 21. The battery brooders and grower cages were housed in an environmentally controlled room with 20 h of fluorescent illumination per day. The temperature was maintained at 31 ℃ on d 1, and was gradually reduced to 22 ℃ by 21 d of age. Body weights and feed intake were recorded on a cage basis at weekly intervals throughout the trial. Mortality was recorded daily. Feed per gain values were corrected for the body weight of any bird that died during the course of the experiment.

3.2. Apparent metabolisable energy (AME) determination

Feed intake and total excreta output of each cage were measured from d 17 to 20 posthatch. Excreta from each cage were pooled, mixed in a blender and sub-sampled. Each sub-sample was freeze-dried, ground to pass through a 0.5-mm sieve and stored in airtight plastic containers at -4 ℃ pending analysis. The diets and excreta samples were analysed for dry matter (DM) and gross energy (GE).

3.3. Ileal digesta collection

For ileal digesta collection, four birds from each cage were euthanised by intravenous injection (1 ml per 2 kg body weight) of sodium pentobarbitone (Provet NZ Pty. Ltd., Auckland, New Zealand). Immediately after euthanasia, the ileum was excised and divided into two parts, the anterior and posterior ileum. The ileum was defined as the portion of the

small intestine extending from Meckel's diverticulum to a point 40 mm proximal to the ileo-caecal junction. Contents of the posterior ileum were collected by gently flushing with distilled water into plastic containers. Digesta were pooled within a cage, lyophilised, ground to pass through a 0.5-mm sieve, and stored at -4 ℃ in airtight plastic containers until laboratory analysis. The diets and digesta samples were analysed for DM, titanium (Ti), nitrogen (N) and starch.

3.4.   Chemical analysis

Dry matter content of the diets, excreta and ileal digesta samples was determined using standard procedures (method 930.15; AOAC, 2005). Duplicate samples were weighed and placed in a drying oven for 24 h at 105 ℃ and the weight was recorded after two hours in a desiccator at room temperature.

Gross energy of the diets and excreta samples was determined by adiabatic bomb calorimetry (Gallenkamp Autobomb, London, UK) standardised with benzoic acid. Diets and ileal digesta samples were assayed for Ti on a UV spectrophotometer following the method of Short et al. (1996).

Nitrogen content of the diets and ileal digesta samples was determined by combustion (method 968.06; AOAC, 2005) using a CNS-200 carbon, nitrogen, and sulphur auto analyser (LECO® Corporation, St. Joseph, MI, USA). Pre-weighed samples were placed into a furnace at 850 ℃ with excess oxygen (O_2) and totally combusted. The combustion products, mainly carbon dioxide (CO_2), water (H_2O), nitrous oxides (NO_x) and nitrogen gas (N_2) were passed through a series of columns to remove H_2O, convert NOx to N_2, and to remove the remaining oxides and excess O_2. The gaseous N_2, carried by helium, was then measured by thermal conductivity and expressed as a percentage of the sample.

Starch content of the diets and ileal digesta samples was measured using an assay kit (Megazyme International Ireland Ltd., Wicklow, Ireland) based on thermostable alpha-amylase and amyloglucosidase (McCleary et al., 1997).

Gelatinised and resistant starch contents of the diets were determined using assay kits (Megazyme International Ireland Ltd., Wicklow, Ireland).

Insoluble, soluble and total NSP contents of the diets were determined using an assay kit (Megazyme International Ireland Ltd., Wicklow, Ireland) based on thermostable alpha-amylase, protease and amyloglucosidase.

3.5. Calculations

The AME values of the diets were calculated using the following formula with appropriate corrections made for differences in DM content.

AME (MJ/kg diet) = [(Feed intake x GE_{diet})-(Excreta output x $GE_{excreta}$)] / Feed intake

Apparent ileal nutrient (N and starch) digestibility coefficients were calculated using the following formula:

Apparent ileal nutrient digestibility = [(Nutrient/Ti)d - (Nutrient/Ti)i] / (Nutrient/Ti)d

Where (Nutrient/Ti)d = ratio of nutrient to Ti in the diet, and

(Nutrient/Ti)i = ratio of nutrient to Ti in the ileal digesta.

3.6. Digestive tract measurements

In all experiments, two birds, with body weights closest to the mean weight of the cage, were selected from each replicate cage and sacrificed by cervical dislocation. The live weight and weight of digestive tract segments from proventriculus to caeca of each bird were determined. The length of each intestinal segment was determined with a flexible tape on a wet glass surface to prevent inadvertent stretching. The length (± 0.1 cm) of the duodenum (from the pyloric junction to the distal-most point of insertion of the duodenal mesentery), the length of the jejunum (from the distal-most point of insertion of the duodenal mesentery to the junction with Meckel's diverticulum), the length of the ileum (from the junction with Meckel's diverticulum to ileocaecal junction) and the sum of the lengths from ostium to tip of each caeca were determined. Following division and freeing of each of these components from any adherent mesentery, their full and empty weights (± 0.1 g) were determined along with those of the proventriculus and gizzard. The weights (± 0.1 g) of liver, spleen and pancreas were also determined.

3.7. Pellet durability

Pellet durability was determined using a Holmen Pellet Tester (New Holmen NHP100 Portable Pellet Durability Tester, TekPro Limited, Willow Park, North Walsham, Norfolk, UK). Clean pellet (i.e. no fines) samples (100 g) were rapidly circulated in an air stream around a perforated test chamber for 30 seconds. Fines were removed continuously through

the perforations during the test cycle. After the test cycle the subject pellets were ejected and weighed manually. Pellet durability index (%) was calculated as the ratio of the pellets not passing through the perforations after test to whole pellets at the start.

3.8.   Pellet hardness

Pellet hardness was tested in a Stable Micro Systems Texture Analyser (TA-XT Plus, Godalming, Surrey, UK) using the method described by Svihus *et al*. (2004). Individual pellet samples (15 per diet) were inserted between a pressure piston and a bar and by increasing pressure applied by means of the pressure piston, the force (Newton) needed to break the pellets was determined.

3.9.   Statistical analysis

The data were analysed by two-way analysis of variance (ANOVA) using the General Linear Models procedure of SAS (2004). Differences were considered to be significant at P < 0.05 and significant differences between means were separated by the Least Significant Difference (LSD) test.

Gross digestive tract measurements of individual birds were subjected to a two-way ANOVA and differences were considered to be significant at P < 0.05 and significant differences between means were separated by the LSD test. A similar model was used for analysis of digesta contents.

CHAPTER 4

Influence of conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed maize- and wheat-based diets[1]

4.1.   Abstract

The influence of conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed maize- and wheat-based diets was examined in this study. The experimental design was a 2×3 factorial arrangement of treatments evaluating two grain types (maize and wheat) and three conditioning temperatures (60, 75 and 90 ℃). Broiler starter diets, each based on one grain (maize or wheat), were formulated and pelleted at the three temperatures. Increasing conditioning temperatures decreased ($P < 0.05$) the weight gain and feed intake in wheat-based diets, but birds fed maize-based diets conditioned at 60 and 90 ℃ had higher ($P < 0.05$) weight gain and feed intake than those fed the diet conditioned at 75 ℃. Increasing conditioning temperatures increased ($P < 0.001$) the feed per gain. Increasing conditioning temperatures improved ($P < 0.05$) pellet durability index (PDI) in wheat-based diets, but had no effect ($P > 0.05$) on PDI in maize-based diets. In wheat-based diets, increasing conditioning temperatures decreased ($P < 0.05$) the ileal digestibility of nitrogen (N) and starch. Ileal N digestibility of maize-based diets conditioned at 60 and 90 ℃ was higher ($P < 0.05$) than the diet conditioned at 75 ℃. Starch digestibility was unaffected ($P > 0.05$) by conditioning temperature in maize-based diets. No effect ($P > 0.05$) of conditioning temperature was found for apparent metabolisable energy (AME). Increasing conditioning temperatures decreased ($P < 0.05$) digestible protein and AME intakes in wheat-based diets, but in maize-based diets, birds fed the diet conditioned at 75 ℃ had lower ($P < 0.05$) digestible protein and AME intakes compared to those fed diets conditioned at 60 and 90 ℃. Small intestine was found to be longer ($P < 0.01$) in birds fed diets conditioned at 75 and 90 ℃ compared to those fed diets conditioned at 60 ℃. Increasing conditioning temperatures increased ($P < 0.001$) the digesta content in the gizzard. Overall, the present data suggest that while the effects of conditioning temperature on weight gain and feed intake of broiler

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starters differed depending on the grain type, feed per gain values were adversely affected by higher conditioning temperatures.

4.2.   Introduction

The technology of poultry feed processing involves a wide range of thermal treatments including extrusion, expansion, conditioning and pelleting. Although pelleting represents the greatest energy expenditure in the feed manufacturing process, when the cost-benefit is considered, pelleting is cost effective and the most widely used thermal processing method. The main aim of pelleting is to agglomerate smaller feed particles by the use of mechanical pressure, moisture and heat (Peisker, 2006). A major step in the pelleting process is conditioning of mash prior to pelleting (Skoch *et al*., 1981), which is generally accomplished by adding steam to the mash feed to be pelleted. Steam has the ability to provide the proper balance of heat and moisture and, because it is relatively inexpensive, easy to introduce and easy to control, it has presented itself as an important component in pelleting process (Wellin, 1976; Behnke and Beyer, 2002).

Offering feed to poultry in pellet form enhances the economics of production by improving feed efficiency and growth performance in broilers (Behnke and Beyer, 2002). These improvements are attributed to decreased feed wastage, higher bulk and nutrient density, no selective feeding, decreased time and energy spent for eating, decreased ingredient segregation, destruction of feed-borne pathogens, thermal modification of starch and protein, improved palatability and inactivation of enzyme inhibitors (Behnke, 1994; Jensen, 2000; Peisker, 2006).

On the other hand, pelleting may result in poor broiler performance if the appropriate temperature is not used during conditioning. Bedford (cited in Creswell and Bedford, 2006) reported a significant reduction in weight gain and increase in feed per gain of broilers fed maize-based diets with pelleting temperature at 93 ℃ compared to 85 ℃. In another study reported by Bedford *et al*. (2003), the negative effects of higher temperature in wheat-based diets were evident once pelleting temperature exceeded 65 ℃. Loss of lysine and arginine due to Maillard complexing with sugars, retrogradation of starch into enzyme-resistant starch which causes loss of available energy, increased viscosity due to solubilisation of non-starch polysaccharides (NSP) and loss of heat-labile vitamins,

exogenous enzymes and crystalline amino acids, are some of the known negative effects of high conditioning temperatures (Creswell and Bedford, 2006).

The ever-increasing cost of feed ingredients underlines the opportunity in feed processing technology to influence broiler performance by increasing the feed value and reducing the cost of feed. Despite its importance, the effects of conditioning temperature on poultry performance have not received much attention. The objectives of the present experiment were to compare the interaction between grain type and conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters and on the quality of pellets.

4.3.   Materials and Methods

4.3.1.   Diets

The experimental design was a 2 × 3 factorial arrangement of treatments evaluating two grain types and three conditioning temperatures. Two diets, each based on one of the grains (maize or wheat), were formulated to meet the Ross 308 strain recommendations for major nutrients for broiler starters (Ross, 2007; Table 4.1). Both diets were isocaloric and isonitrogenous. Each formulated diet was then divided into three equal batches and conditioned at three different temperatures (60, 75 and 90 ºC) by adjusting the steam flow rate. Conditioning time of the mash was 30 seconds and the conditioning temperature was measured at the outlet (close to the exit point) of the conditioner before the mash feed entered the die. The diets were pelleted using a pellet mill (Richard Size Limited Engineers, Orbit 15, Kingston-upon-Hull, UK) capable of manufacturing 180 kg of feed/h and equipped with a die ring (3-mm holes and 35-mm thickness). Representative samples were collected after pelleting for the determination of pellet durability. All diets were manufactured and stored for two weeks prior to the start of the trial and then, prior to feeding, dry matter (DM) content of all diets were determined to ensure that feed intake measurements were not biased by differences in DM content.

4.3.2.   Birds and Housing

Two hundred and eighty eight day-old male broilers (Ross 308), obtained from a commercial hatchery, were allocated to 36 cages as described in Chapter 3. Each of the six

dietary treatments was then randomly assigned to six cages, each housing eight birds. Feed was offered *ad libitum* and water was freely available throughout the trial. Housing conditions were as described in Chapter 3, section 3.1.

Table 4.1. Composition and calculated analysis (g/kg as fed) of the basal diets

Ingredient	Maize-based diet	Wheat-based diet
Maize	617.5	-
Wheat	-	647.2
Soybean meal, 48%	278.6	228.4
Meat and bone meal	80.0	80.0
Soybean oil	8.7	27.6
Limestone	2.3	2.1
Salt	1.6	1.5
Sodium bicarbonate	0.9	0.1
Lysine. HCl	2.3	3.7
DL-methionine	2.0	2.6
L-threonine	0.1	0.8
Trace mineral- vitamin premix[1]	3.0	3.0
Titanium dioxide	3.0	3.0
Calculated analysis		
Metabolisable energy, MJ/kg	12.6	12.6
Crude protein	230	230
Lysine	13.8	13.8
Methionine	5.5	5.6
Methionine + cysteine	9.2	9.2
Threonine	8.5	8.5
Calcium	10.0	10.0
Available phosphorus	5.2	5.2
Sodium	1.6	1.6
Chloride	1.9	1.9
Potassium	8.5	8.4

[1]Supplied per kilogram of diet: antioxidant, 100 mg; biotin, 0.2 mg; calcium pantothenate, 12.8 mg; cholecalciferol, 60 µg; cyanocobalamin, 0.017 mg; folic acid, 5.2 mg; menadione, 4 mg; niacin, 35 mg; pyridoxine, 10 mg; trans-retinol, 3.33 mg; riboflavin, 12 mg; thiamine, 3.0 mg; dl-α-tocopheryl acetate, 60 mg; choline chloride, 638 mg; Co, 0.3 mg; Cu, 3.0 mg; Fe, 25 mg; I, 1 mg; Mn, 125 mg; Mo, 0.5 mg; Se, 200 µg; Zn, 60 mg.

4.3.3.   Performance data

Performance data were recorded as described in Chapter 3, section 3.1.

4.3.4.   Pellet durability

Pellet durability index (PDI) was measured as described in Chapter 3, section 3.7.

4.3.5. Apparent metabolisable energy (AME) determination

The AME determination was carried out between d 17 to 20 posthatch as described in Chapter 3, section 3.2.

4.3.6. Ileal digestibility determination

On d 21, digesta collection was carried out and processed as described in Chapter 3, section 3.3.

4.3.7. Digestive tract measurements

On d 21, two more birds per cage were euthanised by cervical dislocation and digestive tract measurements were carried out as described in Chapter 3, section 3.6.

4.3.8. Chemical analysis

Dry matter, nitrogen (N), gross energy (GE), titanium (Ti), starch and, insoluble, soluble and total NSP contents were determined as described in Chapter 3, section 3.4.

4.3.9. Calculations

The AME values of the diets and apparent ileal nutrient (N and starch) digestibility coefficients were calculated using the formula described in Chapter 3, section 3.5.

4.3.10. Data analysis

The data were analysed as a 2×3 factorial arrangement of treatments, as described in Chapter 3, section 3.9. The cage means were used to derive performance data. For digestive tract measurements, individual birds were considered as the experimental unit.

4.4. Results

4.4.1. Performance and pellet durability index

Mortality during the performance experiment was negligible. Only four out of the 288 birds died and the deaths were not related to any specific treatment. Increasing conditioning

temperatures decreased the weight gain and feed intake in wheat-based diets, whereas the weight gain and feed intake of birds fed maize-based diets conditioned at 60 and 90 °C were similar, but higher than those fed the diet conditioned at 75 °C, resulting in a grain type x conditioning temperature interaction (P < 0.01, weight gain; P < 0.05, feed intake; Table 4.2).

Table 4.2. Influence of grain type and conditioning temperature on weight gain (g/bird), feed intake (g/bird), feed per gain (g feed/g gain) of broiler starters[1] and PDI (%)

	Conditioning temperature, °C	Weight gain	Feed intake	Feed per gain	PDI[2]
Maize	60	1040^a	1272^{bc}	1.228	81.4^{bc}
	75	960^b	1203^d	1.265	81.6^{bc}
	90	1015^a	1279^b	1.261	79.3^{cd}
Wheat	60	1021^a	1338^a	1.315	76.7^d
	75	925^c	1235^{cd}	1.344	82.7^{ab}
	90	908^c	1255^{bc}	1.383	85.1^a
SEM[3]		11.6	14.9	0.0094	0.94
Main effects					
Grain type					
Maize		1005	1251	1.251^b	80.7
Wheat		951	1276	1.347^a	81.5
Conditioning temperature, °C					
60		1030	1305	1.272^b	79.0
75		942	1219	1.304^a	82.1
90		961	1267	1.322^a	82.2
Probabilities, P ≤					
Grain type		***	NS	***	NS
Conditioning temperature		***	***	***	**
Grain type x Conditioning temperature		**	*	0.06	***

[a,b,c,d] Means in a column not sharing a common superscript are significantly different (P < 0.05).
NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.
[1] Each value represents the mean of six replicates (eight birds per replicate).
[2] Each value represents the mean of six replicate samples.
[3] Pooled standard error of mean.

Birds fed maize-based diets had a lower (P < 0.001) feed per gain compared to those fed wheat-based diets. Increasing conditioning temperatures increased (P < 0.001) the feed

per gain, with birds fed diets conditioned at 75 and 90 ºC having higher feed per gain than those fed diets conditioned at 60 ºC. There was, however, a tendency (P = 0.06) for a grain type x conditioning temperature interaction due to the magnitude of changes with increasing conditioning temperatures differing in the two grain types. Increments in feed per gain with increasing conditioning temperatures tended to be greater in wheat-based diets.

There was a grain type x conditioning temperature interaction (P < 0.001) for the PDI. Increasing conditioning temperatures improved PDI in wheat-based diets, but had no effect in maize-based diets.

4.4.2.   Nutrient utilisation, and digestible protein and AME intakes

The influence of the dietary treatments on the apparent ileal digestibility of N and starch, AME, and digestible protein and AME intakes during the 21-d trial period is summarised in Table 4.3. A grain type x conditioning temperature interaction (P < 0.05) was observed for the ileal N digestibility. Increasing conditioning temperatures decreased ileal N digestibility in wheat-based diets, whereas the digestibility of maize-based diets conditioned at 60 and 90 ºC was similar, but higher than the diet conditioned at 75 ºC.

Ileal starch digestibility was unaffected by conditioning temperature in maize-based diets, but reduced with increasing conditioning temperature in wheat-based diets, resulting in a grain type x conditioning temperature interaction (P < 0.01).

The main effect of grain type was significant (P < 0.001) for AME, with greater AME values determined for maize-based diets. The main effect of conditioning temperature and interaction between grain type and conditioning temperature were not significant (P > 0.05) for AME.

Increasing conditioning temperatures decreased the intake of ileal digestible protein and AME in wheat-based diets, but in maize-based diets, birds fed diet conditioned at 75 ºC had a lower digestible protein and AME intakes compared to those fed diets conditioned at 60 and 90 ºC, resulting in a grain type x conditioning temperature interaction (P < 0.001, digestible protein intake; P < 0.05, AME intake).

Table 4.3. Influence of grain type and conditioning temperature on ileal N digestibility, ileal starch digestibility, AME (MJ/kg DM), digestible protein intake (g/bird) and AME intake (MJ/bird, 1-21 d posthatch) in broiler starters[1]

	Conditioning temperature, ℃	Ileal N digestibility	Ileal starch digestibility	AME	Digestible protein intake	AME intake
Maize	60	0.843^a	0.970^a	14.16	247^a	16.26^a
	75	0.819^{bc}	0.975^a	14.19	227^b	15.30^b
	90	0.848^a	0.976^a	14.27	249^a	16.16^a
Wheat	60	0.823^b	0.933^b	13.08	253^a	15.77^{ab}
	75	0.811^{bc}	0.922^b	13.18	230^b	14.54^c
	90	0.802^c	0.898^c	13.10	232^b	14.58^c
SEM[2]		0.0060	0.0056	0.071	2.8	0.184
Main effects						
Grain type						
Maize		0.837	0.974	14.21^a	241	15.91
Wheat		0.812	0.918	13.12^b	238	14.96
Conditioning temperature, ℃						
60		0.833	0.952	13.62	250	16.01
75		0.815	0.948	13.68	229	14.92
90		0.825	0.937	13.69	241	15.37
Probabilities, P ≤						
Grain type		***	***	***	NS	***
Conditioning temperature		*	*	NS	***	***
Grain type x Conditioning temperature		*	**	NS	***	*

[a,b,c] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of six replicates.

[2] Pooled standard error of mean.

4.4.3. Digestive tract measurements

The effects of the dietary treatments on the relative length, relative digesta content, relative empty weight of intestinal segments and relative organ weights are shown in Tables 4.4 and 4.5. Grain type had no significant (P > 0.05) effect on the relative length of any intestinal segments. A significant (P < 0.05 to 0.01) main effect of conditioning temperature was

observed for the relative length of intestinal segments. Small intestine was longer in birds fed diets conditioned at 75 and 90 ºC compared to those fed diets conditioned at 60 ºC. There was no interaction (P > 0.05) between grain type and conditioning temperature for relative length of intestinal segments. Neither the main effects nor their interaction was significant (P > 0.05) for relative length of caeca.

Increasing conditioning temperatures markedly increased relative digesta content of proventriculus in birds fed wheat-based diets, but had no effect on the digesta content of birds fed maize-based diets, resulting in a grain type x conditioning temperature interaction (P < 0.01).

Birds fed maize-based diets had higher (P < 0.001) relative digesta content in the gizzard compared with those fed wheat-based diets. Increasing conditioning temperatures increased (P < 0.001) the relative digesta content in the gizzard, of birds fed diets conditioned at 60 ºC having a lower digesta content compared to those fed diets conditioned at 75 and 90 ºC. However, there was also a tendency (P = 0.08) for an interaction between grain type and conditioning temperature.

Numerical, though not statistically significant, increases were observed in the relative digesta content of small intestine in birds fed maize-based diets, while the reverse was observed in birds fed wheat-based diets, resulting in a grain type x conditioning temperature interaction (P < 0.05). The main effects and their interaction were not significant (P > 0.05) for relative digesta content of caeca.

Relative weight of proventriculus was affected (P < 0.05) by the grain type, with heavier proventriculus in birds fed maize-based diets than those fed wheat-based diets (Table 4.5). A significant grain type x conditioning temperature interaction (P < 0.001) was observed for relative weight of gizzard, because the magnitude of increase in gizzard weight with increasing conditioning temperature was greater in maize-based diets.

Conditioning temperature significantly (P < 0.01) affected relative weight of duodenum, with heavier duodenum in birds fed diets conditioned at 75 ºC compared to those fed diets conditioned at 60 and 90 ºC.

Relative weight of caeca was influenced (P < 0.05) by the grain type, with greater weight in birds fed wheat-based diets than maize-based diets. There was no effect (P > 0.05) of conditioning temperature or interaction for caeca weight.

Conditioning temperature tended (P = 0.06) to affect the relative weight of liver, with liver weight being higher at conditioning temperatures above 60 ℃. No significant (P > 0.05) effect of grain type or interaction was observed. Neither the main effects nor their interaction was significant (P > 0.05) for relative weight of spleen. Birds fed maize-based diets had higher (P < 0.01) pancreas weight than those fed wheat-based diets. No effect (P > 0.05) of conditioning temperature or interaction was observed.

4.4.4.   Non-starch polysaccharide content

The influence of the dietary treatments on insoluble, soluble and total NSP contents of the diets is shown in Table 4.6. While insoluble NSP content of maize-based diet conditioned at 75 ℃ was lower than those conditioned at 60 and 90 ℃, in wheat-based diets, increasing conditioning temperatures increased the insoluble NSP content, resulting in a grain type x conditioning temperature interaction (P < 0.01).

Wheat-based diets had higher soluble (P < 0.05) and total (P < 0.01) NSP contents than maize-based diets. Soluble and total NSP contents were not influenced (P > 0.05) by conditioning temperature or interaction.

Table 4.4. Influence of grain type and conditioning temperature on relative length (cm/kg body weight) and digesta content (g/kg body weight) of the digestive tract of broiler starters[1]

	Conditioning temperature, ºC	Relative length					Relative digesta content			
		Duodenum	Jejunum	Ileum	Small intestine[2]	Caeca	Proventriculus	Gizzard	Small intestine[2]	Caeca
Maize	60	23.6	57.8	61.3	143	13.2	0.891[b]	8.90	34.2[c]	1.352
	75	25.3	63.3	66.3	155	13.9	0.825[b]	11.9	35.9[c]	1.349
	90	24.0	62.9	66.9	152	13.2	0.501[b]	11.8	37.7[bc]	1.562
Wheat	60	22.8	59.3	60.6	144	13.6	0.772[b]	4.10	43.8[a]	1.565
	75	24.9	63.3	63.2	151	14.2	1.883[a]	6.20	42.9[a]	1.745
	90	24.0	62.2	64.4	151	14.0	1.826[a]	10.0	40.7[ab]	1.502
SEM[3]		0.59	1.42	1.67	3.3	0.36	0.2201	0.90	1.27	0.2048
Main effects										
Grain type										
Maize		24.3	61.3	64.8	150	13.4	0.739	10.9[a]	35.9	1.421
Wheat		23.9	61.6	62.7	149	13.9	1.505	6.75[b]	42.4	1.603
Conditioning temperature, ºC										
60		23.2[b]	58.5[b]	60.9[b]	143[b]	13.4	0.831	6.63[b]	38.8	1.463
75		25.1[a]	63.3[a]	64.8[a]	153[a]	14.1	1.377	9.17[a]	39.4	1.532
90		24.0[ab]	62.5[a]	65.7[a]	151[a]	13.6	1.164	10.9[a]	39.2	1.547
Probabilities, P ≤										
Grain type		NS	NS	NS	NS	NS	***	***	***	NS
Conditioning temperature		**	**	*	**	NS	0.06	***	NS	NS
Grain type x Conditioning temperature		NS	NS	NS	NS	NS	**	0.08	*	NS

[a,b,c] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of 12 birds.

[2] Small intestine = duodenum + jejunum + ileum.

[3] Pooled standard error of mean.

Table 4.5. Influence of grain type and conditioning temperature on relative empty weight (g/kg body weight) of the digestive tract and relative organ weights (g/kg body weight) of broiler starters[1]

	Conditioning temperature, ºC	Relative empty weight							Relative organ weight		
		Proventriculus	Gizzard	Duodenum	Jejunum	Ileum	Small intestine[2]	Caeca	Liver	Spleen	Pancreas
Maize	60	3.81	11.7^b	5.41	8.96	6.36	20.7	1.130	26.4	0.834	2.68
	75	4.06	15.4^a	5.71	9.22	6.32	21.1	1.158	27.4	0.866	2.82
	90	3.90	15.4^a	5.37	9.33	6.43	21.1	1.232	28.1	0.880	2.89
Wheat	60	3.70	9.80^d	5.10	8.99	6.28	20.8	1.201	26.2	0.729	2.49
	75	3.67	10.6^{cd}	5.92	9.73	6.93	22.1	1.303	26.9	0.858	2.56
	90	3.75	11.1^{bc}	5.36	9.65	6.73	21.5	1.223	27.4	0.823	2.58
SEM[3]		0.113	0.39	0.185	0.293	0.222	0.52	0.0421	0.61	0.0459	0.093
Main effects											
Grain type											
Maize		3.92^a	14.1	5.50	9.17	6.37	20.9	1.173^b	27.3	0.860	2.79^a
Wheat		3.71^b	10.5	5.46	9.46	6.65	21.5	1.242^a	26.9	0.804	2.54^b
Conditioning temperature, ºC											
60		3.76	10.8	5.27^b	8.98	6.32	20.8	1.165	26.3	0.784	2.59
75		3.86	13.0	5.81^a	9.47	6.63	21.6	1.230	27.2	0.862	2.69
90		3.82	13.1	5.37^b	9.49	6.59	21.3	1.228	27.7	0.852	2.73
Probabilities, P ≤											
Grain type		*	***	NS	NS	NS	NS	*	NS	NS	**
Conditioning temperature		NS	***	**	NS	NS	NS	NS	0.06	NS	NS
Grain type x Conditioning temperature		NS	***	NS	NS	NS	NS	NS	NS	NS	NS

a,b,c,d Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of 12 birds.

[2] Small intestine = duodenum + jejunum + ileum.

[3] Pooled standard error of mean.

Table 4.6. Influence of grain type and conditioning temperature on insoluble, soluble and total NSP contents (g per 100 g, DM) of the diets[1]

	Conditioning temperature, ºC	Insoluble NSP	Soluble NSP	Total NSP[2]
Maize	60	11.6^c	1.37	12.9
	75	10.1^d	0.90	11.0
	90	11.7^{bc}	1.36	13.1
Wheat	60	12.1^b	1.83	14.0
	75	12.8^a	2.58	15.4
	90	13.0^a	2.76	15.7
SEM[3]		0.15	0.486	0.64
Main effects				
Grain type				
Maize		11.1	1.21^b	12.3^b
Wheat		12.6	2.39^a	15.0^a
Conditioning temperature, ºC				
60		11.8	1.60	13.4
75		11.4	1.74	13.2
90		12.3	2.06	14.4
Probabilities, P ≤				
Grain type		***	*	**
Conditioning temperature		**	NS	NS
Grain type x Conditioning temperature		**	NS	NS

[a,b,c,d] Means in a column not sharing a common superscript are significantly different ($P < 0.05$).

NS, not significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

[1] Each value represents the mean of four replicates.

[2] Total NSP = Insoluble NSP + Soluble NSP.

[3] Pooled standard error of mean.

4.5. Discussion

Increasing conditioning temperatures reduced weight gain and feed intake and increased feed per gain in birds fed wheat-based diets. These results agree with those of Bedford *et al*. (2003) who reported a significant depression for weight gain and feed per gain in birds fed

wheat-based diets once pelleting temperature exceeded 65 ℃. The aggressive effect of higher conditioning temperatures on broiler performance was partly attributed by Creswell and Bedford (2006) to an increase in feed viscosity by conditioning temperature. In their study, extract viscosity of the diet was increased by pelleting temperature from 6.5 cPs at 65 ℃ to 7.0, 8.5, 9.3 and 15.2 cPs at conditioning temperatures of 75, 85, 95 and 105 ℃, respectively, due likely to xylan solubilisation and starch gelatinisation. Increased diet viscosity following increasing conditioning temperature was also reported by Cowieson *et al*. (2005b), which was attributed to an increased release of NSP. In the present study, however, soluble NSP content was unaffected by increasing conditioning temperatures. It is noteworthy; however, that viscosity is a composite of soluble carbohydrate concentration and the degree of polymerisation or the molecular weight of carbohydrates (Izydorczyk and Biliaderis, 1992; Cowieson *et al*., 2005b). The viscosity of a solution can be extremely high, even if the solution contains a low concentration of soluble polysaccharides, if the soluble polysaccharides are of a sufficiently high molecular weight (Cowieson *et al*., 2005b). As increasing conditioning temperature can destroy the activity of diet endogenous (Silversides and Bedford 1999; Cowieson *et al*., 2005b) and microbial enzymes (Cowieson *et al*., 2005b) which degrade xylan (Silversides and Bedford 1999; Cowieson *et al*., 2005b), thus contributes to an increase in molecular weight (i.e. less depolymerisation of carbohydrates). Therefore, it is possible to have increased feed viscosity in wheat-based diets conditioned at higher temperatures despite the lack of influence on soluble NSP contents.

Negative effects of higher pelleting temperatures on the weight gain and feed per gain of birds fed maize-based diets have also been reported previously (Creswell and Bedford, 2006). In the present study, feed per gain of birds fed maize-based diets was increased with increasing conditioning temperatures. However, birds fed maize-based diet conditioned at 90 ℃ had higher weight gain and feed intake than those fed diet conditioned at 75 ℃. The reasons for these unexpected findings are unclear, but frictional heat and mechanical shear generated between the die holes and pellets may provide a plausible explanation. During the pelleting process, feed is subjected to two different sources of heat, namely, the heat from the steam injected into the feed in the conditioning chamber and the heat which is produced in the die hole due to friction force and transferred to the feed

passing through the die. In other words, the chemical changes that happen during the pelleting process are caused by these two sources of heat. As conditioning at 90 ºC was accompanied by higher moisture, it may be speculated that the lubricating effect of condensed steam may have decreased the friction through the die, decreasing the heat generated in the die and decreasing the negative effect of the die friction heat on heat-labile nutrients in the feed resulting in higher feed intake and weight gain.

Although wheat has a higher dough-forming capability than maize due to high levels of gluten proteins and pentosan/hexosan hemicelluloses that serve as good pellet binders (Jensen, 2000), pellet durability of wheat-based diets was found to be similar to that of maize-based diets. In contrast, Stevens (1987) and Winowiski (1988) compared pellet durability of diets based on maize and wheat, and reported higher pellet durability for wheat-based diets. It is possible that the higher inclusion (27.6 g/kg) of soybean oil in wheat-based diets compared to maize-based diets (8.7 g/kg) may have contributed to the lack of differences in PDI in the present study.

Increasing conditioning temperatures improved the PDI of wheat-based diets, but had no effect in maize-based diets. This finding may be explained by differences in gelatinisation characteristics of wheat and maize starches, with wheat starch having a lower temperature of gelatinisation (52-65 ºC) than maize (65-77 ºC) (Lund, 1984). In present study, conditioning at 90 ºC probably supplied more heat above the gelatinisation temperature for wheat starch than maize starch, and resulted in an improved PDI in wheat-based diets. However, it should be noted that due to the low moisture content during conditioning, the degree of gelatinisation in pellet diets is usually low and components other than gelatinised starch are major contributors to physical quality of pellets (Svihus *et al.*, 2004). It is noteworthy that in spite of an improvement in PDI of wheat-based diets with increasing conditioning temperature in the present study, weight gain and feed intake of the birds fed these diets were negatively affected. Thus, although it is generally believed that high pellet durability is associated with better performance of birds fed pellet diets (Greenwood and Beyer, 2003; Cutlip *et al.*, 2008), it is evident that high pellet durability did not overcome the negative effects of high conditioning temperature on bird performance in the present study, at least in wheat-based diets.

Increasing conditioning temperatures in wheat-based diets were accompanied by reductions in apparent ileal digestibility of both N and starch, especially at 90 ℃. In maize-based diets, ileal starch digestibility was unaffected by conditioning temperature. However, ileal N digestibility of the maize-based diet conditioned at 75 ℃ was lower than those conditioned at 60 and 90 ℃. These results may suggest that in wheat-based diets the broiler performance was related to changes in N and starch digestibility, whereas, in maize-based diets, changes in N digestibility appear to be of greater importance than the starch digestibility. Increasing conditioning temperature in wheat-based diets decreased digestible protein intake, but birds fed maize-based diet conditioned at 75 ℃ had a lower digestible protein intake compared to those fed diets conditioned at 60 and 90 ℃. These findings were closely associated with the observed changes in feed intake with increasing conditioning temperatures.

Increasing conditioning temperatures had no effect on the AME. Grain type x conditioning temperature interaction was not observed for AME. But when the AME intake is considered, increasing conditioning temperatures in wheat-based diets decreased the AME intake, and birds fed maize-based diet conditioned at 75 ℃ had a lower AME intake compared with those fed diets conditioned at 60 and 90 ℃. Similar to digestible protein intake, the pattern of changes in AME intake was determined largely by changes in feed intake, indicating that conditioning temperature influences nutrient intake through its effect on feed intake.

Small intestine was longer in birds fed diets conditioned at 75 and 90 ℃ compared to those fed diets conditioned at 60 ℃. It seems that in birds fed diets conditioned at temperatures above 60 ℃ the length of small intestine is increased as a response to the decreased nutrient digestibility at higher temperatures. Similar to these findings, Amerah *et al*. (2007b) reported that improvement in bird performance due to pelleting was accompanied by a decrease in the relative length of all segments of the intestinal tract.

Relative gizzard weight was influenced by the interaction between grain type and conditioning temperature. Heavier gizzards and greater gizzard digesta contents in birds fed wheat-based diets conditioned at higher temperatures may be related to the increased PDI of these diets which may increase grinding requirements of the gizzard.

The reasons for the quadratic effects of conditioning temperature on insoluble NSP contents of maize-based diets are unclear. However, it is unlikely that the decrease of 1.5 g insoluble NSP/100 g of the diet conditioned at 75 ºC will be of any practical significance. The observed increase in insoluble NSP content of wheat-based diets at higher conditioning temperatures may not reflect an increase *per se*, but may be related to the destruction of endogenous xylanase and the resultant reduction in solubilisation.

4.6. Conclusions

It is evident from this study that increasing conditioning temperatures decreased the ileal N and starch digestibility, and digestible protein and AME intakes in birds fed wheat-based diets which were accompanied by lowered bird performance. The effects of conditioning temperature, especially at 90 ºC, on the performance of birds fed maize-based diets were unexpected, but this paralleled the pattern observed for ileal N digestibility, digestible protein and AME intakes in these birds. Overall, the present data showed that while increasing conditioning temperature had different effects on weight gain and feed intake of birds fed different grain types, it negatively influenced on feed per gain values of broiler starters. Another important observation in this study was that PDI was not related to bird performance. As increasing conditioning temperature improved PDI only in wheat-based diets, it can be also concluded that effect of conditioning temperature on pellet quality varies between grain types. It would therefore appear that conditioning temperature can have different effects on bird performance in different grains due to chemical and physical changes in feed. Future studies are warranted to evaluate the effects of conditioning temperature on chemical and physical (durability and hardness) characteristics of pellets.

CHAPTER 5

Influence of conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed maize- and sorghum-based diets[2]

5.1.   Abstract

The influence of conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed maize- and sorghum-based diets and pellet quality was examined in this study. The experimental design was a 2×3 factorial arrangement of treatments evaluating two grain types (maize and sorghum) and three conditioning temperatures (60, 75 and 90 ºC). Broiler starter diets, each based on one grain (maize or sorghum) were formulated and pelleted at the three temperatures. The results showed that birds fed diets conditioned at 60 and 90 ºC had a higher (P < 0.01) weight gain than those fed diets conditioned at 75 ºC. Birds fed diets conditioned at 60 and 90 ºC tended (P = 0.07) to have higher feed intake than those fed diets conditioned at 75 ºC. Conditioning temperature had no effect (P > 0.05) on feed per gain. Increasing conditioning temperatures caused gradual improvements in the pellet durability index of maize-based diets, while the improvement was marked in the sorghum-based diet conditioned at 90 ºC. Pellet hardness increased (P < 0.001) with increasing conditioning temperatures, particularly at 90 ºC. In sorghum-based diets, increasing the conditioning temperature to 90 ºC decreased ileal nitrogen (N) and starch digestibility. Ileal N digestibility of the maize-based diets conditioned at 60 and 90 ºC was similar and higher (P < 0.05) than the diet conditioned at 75 ºC. Starch digestibility was unaffected (P > 0.05) by conditioning temperature in maize-based diets. Increasing conditioning temperatures decreased (P < 0.05) the apparent metabolisable energy (AME) of sorghum-based diets, but the AME of maize-based diet conditioned at 75 ºC was higher (P < 0.05) than of that conditioned at 60 ºC and similar to that conditioned at 90 ºC. In both diet types, birds fed diets conditioned at 60 and 90 ºC had a higher (P < 0.05) digestible protein intake compared to those fed diets conditioned at 75 ºC. There was an interaction (P < 0.05 to 0.01) between grain type and conditioning temperature for the relative length of intestinal segments except for the duodenum (P > 0.05). Birds fed diets conditioned at 75 and 90 ºC had greater (P < 0.001)

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gizzard contents compared to those fed diets conditioned at 60 ℃. Increasing the conditioning temperature increased (P < 0.001) the relative gizzard weights in both diet types. In maize-based diets, increasing the conditioning temperature above 60 ℃ increased (P < 0.05) gelatinised starch (GS) content especially at 90 ℃. In sorghum-based diets, while the diet conditioned at 90 ℃ had the highest GS content, GS content of the diet conditioned at 60 ℃ was higher (P < 0.05) than the diet conditioned at 75 ℃. Both diet types conditioned at 90 ℃ had higher (P < 0.05) resistant starch content than the diets conditioned at 60 and 75 ℃. Conditioning temperature had no significant (P > 0.05) effect on non-starch polysaccharide content of the diets. Conditioned-pelleted diets had higher (P < 0.001) GS content compared to those conditioned only. Overall, these results suggest that the effects of conditioning temperature on broiler performance are determined through their counteracting effects on nutrient availability and physical quality of the pellet.

5.2.   Introduction

Broilers are mostly fed pelleted diets. Improved performance of broilers fed pelleted diets is thought to be due to improved nutritional value, decreased feed wastage, reduced energy spent on ingestion and decreased ingredient segregation (Behnke, 1994). The influence of pelleting on bird performance, however, depends on the conditioning temperature used. Moderate thermal treatment of broiler diets appears to improve their nutritional value, which may be attributed to gelatinisation and increased enzyme susceptibility of starch granules, degradation of heat-labile anti-nutrients, destruction of cell walls and improved availability of nutrients (Pickford, 1992; Silversides and Bedford, 1999; Cutlip *et al*., 2008). On the other hand, high temperatures can destroy heat-labile vitamins, enzymes and amino acids, reduce the availability of starch by formation of resistant starch and lower the availability of lysine through Maillard reaction (Pickford, 1992; Silversides and Bedford, 1999). It has been shown that high conditioning temperatures are associated with poor broiler performance, in terms of weight gain, feed per gain and mortality (Creswell and Bedford, 2006; Kenny and Flemming, 2006). It is, however, recognised that high conditioning temperatures are required for proper adhesion of feed particles and to create sanitised and good quality pellets (Thomas and van der Poel, 1996).

Poultry industry depends heavily upon maize as the major source of energy. In some parts of the world, sorghum is an important cereal in poultry diets. Low-tannin sorghum is

considered as having 95% of the relative feeding value of maize for poultry (Rooney, 1990). Although half the world's sorghum production is used for animal feeding (Kim *et al.*, 2000), the influence of thermal processing of sorghum has not received much attention.

Published data on the influence of conditioning temperature on the performance and nutrient utilisation of broilers fed maize- and sorghum-based diets are limited. Kirkpinar and Basmacioglu (2006) showed that conditioning a maize-soybean meal diet at 65 and 75 ℃ had significant positive effects on the weight gain of broilers. Birds fed the diet pelleted at 85 ℃ had lower weight gain, which was similar to those fed the basal mash diet. It was concluded that the best conditioning temperature was 65 ℃. In the study reported in Chapter 4, it was found that increasing conditioning temperatures above 60 ℃ reduced the weight gain and feed intake of broiler starters fed wheat-based diets. On the other hand, unexpectedly the birds fed maize-based diets conditioned at 60 and 90 ℃ had higher weight gain and feed intake than those fed the diet conditioned at 75 ℃. In both diet types, feed per gain was significantly increased with increasing conditioning temperatures.

Nir *et al.* (1994) reported increased weight gain in broilers fed sorghum-based diets steam-pelleted once at 60 ℃ compared to those fed mash diets. Weight gain of birds fed the diets steam-pelleted twice at 60 ℃ was significantly lower compared to those fed the diets steam-pelleted once. Feed intake of birds fed twice steam-pelleted diets was similar to those fed the mash diet, while feed intake was increased by feeding once steam-pelleted diets. It was concluded that twice steam-pelleting at 60 ℃ reduced the beneficial effect of pelleting.

Due to the unexpected effects of conditioning temperature on the weight gain and feed intake of birds fed maize-based diets in the study reported in Chapter 4, it was decided to re-evaluate the effects of conditioning temperature on maize-based diets. The objectives of the present experiment were to compare the interaction between grain type (maize or sorghum) and conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters and on the quality of pellets.

5.3.   Materials and Methods

5.3.1.   Diets

The experimental design was a 2×3 factorial arrangement of treatments evaluating two grain types and three conditioning temperatures. Two diets, each based on one of the grains (maize or sorghum), were formulated to meet the Ross 308 strain recommendations for major nutrients for broiler starters (Ross, 2007; Table 5.1). The diets were formulated to be isocaloric and isonitrogenous. Each formulated diet was then divided into three equal batches and conditioned at three different temperatures (60, 75 and 90 ℃) by adjusting the steam flow rate. Conditioning time of the mash was 30 seconds and the conditioning temperature was measured at the outlet (close to the exit point) of the conditioner before the mash feed entered the die. The diets were pelleted using a pellet mill (Richard Size Limited Engineers, Orbit 15, Kingston-upon-Hull, UK) capable of manufacturing 180 kg of feed/h and equipped with a die ring (3-mm holes and 35-mm thickness). Representative samples were collected after conditioning and after pelleting for the determination of gelatinised starch (GS), resistant starch (RS), and non-starch polysaccharide (NSP) contents. Another set of samples was collected after pelleting for the determination of pellet hardness and durability. All diets were manufactured and stored for two weeks prior to the start of the trial and then, prior to feeding, dry matter (DM) content of all diets were determined to ensure that feed intake measurements were not biased by differences in DM content.

5.3.2.   Birds and Housing

A total of 288 day-old male broilers (Ross 308) was obtained from a commercial hatchery and allocated to 36 cages as described in Chapter 3. Each of the six dietary treatments was then randomly assigned to six cages, each housing eight birds. Feed was offered *ad libitum* and water was freely available throughout the trial. Housing conditions were as described in Chapter 3, section 3.1.

5.3.3.   Performance data

Performance data were recorded as described in Chapter 3, section 3.1.

5.3.4. Pellet quality

Pellet durability index (PDI) and pellet hardness were measured as described in Chapter 3, sections 3.7 and 3.8, respectively.

Table 5.1. Composition and calculated analysis (g/kg as fed) of the basal diets

Ingredient	Maize-based diet	Sorghum-based diet
Maize	617.5	-
Sorghum	-	613.2
Soybean meal, 48%	278.6	262.5
Meat and bone meal	80.0	80.0
Soybean oil	8.7	27.8
Limestone	2.3	2.6
Salt	1.6	1.5
Sodium bicarbonate	0.9	0.3
Lysine. HCl	2.3	3.3
DL-methionine	2.0	2.5
L-threonine	0.1	0.3
Trace mineral- vitamin premix[1]	3.0	3.0
Titanium dioxide	3.0	3.0
Calculated analysis		
Metabolisable energy, MJ/kg	12.6	12.6
Crude protein	230	230
Lysine	13.8	13.8
Methionine	5.5	5.6
Methionine + cysteine	9.2	9.2
Threonine	8.5	8.5
Calcium	10.0	10.0
Available phosphorus	5.2	5.3
Sodium	1.6	1.6
Chloride	1.9	1.9
Potassium	8.5	8.1

[1]Supplied per kilogram of diet: antioxidant, 100 mg; biotin, 0.2 mg; calcium pantothenate, 12.8 mg; cholecalciferol, 60 µg; cyanocobalamin, 0.017 mg; folic acid, 5.2 mg; menadione, 4 mg; niacin, 35 mg; pyridoxine, 10 mg; trans-retinol, 3.33 mg; riboflavin, 12 mg; thiamine, 3.0 mg; dl-α-tocopheryl acetate, 60 mg; choline chloride, 638 mg; Co, 0.3 mg; Cu, 3.0 mg; Fe, 25 mg; I, 1 mg; Mn, 125 mg; Mo, 0.5 mg; Se, 200 µg; Zn, 60 mg.

5.3.5. Apparent metabolisable energy (AME) determination

The AME determination was carried out between d 17 to 20 posthatch as described in Chapter 3, section 3.2.

5.3.6. Ileal digestibility determination

On d 21, digesta collection was carried out and processed as described in Chapter 3, section 3.3.

5.3.7. Digestive tract measurements

On d 21, two more birds per cage were euthanised by cervical dislocation and digestive tract measurements were carried out as described in Chapter 3, section 3.6.

5.3.8. Chemical analysis

Dry matter, nitrogen (N), gross energy (GE), titanium (Ti), starch, GS, RS and, insoluble, soluble and total NSP contents were determined as described in Chapter 3, section 3.4.

5.3.9. Calculations

The AME values of the diets and apparent ileal nutrient (N and starch) digestibility coefficients were calculated using the formula described in Chapter 3, section 3.5.

5.3.10. Data analysis

The data were analysed as a 2×3 factorial arrangement of treatments, as described in Chapter 3, section 3.9. The cage means were used to derive performance data. For digestive tract measurements, individual birds were considered as the experimental unit. Mean of diet samples (conditioned-only and conditioned-pelleted) for GS, RS and NSP contents were separated using student's t-test.

5.4. Results

5.4.1. Performance and pellet quality

Mortality during the performance experiment was negligible. Only five out of the 288 birds died and the deaths were not related to any specific treatment. Weight gain was influenced (P < 0.001) by grain type, with gain of birds fed the maize-based diet being greater than those fed the sorghum-based diet (Table 5.2). There was a significant (P < 0.01) effect of conditioning temperature on weight gain, with birds fed diets conditioned at 60 and 90 ℃

had a higher weight gain than those fed diets conditioned at 75 ºC. There was no interaction (P > 0.05) between grain type and conditioning temperature for weight gain.

Table 5.2. Influence of grain type and conditioning temperature on weight gain (g/bird), feed intake (g/bird), feed per gain (g feed/g gain) of broiler starters[1] and PDI (%) and pellet hardness (Newton)

	Conditioning temperature, ºC	Weight gain	Feed intake	Feed per gain	PDI[2]	Pellet hardness[3]
Maize	60	1074	1294	1.214	46.3^c	17.3
	75	1026	1269	1.238	68.7^b	20.1
	90	1046	1275	1.231	85.5^a	30.4
Sorghum	60	962	1231	1.293	31.4^e	7.90
	75	930	1199	1.289	36.0^d	12.5
	90	961	1255	1.307	83.2^a	23.0
SEM[4]		12.2	14.3	0.0098	0.82	1.00
Main effects						
Grain type						
Maize		1049^a	1279^a	1.228^b	66.8	22.5^a
Sorghum		951^b	1228^b	1.296^a	49.3	14.6^b
Conditioning temperature, ºC						
60		1018^a	1263	1.254	39.5	12.6^c
75		978^b	1234	1.263	52.3	16.3^b
90		1003^a	1265	1.269	84.5	26.5^a
Probabilities, P ≤						
Grain type		***	***	***	***	***
Conditioning temperature		**	0.07	NS	***	***
Grain type x Conditioning temperature		NS	NS	NS	***	NS

[a,b,c,d,e] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of six replicates (eight birds per replicate).

[2] Each value represents the mean of six replicate samples.

[3] Each value represents the mean of 15 replicate samples.

[4] Pooled standard error of mean.

Grain type had a significant (P < 0.001) effect on feed intake. Birds fed maize-based diets consumed more feed than those fed sorghum-based diets. There was a tendency (P = 0.07) for the main effect of conditioning temperature. Birds fed diets conditioned at 60 and

90 ℃ tended to have a higher feed intake than those fed diets conditioned at 75 ℃. No interaction (P > 0.05) between grain type and conditioning temperature was observed for feed intake.

Birds fed maize-based diets had a lower (P < 0.001) feed per gain compared to those fed sorghum-based diets. Conditioning temperature had no effect (P > 0.05) on feed per gain. Grain type x conditioning temperature interaction was not significant (P > 0.05) for feed per gain.

A significant (P < 0.001) grain type x conditioning temperature interaction was observed for PDI. Increasing conditioning temperature caused gradual improvements in the PDI of maize-based diets, while the improvement was marked in sorghum-based diet conditioned at 90 ℃.

Pellet hardness was influenced (P < 0.001) by grain type, with pellets being harder in maize-based diets compared to sorghum-based diets. Hardness increased (P < 0.001) in both diet types with increasing conditioning temperatures. In particular, marked increases were observed when the conditioning temperature was increased from 75 to 90 ℃.

5.4.2. Nutrient utilisation, and digestible protein and AME intakes

The influence of the dietary treatments on the apparent ileal digestibility of N and starch, AME, and digestible protein and AME intakes during the 21-d trial period is summarised in Table 5.3. A significant (P < 0.05) interaction between grain type and conditioning temperature was observed for ileal N digestibility. Increasing the conditioning temperature to 90 ℃ decreased ileal N digestibility in sorghum-based diets, but the digestibility of the maize-based diets conditioned at 60 and 90 ℃ was similar and higher than the diet conditioned at 75 ℃.

Ileal starch digestibility was unaffected by conditioning temperature in maize-based diets, but reduced with increasing the conditioning temperature in sorghum-based diets, resulting in a significant (P < 0.01) grain type x conditioning temperature interaction.

A significant (P < 0.05) interaction between grain type and conditioning temperature was observed for the AME. Increasing conditioning temperatures decreased the AME of sorghum-based diets, but the AME of maize-based diet conditioned at 75 ℃ was higher than of that conditioned at 60 ℃ and similar to that conditioned at 90 ℃.

Table 5.3. Influence of grain type and conditioning temperature on ileal N digestibility, ileal starch digestibility, AME (MJ/kg DM), digestible protein intake (g/bird) and AME intake (MJ/bird, 1-21 d posthatch) in broiler starters[1]

	Conditioning temperature, ºC	Ileal N digestibility	Ileal starch digestibility	AME	Digestible protein intake	AME intake
Maize	60	0.811[a]	0.974[a]	14.80[bc]	241	17.07
	75	0.785[b]	0.976[a]	14.98[a]	229	16.93
	90	0.809[a]	0.981[a]	14.86[ab]	237	16.79
Sorghum	60	0.776[b]	0.937[b]	14.78[bc]	220	16.28
	75	0.770[bc]	0.927[b]	14.71[cd]	212	15.68
	90	0.753[c]	0.914[c]	14.59[d]	217	16.18
SEM[2]		0.0073	0.0044	0.048	3.1	0.184
Main effects						
Grain type						
Maize		0.802	0.977	14.88	236[a]	16.93[a]
Sorghum		0.766	0.926	14.69	216[b]	16.05[b]
Conditioning temperature, ºC						
60		0.794	0.955	14.79	231[a]	16.68
75		0.777	0.951	14.85	221[b]	16.30
90		0.781	0.947	14.73	227[a]	16.49
Probabilities, P ≤						
Grain type		***	***	***	***	***
Conditioning temperature		0.08	NS	0.06	*	NS
Grain type x Conditioning temperature		*	**	*	NS	NS

[a,b,c,d] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of six replicates.

[2] Pooled standard error of mean.

Digestible protein intake was influenced (P < 0.001) by grain type, with higher intake in birds fed maize-based diets than sorghum-based diets. The main effect of conditioning temperature was also significant (P < 0.05). Birds fed diets conditioned at 60 and 90 ºC had a higher digestible protein intake compared to those fed diets conditioned at

75 ℃. No interaction (P > 0.05) between grain type and conditioning temperature was observed for digestible protein intake.

Main effect of grain type (P < 0.001) was observed for AME intake. Birds fed maize-based diets consumed more metabolisable energy than those fed sorghum-based diets. Neither the main effect of conditioning temperature nor the interaction between grain type and conditioning temperature was significant (P > 0.05) for AME intake.

5.4.3. Digestive tract measurements

The effects of the dietary treatments on the relative length, relative digesta content, relative empty weight of intestinal segments and relative organ weights are shown in Tables 5.4 and 5.5. A significant (P < 0.01) main effect of grain type was observed for the relative length of duodenum, with longer duodenum in birds fed sorghum-based diets than those fed maize-based diets. There was an interaction (P < 0.05 to 0.01) between grain type and conditioning temperature for the relative length of intestinal segments except for the duodenum (P > 0.05). Relative length of jejunum and small intestine was unaffected by conditioning temperature in maize-based diets, but reduced with increasing the conditioning temperature (especially from 75 to 90 ℃) in sorghum-based diets. Relative length of ileum increased with increasing the conditioning temperature in maize-based diets, but was unaffected by conditioning temperature in sorghum-based diets.

Grain type influenced (P < 0.001) the relative length of caeca, with longer caeca in birds fed sorghum-based diets than those fed maize-based diets. Conditioning temperature tended (P = 0.09) to affect the relative length of caeca. Birds fed diets conditioned at 75 and 90 ℃ had longer caeca compared to those fed diets conditioned at 60 ℃.

There was an interaction (P < 0.01) between grain type and conditioning temperature for the relative digesta contents of proventriculus. Relative digesta contents of proventriculus were unaffected by conditioning temperature in maize-based diets, but increased with increasing the conditioning temperature in sorghum-based diets. Grain type influenced (P < 0.001) the relative digesta contents of gizzard and small intestine, with greater contents in the small intestine, and lower contents in the gizzard of birds fed sorghum-based diets than those fed maize-based diets. Conditioning temperature significantly (P < 0.001) affected on the relative digesta content of gizzard. Increasing the

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conditioning temperature increased the contents in the gizzard, with birds fed diets conditioned at 75 and 90 ℃ having greater contents compared to those fed diets conditioned at 60 ℃. Neither the main effect of conditioning temperature nor the interaction between grain type and conditioning temperature was significant (P > 0.05) for the relative digesta content in the small intestine.

A significant (P < 0.05) grain type x conditioning temperature interaction was observed for the relative digesta content of caeca. Decreases were observed in the digesta content in birds fed maize-based diets with increasing conditioning temperatures, while the digesta content was unaffected by conditioning temperature in sorghum-based diets.

Relative weight of proventriculus increased with increasing the conditioning temperature in maize-based diets, but was unaffected in sorghum-based diets, resulting in a grain type x conditioning temperature interaction (P < 0.01; Table 5.5).

Grain type significantly (P < 0.001) influenced the relative weight of gizzard. Birds fed maize-based diets had heavier gizzards compared with those fed sorghum-based diets. Increasing the conditioning temperature increased (P < 0.001) the relative gizzard weights in both diet types, as indicated by the lack of interaction (P > 0.05) between grain type and conditioning temperature.

A significant (P < 0.05) interaction between grain type and conditioning temperature was observed for the relative weight of duodenum. Relative weight of duodenum was unaffected by conditioning temperature in maize-based diets, while the empty weight increased by conditioning at 75 ℃ followed by a decrease at 90 ℃ in sorghum-based diets. A significant (P < 0.05 to 0.001) effect of grain type was observed for the relative weight of jejunum, ileum and small intestine. The relative weights were higher in birds fed sorghum-based diets compared to those fed maize-based diets. Relative weights of jejunum, ileum and small intestine were not affected (P > 0.05) by the conditioning temperature. No interaction (P > 0.05) between grain type and conditioning temperature was observed for these components.

Neither the main effects nor their interaction was significant (P > 0.05) for the relative empty weight of caeca.

A significant (P < 0.05) grain type x conditioning temperature interaction was noted for the relative weights of liver and spleen. Relative weight of liver was unaffected by

conditioning temperature in maize-based diets, while the weight decreased with increasing conditioning temperatures in sorghum-based diets. Birds fed maize-based diet conditioned at 75 ℃ had similar spleen weight to those fed diet conditioned at 60 ℃ and higher than those fed diet conditioned at 90 ℃, but birds fed sorghum-based diets conditioned at 60 and 75 ℃ had lighter spleen weight compared to those fed diet conditioned at 90 ℃.

Grain type tended (P = 0.07) to affect the relative weight of pancreas, with pancreas weight being higher in birds fed maize-based diets than those fed sorghum-base diets. No significant (P > 0.05) effect of conditioning temperature or interaction was observed.

Table 5.4. Influence of grain type and conditioning temperature on relative length (cm/kg body weight) and digesta content (g/kg body weight) of the digestive tract of broiler starters[1]

	Conditioning temperature, °C	Relative length					Relative digesta content			
		Duodenum	Jejunum	Ileum	Small intestine[2]	Caeca	Proventriculus	Gizzard	Small intestine[2]	Caeca
Maize	60	24.4	58.2^b	58.9^d	142^d	13.0	0.613^{bc}	8.57	32.2	1.778^{ab}
	75	24.0	59.8^b	62.9^c	147^{cd}	13.7	0.715^{bc}	10.9	34.0	1.334^b
	90	24.2	60.1^b	64.7^{bc}	148^{cd}	14.1	0.482^c	10.7	32.7	1.399^b
Sorghum	60	25.1	66.0^a	69.7^a	160^a	14.5	0.639^{bc}	1.90	46.4	1.616^{ab}
	75	25.3	65.1^a	68.0^{ab}	158^{ab}	15.4	1.141^b	4.49	43.8	1.987^a
	90	25.8	59.6^b	67.8^{ab}	151^{bc}	14.8	1.875^a	6.25	44.6	1.654^{ab}
SEM[3]		0.49	1.27	1.22	2.5	0.40	0.2096	0.640	1.36	0.1641
Main effects										
Grain type										
Maize		24.2^b	59.4	62.2	146	13.6^b	0.604	10.0^a	33.0^b	1.512
Sorghum		25.4^a	63.5	68.5	157	14.9^a	1.218	4.22^b	44.9^a	1.755
Conditioning temperature, °C										
60		24.8	61.9	64.5	151	13.8	0.625	5.38^b	39.0	1.697
75		24.6	62.3	65.4	153	14.6	0.928	7.58^a	38.7	1.675
90		24.9	59.8	66.2	150	14.5	1.178	8.47^a	38.6	1.526
Probabilities, P ≤										
Grain type		**	***	***	***	***	***	***	***	0.07
Conditioning temperature		NS	NS	NS	NS	0.09	*	***	NS	NS
Grain type x Conditioning temperature		NS	**	**	*	NS	**	NS	NS	*

[a,b,c,d] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of 12 birds.

[2] Small intestine = duodenum + jejunum + ileum.

[3] Pooled standard error of mean.

Table 5.5. Influence of grain type and conditioning temperature on relative empty weight (g/kg body weight) of the digestive tract and relative organ weights (g/kg body weight) of broiler starters[1]

	Conditioning temperature, °C	Relative empty weight							Relative organ weight		
		Proventriculus	Gizzard	Duodenum	Jejunum	Ileum	Small intestine[2]	Caeca	Liver	Spleen	Pancreas
Maize	60	3.63[b]	13.7	5.12[bc]	9.39	5.85	20.3	1.039	28.3[b]	0.987[ab]	2.48
	75	4.15[a]	14.0	4.77[c]	8.88	5.92	19.7	1.086	28.6[b]	1.080[a]	2.54
	90	4.06[a]	15.4	4.78[c]	9.47	5.99	19.9	1.081	28.9[b]	0.921[bc]	2.59
Sorghum	60	4.07[a]	9.10	5.33[b]	9.63	6.32	21.4	1.104	31.2[a]	0.830[c]	2.36
	75	3.93[a]	10.5	5.82[a]	10.4	6.66	22.8	1.150	30.7[a]	0.869[c]	2.54
	90	4.18[a]	11.2	4.95[bc]	9.81	6.76	21.9	1.135	28.6[b]	0.987[ab]	2.35
SEM[3]		0.104	0.36	0.173	0.394	0.208	0.69	0.0498	0.60	0.0503	0.079
Main effects											
Grain type											
Maize		3.95	14.4[a]	4.89	9.26[b]	5.92[b]	19.9[b]	1.130	28.6	0.996	2.53
Sorghum		4.06	10.2[b]	5.37	9.96[a]	6.59[a]	22.1[a]	1.069	30.2	0.895	2.42
Conditioning temperature, °C											
60		3.85	11.3[c]	5.22	9.51	6.08	20.9	1.073	29.8	0.908	2.42
75		4.05	12.2[b]	5.30	9.70	6.31	21.3	1.118	29.7	0.970	2.54
90		4.12	13.3[a]	4.86	9.64	6.37	20.9	1.108	28.8	0.956	2.47
Probabilities, P ≤											
Grain type		NS	***	***	*	***	***	NS	**	*	0.07
Conditioning temperature		*	***	*	NS	NS	NS	NS	NS	NS	NS
Grain type x Conditioning temperature		**	NS	*	NS	NS	NS	NS	*	*	NS

[a,b,c] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of 12 birds.

[2] Small intestine = duodenum + jejunum + ileum.

[3] Pooled standard error of mean.

5.4.4. Gelatinised and resistant starch contents

The influence of the dietary treatments on GS and RS contents of the diets is shown in Table 5.6. There was a significant ($P < 0.05$) interaction between grain type and conditioning temperature for GS content. In maize-based diets, increasing the conditioning temperature above 60 ºC was accompanied with higher contents of GS especially at 90 ºC. In sorghum-based diets, while the diet conditioned at 90 ºC had the highest GS content, GS content of the diet conditioned at 60 ºC was higher than the diet conditioned at 75 ºC.

Table 5.6. Influence of grain type and conditioning temperature on GS and RS contents (g per 100 g total starch, DM) of the diets[1]

	Conditioning temperature, ºC	Gelatinised starch	Resistant starch
Maize	60	16.0^c	2.14
	75	16.9^b	2.13
	90	19.9^a	3.17
Sorghum	60	13.0^d	2.36
	75	11.9^e	3.05
	90	15.3^c	4.01
SEM[2]		0.31	0.271
Main effects			
Grain type			
Maize		17.6	2.48^b
Sorghum		13.4	3.14^a
Conditioning temperature, ºC			
60		14.5	2.25^b
75		14.4	2.59^b
90		17.6	3.59^a
Probabilities, P ≤			
Grain type		***	***
Conditioning temperature		***	***
Grain type x Conditioning temperature		*	NS

^{a,b,c,d,e} Means in a column not sharing a common superscript are significantly different ($P < 0.05$).
NS, not significant; * $P < 0.05$; *** $P < 0.001$.
[1] Each value represents the mean of four replicate samples.
[2] Pooled standard error of mean.

Grain type significantly (P < 0.001) affected the RS content. Sorghum-based diets had higher RS content than maize-based diets. The main effect of conditioning temperature on RS was significant (P < 0.001). The diets conditioned at 90 ℃ had higher RS content than the diets conditioned at 60 and 75 ℃.

5.4.5.   Non-starch polysaccharide content

The influence of the dietary treatments on insoluble, soluble and total NSP contents of the diets is shown in Table 5.7. Maize-based diets had a higher (P < 0.001) insoluble NSP content than sorghum-based diets. Conditioning temperature had no significant (P > 0.05) effect on the insoluble NSP content of the diets. No significant (P > 0.05) grain type x conditioning temperature interaction was observed for insoluble NSP content.

Neither the main effects nor the interaction was significant (P > 0.05) for soluble NSP content. Grain type influenced (P < 0.05) the total NSP content. Maize-based diets had higher total NSP than sorghum-based diets. Neither conditioning temperature nor grain type x conditioning temperature interaction was significant (P > 0.05) for total NSP content.

5.4.6.   Effects of pellet die on GS, RS and NSP contents

To investigate the effects of pellet die (more accurately frictional heat of die holes), diet samples after conditioning and before passing through the pellet die (conditioned-only) were analysed for GS, RS and NSP contents and compared with the conditioned and pelleted samples (Table 5.8). Pellet die had a significant (P < 0.001) effect on GS content, with conditioned and pelleted samples having higher GS contents compared to those conditioned only.

There was no effect (P > 0.05) of pellet die on RS content of any of the treatment diets. Pellet die had no effect (P > 0.05) on total NSP content of the diets, except for the maize-based diet conditioned at 60 ℃ (P < 0.05).

Table 5.7. Influence of grain type and conditioning temperature on insoluble, soluble and total NSP contents (g per 100 g, DM) of the diets[1]

	Conditioning temperature, ºC	Insoluble NSP	Soluble NSP	Total NSP[2]
Maize	60	11.1	1.097	12.2
	75	10.9	0.874	11.8
	90	11.1	1.115	12.2
Sorghum	60	8.98	0.913	9.89
	75	9.30	1.156	10.5
	90	9.72	0.895	10.6
SEM[3]		0.342	0.3844	0.63
Main effects				
Grain type				
Maize		11.1^a	1.029	12.1^a
Sorghum		9.33^b	0.988	10.3^b
Conditioning temperature, ºC				
60		10.0	1.005	11.0
75		10.1	1.015	11.1
90		10.4	1.005	11.4
Probabilities, P ≤				
Grain type		***	NS	*
Conditioning temperature		NS	NS	NS
Grain type x Conditioning temperature		NS	NS	NS

^{a,b} Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; *** P < 0.001.

[1] Each value represents the mean of four replicate samples.

[2] Total NSP = Insoluble NSP + Soluble NSP.

[3] Pooled standard error of mean.

Table 5.8. Influence of pellet die on GS and RS contents (g per 100 g total starch, DM) and total NSP content (g per 100 g, DM) of the diets[1]

	Conditioning temperature, °C	Gelatinised starch			Resistant starch			Total NSP[2,6]		
		Before pelleting[3]	After pelleting[4]	Difference[5]	Before pelleting[3]	After pelleting[4]	Difference[5]	Before pelleting[3]	After pelleting[4]	Difference[5]
Maize	60	8.70	16.0	7.29***	1.95	2.14	0.19[NS]	11.6	12.2	0.56*
	75	12.3	16.9	4.66***	2.91	2.13	-0.78[NS]	11.6	11.8	0.18[NS]
	90	13.5	19.9	6.47***	2.94	3.17	0.23[NS]	12.5	12.2	-0.26[NS]
Sorghum	60	7.72	13.0	5.24***	2.79	2.36	-0.43[NS]	10.1	9.89	-0.25[NS]
	75	6.95	11.9	4.95***	2.87	3.05	0.18[NS]	9.91	10.5	0.54[NS]
	90	10.2	15.3	5.11***	4.81	4.01	-0.80[NS]	10.6	10.6	-0.02[NS]

NS, not significant; * P < 0.05; *** P < 0.001.

[1] Each value represents the mean of four replicate samples.

[2] Total NSP = Insoluble NSP + Soluble NSP.

[3] Before pelleting = Conditioned-only samples.

[4] After pelleting = Conditioned and pelleted samples.

[5] Difference= After pelleting – Before pelleting.

[6] Means of conditioned-only and conditioned-pelleted diet samples were not (P > 0.05) significantly different for insoluble and soluble NSP contents.

5.5.   Discussion

Previous research (Chapter 4) indicated that increasing conditioning temperatures had different effects on the feed value and physical characteristics of diets based on maize and wheat. In that study, it was found that increasing the conditioning temperature above 60 ℃ negatively affected the weight gain and feed intake in birds fed wheat-based diets. In birds fed maize-based diets conditioned at 60 and 90 ℃, however, weight gain and feed intake were higher than those fed diet conditioned at 75 ℃. In both diet types, feed per gain deteriorated at higher conditioning temperatures. In the current study, in both maize- and sorghum-based diets, increasing the conditioning temperature from 60 to 75 ℃ reduced the weight gain, but this was restored in birds fed diets conditioned at 90 ℃. A tendency was also observed for birds fed diets conditioned at 60 and 90 ℃ having higher feed intake than those fed diets conditioned at 75 ℃. These results are in contrast with those by Bedford (cited in Creswell and Bedford, 2006) who reported a significant reduction in weight gain of broilers fed maize-based diets with pelleting temperature at 93 ℃ compared to 85 ℃. However, negative effects of higher pelleting temperatures on the weight gain of birds fed maize-based diets have also been reported by Kirkpinar and Basmacioglu (2006). They showed that pelleting a maize-soybean meal diet at 65 ℃ resulted in higher weight gain compared to the basal mash diet and diets pelleted at 75 and 85 ℃. Increasing pelleting temperature to 75 and 85 ℃ resulted in a significant reduction in weight gain of broilers to an extent that birds fed on diets pelleted at 85 ℃ had weight gains similar to those fed the basal mash diet. Pellet quality was not reported in these two studies.

The reasons for the unexpected findings in the current study are unclear, but an explanation may be provided by taking into account the effect of conditioning temperature on pellet quality. It appears that weight gain and feed intake responses of broilers fed diets conditioned at different temperatures may reflect the balance between nutrient availability on one hand and pellet quality on the other. Whilst conditioning at 75 ℃ improved the durability (32%) and hardness (29%) of the pellets compared to 60 ℃, these improvements appear not sufficient enough to overcome the probable negative effects of conditioning at 75 ℃ on nutrient availability. But improvements in pellet durability (114%) and hardness (110%) due to conditioning at 90 ℃ compared to 60 ℃ seem to overcome the negative

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effects of conditioning at 90 ºC on nutrient availability and restore the weight gain and feed intake.

Feed per gain was not affected by increasing conditioning temperatures in present study, a finding which is in contrast to our previous research (Chapter 4) and those reported by Creswell and Bedford (2006). The performance results in current study are congruent to research by Cutlip *et al.* (2008) who reported similar weight gain and better feed efficiency in broilers fed diets pelleted at high (93.3 ºC) temperature compared with those fed diets pelleted at low (82.2 ºC) temperature. They attributed these results to an associated increase in PDI and decreased total fines in high (93.3 ºC) temperature pellets. They showed that a 4.0 percentage improvement in the PDI of high temperature pelleted diets, compared to low temperature pelleted diets, resulted in a 20-point decrease in feed per gain while maintaining similar weight gain. Several studies have also reported that higher pellet quality (Moritz *et al.*, 2001; 2003; Hott *et al.*, 2008) along with low levels of fines can improve broiler performance (Proudfoot and Sefton, 1978; Behnke and Beyer, 2002). Considering the documented beneficial effect of higher pellet quality on broiler performance, it is reasonable to assume that improvements in the PDI due to conditioning at 75 and 90 ºC (13 and 45 percentage points, respectively), compared with conditioning at 60 ºC, may be sufficient enough to overcome any deterioration in feed per gain values at higher temperature. In other words, the lack of significant difference between the feed per gain of birds fed diets conditioned at the different temperatures in present study despite having different AME contents and digestibility of N in both diet types and starch (in sorghum-based diets) can lend support to the highlighted effect of pellet quality in restoring the performance responses of birds fed diets in which their metabolisable energy contents and nutrient digestibility were altered by conditioning temperature.

The positive effects of pellet quality on performance can be considered from two points of view, namely, pellet durability and hardness. More durable pellets can improve performance by increasing the nutrient density (Jensen *et al.*, 1962), decreasing the level of fines and feed wastage and, more importantly, reducing the energy spent on ingestion and shifting it to productive energy (Reddy *et al.*, 1961; 1962; Jensen, 2000). Pellet hardness may have a stimulatory effect on the development of gizzard, with positive effects on nutrient utilisation. Harder pellets will require higher degree of mechanical grinding which

in turn will lead to a well-developed gizzard. The larger gizzard and increased gizzard digesta content observed in the present study with increasing conditioning temperatures lend support to this thesis. Garcia *et al*. (2007) reported an increase in gizzard/intestine weight ratio was accompanied by an increase in AMEn values. They suggested that the gizzard/intestine weight ratio was an efficient means for predicting variations in AMEn responses observed with xylanase and antibiotic supplementation. Nir *et al.* (1994) and Hetland and Svihus (2001) reported greater gizzard development in birds fed coarsely ground diets. These researchers concluded that coarse particles tend to remain longer in the gizzard, increasing the mechanical stimulation of this organ. A more developed gizzard is associated with developed gizzard muscles (Preston *et al*., 2000; Svihus, 2010), increased grinding activity (Nir *et al*., 1994; Amerah *et al*., 2007a,b; Svihus, 2010), increased pancreatic enzyme secretion through increased release of cholecystokinin (Svihus, 2010), and improved gastrointestinal tract motility (Ferket, 2000; Gonzalez-Alvarado *et al*., 2008), resulting in improved nutrient digestion and energy utilisation (Carre, 2000). Restored ileal N digestibility in birds fed maize-based diet conditioned at 90 ℃ may be partly explained by more developed gizzard in these birds. An increased gizzard weight and gizzard digesta content due to increasing conditioning temperatures was also observed in birds fed sorghum-based diets, but it failed to restore the N and starch digestibility in the diet conditioned at 90 ℃. It appears that the effectiveness of an increased grinding activity of gizzard on digestion of nutrients varies depending on grain type and the magnitude of chemical changes caused by conditioning temperature. The negative effects of conditioning at 90 ℃ on N and starch in sorghum-based diets were much larger than those in maize-based diets to an extent that the observed increases in pellet hardness and gizzard size were not able overcome them resulting in lower N and starch digestibility in the sorghum-based diet conditioned at 90 ℃. Bryden *et al*. (2009) suggested that steam-pelleting of sorghum-based diets at temperatures above 90 ℃ may provide sufficient 'moist-heat' to induce disulphide linkages in kafirin and compromise protein and starch digestibility, although this may be offset by extensive starch gelatinisation. Results from the present study showed that steam-conditioning the sorghum-based diet at 90 ℃ resulted only in 2.3 g more GS per 100 g starch, compared to conditioning at 60 ℃, which may be was not sufficient to offset the compromised N and starch digestibility.

Increasing the conditioning temperature in sorghum-based diets resulted in reductions in the apparent ileal digestibility of both N and starch, especially at 90 ºC. The poorer ileal N digestibility of sorghum-based diet conditioned at 90 ºC may be explained by formation of enzyme-resistant disulphide-bonded oligomeric proteins that occurs to a greater extent in sorghum than in maize (Duodu *et al.*, 2002). Lower digestibility of starch in birds fed sorghum-based diet conditioned at 90 ºC is consistent with the significant formation of RS (70 and 31% more RS compared to the sorghum-based diets conditioned at 60 and 75 ºC, respectively) in this diet (Table 5.6). The observed reduction in the AME content of sorghum-based diets with increasing conditioning temperatures (Table 5.3) may be partly explained by the formation of enzyme-resistant starch. It must be noted that even the formation of a small percentage of RS may make a portion of feed energy unavailable to the birds. In maize-based diets, the apparent ileal starch digestibility was unaffected by higher conditioning temperatures. However, ileal N digestibility of the diets conditioned at 60 and 90 ºC was higher than those conditioned at 75 ºC. The results for maize-based diets in this study are similar to the findings of the previous study (Chapter 4), indicating that broiler performance in maize-based diets is influenced more by changes in N digestibility than starch digestibility.

Increasing conditioning temperatures decreased the AME of sorghum-based diets, but the AME of maize-based diet conditioned at 75 ºC was higher than of that conditioned at 60 ºC and similar to that conditioned at 90 ºC. But when the AME intake is considered, increasing conditioning temperatures had no effect on AME intake of both diet types. It seems that changes in dietary AME values due to conditioning at different temperatures were evened out by differences in feed intake.

Increasing conditioning temperatures resulted in higher GS content of maize-based diets, especially at 90 ºC. In sorghum-based diets, while the diet conditioned at 90 ºC had the highest GS content, GS content of the diet conditioned at 60 ºC was higher than the diet conditioned at 75 ºC. Presence of water is a prerequisite to initiate starch gelatinisation (Camire *et al.*, 1990; Thomas *et al.*, 1998). As only around 30 g/kg moisture is added to feed during the steam-conditioning process, water is considered as a limiting factor to fully gelatinise starch (Thomas *et al.*, 1998). Moritz *et al.* (2001) reported a notable increase in starch gelatinisation in a maize-soybean meal diet with increased additions of moisture. As

conditioning temperatures in the current study were increased by increasing the flow rate of steam, more moisture was added to diets at higher temperatures resulting in increased GS contents. However, the reasons for the unexpectedly lower GS content in sorghum-based diet conditioned at 75 ℃ compared to that conditioned at 60 ℃ are unclear. Stevens (1987) also reported that increasing the conditioning temperature from 23 (dry-pelleting) to 80 ℃ (steam-conditioning prior to pelleting) resulted in a decrease in the gelatinisation extent of whole pellet (100% maize diet) from 41.9 to 28%. He concluded that as higher conditioning temperature (80 ℃) was accompanied by higher moisture, lubricating effect of steam conditioning decreased friction through the die, causing a decrease of starch gelatinisation. Taylor and Dewar (2001) reported that the temperature at which sorghum starch gelatinises (68-78 ℃) exceeds that of maize (62-72 ℃), implying that sorghum-based diets may require higher conditioning temperatures than maize-based diets to achieve comparable pellet quality. Thus, it is possible that conditioning temperature at 75 ℃ could initiate starch gelatinisation in maize-based diets but not in sorghum-based diets, resulting in the observed significant grain type x conditioning temperature interaction for GS content.

Gelatinised starch content of all dietary treatments increased after passing through the die (conditioned-pelleted diets) compared to the samples before die (conditioned-only). This finding is in agreement with previous reports (Heffner and Pfost, 1973; Skoch *et al*., 1981; 1983a,b; Stevens, 1987) which have shown that pelleting had a greater effect on starch gelatinisation than steam conditioning. Increasing the RS content of both diet types with increasing conditioning temperatures and a lack of significant difference between RS content of the diets before and after pelleting showed that RS contents of the diets were affected only by steam conditioning and not the pellet die.

5.6.   Conclusions

In the present study, increasing conditioning temperature from 60 to 75 ℃ decreased the weight gain of birds fed both maize- and sorghum-based diets, but the growth was restored in birds fed diets conditioned at 90 ℃. There was also a tendency for the birds fed diets conditioned at 60 and 90 ℃ to have higher feed intake than those fed diets conditioned at 75 ℃. The exact reasons for the restoration of weight gain and feed intake in birds fed diets conditioned at 90 ℃ are not clear, but it is possible that these findings may be explained on the basis of marked improvements determined for pellet durability and hardness in the diets

conditioned at 90 ºC. The lack of significant differences between feed per gain of birds fed diets conditioned at different temperatures may also be explained by the better pellet quality at higher conditioning temperatures. Another important finding of this study was that while pellet die had a greater effect on the formation of GS than steam conditioning, RS contents of the diets were affected only by steam conditioning. Resistant starch formation and probable promotion of disulphide linkages in kafirin in sorghum-based diet conditioned at 90 ºC may be the reasons for the lowered ileal starch digestibility and AME of this diet. Overall, these data suggest that when evaluating the effects of different conditioning temperatures on bird performance, consideration must be given to the potential influence on both nutrient availability and pellet quality. Whilst pellet quality is generally defined on the basis of PDI (ASAE, 1997), the present results indicate that hardness is another important characteristic of pellet that also must be taken into account (Thomas and van der Poel, 1996). To better understand the effects of conditioning temperature, *per se*, on nutrient utilisation and bird performance, future studies are warranted to differentiate the effects of conditioning temperature from feed form.

CHAPTER 6

Influence of feed form and conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed wheat-based diets[3]

6.1. Abstract

The influence of feed form and conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters fed wheat-based diets was examined in this study. Two feed forms (mash and pellet) and four conditioning temperatures: 20 ℃ (dry-conditioning), 60, 75 and 90 ℃ (steam-conditioning) were evaluated in a 2×4 factorial arrangement of treatments. In mash diets, weight gain of birds fed the diet conditioned at 60 ℃ was higher ($P < 0.05$) than those fed diets conditioned at 75 and 90 ℃, and similar to those fed diet conditioned at 20 ℃. In pellet diets, while steam-conditioning increased ($P < 0.05$) the weight gain compared to dry-conditioning, birds fed diets conditioned at 60, 75 and 90 ℃ had similar weight gains. Pelleting increased ($P < 0.001$) the feed intake. Birds fed diets conditioned at 20 ℃ had lower ($P < 0.01$) feed intake than those fed diets conditioned at 60 and 90 ℃ and similar to those fed diets conditioned at 75 ℃. In mash diets, birds fed the diet conditioned at 90 ℃ had higher ($P < 0.05$) feed per gain than those fed diets conditioned at 20 and 60 ℃, but similar to those fed the diet conditioned at 75 ℃. In pellet diets, while steam-conditioning decreased ($P < 0.05$) the feed per gain, birds fed steam-conditioned diets (at 60, 75 and 90 ℃) had similar feed per gain. Pellet durability and hardness increased ($P < 0.001$) with steam-conditioning and increasing conditioning temperatures. Pelleting reduced ($P < 0.001$) ileal nitrogen digestibility of the diets. Nitrogen digestibility of diets conditioned at 60 and 75 ℃ was similar and higher ($P < 0.01$) than those conditioned at 20 and 90 ℃. In mash diets, the diet conditioned at 60 ℃ had starch digestibility higher ($P < 0.05$) than diet conditioned at 90 ℃, but similar to those conditioned at 20 and 75 ℃. In pellet diets, those conditioned at 60 and 90 ℃ had higher ($P < 0.05$) starch digestibility than the diet conditioned at 20 ℃, but similar to the diet conditioned at 75 ℃. Higher ($P < 0.001$) apparent metabolisable energy (AME) values were determined for mash diets. The AME content of diets conditioned at 60 ℃ was similar to those conditioned at 75 ℃ and higher ($P < 0.05$) than diets conditioned at 20 and 90 ℃.

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[3] Animal Feed Science and Technology (2011) 168: 88-99.

In both feed forms, the diet conditioned at 90 ℃ had the highest (P < 0.05) gelatinised starch content. In mash diets, while the diets conditioned at 20, 60 and 75 ℃ had similar resistant starch (RS) content, the diet conditioned at 90 ℃ had the highest (P < 0.05) RS content. In pellet diets, the diets conditioned at 20 and 90 ℃ had higher (P < 0.05) levels of RS content than the diet conditioned at 60 ℃, but similar to the diet conditioned at 75 ℃. Overall, the current results suggest that in mash diets, increasing conditioning temperatures above 60 ℃ had negative effects on weight gain, feed per gain and nutrient utilisation of broiler starters. But the deterioration in performance parameters caused by conditioning at higher temperatures was restored when steam-conditioned mash diets were pelleted.

6.2. Introduction

It is generally accepted that pelleting of feeds enhances the economics of production by improving the growth responses in broilers (Behnke and Beyer, 2002). There is no consensus, however, regarding the factors contributing to the observed improvements, though chemical and physical changes occurring during pelleting appear to be largely responsible (Saunders, 1975). Bolton (1960) reported that pelleting improved the weight gain and feed efficiency, but the digestibility of nutrients was not affected. Hussar and Robblee (1962) reported that re-ground pellets did not affect early bird (7-14 d) performance. However, as the birds grew older (28-49 d), those fed whole pellets had better weight gain and feed efficiency compared with those fed re-ground pellets. Generally, weight gain and feed efficiency of birds fed re-ground pellets were superior to those fed mash. Jones *et al.* (1995) demonstrated that physical form is responsible for the enhanced performance of pellet diets. These studies have shown that, even though small responses were obtained by feeding re-ground pellets, a much greater response was obtained by feeding whole pellets.

Some studies (Hussar and Robblee, 1962; Hull *et al.*, 1968) have investigated the importance of intact pellets *per se* and chemical changes during pelleting by comparing intact pellets with re-ground pellets. To our knowledge, no studies have simultaneously examined the effects of feed form and conditioning temperature on the performance and nutrient utilisation of broilers. Considering the fact that probable chemical changes in pellets caused by pellet die can be carried over even after grinding the pellets, one of the

objectives of this study was to differentiate the effects of conditioning temperature from feed form.

Previous studies (Chapters 4 and 5) in this thesis have shown that the performance of broiler starters fed diets conditioned at different temperatures may reflect a balance between nutrient availability and pellet quality. While nutrient availability is adversely affected at higher conditioning temperatures, pellet quality improves. If the improvements in pellet quality gained by applying higher conditioning temperatures are sufficient enough to overcome the negative effects of high conditioning temperatures on nutrient availability, then the bird performance will be largely restored due to the fact that the improvement in productive energy achieved from feeding high quality pellets can offset the lowered nutrient availability (Moritz *et al*., 2001; 2003); otherwise, bird performance will deteriorate. The fact that these factors can overcome the effect of each other is relevant in determining the broiler performance. It can therefore be hypothesised that birds fed diets steam-conditioned at similar temperatures but differing in feed form (mash vs. pellet) may show different patterns of growth response. To test this hypothesis, the present experiment was designed to compare the interaction between feed form (mash or pellet) and conditioning temperature on the performance, nutrient utilisation and digestive tract development of broiler starters.

6.3.   Materials and Methods

6.3.1.   Diets

The experimental design was a 2×4 factorial arrangement of treatments, which included two feed forms and four conditioning temperatures. Whole wheat was ground in a hammer mill (Bisley's Farm Machinery, Auckland, New Zealand) to pass through a screen size of 7.0 mm for coarse grade. A wheat-soybean meal diet was formulated to meet the Ross 308 strain recommendations for major nutrients for broiler starters (Ross, 2007; Table 6.1). The formulated diet was divided into eight equal batches. The first four batches were conditioned at four different temperatures: 20 ℃ (dry-conditioning), 60, 75 and 90 ℃ (steam-conditioning) by adjusting the steam flow rate. All diets were collected at the outlet of the conditioner (before entering the pellet press). Representative mash samples were collected for the determination of particle size distribution and feed hardness. The second

four batches were similarly conditioned at the four temperatures and pelleted using a pellet mill (Richard Size Limited Engineers, Orbit 15, Kingston-upon-Hull, UK) capable of manufacturing 180 kg of feed/h and equipped with a die ring (3-mm holes and 35-mm thickness). Representative pellet samples were collected and particle size distribution, feed hardness, pellet durability and pellet hardness were determined. Conditioning time of the mash was 30 seconds and the conditioning temperature was measured at the outlet (close to the exit point) of the conditioner before the mash feed entered the die. All diets were manufactured and stored for two weeks prior to the start of the trial and then, prior to feeding, dry matter (DM) content of all diets were determined to ensure that feed intake measurements were not biased by differences in DM content.

6.3.2. Birds and Housing

Three hundred and eighty four day-old male broilers (Ross 308), obtained from a commercial hatchery, were allocated to 48 cages as described in Chapter 3. Each of the eight dietary treatments was then randomly assigned to six cages, each housing eight birds. Feed was offered *ad libitum* and water was freely available throughout the trial. Housing conditions were as described in Chapter 3, section 3.1.

6.3.3. Performance data

Performance data were recorded as described in Chapter 3, section 3.1. Feed per gain values were also adjusted to 1 kg weight gain to correct for variations in weight gain among mash and pellet fed birds.

6.3.4. Determination of particle size distribution

Particle size analysis of the diets was carried out by wet sieving using the method described by Lentle *et al*. (2006). Weighed sample (200 g) of each diet was divided in two sub-samples. One was dried at 80 ºC in a forced draft oven for 3 d to determine the dry matter (DM) content and, the other was soaked in water (100 g feed in 400 ml water) and left to stand for one hour prior to sieving to ensure adequate hydration. Feed samples were then washed through a set of six steel sieves (Endecotts Ltd., London, UK) for 5 min. The sieve sizes were 2, 1, 0.5, 0.212, 0.106 and 0.075 mm. The contents of each of the sieves were subsequently washed onto dried, pre-weighed filter papers, dried in a forced draft oven at

80 ºC for 24 h and re-weighed. The dry weights of particles retained by each sieve were expressed as percent of total DM recovered.

Table 6.1. Composition and calculated analysis (g/kg as fed) of the basal diet

Ingredient	Composition
Wheat	647.2
Soybean meal, 48%	228.4
Meat and bone meal	80.0
Soybean oil	27.6
Limestone	2.1
Salt	1.5
Sodium bicarbonate	0.1
Lysine. HCl	3.7
DL-methionine	2.6
L-threonine	0.8
Trace mineral- vitamin premix[1]	3.0
Titanium dioxide	3.0
Calculated analysis	
Metabolisable energy, MJ/kg	12.6
Crude protein	230
Lysine	13.8
Methionine	5.6
Methionine + cysteine	9.2
Threonine	8.5
Calcium	10.0
Available phosphorus	5.2
Sodium	1.6
Chloride	1.9
Potassium	8.4

[1]Supplied per kilogram of diet: antioxidant, 100 mg; biotin, 0.2 mg; calcium pantothenate, 12.8 mg; cholecalciferol, 60 µg; cyanocobalamin, 0.017 mg; folic acid, 5.2 mg; menadione, 4 mg; niacin, 35 mg; pyridoxine, 10 mg; trans-retinol, 3.33 mg; riboflavin, 12 mg; thiamine, 3.0 mg; dl-α-tocopheryl acetate, 60 mg; choline chloride, 638 mg; Co, 0.3 mg; Cu, 3.0 mg; Fe, 25 mg; I, 1 mg; Mn, 125 mg; Mo, 0.5 mg; Se, 200 µg; Zn, 60 mg.

6.3.5.   Pellet quality

Pellet durability index (PDI) and pellet hardness of pellet diets were measured as described in Chapter 3, sections 3.7 and 3.8, respectively.

6.3.6. Feed hardness

Feed hardness of all diets was measured using a Micro Hammer Mill (Stenvert Hardness Tester, Glen Creston Ltd., Stanmore, England). Feed samples (20 g) were ground using the micro hammer mill (5692 rpm) equipped with a 0.2 mm sieve and the energy (KJ) needed to grind the samples was determined. The average of six measurements constituted the hardness of the feed samples.

6.3.7. Apparent metabolisable energy (AME) determination

The AME determination was carried out between d 17 to 20 posthatch as described in Chapter 3, section 3.2.

6.3.8. Ileal digestibility determination

On d 21, digesta collection was carried out and processed as described in Chapter 3, section 3.3.

6.3.9. Digestive tract measurements

On d 21, two more birds per cage were euthanised by cervical dislocation and digestive tract measurements were carried out as described in Chapter 3, section 3.6.

6.3.10. Chemical analysis

Dry matter, nitrogen (N), gross energy (GE), titanium (Ti), starch, gelatinised (GS) and resistant starch (RS) contents were determined as described in Chapter 3, section 3.4.

6.3.11. Calculations

The AME values of the diets and apparent ileal nutrient (N and starch) digestibility coefficients were calculated using the formula described in Chapter 3, section 3.5.

6.3.12. Data analysis

The data were analysed as a 2×4 factorial arrangement of treatments, as described in Chapter 3, section 3.9. The cage means were used to derive performance data. For digestive tract measurements, individual birds were considered as the experimental unit.

6.4. Results

6.4.1. Particle size distribution

Particle size distributions of the mash and pellet diets, determined by wet sieving, are shown in Figures 6.1 and 6.2, respectively.
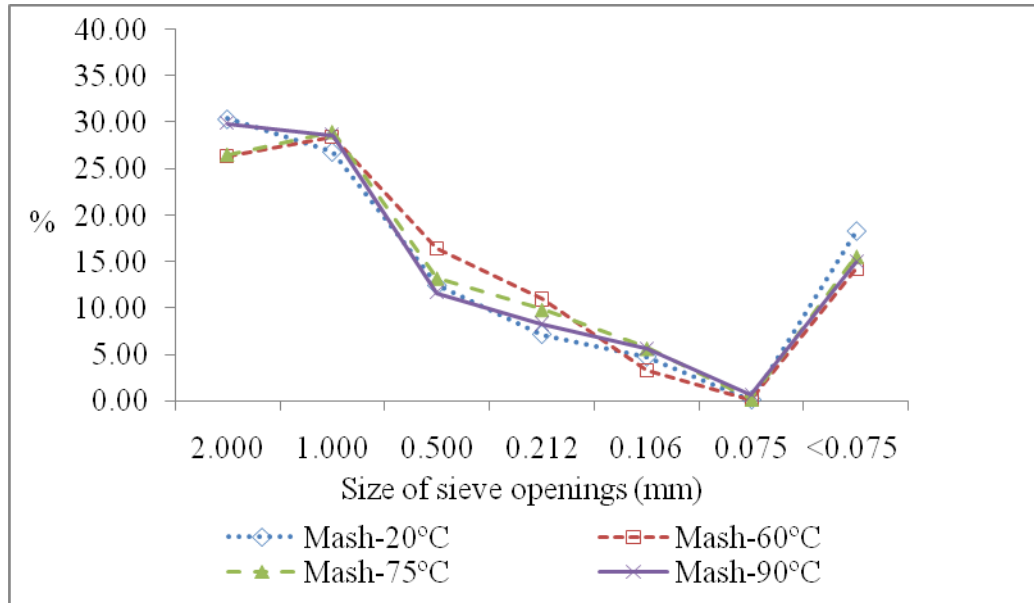
Figure 6.1. Particle size distribution of mash diets
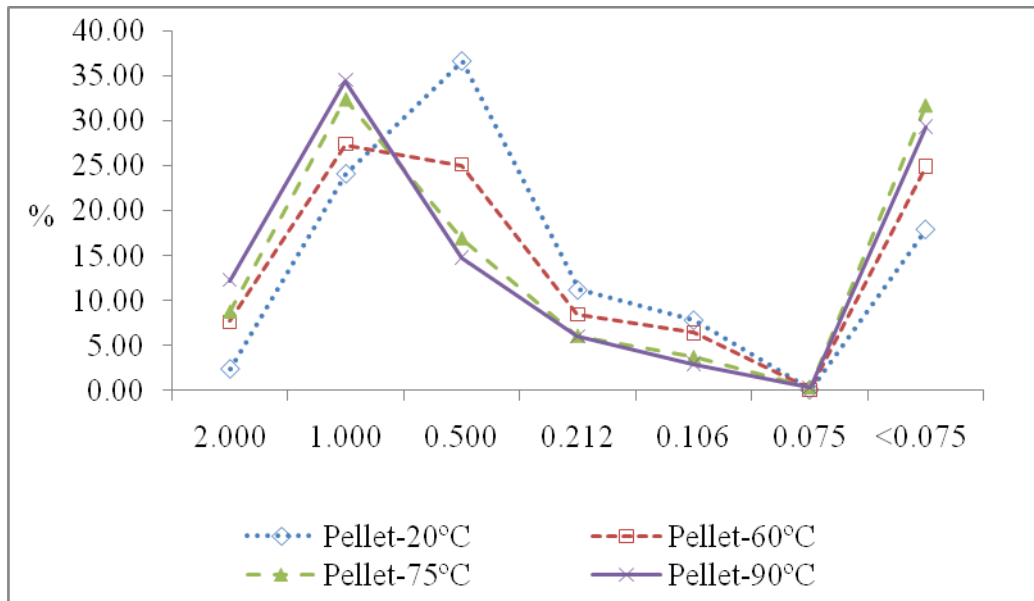
Figure 6.2. Particle size distribution of pellet diets

Comparisons showed that pelleting reduced the relative proportion of coarse particles > 2 mm and increased the proportion of fine particles < 0.075 mm in diet samples. While mash diets conditioned at different temperatures showed almost identical particle size distributions (Figure 6.1), in pellet diets, increasing conditioning temperatures increased the proportion of particles > 1 mm (Figure 6.2).

6.4.2.   Performance, feed hardness and pellet quality

Mortality during the performance experiment was negligible. Only four out of the 384 birds died and the deaths were not related to any specific treatment.

A significant (P < 0.001) interaction between feed form and conditioning temperature was observed for the weight gain (Table 6.2). In mash diets, birds fed diet conditioned at 60 ºC had a higher weight gain than those fed diets conditioned at 75 and 90 ºC and similar to those fed diet conditioned at 20 ºC. In pellet diets, while applying steam during conditioning increased weight gain compared to those fed the dry-conditioned diet, birds fed steam-conditioned diets at 60, 75 and 90 ºC had similar weight gains.

Birds fed pellet diets consumed more (P < 0.001) feed than those fed mash diets. Feed intake was significantly (P < 0.01) influenced by conditioning temperature. Birds fed diets conditioned at 60 and 90 ºC had higher feed intake than those fed diets conditioned at 20 ºC and similar to those fed diets conditioned at 75 ºC. Similar feed intake was observed for the birds fed diets conditioned at 20 and 75 ºC.

A significant (P < 0.01) feed form x conditioning temperature interaction was observed for feed per gain due to the pattern of changes with increasing conditioning temperatures differing in the two feed forms. In mash diets, increasing conditioning temperatures increased the feed per gain, with birds fed diet conditioned at 90 ºC having similar feed per gain to those fed diet conditioned at 75 ºC, but higher than those fed diets conditioned at 20 and 60 ºC. In pellet diets, while applying steam to the conditioner decreased the feed per gain compared to dry-conditioning, birds fed diets steam-conditioned at the different temperatures had similar feed per gain values.

There was a significant (P < 0.001) feed form x conditioning temperature interaction for adjusted feed per gain. In mash diets, increasing conditioning temperatures above 60 ºC increased adjusted feed per gain, with birds fed diets conditioned at 75 and 90

ºC having higher adjusted feed per gain than those fed diet conditioned at 60 ºC, but similar to those fed diet conditioned at 20 ºC. In pellet diets, while introducing steam to the conditioner decreased the adjusted feed per gain compared to the dry-conditioned diet, birds fed diets steam-conditioned at the different temperatures had similar adjusted feed per gains.

Table 6.2. Influence of feed form and conditioning temperature on the weight gain (g/bird), feed intake (g/bird), feed per gain (g feed/g gain), adjusted feed per gain[1] (g feed/kg gain) of broiler starters[2], and feed hardness (KJ), PDI (%) and pellet hardness (Newton)

Feed form	Conditioning temperature, ºC	Weight gain	Feed intake	Feed per gain	Adjusted feed per gain	Feed hardness[3]	PDI[3]	Pellet hardness[4]
Mash	20	873[bc]	1126	1.289[d]	1.477[bc]	1.98[c]	-	-
	60	908[b]	1174	1.303[cd]	1.436[cd]	1.97[c]	-	-
	75	852[c]	1119	1.319[bcd]	1.550[ab]	1.97[c]	-	-
	90	869[c]	1179	1.358[b]	1.569[ab]	2.13[b]	-	-
Pellet	20	885[bc]	1253	1.420[a]	1.611[a]	0.88[f]	13.7[d]	8.76[d]
	60	1006[a]	1348	1.340[bcd]	1.333[d]	1.57[e]	67.2[c]	19.7[c]
	75	981[a]	1327	1.353[bc]	1.379[cd]	1.78[d]	69.6[b]	24.0[b]
	90	1014[a]	1322	1.342[bcd]	1.325[d]	2.88[a]	74.1[a]	37.7[a]
SEM[5]		13.3	18.5	0.018	0.039	0.036	0.58	1.01
Main effects								
Feed form								
Mash		875	1150[b]	1.317	1.508	2.01	-	-
Pellet		965	1308[a]	1.368	1.426	1.78	-	-
Conditioning temperature, ºC								
20		879	1190[b]	1.354	1.544	1.43	-	-
60		947	1244[a]	1.318	1.394	1.77	-	-
75		911	1214[ab]	1.334	1.472	1.88	-	-
90		934	1244[a]	1.351	1.458	2.51	-	-
Probabilities, P ≤								
Feed form		***	***	**	**	***	-	-
Conditioning temperature		***	**	NS	**	***	***	***
Feed form x Conditioning temperature		***	NS	**	***	***	-	-

a,b,c,d,e,f Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; ** P < 0.01; *** P < 0.001.

[1] Feed per gain values were adjusted for 1 kg of weight gain.

[2] Each value represents the mean of six replicates (eight birds per replicate).

[3] Each value represents the mean of six replicate samples.

[4] Each value represents the mean of 15 replicate samples.

[5] Pooled standard error of mean.

A significant (P < 0.001) feed form x conditioning temperature interaction was observed for feed hardness. In mash diets, the diet conditioned at 90 ºC had a harder texture than those conditioned at 20, 60 and 75 ºC. In pellet diets, while increases were observed by introducing steam to the conditioner, increasing conditioning temperatures increased feed hardness which was particularly marked by conditioning at 90 ºC.

Pellet durability and hardness increased (P < 0.001) with steam-conditioning and increasing conditioning temperatures.

6.4.3. Nutrient utilisation, and digestible protein and AME intakes

The influence of dietary treatments on the apparent ileal digestibility of N and starch, AME, and digestible protein and AME intakes during the 21-d trial period is summarised in Table 6.3. Pelleting reduced (P < 0.001) the ileal N digestibility of diets. Conditioning temperature influenced (P < 0.01) the ileal N digestibility. Nitrogen digestibility of diets conditioned at 60 and 75 ºC were similar, higher than those conditioned at 20 and 90 ºC.

There was a significant (P < 0.05) feed form x conditioning temperature interaction for ileal starch digestibility. In mash diets, increasing conditioning temperatures decreased the ileal starch digestibility, with the diet conditioned at 90 ºC having lower digestibility than that conditioned at 60 ºC, but similar to those conditioned at 20 and 75 ºC. In pellet diets, those diets conditioned at 60 and 90 ºC had similar starch digestibility to the diet conditioned at 75 ºC, but higher than the diet conditioned at 20 ºC.

Pelleting decreased (P < 0.001) the AME value of the diets. A significant (P < 0.05) effect of conditioning temperature on AME was observed. Apparent metabolisable energy content of the diets conditioned at 60 ºC was similar to those conditioned at 75 ºC and higher than the diets conditioned at 20 and 90 ºC.

Birds fed pellet diets consumed higher (P < 0.001) digestible protein than those fed mash diets (Table 6.3). The main effect of conditioning temperature was significant (P < 0.01) for digestible protein intake. Birds fed steam-conditioned diets had similar digestible protein intakes and higher than those fed dry-conditioned diets. However, there was also a tendency (P = 0.07) for interaction between feed form and conditioning temperature.

Table 6.3. Influence of feed form and conditioning temperature on ileal N digestibility, ileal starch digestibility, AME (MJ/kg DM), digestible protein intake (g/bird) and AME intake (MJ/bird, 1-21 d posthatch) in broiler starters[1]

	Conditioning temperature, ºC	Ileal N digestibility	Ileal starch digestibility	AME	Digestible protein intake	AME intake
Mash	20	0.847	0.959^{ab}	14.10	219	14.17^{de}
	60	0.869	0.977^{a}	14.18	235	14.73^{cd}
	75	0.855	0.940^{ab}	13.92	220	13.77^{e}
	90	0.847	0.913^{b}	13.88	230	14.45^{d}
Pellet	20	0.818	0.756^{d}	13.40	236	15.14^{c}
	60	0.836	0.842^{c}	13.75	259	16.73^{a}
	75	0.849	0.805^{cd}	13.71	260	16.28^{ab}
	90	0.822	0.834^{c}	13.42	249	15.85^{b}
SEM[2]		0.0067	0.0179	0.096	4.5	0.225
Main effects						
Feed form						
Mash		0.855^{a}	0.947	14.02^{a}	226^{b}	14.26
Pellet		0.831^{b}	0.809	13.56^{b}	250^{a}	15.90
Conditioning temperature, ºC						
20		0.833^{b}	0.858	13.75^{b}	228^{b}	14.65
60		0.854^{a}	0.909	13.96^{a}	244^{a}	15.62
75		0.852^{a}	0.872	13.83^{ab}	238^{a}	14.77
90		0.835^{b}	0.874	13.65^{b}	239^{a}	15.09
Probabilities, P ≤						
Feed form		***	***	***	***	***
Conditioning temperature		**	*	*	**	***
Feed form x Conditioning temperature		NS	*	NS	0.07	**

^{a,b,c,d,e} Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of six replicates.

[2] Pooled standard error of mean.

A significant feed form x conditioning temperature interaction (P < 0.01) was observed for AME intake. In mash diets, birds fed diets conditioned at 60 and 90 ºC had higher AME intakes than those fed diet conditioned at 75 ºC and similar to those fed diet

conditioned at 20 ℃. In pellet diets, birds fed diet conditioned at 60 ℃ consumed more energy than those fed diets conditioned at 20 and 90 ℃, but similar to those fed diet conditioned at 75 ℃.

6.4.4.   Digestive tract measurements

The effects of dietary treatments on the relative length, relative digesta content, relative empty weight of intestinal segments and relative organ weights are shown in Tables 6.4 and 6.5. A significant effect of feed form was observed for the relative length of duodenum (P < 0.001) and ileum (P < 0.05). Birds fed mash diets had longer duodenum and ileum than those fed pellet diets. Conditioning temperature influenced (P < 0.01) the relative length of duodenum and ileum. Birds fed diets conditioned at 20 ℃ had longer duodenum and ileum than those fed diets conditioned at 60 and 90 ℃, but similar to those fed diets conditioned at 75 ℃. However, there was also a tendency for interaction between feed form and conditioning temperature for the relative length of duodenum (P = 0.052) and ileum (P = 0.08).

A significant (P < 0.01) feed form x conditioning temperature interaction was observed for the relative length of jejunum. In pellet diets, increasing conditioning temperatures decreased the jejunum length steadily; however, in mash diets, birds fed diet conditioned at 75 ℃ had longer jejunum than those fed diet conditioned at 60 ℃ and similar to those fed diets conditioned at 20 and 90 ℃.

There was a significant (P < 0.01) interaction between feed form and conditioning temperature for the relative length of small intestine. In pellet diets, birds fed diet conditioned at 20 ℃ had longer small intestine than those fed steam-conditioned diets (60, 75 and 90 ℃), but in mash diets, birds fed diet conditioned at 75 ℃ had longer small intestine than those fed diets conditioned at 60 and 90 ℃, but similar to those fed diet conditioned at 20 ℃.

Pelleting decreased (P < 0.001) the relative length of caeca. Conditioning temperature significantly (P < 0.001) altered the length of caeca. Relative length of caeca in birds fed diets conditioned at 20 ℃ was higher than those fed diets conditioned at 60 and 90 ℃ and similar to those fed diets conditioned at 75 ℃.

Pelleting resulted in higher (P < 0.001) relative digesta content of proventriculus. Neither the main effect of conditioning temperature nor the interaction between feed form and conditioning temperature was significant (P > 0.05) for the relative digesta content of proventriculus.

A significant (P < 0.001) effect of feed form was observed for the relative digesta content of gizzard. Birds fed mash diets had considerably higher digesta content in the gizzard compared with those fed pellet diets. While there was no effect (P > 0.05) of conditioning temperature on the relative digesta content of gizzard, a tendency (P = 0.09) was observed for feed form x conditioning temperature interaction.

Relative digesta content in the small intestine was not influenced (P > 0.05) by the feed form. Conditioning temperature significantly (P < 0.05) affected the relative digesta content of small intestine. Birds fed diets conditioned at 90 ℃ had greater content than those fed diets conditioned at 60 ℃, but similar to those fed diets conditioned at 20 and 75 ℃. No interaction (P > 0.05) between feed form and conditioning temperature was observed.

Pelleting reduced (P < 0.01) relative digesta content of caeca. Conditioning temperature affected (P < 0.05) the relative digesta content of caeca. Birds fed diets conditioned at 20 ℃ had greater content than those fed diets conditioned at 60 and 90 ℃, but similar to those fed diets conditioned at 75 ℃. No significant (P > 0.05) feed form x conditioning temperature interaction was observed.

Relative empty weights of proventriculus and gizzard were reduced (P < 0.001) by pelleting (Table 6.5). Neither the main effect of conditioning temperature nor the interaction between feed form and conditioning temperature was significant (P > 0.05) for the relative empty weights of these organs.

A significant (P < 0.05) feed form x conditioning temperature interaction was observed for the relative empty weight of duodenum. Birds fed mash diets had similar duodenum weight, however, in pellet diets, birds fed diet conditioned at 90 ℃ had higher duodenum weight than those fed diet conditioned at 75 ℃, but similar to those fed diets conditioned at 20 and 60 ℃.

Pelleting decreased (P < 0.01) the relative empty weight of jejunum. Neither the main effect of conditioning temperature nor the interaction between feed form and

conditioning temperature was significant (P > 0.05) for the relative empty weight of jejunum.

A significant (P < 0.05) feed form x conditioning temperature interaction was observed for the relative empty weight of ileum. Birds fed mash diets had similar ileum weight, but in pellet diets, birds fed the diet conditioned at 90 ℃ had higher ileum weight than those fed diet conditioned at 75 ℃, but similar to those fed diets conditioned at 20 and 60 ℃.

A significant (P < 0.01) feed form x conditioning temperature interaction was observed for the relative weight of small intestine. In mash diets, birds fed the diet conditioned at 75 ℃ had higher small intestine weight than those fed diet conditioned at 90 ℃ and similar to those fed diets conditioned at 20 and 60 ℃. In pellet diets, birds fed diets conditioned at 60 and 90 ℃ had similar small intestine weight to the diet conditioned at 20 ℃ but higher than those fed diet conditioned at 75 ℃.

Birds fed mash diets had higher (P < 0.01) relative empty weight of caeca. Conditioning temperature affected (P < 0.001) the relative empty weight of caeca. While birds fed dry-conditioned diets had the highest caeca weight, birds fed diets conditioned at 60 ℃ had lower caeca weight than those fed diets conditioned at 75 ℃ and similar to those fed diets conditioned at 90 ℃. No significant (P > 0.05) feed form x conditioning temperature interaction was observed.

Conditioning temperature influenced (P < 0.001) the relative weight of liver, with liver weights being similar in steam-conditioned diets and higher than the dry-conditioned diets. No significant (P > 0.05) effect of feed form or interaction was observed.

There was a significant (P < 0.01) feed form x conditioning temperature interaction for the relative weight of spleen. Birds fed mash diets had similar spleen weight, but in the pellet diets, birds fed diet conditioned at 75 ℃ had the highest spleen weight.

Mash-fed birds had higher (P < 0.001) relative pancreas weight. Neither the main effect of conditioning temperature nor the interaction between feed form and conditioning temperature was significant (P > 0.05).

Table 6.4. Influence of feed form and conditioning temperature on relative length (cm/kg body weight) and digesta content (g/kg body weight) of the digestive tract of broiler starters[1]

	Conditioning temperature, ℃	Relative length					Relative digesta content			
		Duodenum	Jejunum	Ileum	Small intestine[2]	Caeca	Proventriculus	Gizzard	Small intestine[2]	Caeca
Mash	20	28.6	71.5[abc]	78.3	178[ab]	17.6	0.692	15.5	42.3	2.520
	60	28.4	69.5[bcd]	72.3	172[bc]	16.3	0.646	15.8	39.5	1.925
	75	29.2	75.0[a]	79.2	185[a]	17.3	1.450	15.1	42.5	2.190
	90	27.0	71.9[ab]	75.1	172[bc]	15.8	0.790	15.9	41.2	1.862
Pellet	20	28.3	74.8[a]	79.5	183[ab]	16.7	1.683	4.82	41.8	1.855
	60	25.5	70.7[abc]	71.3	167[c]	15.0	2.530	7.21	38.9	1.438
	75	25.0	66.7[cd]	70.7	162[c]	15.3	2.260	8.84	41.0	2.010
	90	24.9	65.2[d]	71.6	162[c]	14.6	1.753	8.50	45.5	1.355
SEM[3]		0.70	1.82	1.91	3.9	0.42	0.3240	0.884	1.36	0.2443
Main effects										
Feed form										
Mash		28.3[a]	72.0	76.3[a]	177	16.7[a]	0.877[b]	15.6[a]	41.4	2.120[a]
Pellet		25.9[b]	69.3	73.3[b]	168	15.4[b]	2.010[a]	7.34[b]	41.9	1.666[b]
Conditioning temperature, ℃										
20		28.4[a]	73.2	78.9[a]	180	17.2[a]	1.188	10.1	42.1[ab]	2.190[a]
60		27.0[b]	70.1	71.8[b]	169	15.6[bc]	1.494	11.5	39.2[b]	1.671[b]
75		27.2[ab]	70.6	75.2[ab]	173	16.4[ab]	1.833	11.9	41.8[ab]	2.100[ab]
90		25.9[b]	68.6	73.3[b]	167	15.2[c]	1.292	12.2	43.4[a]	1.619[b]
Probabilities, P ≤										
Feed form		***	*	*	**	***	***	***	NS	**
Conditioning temperature		**	0.08	**	**	***	NS	NS	*	*
Feed form x Conditioning temperature		0.052	**	0.08	**	NS	NS	0.09	NS	NS

[a,b,c,d] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of 12 birds.

[2] Small intestine = duodenum + jejunum + ileum.

[3] Pooled standard error of mean.

Table 6.5. Influence of feed form and conditioning temperature on relative empty weight (g/kg body weight) of the digestive tract and relative organ weights (g/kg body weight) of broiler starters[1]

	Conditioning temperature, ºC	Relative empty weight							Relative organ weight		
		Proventriculus	Gizzard	Duodenum	Jejunum	Ileum	Small intestine[2]	Caeca	Liver	Spleen	Pancreas
Mash	20	4.32	15.5	5.38^{ab}	11.1	8.18^{ab}	24.9^{ab}	1.509	27.6	0.958^{ab}	2.46
	60	4.29	15.9	5.73^{a}	11.6	7.49^{bc}	25.1^{ab}	1.161	29.3	0.819^{bc}	2.67
	75	4.41	15.0	5.76^{a}	11.4	8.24^{ab}	25.9^{a}	1.329	28.8	0.850^{abc}	2.73
	90	4.07	14.4	5.26^{ab}	11.0	7.89^{abc}	24.1^{b}	1.280	29.4	0.941^{ab}	2.63
Pellet	20	3.83	9.69	5.33^{ab}	10.1	7.93^{abc}	23.7^{bc}	1.321	26.8	0.736^{c}	2.25
	60	3.83	10.5	5.48^{ab}	10.6	7.96^{abc}	24.3^{ab}	1.145	28.6	0.777^{c}	2.22
	75	3.81	10.4	4.90^{b}	10.2	7.33^{c}	22.2^{c}	1.200	29.6	0.976^{a}	2.25
	90	3.96	10.5	5.60^{a}	11.0	8.46^{a}	24.9^{ab}	1.132	28.1	0.819^{bc}	2.27
SEM[3]		0.137	0.44	0.205	0.38	0.289	0.63	0.0521	0.51	0.0506	0.114
Main effects											
Feed form											
Mash		4.27^{a}	15.2^{a}	5.53	11.3^{a}	7.95	25.0	1.316^{a}	28.8	0.894	2.62^{a}
Pellet		3.86^{b}	10.3^{b}	5.33	10.5^{b}	7.92	23.8	1.201^{b}	28.2	0.828	2.24^{b}
Conditioning temperature, ºC											
20		4.08	12.7	5.35	10.6	8.05	24.3	1.411^{a}	27.2^{b}	0.847	2.35
60		4.05	13.2	5.61	11.1	7.72	24.7	1.153^{c}	28.9^{a}	0.798	2.44
75		4.11	12.7	5.35	10.8	7.79	24.1	1.264^{b}	29.1^{a}	0.913	2.50
90		4.01	12.3	5.43	11.0	8.17	24.5	1.206^{bc}	28.8^{a}	0.882	2.45
Probabilities, P ≤											
Feed form		***	***	NS	**	NS	**	**	NS	0.07	***
Conditioning temperature		NS	NS	NS	NS	NS	NS	***	***	NS	NS
Feed form x Conditioning temperature		NS	NS	*	NS	*	**	NS	NS	**	NS

^{a,b,c} Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of 12 birds.

[2] Small intestine = duodenum + jejunum + ileum.

[3] Pooled standard error of mean.

6.4.5. Gelatinised and resistant starch contents

The influence of dietary treatments on GS and RS contents of the diets and RS:GS ratio is shown in Table 6.6.

Table 6.6. Influence of feed form and conditioning temperature on GS and RS contents (g per 100 g total starch, DM) and RS:GS ratio[1] of the diets

	Conditioning temperature, ºC	Gelatinised starch	Resistant starch	RS:GS ratio
Mash	20	5.24^e	0.95^{cd}	18.2^a
	60	5.82^d	1.01^{bc}	17.4^{ab}
	75	5.59^{de}	0.93^{cd}	16.7^b
	90	8.27^c	1.11^a	13.4^c
Pellet	20	10.1^b	1.05^{ab}	10.4^{ef}
	60	8.23^c	0.90^d	10.9^{de}
	75	8.18^c	0.98^{bcd}	11.9^d
	90	10.9^a	1.04^{ab}	9.52^f
SEM[2]		0.135	0.029	0.44
Main effects				
Feed form				
Mash		6.23	1.00	16.4
Pellet		9.37	0.99	10.7
Conditioning temperature, ºC				
20		7.68	1.00	14.3
60		7.03	0.95	14.1
75		6.89	0.95	14.3
90		9.60	1.07	11.5
Probabilities, P ≤				
Feed form		***	NS	***
Conditioning temperature		***	**	***
Feed form x Conditioning temperature		***	**	***

[a,b,c,d,e,f] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; ** P < 0.01; *** P < 0.001.

[1] Each value represents the mean of four replicate samples.

[2] Pooled standard error of mean.

There was a significant (P < 0.001) interaction between feed form and conditioning temperature for the GS content of the diets. In mash diets, while the diet conditioned at 90 ℃ had the highest GS content, GS content of the diet conditioned at 60 ℃ was similar to the diet conditioned at 75 ℃ and higher than the diet conditioned at 20 ℃. In pellet diets, the diet conditioned at 90 ℃ had the highest level of GS; however, GS content of the diet conditioned at 20 ℃ was higher than the diets conditioned at 60 and 75 ℃.

A significant (P < 0.01) feed form x conditioning temperature interaction was observed for the RS content of the diets. In mash diets, while the diets conditioned at 20, 60 and 75 ℃ had similar RS contents, the diet conditioned at 90 ℃ had the highest RS content. In pellet diets, the diets conditioned at 20 and 90 ℃ had similar level of RS content to the diet conditioned at 75 ℃ but higher than the diet conditioned at 60 ℃.

There was an interaction (P < 0.001) between feed form and conditioning temperature for the RS:GS ratio. In mash diets, increasing the conditioning temperature to 90 ℃ decreased the RS:GS ratio. In pellet diets, increasing the conditioning temperature to 90 ℃ decreased the RS:GS ratio to an extent similar to the diet conditioned at 20 ℃ but lower than the diets conditioned at 60 and 75 ℃.

6.5.   Discussion

Particle size analysis showed that the passage of diets through the pellet die, regardless of conditioning temperature, reduced the proportion of coarse particles over 2 mm and increased the proportion of fine particles lower than 0.075 mm. These findings are in accordance with previous results of Engberg *et al*. (2002), Svihus *et al*. (2004), Péron *et al*. (2005) and Amerah *et al*. (2007b) who reported that pelleting reduced feed particle size. Svihus *et al*. (2004) speculated that, during pelleting, the large particles are particularly prone to grinding due to the narrow gap between the pellet rollers and the pellet die, and this may explain why the pelleting process tends to even out differences in particle size distribution. Whilst mash diets conditioned at different temperatures showed almost identical particle size distributions, wet sieving of pellet diets indicated differences in particle size distribution between diets conditioned at different temperatures, especially in the proportion of particles > 1 mm. The proportion of particles > 1 mm in mash diets conditioned at 20, 60, 75 and 90 ℃ was 57.2, 54.9, 55.5 and 58.6%, respectively. The proportion of particles > 1 mm in pellet diets conditioned at 20, 60, 75 and 90 ℃ was 26.5,

35.0, 41.2 and 46.7%, respectively. These data suggest that frictional force generated inside the pellet die caused further grinding of feed particles. The lower proportion of particles > 1 mm in dry-conditioned pellet diet (conditioned at 20 ℃) indicates that the grinding effect of the pellet die is much stronger when a non steam-conditioned diet is passed through the pellet die. As conditioning temperatures in this study were increased by increasing the steam flow rate, more moisture was added to diets at higher conditioning temperatures. The lubricative effect of moisture resulted in decreased frictional force in die holes and higher proportion of coarse particles in higher-temperature conditioned pellet diets.

Our previous studies (Chapters 4 and 5) have shown that the weight gain of broiler starters was affected by both the nutritional and physical quality changes in pellets caused by steam conditioning and pelleting at different temperatures. Application of higher conditioning temperatures during the pelleting process decreased N and starch digestibility in wheat- (Chapter 4) and sorghum-based (Chapter 5) diets, but improved the physical quality of the pellets. These opposing effects led to some unexpected findings in terms of growth performance in the two previous studies. Therefore, to better understand the effects of conditioning temperature on bird performance, the current study was designed to differentiate the effects of conditioning temperature from feed form. In the present study, in mash diets, increasing the conditioning temperature above 60 ℃ reduced the weight gain. In pellet diets, while introducing the steam to the conditioner increased the weight gain regardless of temperature compared to the dry-conditioned diet, steam-conditioning at the different temperatures resulted in similar weight gains. Thus, weight gain reductions observed in mash diets conditioned at 75 and 90 ℃ compared to 60 ℃ was restored when the mash diets conditioned at 75 and 90 ℃ were pelleted. In mash diets, feed per gain values deteriorated with increasing conditioning temperatures, with birds fed the diet steam-conditioned at 90 ℃ having feed per gain values higher than those fed the diets steam-conditioned at 20 and 60 ℃. In pellet diets, although the application of steam to the conditioning process resulted in marked improvements in feed per gain, birds fed diets conditioned at 60, 75 and 90 ℃ had similar feed per gain values. Similar to weight gain data, the deterioration of feed per gain in birds fed the mash diet conditioned at 90 ℃ was restored when feed form was altered from mash to pellet.

Based on the performance deterioration of birds fed mash-based diets steam-conditioned at temperatures above 60 ℃, it can be speculated that higher conditioning temperatures *per se* negatively affect the performance of broiler starters. However, when the feed form was changed from mash to pellet, the better pellet quality achieved at higher conditioning temperatures restored the performance of broiler starters. The magnitude of this restoration is determined by the balance between the negative effect of high conditioning temperatures on nutrient availability and the positive effect on pellet quality improvements. Due to these opposing effects, broiler feeding trials using pellet diets conditioned at different temperatures have not always produced consistent results. Raastad and Skrede (cited in Creswell and Bedford, 2006) reported lower body weights when the conditioning temperature was increased from 69 to 86 ℃. Increasing the conditioning temperature from 69 to 78 ℃ had no effect on feed per gain, but feed per gain was poorer when the temperature was increased from 78 to 86 ℃, especially during the 1-21 d period. In contrast, Cowieson *et al.* (2005a) found that in broilers fed maize-based diets, increasing pelleting temperature from 70 to 85 ℃ resulted in higher weight gain.

Steam-conditioned pellet diets, irrespective of conditioning temperature, were more durable and harder than the dry-conditioned pellet diet. Although dry-conditioned pellet diet had higher content of GS than pellet diets conditioned at 60 and 75 ℃, its pellet durability and hardness were lower. The dry-conditioned pellet diet was visually observed to consist of less than 10% intact pellets, but as it had been passed through the pellet die, it was considered as pellet diet. One explanation for the poor pellet quality, despite higher content of GS, could be the lower moisture content in this diet (115 g moisture/kg of diet compared to 133, 146 and 152 g/kg in pellet diets steam-conditioned at 60, 75 and 90 ℃, respectively). This finding highlights the critical effect of moisture in agglomerating and binding the feed particles. Although the mechanical fractional force in pellet die may cause more gelatinisation, the ability of the GS to bond and agglomerate feed particles depends heavily on the presence of water. Both heating and the presence of water are prerequisites for starch gelatinisation (Kim *et al.*, 2000; Parker and Ring, 2001; Svihus *et al.*, 2005), but it is the presence of water which allows linear and cyclic molecules of ruptured starch granules to hydrate and become sticky (Hasting and Higgs, 1978). Increased pellet durability gained through increasing the moisture content of the feed is well documented

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(Fairchild and Greer, 1999; Moritz *et al.*, 2001; 2002; 2003; Lundblad *et al.*, 2009). Moritz *et al.* (2003) reported that moisture addition (25 and 50 g/kg) in the form of water to a maize-based broiler diet decreased starch gelatinisation while increasing the pellet durability. In the present study, steam-conditioning of diets at 60, 75 and 90 ºC increased the pellet durability by 391, 408 and 441%, respectively, compared to the dry-conditioned diet (conditioned at 20 ºC). The corresponding improvements in pellet hardness were 125, 174 and 330%, respectively. While the pellet diet conditioned at 90 ºC had the highest pellet durability and hardness due probably to higher GS content and moisture, the pellet diet conditioned at 75 ºC was also more durable and harder than that conditioned at 60 ºC despite having similar GS contents. Based on these findings, it appears that although starch gelatinisation has a large influence on the pellet quality, moisture content of the diet is also critical for good pellet quality.

Increases observed in feed hardness in pellet diets due to the introduction of steam and increasing conditioning temperatures were as expected. But higher feed hardness in mash diet conditioned at 90 ºC compared to the other mash diets suggests that the effects of higher conditioning temperatures on feed hardness are not only limited to the pellet diets but can be seen even in mash diets.

Pelleting reduced the AME and ileal N and starch digestibility of the diets. Similar to this finding, Amerah *et al.* (2007b) reported lower nitrogen-corrected AME in birds fed pellet diets (11.8 MJ/kg) compared to those fed mash diets (12.5 MJ/kg). Effect of pelleting on starch digestibility in wheat is well documented (Svihus, 2001; Svihus and Hetland, 2001). Svihus and Hetland (2001) hypothesised that the higher intake of wheat-based pellet diets increases the starch load in the gut and lowers the digestibility of starch. According to Zimonja *et al.* (2007), amylose-lipid complex formation during feed processing can reduce starch digestibility.

Steam-conditioning at 60 and 75 ºC increased the ileal N digestibility compared to the diets dry-conditioned at 20 ºC, but steam-conditioning at 90 ºC reduced the digestibility to an extent which was less than those of diets steam-conditioned at 60 and 75 ºC and similar to the diets dry-conditioned at 20 ºC. It would seem that the improvement in N digestibility gained by the introduction of steam to the conditioner disappears when conditioning temperature reached to 90 ºC. High processing temperatures may result in

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formation of Maillard products (Thomas *et al.*, 1998), which may explain the impaired N digestibility at 90 ℃. The improvements in N digestibility in birds fed diets conditioned at 60 and 75 ℃ in the present study could be explained, in part, by protein denaturation that may have occurred during the steam-conditioning process. According to Thomas *et al.* (1998), a combination of shear, heat, residence time and water during processing results to partial denaturation of the protein in the feed. In general, heating improves the digestibility of proteins by inactivating enzyme inhibitors and denaturing the protein which may expose new sites for enzyme attack (Camire *et al.*, 1990).

Increasing conditioning temperatures above 60 ℃ in mash diets reduced the ileal starch digestibility. Formation of resistant starch could explain, at least in part, the reduction in starch digestibility of the diet conditioned at 90 ℃. In pellet diets, the diet conditioned at 90 ℃ unexpectedly showed similar starch digestibility to those conditioned at 60 and 75 ℃. This finding can be less readily explained, but could be due to significantly higher GS content in this diet. Although higher content of RS was also observed in the pellet diet conditioned at 90 ℃, but the RS:GS ratio was lower in this diet compared to the diets conditioned at 60 and 75 ℃. Another possible explanation for this finding could be the marked increase in pellet hardness achieved by conditioning at 90 ℃. It is possible that, harder pellets are retained longer in the gizzard and, provide better mixing of digesta with endogenous enzymes and improve nutrient utilisation. Parsons *et al.* (2006) demonstrated that offering pellets of hard texture to broilers improved N and lysine retention compared with broilers fed soft pellets.

Pelleting reduced the relative length of all segments of small intestine and caeca. Similar findings have been reported by Nir *et al.* (1994). It appears that the changes in the length of small intestine and caeca may be due to nutrient digestibility changes caused by chemical and physical alterations in the diet. Amerah *et al.* (2007b) reported that improvement in bird performance, which was achieved with pelleting in their study, was associated by a decrease in the relative length of all segments of the intestinal tract. It might be concluded that the lowered length of small intestine in birds fed the diets steam-conditioned at 60 ℃ compared to those fed diets dry-conditioned at 20 ℃ is a natural response to higher nutrient digestibility.

The present data showed that the relative gizzard weight and contents were lower in birds fed pellet diets than those fed mash diets, a finding that is similar to those of previous studies (Nir *et al.*, 1994; Preston *et al.*, 2000; Amerah *et al.*, 2007b). The lowest relative gizzard and content weights were observed for the dry-conditioned pellet diet. This diet had the lowest proportion of coarse particles due to a high mechanical friction force in the pellet die, which may have served to exacerbate the differences between this diet and other diets. Amerah *et al.* (2007b) suggested that pelleting decreases the grinding requirement of the gizzard so that its function is reduced to that of a transit organ. As conditioning at different temperatures can alter the mechanical friction force, it is reasonable to suggest that part of conditioning temperature effects on bird performance and even nutrient utilisation may be attributed to its effect on feed particle size.

6.6. Conclusions

Overall, the present data showed that in mash diets, increasing conditioning temperatures *per se* above 60 ℃ had negative effects on weight gain, feed per gain and nutrient utilisation of broiler starters. But in pellet diets, steam-conditioning at temperatures above 60 ℃ improved pellet quality and the better pellet quality resulted in the restoration of the deteriorated performance parameters. Lower durability and hardness in the dry-conditioned pellet diet, despite having higher content of GS, shows that the ability of GS to bond and agglomerate feed particles depends heavily on the presence of water. Future studies are warranted to investigate possible ways of maintaining higher nutrient digestibility and energy utilisation obtained by steam-conditioning at low temperatures while simultaneously achieving a good pellet quality without using high conditioning temperatures.

CHAPTER 7

Effect of improved pellet quality from the addition of a pellet binder or/and moisture to a wheat-based diet conditioned at different temperatures on performance and nutrient utilisation of broilers

7.1.   Abstract

The effect of a commercial pellet binder or/and moisture addition on pellet quality, performance and nutrient utilisation of broilers fed wheat-based diets was examined in this study. The experimental treatments were as follows: Treatment 1, basal diet conditioned at 60 ℃; Treatment 2, 3 g/kg commercial pellet binder added to the basal diet prior to conditioning at 60 ℃; Treatment 3, 24 g/kg moisture added to the basal diet prior to conditioning at 60 ℃; Treatment 4, 3 g/kg commercial pellet binder plus 24 g/kg moisture added to the basal diet prior to conditioning at 60 ℃; Treatment 5, basal diet conditioned at 90 ℃; Treatment 6, 3 g/kg commercial pellet binder added to the basal diet prior to conditioning at 90 ℃. During the starter period (d 1 to 21), pellet binder or/and moisture addition to the diets conditioned at 60 ℃ had no effect (P > 0.05) on performance parameters compared to the diet conditioned at 60 ℃ with no pellet binder or moisture addition; however, pellet binder addition to the diet conditioned at 90 ℃ increased (P < 0.05) weight gain and feed intake and improved (P < 0.05) feed per gain compared to the diet conditioned at 90 ℃ with no pellet binder. During the finisher period (d 22 to 35), dietary treatments had no effect (P > 0.05) on performance parameters. Over the whole trial period (d 1 to 35), the weight gain was influenced (P < 0.001) by dietary treatments, with birds fed the diet conditioned at 90 ℃ with no pellet binder having lower weight gains than those fed the other dietary treatments. Among starter diets conditioned at 60 ℃, moisture addition, individually or in combination with pellet binder, resulted in higher (P < 0.05) pellet durability index (PDI) and pellet hardness compared to the diets without and with pellet binder addition. Starter diet conditioned at 90 ℃ with pellet binder had the highest (P < 0.05) pellet hardness followed by the diet conditioned at 90 ℃ without pellet binder. In finisher diets conditioned at 60 ℃, moisture addition, individually or in combination with pellet binder, increased (P < 0.05) PDI compared to the diets without or with pellet binder. Steam-conditioning at 90 ℃, regardless of pellet binder addition, resulted in lower apparent

metabolisable energy compared to all diets conditioned at 60 ℃. Dietary treatments had no effect (P > 0.05) on apparent ileal digestibility of nitrogen and starch in finisher diets. Among starter diets, the diet conditioned at 90 ℃ with pellet binder had the highest (P < 0.05) gelatinised starch (GS) content followed by the diet conditioned at 90 ℃ without pellet binder. Starter diet conditioned at 60 ℃ with no pellet binder or moisture addition had the lowest (P < 0.05) resistant starch content compared to the other dietary treatments. The finisher diets conditioned at 90 ℃ without or with pellet binder had the highest (P < 0.05) GS content. Resistant starch content of finisher diets was unaffected (P > 0.05) by dietary treatments. Overall, these results illustrate possibilities for high quality pellets to be manufactured through the addition of pellet binder or/and moisture without the need for high conditioning temperatures.

7.2.   Introduction

To optimise feed efficiency and growth responses of broilers, pellet feeding is not enough. The physical quality of pellets and their ability to withstand handling stresses must also be taken into account (Briggs *et al*., 1999). The benefits of feeding high quality pellets to broilers are well documented (Proudfoot and Sefton, 1978; Moritz *et al.*, 2001; Behnke and Beyer, 2002; Moritz *et al.*, 2003; Cutlip *et al.*, 2008; Hott *et al.*, 2008; Corzo *et al*., 2011). But consideration should also be given to the potential negative effects of the strategies employed to improve pellet quality on nutrient availability. More specifically, high heat and moisture applied during steam-conditioning may induce chemical changes which may be detrimental to nutrient availability and may reduce or completely negate the benefits of pelleting (Moritz and Lilly, 2010).

Negative effects of higher conditioning temperatures on the weight gain and feed per gain of broilers have been reported previously (Bedford *et al*., 2003; Creswell and Bedford, 2006; Kirkpinar and Basmacioglu, 2006). Previous studies in this thesis (Chapters 4 and 5) have shown that the performance of broiler starters fed diets conditioned at different temperatures might reflect a balance between nutrient availability and pellet quality. While nutrient availability is adversely affected at higher conditioning temperatures, pellet quality improves. The fact that these factors can overcome the effect of each other is relevant in determining the broiler performance. The data reported in Chapter 6 showed that in mash diets, increasing conditioning temperatures above 60 ℃ had

negative influence on nutrient utilisation and performance of broiler starters. But in pellet diets, conditioning at 90 ℃ improved pellet quality and the better pellet quality resulted in the restoration of deteriorated performance. Based on these results, it was attempted in the present study, to investigate possible ways of achieving high nutrient utilisation obtained by steam-conditioning at low temperatures while simultaneously maintaining good pellet quality without using high conditioning temperatures.

A number of strategies can be employed to manufacture high physical quality pellets. However, challenges remain in the implementation of such strategies which are favourable to feed particles adhesion and not detrimental to nutrient availability (Moritz and Lilly, 2010). Overall profitability of broiler industry may be improved if the relationship between feed manufacture strategies, physical pellet quality, and nutrient availability is well understood (Moritz and Lilly, 2010). The objectives of the present experiment were to examine the effect of a commercial pellet binder or/and moisture addition on the quality of pellets and, performance and nutrient utilisation of broilers.

7.3.   Materials and Methods

7.3.1.   Diets

Broiler starter and finisher diets, based on wheat, were formulated to meet the Ross 308 strain recommendations for major nutrients (Ross, 2007; Table 7.1). The experimental treatments were as follows: Treatment 1, basal diet conditioned at 60 ℃; Treatment 2, 3 g/kg commercial pellet binder (Mastercube; Kiotechagil, Reading, UK) added to the basal diet prior to conditioning at 60 ℃; Treatment 3, 24 g/kg moisture added to the basal diet prior to conditioning at 60 ℃; Treatment 4, 3 g/kg commercial pellet binder plus 24 g/kg moisture added to the basal diet prior to conditioning at 60 ℃; Treatment 5, basal diet conditioned at 90 ℃; Treatment 6, 3 g/kg commercial pellet binder added to the basal diet prior to conditioning at 90 ℃. Conditioning time of the mash was 30 seconds and conditioning temperature was measured at the outlet (close to the exit point) of the conditioner before the mash feed entered the die. To confirm the differences in moisture content due to conditioning at 60 and 90 ℃, samples of basal diets conditioned at 60 and 90 ℃ (Treatments 1 and 5) were collected immediately from the conditioner outlet (before entering the pellet die) into airtight plastic containers. The containers were then sealed, left

to cool down and moisture content of the samples was determined (method 930.15; AOAC, 2005). The determined moisture difference of 24 g/kg was considered as the moisture level to be added to the treatments with moisture addition (Treatments 3 and 4). Pellet binder or/and moisture were added to the basal mash diet in a single-screw paddle mixer (Bonser Engineering Co. Pty. Ltd., Merrylands, Australia). Moisture was added using tap water and a manual garden sprayer following the method of Moritz *et al*. (2003). After addition of pellet binder or/and moisture, mash diets were allowed to mix for 10 minutes, followed by the addition of soybean oil and mixed for another 10 minutes. All diets were pelleted using a pellet mill (Richard Size Limited Engineers, Orbit 15, Kingston-upon-Hull, UK) capable of manufacturing 180 kg of feed/h and equipped with a die ring (3-mm holes and 35-mm thickness). The pellets manufactured for starter and finisher periods differed in length (3 and 6 mm, respectively). Representative samples of the diets were collected after pelleting for the determination of pellet durability, pellet hardness and chemical analysis. All diets were manufactured and stored for two weeks prior to the start of the trial and then, prior to feeding, dry matter (DM) content of all diets were determined to ensure that feed intake measurements were not biased by differences in DM content.

7.3.2.   Birds and Housing

A total of 288 day-old male broilers (Ross 308) was obtained from a commercial hatchery and allocated to 36 cages as described in Chapter 3. Each of the six dietary treatments was then randomly assigned to six cages, each housing eight birds. Feed was offered *ad libitum* and water was freely available throughout the trial. Housing conditions were as described in Chapter 3, section 3.1.

7.3.3.   Performance data

Performance data were recorded as described in Chapter 3, section 3.1.

7.3.4.   Pellet quality

Pellet durability index (PDI) and pellet hardness of the diets were measured as described in Chapter 3, sections 3.7 and 3.8, respectively.

7.3.5. Apparent metabolisable energy (AME) determination

The AME determination was carried out between d 17 to 20 posthatch as described in Chapter 3, section 3.2.

Table 7.1. Composition and calculated analysis (g/kg as fed) of the basal diets

Ingredient	Starter (d 1 to 21)	Finisher (d 22 to 35)
Wheat	631.6	685.4
Soybean meal, 48%	242.8	199.8
Meat and bone meal	80.0	61.0
Soybean oil	31.1	38.2
Limestone	1.5	3.5
Salt	1.7	1.9
Sodium bicarbonate	1.3	0.7
Lysine. HCl	2.7	1.6
DL-methionine	3.3	2.5
L-threonine	1.0	0.4
Trace mineral- vitamin premix[1]	3.0	2.0
Titanium dioxide	0	3.0
Calculated analysis		
Metabolisable energy, MJ/kg	12.66	12.98
Crude protein	232	207
Lysine	13.4	10.9
Methionine	6.4	5.2
Methionine + cysteine	10.1	8.6
Threonine	8.9	7.4
Calcium	9.8	8.5
Available phosphorus	5.2	4.2
Sodium	2.0	1.8
Chloride	2.0	2.0
Potassium	8.6	7.7

[1]Supplied per kilogram of diet: antioxidant, 100 mg; biotin, 0.2 mg; calcium pantothenate, 12.8 mg; cholecalciferol, 60 µg; cyanocobalamin, 0.017 mg; folic acid, 5.2 mg; menadione, 4 mg; niacin, 35 mg; pyridoxine, 10 mg; trans-retinol, 3.33 mg; riboflavin, 12 mg; thiamine, 3.0 mg; dl-α-tocopheryl acetate, 60 mg; choline chloride, 638 mg; Co, 0.3 mg; Cu, 3.0 mg; Fe, 25 mg; I, 1 mg; Mn, 125 mg; Mo, 0.5 mg; Se, 200 µg; Zn, 60 mg.

7.3.6. Ileal digestibility determination

On d 35, digesta collection was carried out and processed as described in Chapter 3, section 3.3.

7.3.7. Weights of proventriculus and gizzard

On d 35, two more birds per cage were euthanised by cervical dislocation and empty weights of proventriculus and gizzard were determined as described in Chapter 3, section 3.6.

7.3.8. Chemical analysis

Dry matter, nitrogen (N), gross energy (GE), titanium (Ti), starch, gelatinised (GS) and resistant starch (RS) contents were determined as described in Chapter 3, section 3.4.

7.3.9. Calculations

The AME values of starter diets and apparent ileal nutrient (N and starch) digestibility coefficients of finisher diets were calculated using the formula described in Chapter 3, section 3.5.

7.3.10. Data analysis

The data were analysed by a one-way ANOVA using the General Linear Models procedure of SAS (2004) in a completely randomised design. The cage means were used as the experimental units. Differences were considered to be significant at $P < 0.05$, and significant differences between means were separated by the Least Significant Difference test.

7.4. Results

7.4.1. Performance

Mortality during the performance experiment was negligible. Only seven out of the 288 birds died and the deaths were not related to any specific treatment.

During the starter period (d 1 to 21), birds fed diets conditioned at 60 ℃, regardless of pellet binder or/and moisture addition, gained more ($P < 0.05$) weight than those fed diets conditioned at 90 ℃ without or with pellet binder (Table 7.2). Addition of pellet binder or/and moisture to the diets conditioned at 60 ℃ had no effect ($P > 0.05$) on weight gain, feed intake and feed per gain. Pellet binder addition to the diet conditioned at 90 ℃

increased (P < 0.05) weight gain and feed intake and improved (P < 0.05) feed per gain compared to the diet conditioned at 90 ℃ with no pellet binder.

During the finisher period (d 22 to 35; Table 7.2), dietary treatments had no effect (P > 0.05) on performance parameters.

Over the whole trial period (d 1 to 35, Table 7.2), only the weight gain was influenced (P < 0.001) by dietary treatments. Birds fed the diet conditioned at 90 ℃ with no pellet binder addition had lower (P < 0.05) weight gains than those fed the other dietary treatments. There was a tendency (P = 0.06) for dietary treatments to affect feed intake. Birds fed the diet conditioned at 90 ℃ with no pellet binder addition tended to have a similar feed intake to those fed the diets conditioned at 60 ℃ without or with pellet binder, but lower than those fed the other diets. The dietary treatments had no effect (P > 0.05) on feed per gain.

7.4.2. Pellet quality

In starter diets, PDI and pellet hardness were influenced (P < 0.001) by dietary treatments (Table 7.3). Pellet durability of the diet conditioned at 60 ℃ with pellet binder and moisture addition was similar (P > 0.05) to the diet conditioned at 90 ℃ with pellet binder, but higher (P < 0.05) than other dietary treatments. Among starter diets conditioned at 60 ℃, moisture addition, individually or in combination with pellet binder, resulted in higher (P < 0.05) PDI and pellet hardness compared to diets without and with pellet binder addition. Starter diets conditioned at 90 ℃ with pellet binder had the highest pellet hardness followed by the diet conditioned at 90 ℃ without pellet binder.

Among finisher diets, those conditioned at 90 ℃, regardless of pellet binder addition, had higher (P < 0.05) PDI and pellet hardness than the diets conditioned at 60 ℃ (Table 7.3). In finisher diets conditioned at 60 ℃, while the diet with combination of pellet binder and moisture had the highest PDI, moisture addition increased (P < 0.05) the PDI compared to the diets without or with pellet binder. Among finisher diets conditioned at 60 ℃, moisture addition, individually or in combination with pellet binder, increased (P < 0.05) the pellet hardness compared to the diet without pellet binder and moisture.

Table 7.2. Influence of the dietary treatments on weight gain (g/bird), feed intake (g/bird) and feed per gain (g feed/g gain) of broilers during starter (d 1 to 21), finisher (d 22 to 35) and whole trial (d 1 to 35) periods[1]

	Starter period			Finisher period			Whole trial period		
	Weight gain	Feed intake	Feed per gain	Weight gain	Feed intake	Feed per gain	Weight gain	Feed intake	Feed per gain
60 °C	1090^a	1442^{ab}	1.353^{ab}	1607	2655	1.703	2697^a	4097	1.557
60 °C- Pellet binder	1090^a	1455^a	1.340^b	1584	2636	1.688	2674^a	4091	1.543
60 °C- Moisture	1103^a	1459^a	1.331^b	1643	2737	1.697	2745^a	4196	1.547
60 °C- Pellet binder + Moisture	1095^a	1461^a	1.342^b	1640	2746	1.709	2735^a	4207	1.559
90 °C	975^c	1343^c	1.376^a	1578	2599	1.667	2553^b	3942	1.554
90 °C- Pellet binder	1047^b	1398^b	1.335^b	1637	2750	1.679	2684^a	4148	1.545
Probabilities, P ≤	***	***	*	NS	NS	NS	***	0.06	NS
SEM^2	8.4	17.6	0.0103	21.7	49.2	0.0147	26.3	63.2	0.0119

[a,b,c] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; *** P < 0.001.

[1] Each value represents the mean of six replicates (eight birds per replicate).

[2] Pooled standard error of mean.

7.4.3.   Nutrient utilisation

All starter diets conditioned at 60 ℃ were determined to have similar AME values. However, conditioning at 90 ℃, regardless of pellet binder addition, resulted in lower (P < 0.05) AME compared to diets conditioned at 60 ℃ (Table 7.3).

Apparent ileal digestibility of N and starch in finisher diets was unaffected (P > 0.05) by dietary treatments.

7.4.4.   Weights of proventriculus and gizzard

The effects of dietary treatments on the relative empty weight of proventriculus and gizzard are shown in Table 7.4. Neither the relative weight of proventriculus nor gizzard was influenced (P > 0.05) by dietary treatments.

7.4.5.   Gelatinised and resistant starch contents

The influence of dietary treatments on GS and RS contents of starter and finisher diets is shown in Table 7.5. Gelatinised starch content of starter diets was influenced (P < 0.001) by dietary treatments. Among starter diets, the diet conditioned at 90 ℃ with pellet binder had the highest GS content followed by the diet conditioned at 90 ℃ without pellet binder. In starter diets conditioned at 60 ℃, the diet with pellet binder addition and the diet with moisture addition had the highest and lowest GS content, respectively.

Resistant starch content of starter diets was influenced (P < 0.05) by dietary treatments. The diet conditioned at 60 ℃ with no pellet binder or moisture addition had the lowest RS content compared to the other dietary treatments.

Gelatinised starch content of finisher diets was influenced (P < 0.001) by dietary treatments. Whilst the diets conditioned at 90 ℃ without or with pellet binder had the highest GS content, the moisture-added diets conditioned at 60 ℃, regardless of pellet binder addition, had the lowest GS contents.

Resistant starch content of finisher diets was unaffected (P > 0.05) by dietary treatments.

Table 7.3. Influence of the dietary treatments on PDI (%), pellet hardness (Newton), AME (MJ/kg DM), ileal N and starch digestibility in broilers[1]

	Starter diet			Finisher diet			
	PDI[2]	Pellet hardness[3]	AME	PDI[2]	Pellet hardness[3]	Ileal N digestibility	Ileal starch digestibility
60 ℃	56.5^d	14.9^d	13.50^a	74.1^d	24.3^c	0.774	0.850
60 ℃- Pellet binder	63.1^c	18.0^d	13.49^a	73.9^d	27.3^{bc}	0.794	0.850
60 ℃- Moisture	67.2^b	23.9^c	13.54^a	84.7^c	30.8^b	0.775	0.858
60 ℃- Pellet binder + Moisture	70.2^a	23.4^c	13.48^a	89.7^b	29.4^b	0.774	0.841
90 ℃	63.2^c	28.4^b	13.26^b	92.8^a	41.7^a	0.774	0.869
90 ℃- Pellet binder	69.6^{ab}	37.8^a	13.19^b	93.1^a	45.7^a	0.760	0.861
Probabilities, P ≤	***	***	*	***	***	NS	NS
SEM[4]	0.86	1.27	0.0759	0.51	1.63	0.0132	0.0226

[a,b,c,d] Means in a column not sharing a common superscript are significantly different (P < 0.05).

NS, not significant; * P < 0.05; *** P < 0.001.

[1] Each value represents the mean of six replicates.

[2] Each value represents the mean of six replicate samples.

[3] Each value represents the mean of 15 replicate samples.

[4] Pooled standard error of mean.

Table 7.4. Influence of the dietary treatments on relative empty weight (g/kg body weight) of proventriculus and gizzard of broilers[1]

	Proventriculus	Gizzard
60 ℃	2.33	6.88
60 ℃- Pellet binder	2.33	6.91
60 ℃- Moisture	2.23	6.81
60 ℃- Pellet binder + Moisture	2.61	6.84
90 ℃	2.17	7.23
90 ℃- Pellet binder	2.33	7.26
Probabilities, $P \leq$	NS	NS
SEM[2]	0.112	0.259

NS, not significant.

[1] Each value represents the mean of 12 birds.

[2] Pooled standard error of mean.

Table 7.5. Influence of the dietary treatments on GS and RS contents (g/100 g total starch, DM) of the diets[1]

	Starter diet		Finisher diet	
	Gelatinised starch	Resistant starch	Gelatinised starch	Resistant starch
60 ℃	9.38^{cd}	1.088^{b}	8.50^{b}	1.139
60 ℃- Pellet binder	9.53^{c}	1.257^{a}	8.05^{bc}	1.128
60 ℃- Moisture	8.84^{d}	1.259^{a}	7.78^{c}	1.245
60 ℃- Pellet binder + Moisture	9.33^{cd}	1.256^{a}	7.89^{c}	1.166
90 ℃	13.7^{b}	1.229^{a}	11.8^{a}	1.243
90 ℃- Pellet binder	14.3^{a}	1.284^{a}	11.3^{a}	1.184
Probabilities, $P \leq$	***	*	***	NS
SEM[2]	0.188	0.0370	0.164	0.0394

[a,b,c,d] Means in a column not sharing a common superscript are significantly different ($P < 0.05$).

NS, not significant; * $P < 0.05$; *** $P < 0.001$.

[1] Each value represents the mean of four replicate samples.

[2] Pooled standard error of mean.

7.5. Discussion

Previous research (Chapter 6) showed that the deterioration in the performance of broiler starters feeding mash diets conditioned at temperatures above 60 ℃ was restored when the diets were pelleted. Improved pellet quality due to conditioning at higher temperature accounted for these findings. Based on these results, it was attempted in the present study to maintain high nutrient digestibility and energy utilisation by conditioning at 60 ℃ as well as to manufacture high quality pellets without applying high conditioning temperatures.

In the current study, during the starter period, conditioning at 90 ℃, regardless of pellet binder addition, reduced the weight gain compared to dietary treatments conditioned at 60 ℃. Whilst addition of pellet binder or/and moisture to the diets conditioned at 60 ℃ resulted in similar performance parameters, addition of pellet binder to the diets conditioned at 90 ℃ increased weight gain and feed intake and improved feed per gain compared to the diet conditioned at 90 ℃ without pellet binder. Considering the effect of dietary treatments on PDI and pellet hardness of starter diets, the observed performance of broiler starters becomes more interesting. Addition of pellet binder and moisture, individually or in combination, to diets conditioned at 60 ℃ improved pellet durability to different degrees compared to the diet conditioned at 60 ℃ without pellet binder and moisture addition. Pellet hardness of starter diets conditioned at 60 ℃ was also increased by moisture addition individually and in combination with pellet binder. But these improvements had no effect on the growth responses of birds. Conversely, among diets conditioned at 90 ℃, higher PDI and pellet hardness observed in the pellet binder added diet compared to the diet without pellet binder, resulted in better broiler performance. Based on these observations, it may be concluded that the effectiveness of higher pellet quality on improving growth responses of the birds depends on the effects of conditioning temperature on nutrient availability of the diets. It seems that similar AME values of the diets conditioned at 60 ℃ did not leave any room for the higher pellet quality achieved by addition of pellet binder and moisture, individually or in combination, to further improve the performance. But lower AME values of diets conditioned at 90 ℃ were compensated by the higher pellet quality due to pellet binder addition, and resulted in higher weight gain and feed intake and an improved feed per gain compared to the diet with no pellet binder. It seems plausible that pellet binder addition to the diet conditioned at 90 ℃ may create pellets of high

quality to offset lower AME values of diets conditioned at 90 ºC. It has been suggested that high quality pellets reduce energy spent for ingestion, creating the potential to reduce dietary energy requirements (Moran, 1989). Moritz *et al*. (2001) reported that broilers fed high moisture (853 g/kg DM) maize-based crumble diets grow equally well as compared to those fed low moisture (927 g/kg DM) crumble diets. They concluded that an increase in productive energy gained through higher quality crumbles and higher starch gelatinisation due to moisture addition possibly offset the nutrient dilution. Moritz *et al*. (2003) showed that feeding lower energy (5% less than NRC recommended levels) diets with pre-pelleting moisture addition produced feed efficiency equivalent to broilers fed maize-soybean diets containing NRC-recommended energy levels. They speculated that higher pellet durability achieved by moisture addition could have reduced the bird activity related to feed prehension and energy spent for consuming pellets, thereby offsetting the energy dilution in low energy diets.

Performance parameters were unaffected by dietary treatments during the finisher period. However, over the whole trial period, birds offered the diet conditioned at 90 ºC with no pellet binder addition had lower weight gains compared to those offered other dietary treatments. These birds also tended to have the lowest feed intake. Therefore, the negative effects of higher conditioning temperature on weight gain and to some extent feed intake of the birds are not only limited to the starter period, but also can be seen over the grow-out period. Reduced weight gain of birds fed the diet conditioned at 90 ºC with pellet binder during the starter period was restored in the whole trial period. It has been shown that improved pellet quality, through moisture addition, significantly increased adjusted feed efficiency (adjusted for moisture content; Moritz *et al*., 2001) and produced equivalent broiler performance despite a lower dietary energy levels (Moritz *et al*., 2003) during the finisher (21-42 d) period.

Interestingly, the addition of moisture, individually or in combination with pellet binder, to starter diets conditioned at 60 ºC not only improved PDI and pellet hardness compared to other diets conditioned at 60 ºC, but also resulted in higher PDI than the diet conditioned at 90 ºC without pellet binder. Among finisher diets conditioned at 60 ºC, moisture addition increased the PDI compared to the pellet binder added diet and the diet with no pellet binder and moisture addition. In agreement, Lundblad *et al*. (2009) showed a significant increase in PDI of barley- and maize-based diets with water addition. An increased PDI due to moisture addition to maize-based diets has also been previously shown (Moritz *et al*., 2001; 2002; 2003). In contrast, Hott *et al*. (2008)

reported no effect of moisture addition on PDI of broiler diets manufactured at a pilot feed milling facility. This was attributed to the high PDI of the control diet, which did not leave too much space for improvement. Hemmingsen *et al*. (2008) studied water adsorption of some ingredients (barley, wheat, dehulled oats, soybean meal and rapeseed meal) following exposure to moist air at 80 ℃ or water in the liquid state (20 and 80 ℃), and reported that starchy ingredients (barley, wheat and dehulled oats) showed greatest water adsorption in liquid water at 80 ℃ and low water adsorption in moist air at the same temperature. The protein-rich ingredients (soybean meal and rapeseed meal) showed highest water adsorption in moist air at 80 ℃. They speculated that effect of ingredient composition on pellet quality seems to be determined by the water adsorption pattern of the feed ingredients. As commercially manufactured pellet diets generally contain several ingredients, they suggested that a combination of steam and water should be used to optimise the effect of conditioning during the pelleting process. This could be a reason for increased pellet quality observed in moisture added treatments conditioned at 60 ℃ as the diets were based on wheat and soybean meal.

Pellet binder addition to the starter diets increased the PDI at both conditioning temperatures and pellet hardness at 90 ℃. Pfost (1964) showed that the addition of a lignin pellet binder (calcium lignosulphonate) to turkey and layer diets significantly increased pellet durability. In contrast to starter diets, pellet binder addition to the finisher diets conditioned at 60 and 90 ℃ was not associated with any improvement in pellet durability and hardness. High pellet durability and hardness of the finisher diets without pellet binder may explain this lack of effect. The observed differences in the pattern of changes in PDI and pellet hardness of starter and finisher diets may be related, in part, to differences in the length of pellets.

Moisture addition individually to starter and finisher diets conditioned at 60 ℃ reduced the GS content. Considering the observed positive effects of moisture addition to starter and finisher diets conditioned at 60 ℃ on pellet durability and hardness, it may be concluded that although starch gelatinisation has a positive effect on pellet quality, higher pellet quality may not always be associated with higher degree of starch gelatinisation (Moritz *et al*., 2003). These findings are congruent to research by Moritz *et al*. (2003) who reported that moisture addition, regardless of dietary energy density, decreased pellet starch gelatinisation while simultaneously increasing pellet durability. Previous studies (Stevens, 1987; Chapters 5 and 6) have shown that frictional heat generated in die holes has a marked effect on starch gelatinisation. Therefore, it seems

plausible that lubricating effects of added moisture could decrease the die hole frictional heat, and decreased the GS content of the diet (Moritz *et al*., 2003). One explanation for the higher pellet quality of moisture-containing diets despite lower GS content may be that in a normal conditioning process, the moisture, injected as steam, is held largely on the surface of the starch-containing feed particles rather than permeating the starch granules (Smith, 1959); but moisture addition at the mixer provided better moisture permeation to the starch granules and this better moisture permeation could have resulted in a lower but uniform starch gelatinisation through the entire pellet. According to Moritz *et al*. (2003), a small amount of gelatinisation evenly distributed throughout the pellet may be more effective in binding feed particles than high amounts of localised gelatinisation. In contrast to our finding, Moritz *et al*. (2001) reported that moisture addition to a maize-soybean based broiler diet resulted in marked increases in starch gelatinisation and pellet durability. Another possible explanation for this observation is that while starch gelatinisation favours pellet quality but it is not the main factor determining the pellet quality. Bernardin and Kasarda (1973) showed rapid changes of the wheat endosperm matrix protein into long and sticky protein fibrils upon exposure to the moisture. These hydrated protein fibrils spread out from the mass of endosperm with starch granules and suspended particulates adhering to their surface. They suggested that these fibrils are the structural elements forming the cohesive matrix of dough. Therefore, it is possible that moisture addition to wheat-based diets either through addition of water or steam-conditioning can form protein fibrils that might contribute to agglomerating feed particles more efficiently than GS.

7.6.   Conclusions

In conclusion, the negative effects of higher conditioning temperature on weight gain and, to some extent, on feed intake of broilers were not only limited to the starter period, but can also be carried over the whole grow-out period. The current study also illustrates possibilities for high quality pellets to be manufactured by the addition of pellet binder or/and moisture to a mash diet without the need for high conditioning temperatures. In view of the differences observed between the quality of starter and finisher pellets, future studies to investigate the effects of pellet size (diameter and length) on pellet quality and nutrient utilisation of broilers will be of interest.

CHAPTER 8

Influence of pellet diameter and length on the quality of pellets and, performance, nutrient utilisation and digestive tract development of broilers fed wheat-based diets

8.1.   Abstract

The influence of pellet diameter and length on the quality of pellets and, performance, nutrient utilisation and digestive tract development of broilers fed wheat-based diets was examined in this study. The study was conducted as a 2×2 factorial arrangement of treatments to evaluate the effects of two pellet diameters (3- and 4.76-mm) and two pellet lengths (3- and 6-mm). From 0 to 9 d of age, all birds were offered a common starter diet pelleted with a 3-mm diameter die and 3-mm length. Broiler grower (d 10 to 21) and finisher (d 22 to 42) diets, based on wheat, were formulated and then subjected to the four different treatments. During the grower period (d 10 to 21), birds fed pellets of 6-mm length had greater ($P < 0.05$) weight gain than those fed 3-mm length pellets. Neither main effects of pellet diameter and pellet length nor the interaction were significant ($P > 0.05$) for feed intake. Feeding 6-mm length pellets decreased ($P < 0.05$) feed per gain compared to 3-mm length pellets. During the finisher (d 22 to 42) and whole trial (d 10 to 42) periods, neither the main effects nor the interaction were significant ($P > 0.05$) for weight gain and feed intake. While different pellet lengths had no effect ($P > 0.05$) on feed per gain values at 3-mm pellet diameter, increasing the pellet length decreased ($P < 0.05$) feed per gain at 4.76-mm pellet diameter. In grower diets, increasing pellet diameter and pellet length reduced ($P < 0.001$) the gelatinised starch (GS) content of the diets. In finisher diets, GS content of 3-mm diameter pellets did not change ($P > 0.05$) with increasing the pellet length but decreased ($P < 0.05$) in 4.76-mm diameter pellets. In grower and finisher diets, increments in intact pellet weight, pellet durability index and pellet hardness with increasing pellet length were greater in 3-mm diameter pellets than those with 4.76-mm diameter. Increasing pellet length from 3- to 6-mm increased ($P < 0.05$) apparent metabolisable energy values. Neither main effects nor the interaction were significant ($P > 0.05$) for ileal nitrogen and starch digestibility. Increasing pellet diameter ($P < 0.01$) and pellet length ($P < 0.05$) reduced the relative length of duodenum. Increasing pellet length reduced ($P < 0.05$) the relative length of caeca. Birds fed 3-mm diameter pellets had heavier ($P < 0.05$)

proventriculus compared to those fed 4.76-mm diameter pellets. Neither main effects nor the interaction were significant (P > 0.05) for relative length of jejunum, ileum and small intestine, and relative weight of gizzard, small intestine and caeca. Overall, the current results suggest that increasing the pellet length from 3- to 6-mm improved the weight gain and feed per gain during the grower period (d 10 to 21). While the positive effect on weight gain disappeared as the birds grew older, improvements in feed per gain were maintained over the finisher (d 22 to 42) and whole grow-out (d 10 to 42) periods only in 4.76-mm diameter pellets. Small diameter die holes and longer pellet lengths may be considered as potential manipulations to manufacture high quality pellets under low conditioning temperature.

8.2.   Introduction

The importance of physical quality of pellets in improving growth responses is well recognised in the broiler industry (Proudfoot and Sefton, 1978; Moritz *et al*., 2001; Behnke and Beyer, 2002; Moritz *et al*., 2003; Cutlip *et al*., 2008; Hott *et al*., 2008; Corzo *et al*., 2011). Moreover, feed is too expensive to waste; so pellet quality has an economic value (Löwe, 2005). To create high physical quality pellets, a better understanding of factors affecting pellet quality is necessary. According to Reimer (Cited in Behnke, 2001), pellet quality depends proportionally on the following factors: 40% feed formulation, 20% feed particle size, 20% steam-conditioning, 15% pellet die specification, and 5% cooling and drying process. Feed ingredients have a marked impact on pellet quality. Achieving high quality pellets through manipulating diet formulation, however, has become relatively difficult due to the fact that least-cost diet formulation is the primary concern of the poultry nutritionists as well as the use of concepts such as ideal protein in feed formulations which eliminates the need for high dietary protein levels.

Published data on the effect of feed particle size on pellet quality are contradictory (Reece *et al*., 1986; Stevens, 1987; Angulo *et al*., 1996; Thomas *et al*., 1998; Dozier, 2003; Svihus *et al*., 2004; Amerah *et al*., 2007b). In general, coarsely-ground particles are believed to compromise the pellet quality, although there is no objective evidence to support this claim (Amerah *et al*., 2007b).

According to Dozier (2003), steam-conditioning has more impact on pellet quality than any other feed manufacturing process. Some researchers have investigated the effects of steam-conditioning process parameters such as steam pressure (Stevens,

1987; Briggs *et al*., 1999; Maier and Briggs, 2000; Cutlip *et al*., 2008), conditioning temperature (Pfost, 1964; Skoch *et al*., 1981; Spring *et al*., 1996; Cutlip *et al*., 2008) and retention time (Briggs *et al*., 1999; Maier and Briggs, 2000; Plattner, 2002) on pellet quality. It should be noted, however, that manufacture of high quality pellets is equally important as creating diets that are highly digestible and readily available to the bird (Lilly *et al*., 2011). Increasing conditioning temperature improves the pellet quality, but high heat and moisture applied during steam-conditioning may induce chemical changes which may be detrimental to nutrient availability and may reduce or completely negate the benefits of pelleting (Moritz and Lilly, 2010).

Based on our previous research (Chapter 6), demonstrating the negative effects of conditioning temperatures above 60 ºC *per se* on nutrient utilisation, studies were designed to evaluate possible strategies to manufacture high physical quality pellets without applying high conditioning temperatures. The study reported in Chapter 7 showed the possibility of creating pellets of high quality through the addition of pellet binder or/and moisture to broiler diets without the need for conditioning temperatures above 60 ºC. In that study (Chapter 7), it was observed that increased pellet length of finisher diets compared to starter diets, while maintaining the same die-hole diameter (3 mm), improved pellet quality, although the composition of the two diets was different. Pellet length is not usually considered when pellet quality is defined by durability and percentage of fines, but high quality pellets may be of longer length than pellets of lesser quality (Cutlip *et al*., 2008). Despite the effect of frictional force generated inside the die hole during pelleting process on binding characteristics of feed ingredients (Pfost, 1971; Heffner and Pfost, 1973; Skoch *et al*., 1981; 1983a,b; Stevens, 1987), studies examining the effect of die hole (pellet) diameter on pellet quality are scarce. According to Heffner and Pfost (1973), there is a relationship between die hole diameter, starch gelatinisation and pellet durability. Reducing the die hole diameter can produce more gelatinised starch and more durable pellets.

Based on above discussion, it was hypothesised that manipulation of pellet size (diameter and length) may provide another potential approach to improve pellet quality at low conditioning temperatures. To test this hypothesis, the present experiment was designed to examine the effect of pellet diameter and length on the quality of pellets and, performance, nutrient utilisation and digestive tract development of broilers fed wheat-based diets.

8.3.   Materials and Methods

8.3.1.   Diets

The study was conducted as a 2×2 factorial arrangement of treatments to evaluate the effects of two pellet diameters (3- and 4.76-mm) and two pellet lengths (3- and 6-mm). Broiler grower (d 10 to 21) and finisher (d 22 to 42) diets were formulated to meet the Ross 308 strain recommendations for major nutrients (Ross, 2007; Table 8.1).

Table 8.1. Composition and calculated analysis (g/kg as fed) of the basal diets

Ingredient	Grower (d 10 to 21)	Finisher (d 22 to 42)
Wheat	650.0	680.5
Soybean meal, 48%	228.5	189.0
Meat and bone meal	65.6	60.8
Soybean oil	41.1	53.3
Limestone	3.4	3.6
Salt	1.8	1.9
Sodium bicarbonate	1.4	0.7
Lysine. HCl	2.4	2.0
DL-methionine	3.0	2.6
L-threonine	0.8	0.6
Trace mineral- vitamin premix[1]	2.0	2.0
Titanium dioxide	0.0	3.0
Enzyme[2]	0.1	0.1
Calculated analysis		
Metabolisable energy, MJ/kg	12.97	13.39
Crude protein	220	202
Lysine	12.4	10.9
Methionine	6.0	5.3
Methionine + cysteine	9.5	8.6
Threonine	8.3	7.5
Calcium	9.0	8.5
Available phosphorus	4.5	4.2
Sodium	2.0	1.8
Chloride	2.0	2.0
Potassium	8.2	7.6

[1]Supplied per kilogram of diet: antioxidant, 100 mg; biotin, 0.2 mg; calcium pantothenate, 12.8 mg; cholecalciferol, 60 µg; cyanocobalamin, 0.017 mg; folic acid, 5.2 mg; menadione, 4 mg; niacin, 35 mg; pyridoxine, 10 mg; trans-retinol, 3.33 mg; riboflavin, 12 mg; thiamine, 3.0 mg; dl-α-tocopheryl acetate, 60 mg; choline chloride, 638 mg; Co, 0.3 mg; Cu, 3.0 mg; Fe, 25 mg; I, 1 mg; Mn, 125 mg; Mo, 0.5 mg; Se, 200 µg; Zn, 60 mg.

[2]Avizyme 1502 (Danisco Animal Nutrition, Marlborough, UK).

Each of grower and finisher diets was then subjected to four pelleting treatments: 1) pelleted with a 3-mm die and 3-mm length, 2) pelleted with a 3-mm die and 6-mm length, 3) pelleted with a 4.76-mm die and 3-mm length, 4) pelleted with a 4.76-mm die and 6-mm length. All diets were steam-conditioned at 60 ºC for 30 seconds and pelleted using a pellet mill (Richard Size Limited Engineers, Orbit 15, Kingston-upon-Hull, UK) capable of manufacturing 180 kg of feed/h. Representative diet samples were collected for the determination of gelatinised starch (GS), intact pellet weight, pellet durability and pellet hardness.

8.3.2.   Birds and Housing

Two hundred and fifty day-old male broilers (Ross 308), obtained from a commercial hatchery, were allocated to cages in electrically heated battery brooders. From 0 to 9 d of age, all birds were offered a common starter diet pelleted with a 3-mm diameter die and 3-mm length. On d 10, 192 birds were allocated to 24 cages as described in Chapter 3. Each of the four dietary treatments was then randomly assigned to six cages, each housing eight birds. Feed was offered *ad libitum* and water was freely available throughout the trial. Housing conditions were as described in Chapter 3, section 3.1.

8.3.3.   Performance data

Performance data were recorded on d 10, 14, 21, 28, 35 and 42 as described in Chapter 3, section 3.1.

8.3.4.   Intact pellet weight

Intact pellet weight was measured by weighing individual pellets (15 per diet) using a Mettler balance (Mettler Instrumente AG, CH-8606, Greifensee, Zürich, Switzerland).

8.3.5.   Pellet quality

Pellet durability index (PDI) and pellet hardness of the diets were measured as described in Chapter 3, sections 3.7 and 3.8, respectively.

8.3.6.   Apparent metabolisable energy (AME) determination

The AME determination was carried out between d 17 to 20 posthatch as described in Chapter 3, section 3.2.

8.3.7. Ileal digestibility determination

On d 42, digesta collection was carried out and processed as described in Chapter 3, section 3.3.

8.3.8. Digestive tract measurements

On d 42, two more birds per cage were euthanised by cervical dislocation and digestive tract measurements were carried out as described in Chapter 3, section 3.6.

8.3.9. Chemical analysis

Dry matter (DM), nitrogen (N), gross energy (GE), titanium (Ti), starch and GS contents were determined as described in Chapter 3, section 3.4.

8.3.10. Calculations

The AME values of grower diets and apparent ileal nutrient (N and starch) digestibility coefficients of finisher diets were calculated using the formula described in Chapter 3, section 3.5.

8.3.11. Data analysis

The data were analysed as a 2×2 factorial arrangement of treatments, as described in Chapter 3, section 3.9. The cage means were used to derive performance data. For digestive tract measurements, individual birds were considered as the experimental unit.

8.4. Results

8.4.1. Performance

Mortality during the performance experiment was negligible. Only five out of the 192 birds died and the deaths were not related to any specific treatment.

During the grower period (d 10 to 21), weight gain was influenced ($P < 0.05$) by pellet length, with gain of birds fed pellets of 6-mm length being greater than those fed 3-mm length pellets (Table 8.2). There was no effect of pellet diameter and pellet diameter x pellet length interaction ($P > 0.05$) for weight gain. Neither main effects of pellet diameter and pellet length nor the interaction were significant ($P > 0.05$) for feed intake. Feeding long (6-mm) pellets decreased ($P < 0.05$) feed per gain compared to

short (3-mm) pellets. There was no effect (P > 0.05) of pellet diameter and interaction between pellet diameter and pellet length for feed per gain.

During the finisher (d 22 to 42) and whole trial (d 10 to 42) periods, neither main effects of pellet diameter and pellet length nor the interaction were significant (P > 0.05) for weight gain and feed intake (Table 8.2). Pellet diameter and pellet length had no influence (P > 0.05) on feed per gain. However, a significant (P < 0.01, finisher period; P < 0.05, whole trial period) pellet diameter x pellet length interaction was observed for feed per gain due to the pattern of changes with different pellet lengths differing in the two pellet diameters. While at 3-mm pellet diameter, pellet length had no effect (P > 0.05) on feed per gain, increasing pellet length from 3- to 6-mm decreased (P < 0.05) feed per gain at 4.76-mm pellet diameter.

8.4.2. Gelatinised starch content

The influence of dietary treatments on GS content of the diets is shown in Table 8.3. In grower diets, main effects of pellet diameter and pellet length were observed (P < 0.001) for GS content. Increasing pellet diameter and pellet length reduced the GS content of the diets. In finisher diets, main effects of pellet diameter (P < 0.01) and pellet length (P < 0.001) were observed for GS content. There was, however, an interaction of pellet diameter x pellet length (P < 0.001) for GS content. Gelatinised starch content of 3-mm diameter pellets did not change (P > 0.05) with increasing the pellet length but decreased (P < 0.05) in 4.76-mm diameter pellets.

8.4.3. Intact pellet weight

In grower and finisher diets, main effects of pellet diameter and pellet length were observed (P < 0.001) for the intact pellet weight (Table 8.3). However, an interaction of pellet diameter x pellet length in both grower (P < 0.001) and finisher (P < 0.05) diets was also observed. Increments in intact pellet weight with increasing pellet length were greater in 3-mm diameter pellets than those with 4.76-mm diameter.

Table 8.2. Influence of pellet diameter (PD, mm) and pellet length (PL, mm) on the weight gain (g/bird), feed intake (g/bird) and feed per gain (g feed/g gain) of broilers[1] during grower (d 10 to 21), finisher (d 22 to 42) and whole trial (d 10 to 42) periods

Treatment		Grower period			Finisher period			Whole trial period		
PD	PL	Weight gain	Feed intake	Feed per gain	Weight gain	Feed intake	Feed per gain	Weight gain	Feed intake	Feed per gain
3	3	727	1053	1.448	2317	4049	1.761^{ab}	3044	5102	1.685^{ab}
3	6	750	1066	1.422	2323	4069	1.794^{a}	3073	5135	1.700^{ab}
4.76	3	723	1044	1.443	2278	4031	1.792^{a}	3001	5075	1.706^{a}
4.76	6	740	1047	1.431	2360	4016	1.755^{b}	3100	5063	1.675^{b}
SEM[2]		7.4	9.6	0.0087	42.1	68.4	0.0111	47.0	74.3	0.0084
Main effects										
PD (mm)										
3		739	1060	1.435	2320	4059	1.777	3058	5119	1.692
4.76		732	1045	1.437	2319	4023	1.774	3050	5069	1.691
PL (mm)										
3		725^{b}	1049	1.446^{a}	2297	4040	1.776	3022	5089	1.695
6		745^{a}	1057	1.427^{b}	2341	4042	1.774	3086	5099	1.688
Probabilities, P $\leq$										
PD		NS	NS	NS	NS	NS	NS	NS	NS	NS
PL		*	NS	*	NS	NS	NS	NS	NS	NS
PD x PL		NS	NS	NS	NS	NS	**	NS	NS	*

NS, not significant; * P < 0.05; ** P < 0.01.
[1] Each value represents the mean of six replicates (eight birds per replicate).
[2] Pooled standard error of mean.

8.4.4. Pellet quality

In grower diets, pellet diameter had no influence (P > 0.05) but main effect of pellet length (P < 0.001) was observed for PDI and pellet hardness (Table 8.3). However, an interaction of pellet diameter x pellet length (P < 0.001) was also observed for PDI and pellet hardness due to the magnitude of changes with increasing pellet length differing in the two pellet diameters. Increments in PDI and pellet hardness with increasing pellet length were greater in 3-mm diameter pellets (28 and 81% improvements in PDI and pellet hardness, respectively) than those with 4.76-mm diameter (9.5 and 24% in PDI and pellet hardness, respectively).

In finisher diets, while the main effect of pellet diameter (P < 0.05) was observed only for PDI, pellet length influenced (P < 0.001) PDI and pellet hardness. However, as the magnitude of PDI and pellet hardness changes with increasing pellet length differed in the two pellet diameters; a pellet diameter x pellet length interaction (P < 0.001) was also observed. Similar to grower diets, increments in PDI and pellet hardness with increasing pellet length were greater in 3-mm diameter pellets (30 and 86% improvement in PDI and pellet hardness, respectively) than those with 4.76-mm diameter (4 and 23% in PDI and pellet hardness, respectively).

8.4.5. Nutrient utilisation

Pellet diameter had no influence (P > 0.05) but a significant (P < 0.05) main effect of pellet length was observed for the AME (Table 8.3). Increasing pellet length from 3- to 6-mm increased AME values. There was, however, a tendency (P = 0.07) for pellet diameter x pellet length interaction for AME. Increasing pellet length from 3- to 6-mm tended to have no influence on AME in 3-mm diameter pellets but increased the AME in 4.76-mm diameter pellets. Neither main effects nor the interaction were significant (P > 0.05) for ileal N and starch digestibility.

8.4.6. Digestive tract measurements

The effects of dietary treatments on the relative length and empty weight of the digestive tract of the broilers are shown in Table 8.4. Main effects of pellet diameter (P < 0.01) and pellet length (P < 0.05) were observed for relative length of duodenum. Increasing pellet diameter and pellet length reduced the relative length of duodenum.

Neither main effects nor the interaction were significant (P > 0.05) for relative length of jejunum, ileum and small intestine. While there was a tendency (P = 0.10) for the main effect of pellet diameter for the relative length of caeca, main effect of pellet length (P < 0.05) was observed. Increasing pellet length reduced the relative length of caeca.

Main effect of pellet diameter was observed for relative weight of proventriculus (P < 0.05), with birds fed 3-mm diameter pellets having heavier proventriculus compared to those fed 4.76-mm diameter pellets. Neither main effect of pellet length nor the interaction was significant (P > 0.05) for relative weight of proventriculus. Neither main effects nor the interaction were significant (P > 0.05) for relative weight of gizzard, small intestine and caeca.

Table 8.3. Influence of pellet diameter (PD, mm) and pellet length (PL, mm) on GS content[1] (g per 100 g total starch, DM), intact pellet weight (g), PDI (%) and pellet hardness (Newton) of the diets, and AME (MJ/kg DM), ileal N and starch digestibility in broilers[2]

Treatment		Grower diet					Finisher diet					
PD	PL	GS	Pellet weight[4]	PDI[3]	Pellet hardness[4]	AME	GS	Pellet weight[4]	PDI[3]	Pellet hardness[4]	Ileal N digestibility	Ileal starch digestibility
3	3	12.45	0.032[d]	66.5[d]	18.7[d]	13.86	9.76[a]	0.036[d]	52.9[d]	15.9[d]	0.800	0.951
3	6	11.11	0.075[c]	85.0[a]	33.8[a]	13.88	9.68[a]	0.066[c]	69.0[a]	29.6[a]	0.777	0.946
4.76	3	10.28	0.082[b]	72.6[c]	23.5[c]	13.66	9.94[a]	0.086[b]	61.0[c]	19.4[c]	0.792	0.953
4.76	6	9.71	0.137[a]	79.5[b]	29.2[b]	13.92	6.81[b]	0.124[a]	63.6[b]	23.8[b]	0.783	0.946
SEM[5]		0.212	0.0016	0.34	1.30	0.063	0.341	0.0018	0.49	1.07	0.0115	0.0090
Main effects												
PD (mm)												
3		11.78[a]	0.054	75.8	26.3	13.87	9.72	0.051	60.9	22.8	0.788	0.948
4.76		9.99[b]	0.110	76.0	26.3	13.79	8.38	0.105	62.3	21.6	0.787	0.950
PL (mm)												
3		11.36[a]	0.057	69.6	21.1	13.76[b]	9.85	0.061	56.9	17.7	0.796	0.952
6		10.41[b]	0.106	82.3	31.5	13.90[a]	8.24	0.095	66.3	26.7	0.780	0.946
Probabilities, P ≤												
PD		***	***	NS	NS	NS	**	***	*	NS	NS	NS
PL		***	***	***	***	*	***	***	***	***	NS	NS
PD x PL		0.09	***	***	***	0.07	***	*	***	***	NS	NS

NS, not significant; * P < 0.05; ** P < 0.01; *** P < 0.001.
[1] Each value represents the mean of four replicates.
[2] Each value represents the mean of six replicates.
[3] Each value represents the mean of six replicate samples.
[4] Each value represents the mean of 15 replicate samples.
[5] Pooled standard error of mean.

Table 8.4. Influence of pellet diameter (PD, mm) and pellet length (PL, mm) on relative length (cm/kg body weight) and empty weight (g/kg body weight) of the digestive tract of the broilers[1]

Treatment		Relative length					Relative empty weight			
PD	PL	Duodenum	Jejunum	Ileum	Small intestine[2]	Caeca	Proventriculus	Gizzard	Small intestine[2]	Caeca
3	3	10.50	26.4	27.0	63.9	7.23	2.48	6.01	13.42	0.870
3	6	9.84	26.1	26.0	61.9	6.71	2.82	5.98	12.93	0.784
4.76	3	9.71	26.4	26.4	62.5	6.84	2.27	6.24	13.41	0.830
4.76	6	9.18	25.4	26.1	60.7	6.65	2.34	6.29	12.68	0.833
SEM[3]		0.225	0.71	0.66	1.38	0.135	0.153	0.209	0.390	0.0419
Main effects										
PD (mm)										
3		10.17[a]	26.2	26.5	62.9	6.97	2.65[a]	5.99	13.17	0.827
4.76		9.45[b]	25.9	26.2	61.6	6.74	2.31[b]	6.27	13.04	0.831
PL (mm)										
3		10.11[a]	26.4	26.7	63.2	7.03[a]	2.38	6.13	13.41	0.850
6		9.51[b]	25.7	26.0	61.3	6.68[b]	2.58	6.13	12.80	0.808
Probabilities, P ≤										
PD		**	NS	NS	NS	0.10	*	NS	NS	NS
PL		*	NS	NS	NS	*	NS	NS	NS	NS
PD x PL		NS	NS	NS	NS	NS	NS	NS	NS	NS

NS, not significant; * P < 0.05; ** P < 0.01.

[1] Each value represents the mean of 12 birds.

[2] Small intestine = duodenum + jejunum + ileum.

[3] Pooled standard error of mean.

8.5.   Discussion

Our attempts to manufacture high quality pellets at low conditioning temperatures, initiated in the study reported in Chapter 7, continued in the current study. In view of the differences observed between the quality of starter and finisher pellets in the previous study (Chapter 7), pellet size (diameter and length) manipulation was considered as another possible approach to improve pellet quality at low conditioning temperatures. In the current study, PDI and pellet hardness of both grower and finisher diets were improved by increasing the pellet length from 3- to 6-mm. Although PDI and pellet hardness improvements were observed at both pellet diameters (3- and 4.76 mm), increments with increasing pellet length were greater in 3-mm diameter pellets than those with 4.76-mm diameter. In 3-mm diameter grower pellets, increasing the pellet length improved PDI and pellet hardness by 28 and 81%, respectively. Corresponding improvements in 4.76-mm diameter grower pellets were much lower (9.5 and 24%, respectively). A similar trend was observed for finisher diets, with 30 and 86% improvements in PDI and pellet hardness, respectively, in 3-mm diameter pellets compared to 4 and 23% improvements in PDI and pellet hardness, respectively, in 4.76-mm diameter pellets. Wood (1987) reported a linear relationship (r = 0.89) between pellet length and durability, and observed that the variability in pellet length decreased with increasing durability. Interestingly, the diet with 3-mm diameter and 6-mm length had the highest PDI and pellet hardness in both grower and finisher diets. Cerrate *et al*. (2009) reported better pellet quality (determined as a percentage of retained pellets after shaking on a 2-mm screen sieve) in the diet pelleted using 1.59-mm diameter die hole compared to that of 3.17-mm diameter die hole (96 vs. 83%). A strong positive effect of decreased die-hole diameter (from 5 to 3 mm) on the PDI in maize-soy and maize-barley-soy diets has also been reported by Miladinovic and Svihus (2010). Stevens (1987) reported higher degree of gelatinisation in the outer portion of the pellet compared to the whole pellet. He suggested that frictional heat and mechanical shear generated next to the surface of the die hole were responsible for the substantial degree of gelatinisation. Therefore, it is plausible that using a die with small diameter holes may enhance frictional forces and provide more heat transfer and gelatinisation to the core of the pellet. Moreover, according to Löwe (2005) and Miladinovic and Svihus (2010), the most sensitive part of the pellet is the surface of the break resulting from cutting the pressed and extruded feed into cylindrical pieces. The number of these

sensitive breaks depends on the pellet length. Short pellets yield a higher number per mass than longer pellets which means more possibilities to create abrasion and fines (Löwe, 2005). It seems plausible that using small diameter die holes through increasing, and possibly uniformly distributed, starch gelatinisation, and longer pellet lengths through decreasing the number of sensitive breaks (Löwe, 2005), may have an additive effect on pellet quality. Considering the consistency of PDI and pellet hardness results in both grower and finisher diets, it may be suggested that pellet diameter and pellet length have a consistent effect on pellet quality regardless of the pellet quality test used.

Higher GS content in 3-mm diameter grower pellets compared to pellets with 4.76-mm diameter in current study was as expected and is in agreement with study by Heffner and Pfost (1973) who reported that reducing the pellet diameter can produce more GS. However, the tendency for reduced GS content in grower pellets at both diameters and in 4.76-mm diameter finisher pellets with increasing pellet lengths cannot be readily explained. One probable explanation might be that increasing the gap between pellet die and knives to create longer pellets can decrease the retention time of feed in die hole, thus reducing GS content.

Latshaw and Moritz (2009) showed that broilers fed pellets had lower heat increment and utilised more of the feed energy for productive purposes than those fed mash. Moran (1989) suggested that high quality pellets reduce energy spent for ingestion, resulting in reduced dietary energy requirements. In current study, the greater pellet durability and hardness in both grower and finisher diets with 3-mm diameter and 6-mm length, compared to those with 3-mm diameter and 3-mm length, should have improved broiler performance, but no such effect was observed. This finding is, to some extent, similar to the results of the previous trial (Chapter 7) showing that pellet quality improvements due to pellet binder or/and moisture addition had no effect on the growth responses of birds fed diets conditioned at 60 ℃, but resulted in better performance in those fed diets conditioned at 90 ℃. It appears that similar AME values, which were observed in diets conditioned at 60 ℃ in the previous study (Chapter 7) and, in diets with 3-mm diameter and 3-mm length and diets with 3-mm diameter and 6-mm length in the current study, do not leave any room for the higher pellet quality to further improve the performance. The better broiler performance with higher pellet quality achieved by pellet binder addition in diets conditioned at 90 ℃ (Chapter 7), which were determined to have lower AME values, lends some support to this thesis. If the higher pellet quality can offset the lowered AME caused by higher conditioning temperature,

then it is reasonable to assume that the ability of higher pellet quality, achieved by application of conditioning temperatures which are not detrimental to AME, in offsetting the energy dilution can be favourably used to reduce dietary energy content. In other words, high pellet quality may serve as a non-nutritional factor to meet a portion of energy requirements of the bird. Moritz *et al*. (2003) showed that higher pellet durability achieved by moisture addition offset the energy dilution (5% less energy than NRC recommended levels) and resulted in feed efficiency equivalent to diets containing NRC-recommended energy levels.

During the grower period (d 10 to 21), increasing the pellet length resulted in higher weight gain and improved feed per gain, irrespective of pellet diameter. This finding may be explained, at least in part, by the higher AME values of 6-mm grower pellets. During the finisher period (d 22 to 42), however, no effect of pellet diameter and pellet length was observed for weight gain and feed intake. In this period, increasing the pellet length improved feed per gain only in 4.76-mm diameter pellets. Cerrate *et al*. (2008) showed that at 7 d, birds fed a maize-based diet pelleted with a 1.59 mm die had similar body weight to those fed a similar diet pelleted with a 2.38 mm die but higher body weight than birds fed the diet pelleted with a 3.17 mm die. Birds fed the diet pelleted with the 1.59 mm die consumed the greatest amount of feed during the 0-7 d period while those fed the diet pelleted with the 3.17 mm die consumed the least feed. The higher weight gain and feed intake with 1.59 mm diameter pellets were attributed to a more appropriate pellet size for the oral cavity of birds at this age (Moran, 1989) and an improved nutritive value due to higher gelatinisation of starch as the pellet die diameter is reduced (Heffner and Pfost, 1973). Pellet quality, however, was not reported in their study. Birds fed diets pelleted with different die sizes (1.59, 2.38 or 3.17 mm) had similar feed per gain during 0-7 d. However, at 14 d and following feeding a common crumbled diet to all birds between 7-14 d of age, these positive effects on body weight disappeared. Cerrate *et al*. (2009) reported that body weights, feed intake and feed per gain at 13 d did not differ between birds fed diets pelleted with 1.59 mm or 3.17 mm die, despite better pellet quality (determined as a percentage of retained pellets after shaking on a 2-mm screen sieve) of 1.59-mm pellets compared to 3.17-mm pellets (96 vs. 83%).

Interestingly, in the current study, the positive effect of increased pellet length on feed per gain was maintained over finisher and whole grow-out periods only in 4.76-mm diameter pellets and not in 3-mm diameter pellets, despite the fact the latter diet had

a better pellet quality. The highest intact pellet weight observed in this diet may account for this finding. One of the effects of pelleting on feed efficiency is reduction in feed energy used for maintenance and, therefore, improved productive energy (Nir *et al*., 1994). High intact pellet weight means less time, physical activity and energy expended to pick the same amount of feed, more nutrients per unit of feeding energy spent (Scheideler, 1991; Jones *et al*., 1995), more energy available for growth (Jensen *et al*., 1962) and better feed efficiency. Although not conclusive, based on the current results, it may be speculated that a high pellet quality *per se* is not the cause of improved feed per gain but rather the actual weight of pellet which may reduce maintenance energy and divert more energy for productive purposes.

Increasing the pellet length from 3- to 6-mm increased the AME values. As increasing the pellet length was also associated with significant improvements in PDI and pellet hardness, it may be hypothesised that harder and more durable pellets tend to remain longer in the digestive tract and provide better chance for substrates to mix with digestive enzymes. Parsons *et al*. (2006) speculated that pellet texture and particle size may have similar effects on broilers. They compared two different pellet textures, namely, soft (1,662 g of pellet breaking force) and hard (1,856 g of pellet breaking force) and reported that broilers fed hard pellets had improved N and lysine retention and N-corrected true metabolisable energy compared to those fed soft pellets.

The lack of influence of pellet diameter and length on ileal N and starch digestibility of the finisher diets measured at d 42 was not surprising, as all diets were subjected to a similar conditioning process in terms of temperature and time. Since gelatinisation enhances starch availability for enzymatic degradation, higher GS content of the finisher diet with 4.76-mm diameter and 3-mm length compared to that with 4.76-mm diameter and 6-mm length pellets may be expected to increase starch digestibility but that was not the case. This finding may be explained by the difference of GS content of these two diets (9.94 and 6.81 g/100 g total starch in 4.76-mm diameter and 3-mm length finisher diet compared to the finisher diet with 4.76-mm diameter and 6-mm length, respectively). As the basal finisher diet included 453 g total starch/kg of diet (DM), the 4.76-mm diameter and 3-mm length finisher diet had only about 14.2 g more GS/kg of diet compared to the finisher diet with 4.76-mm diameter and 6-mm length, which probably was not enough to increase the digestibility of starch. It has been suggested that the effect of gelatinisation on starch digestion may be of modest importance (Svihus *et al*., 2004; Zimonja *et al*., 2008) since conventional

pelleting process has been shown to gelatinise only small amounts of starch (Pfost, 1971; Skoch 1981; 1983a,b; Svihus *et al.*, 2004; Zimonja *et al.*, 2007; 2008). Lack of starch digestibility responses may also be due to the relatively mature digestive enzyme system at d 42 and the inclusion of exogenous xylanase (Avizyme 1502) to the diets in the current study. These two reasons may explain high starch digestibility values observed in current study compared to starch digestibility of pellet diets reported in previous studies (Chapters 6 and 7).

8.6. Conclusions

Overall, the present data showed that increasing the pellet length from 3- to 6-mm during the grower period (d 10 to 21) positively influenced the weight gain and feed per gain of broilers. While the weight gain response disappeared as the birds grew older, improvements in feed per gain was maintained over the finisher and whole grow-out periods in 4.76-mm diameter pellets and not in 3-mm diameter pellets despite their better pellet quality. It was speculated that a better pellet quality *per se* is not the cause of improved feed per gain but rather the weight of intact pellets which may positively affect the productive energy. Increasing the pellet length from 3- to 6-mm improved PDI and pellet hardness at both pellet diameters (3- and 4.76 mm), but pellets of 3-mm diameter and 6-mm length had the highest PDI and pellet hardness. This pattern was observed in both grower and finisher diets. It seems plausible that using small diameter die holes and longer pellet lengths may have an additive effect on pellet quality, and may provide opportunities to produce high quality pellets under low conditioning temperature.

CHAPTER 9

General discussion

9.1.   Introduction

With ever-rising cost of poultry feed ingredients, feed is too precious to be wasted. Feed wastage is not limited to the feed which is not ingested by the bird and spilled during feeding (physical feed wastage), but also comprises of the feed (more accurately the feed nutrients) which is not digested by the bird (nutritional feed wastage). Pelleting, the preferred method of processing broiler feed, is the greatest energy cost item in the feed manufacturing process. The importance of feeding high physical quality pellets to broilers is well recognised. However, if the strategies applied during pelleting to create high quality pellets lower the availability of nutrients, then feed nutrient wastage will unwittingly increase.

The major issue of concern is the application of high conditioning temperatures to manufacture pellets. The conditioner temperatures which are employed in New Zealand generally range between 85 and 90 ºC. The primary aim of using such high temperatures is to manufacture high physical quality as well as sterilised pellets, but this practise may not favour high nutrient availability. The true impact of conditioning temperature on nutrient availability and bird performance has not been clearly delineated due to the combined effects of conditioning and pelleting when investigating pelleted diets. By differentiating the effects of conditioning temperature from feed form (Chapter 6), it was observed that application of high conditioning temperatures *per se* adversely influences nutrient digestibility and broiler performance. It was also observed, when high-temperature conditioned mash diets are pelleted, the better pellet quality may (or may not) restore the performance of broilers. The present findings suggest that the balance between the negative effect of high conditioning temperatures on nutrient availability and the positive effect on pellet quality determines the probability and magnitude of this restoration. The work reported herein also showed that pre-conditioning addition of moisture in the form of water, and to lesser extent pellet binder addition (Chapter 7), as well as using a small diameter die hole and longer pellet length (Chapter 8) provide opportunities to produce high physical quality pellets without the need for high conditioning temperatures. These data suggest the possibility for high

physical pellet quality to be used as a non-nutritional factor to meet a fraction of the energy requirement of birds, if highly-digestible high quality pellets are manufactured.

9.2. Influence of conditioning temperature on the NSP content

High conditioning temperatures have been shown to increase feed viscosity (Samarasinghe *et al*., 2000; Cowieson *et al*., 2005b; Creswell and Bedford, 2006) as well as intestinal viscosity (Zimonja *et al*., 2008). An increased solubility of NSP largely accounted for the higher viscosity (Nissinen, 1994; Silversides and Bedford 1999). However, data reported in Chapter 5 showed that insoluble, soluble and total NSP contents of the maize- and sorghum-based diets were unaffected by increasing conditioning temperatures. Similar results were observed in Chapter 4 for the effect of conditioning temperature on soluble and total NSP contents of the maize- and wheat-based diets. However, different trends were observed with increasing conditioning temperatures in the insoluble NSP content of maize- and wheat-based diets (Chapter 4). Insoluble NSP content of maize-based diet conditioned at 75 ºC was lower than those conditioned at 60 and 90 ºC. However, in wheat-based diets, those diets conditioned at 75 and 90 ºC showed similar insoluble NSP contents, but higher than those conditioned at 60 ºC. While the reasons for the quadratic effects on the insoluble NSP content of maize-based diets (Chapter 4) are unclear, it is unlikely that the decrease of 1.5 g insoluble NSP/100 g of the diet at 75 ºC will be of any practical significance. Although conditioning temperature had no influence on the soluble NSP content in studies reported in Chapters 4 and 5, it may have been possible for feed viscosity to increase in high-temperature conditioned diets due to the inactivation of endogenous carbohydrate-degrading enzymes (Silversides and Bedford 1999; Cowieson *et al*., 2005b) resulting in an increase in the molecular weight of NSP (Izydorczyk and Biliaderis, 1992; Cowieson *et al*., 2005b). Higher degree of GS in diets conditioned at high temperatures could also result in increased feed viscosity (Creswell and Bedford, 2006).

9.3. Influence of conditioning temperature on the GS content

Increasing the conditioning temperature from 60 to 75 ºC was accompanied with higher content of GS in maize- and lower content in sorghum-based diets (Chapter 5). Both mash and pellet forms of wheat-based diets conditioned at 60 and 75 ºC showed similar GS contents (Chapter 6). However, data reported in Chapters 5, 6 and 7 showed that increasing the conditioning temperature from 60 to 90 ºC, regardless of grain type, feed

form and pellet binder or moisture addition, increased the GS content of diets. Variable responses of different grains to increasing conditioning temperatures from 60 to 75 ℃ may be explained by differences in gelatinisation characteristics, especially temperatures at which wheat (52-65 ℃, Lund, 1984), maize (65-70.6 ℃, Lund, 1984; 62-72 ℃, Taylor and Dewar, 2001) and sorghum (68-78 ℃, Taylor and Dewar, 2001) starches gelatinise. This may imply that at conditioning temperatures (75 ℃) close to the gelatinisation temperature range of grains, effects of other pelleting parameters such as pellet die friction will be more pronounced, leading to inconsistent results. However, when the conditioning temperature is higher (90 ℃) than the gelatinisation temperature range of grains, increases in the GS content are more consistent.

9.4. Influence of conditioning temperature on the RS content

Data reported in Chapter 5 showed that both maize- and sorghum-based diets conditioned at 90 ℃ had higher RS contents than those conditioned at 60 and 75 ℃. In the study reported in Chapter 6, mash diet conditioned at 90 ℃ had the highest RS content while the diets conditioned at 20, 60 and 75 ℃ had similar RS contents. Pellet diets conditioned at 20 and 90 ℃ had RS contents similar to that conditioned at 75 ℃, but higher than the diet conditioned at 60 ℃. In Chapter 7, the starter diet conditioned at 60 ℃ with no pellet binder or moisture addition had the lowest RS content compared to other dietary treatments.

Although it has been hypothesised that high conditioning temperatures can reduce the availability of starch by formation of resistant starch (Pickford, 1992; Silversides and Bedford, 1999), the current study, to our knowledge, is the first study reporting the effect of conditioning temperature on RS formation. It seems that, in general, steam-conditioning at 60 ℃ was the most optimal, resulting in the least degree of RS formation. It must be noted that even the formation of a small percentage of RS may make a portion of feed energy unavailable to the birds. The observed reduction in the AME content of sorghum-based diets with increasing conditioning temperatures (Chapter 5) and the lower AME content, associated with higher RS content, of the mash and pellet diets conditioned at 90 ℃ compared to 60 ℃ (Chapter 6) lend some support to this thesis.

9.5. Influence of pellet die on GS, RS and NSP contents

It has been reported that pelleting has a greater effect on starch gelatinisation than steam conditioning (Pfost, 1971; Heffner and Pfost, 1973; Skoch *et al.*, 1981; 1983a,b; Stevens, 1987). In agreement with previous reports, in the study reported in Chapter 5, GS content of all dietary treatments increased after passing through the die (conditioned-pelleted samples) compared to samples that were not passed through the die (conditioned-only samples). A perusal of the GS content of the diets reported in Chapter 6 (Table 6.6) suggests that all pellet diets had higher GS contents than their respective mash diets. Increased gelatinisation due to pelleting is attributed to the frictional heat and mechanical shear generated when the mash passes through the pellet die holes (Skoch *et al.*, 1981; 1983a,b; Stevens, 1987).

The effect of pellet die on RS and NSP contents of diets has not been previously reported. Lack of difference between RS content of the diets before and after pelleting (Chapter 5) and the absence of feed form effect on the RS content of the diets (Chapter 6) indicate that RS content of the diets was not affected by the pellet die. Similarly, in general, insoluble, soluble and total NSP contents of the diets were not influenced by pellet die.

9.6. Influence of conditioning temperature on feed particle size

A number of studies have shown that pelleting can reduce feed particle size (Engberg *et al.*, 2002; Svihus *et al.*, 2004; Péron *et al.*, 2005; Amerah *et al.*, 2007b). The work reported in Chapter 6 similarly showed that pelleting, regardless of conditioning temperature, reduced the proportion of coarse particles and increased the proportion of fine particles. Svihus *et al.* (2004) speculated that the narrow gap between the pellet roller and pellet die is responsible for size reduction of large particles during the pelleting process. There are no previous studies investigating the effect of conditioning temperature on feed particle size. Data reported in Chapter 6 showed that while different conditioning temperatures resulted in almost identical particle size distributions in mash diets, increasing conditioning temperatures gradually increased the proportion of particles > 1 mm in pellet diets. These data suggest that frictional force inside the die hole can further grind the coarse particles to smaller particles. The lowest proportion of particles > 1 mm in dry-conditioned pellet diet (conditioned at 20 ℃), indicating a strong grinding effect of the pellet die when a non steam-conditioned diet is passed through the pellet die, lends support to this argument. As steam-conditioning at different

temperatures can alter the mechanical friction force in the pellet die, it is possible that part of conditioning temperature effect on bird performance and even nutrient utilisation may be attributed to it's effect on feed particle size.

9.7. Influence of conditioning temperature on starch and N digestibility

In most of the studies reported in this thesis, the influence of conditioning temperature on the apparent ileal digestibility of starch and N was studied. It was shown that digestibility responses of birds to conditioning temperature differed depending on the grain used. Ileal starch digestibility of broiler starters fed maize-based diets was unaffected by conditioning temperature (Chapters 4 and 5), but was reduced with increasing conditioning temperatures in wheat- (Chapter 4) and sorghum-based diets (Chapter 5). Although the work reported in Chapter 6 demonstrated similar starch digestibility for the pelleted wheat-based diets conditioned at 60, 75 and 90 ℃, there was lower starch digestibility in the mash diet conditioned at 90 ℃ than that conditioned at 60 ℃. These findings demonstrated the negative effects of high conditioning temperature *per se* on ileal starch digestibility. Lower digestibility of starch in birds fed sorghum- (Chapter 5) and wheat-based mash diets (Chapter 6) conditioned at 90 ℃ was associated with significant formation of RS in these diets (Tables 5.6 and 6.6), indicating that deterioration of starch digestibility due to conditioning at 90 ℃ may be partially explained by RS formation. According to Zimonja *et al*. (2007), amylose-lipid complex formation during feed processing may further contribute in reducing starch digestibility.

Increasing the conditioning temperature to 90 ℃ decreased ileal N digestibility in wheat- (Chapters 4 and 6) and sorghum-based diets (Chapter 5). High processing temperatures may result in formation of Maillard products (Thomas *et al.*, 1998) and lower N digestibility. The poorer ileal N digestibility of sorghum-based diet conditioned at 90 ℃ may be further explained by the formation of enzyme-resistant disulphide-bonded oligomeric proteins (Duodu *et al.*, 2002). Interestingly, in both trials investigating the influence of conditioning temperature on maize-based diets (Chapters 4 and 5), ileal N digestibility of the diet conditioned at 75 ℃ was lower than those conditioned at 60 and 90 ℃. These unexpected results for maize-based diets cannot be readily explained.

Data reported in Chapter 6 demonstrated that pelleting reduced the ileal starch and N digestibility of wheat-based diets. Lower starch digestibility in pelleted wheat-

based diets has been attributed to higher intake of pellet diets (Svihus, 2001) and the resultant starch overload in the small intestine (Svihus and Hetland, 2001).

9.8. Influence of conditioning temperature on physical pellet quality

With the exception of our first study (Chapter 4), in which conditioning temperature had no effect on the PDI of maize-based diets, the work reported in this thesis demonstrated the positive effect of increasing conditioning temperatures, irrespective of the temperature used, on the physical pellet quality of wheat- (PDI, Chapter 4; PDI and pellet hardness, Chapter 6), maize- (PDI and pellet hardness, Chapter 5) and sorghum-based diets (PDI and pellet hardness, Chapter 5). However, the greatest improvements were observed at the conditioning temperature of 90 ℃. In a study by Spring *et al*. (1996), increased pellet hardness due to pelleting a barley-wheat-soy diet at 60, 70, 80, 90 and 100 ℃ was reported, with marked improvements at 90 and 100 ℃. Similarly, in the study reported in Chapter 7, both starter and finisher wheat-based diets conditioned at 60 ℃ without pellet binder and moisture addition had lower PDI and pellet hardness compared to those conditioned at 90 ℃ without pellet binder. Positive effect of higher temperatures during steam-conditioning on pellet quality has been previously reported (Pfost, 1964; Skoch *et al*., 1981; Spring *et al*., 1996; Cutlip *et al*., 2008).

9.9. Pellet durability test or pellet hardness test, which one is best?

Although findings in this work illustrated that overall improvements in PDI and pellet hardness due to increasing conditioning temperatures (Chapters 5, 6 and 7), pellet binder or/and moisture addition (Chapter 7) and increasing pellet diameter and length (Chapter 8) were in the same direction, a closer examination of the data shows that in most studies the magnitude of improvement in pellet hardness was higher than PDI. Therefore, it may be hypothesised that the effect of different treatments on the ability of pellets to withstand fragmentation is more pronounced than abrasion resistance. Then it is possible that positive effects of some manipulations on pellet hardness, as a parameter of pellet quality, are not recognised when only the PDI is determined. Parsons *et al*. (2006) reported different pellet hardness (1,662 and 1,856 g of pellet breaking force for soft and hard pellets, respectively) for pellets with similar durability. As pellet quality is usually determined through durability-testing in most feed mills, it can be suggested that to obtain a better understanding of the effects of different manipulations on physical pellet quality, measurement of both PDI and pellet hardness must be considered.

9.10. Influence of conditioning temperature on broiler performance: A balance between nutrient availability and physical pellet quality

Data reported in Chapter 4 showed that increasing the conditioning temperature above 60 ℃ reduced weight gain and feed intake in birds fed wheat-based diets, but birds fed maize-based diets conditioned at 60 and 90 ℃ had higher weight gain and feed intake than those fed the diet conditioned at 75 ℃. In both diet types, feed per gain deteriorated at higher conditioning temperatures. Due to the unexpected effects of conditioning temperature on the weight gain and feed intake of birds fed maize-based diets (Chapter 4), it was decided to re-evaluate the effects of conditioning temperature on maize-based diets as well as sorghum-based diets in the subsequent study (Chapter 5). In both maize- and sorghum-based diets, increasing the conditioning temperature from 60 to 75 ℃ reduced the weight gain, but this was restored in birds fed diets conditioned at 90 ℃. Birds fed diets conditioned at 60 and 90 ℃ tended to have higher feed intake than those fed diets conditioned at 75 ℃. Feed per gain was not affected by increasing conditioning temperatures (Chapter 5). The positive effects of higher conditioning temperatures on pellet quality, in terms of durability and hardness, accounted for the restored weight gain and feed intake at 90 ℃ as well as the lack of significant difference between the feed per gain of birds fed diets conditioned at different temperatures. It appears that weight gain and feed intake responses of broilers fed diets conditioned at different temperatures reflected a balance between nutrient availability and pellet quality. The fact that these factors can overcome the effect of each other is relevant in determining the broiler performance. If this hypothesis was true, then different patterns of growth response should have been observed in birds fed diets steam-conditioned at similar temperatures but differing in feed form (mash vs. pellet). Data reported in Chapter 6 provided further evidence to support our hypothesis. The data showed that in mash diets increasing conditioning temperatures *per se* above 60 ℃ negatively affected the nutrient utilisation and performance of broiler starters. However, when the diets were pelleted, better pellet quality achieved at temperatures above 60 ℃ restored the performance. Magnitude of this restoration is determined by the balance between the negative effect of high conditioning temperatures on nutrient availability and the positive effect on pellet quality. To our knowledge, the study reported in Chapter 6 is the first study differentiating the effects of conditioning temperature from feed form.

Data reported in Chapter 7 also showed that conditioning at 90 ℃, regardless of pellet binder addition, reduced the weight gain during the starter period (d 1 to 21), compared to dietary treatments conditioned at 60 ℃. Over the whole trial period (d 1 to 35), birds offered the diet conditioned at 90 ℃ with no pellet binder addition had lower weight gains compared to those offered diets conditioned at 60 ℃. These birds also tended to have the lowest feed intake. This study showed that the negative effects of higher conditioning temperature on weight gain, and to some extent feed intake, of the birds is not limited to the starter period, but can also be carried over the grow-out period.

9.11.   Possible solutions to manufacture high physical quality pellets

Possible solutions to manufacture high physical quality pellets at low conditioning temperatures were investigated in studies reported in Chapters 7 and 8. Data reported in Chapter 7 showed that the addition of pellet binder, individually, to diets conditioned at 60 ℃ improved the PDI of starter diet compared to that conditioned at 60 ℃ without pellet binder and moisture addition. Pellet binder addition had no effect on the pellet hardness of starter diets and PDI and hardness of finisher diets. However, moisture addition, alone or in combination with pellet binder, to diets conditioned at 60 ℃ significantly improved pellet quality in terms of durability and hardness in both starter and finisher diets. These findings illustrated that pre-conditioning moisture addition in the form of water can be considered a possible strategy to manufacture high quality pellets even at low conditioning temperatures. These data (Chapter 7) also suggested that moisture addition is more effective than pellet binder in determining pellet quality under low conditioning temperatures. The reasons for higher pellet quality associated with moisture addition have been discussed in Chapter 2, section 2.4.2.2. Several studies have reported the positive effects of increasing moisture content of feed on pellet quality (Fairchild and Greer, 1999; Moritz *et al*., 2001; 2002; 2003; Lundblad *et al*., 2009). However, the study reported in Chapter 7 is the first study providing evidence for these positives effects even at low conditioning temperatures.

Data reported in Chapter 8 also showed that, irrespective of the pellet diameter, PDI and pellet hardness of both grower and finisher diets were improved by increasing the pellet length from 3- to 6-mm. Pellets with 3-mm diameter and 6-mm length had the highest PDI and pellet hardness in both grower and finisher diets. The positive effect of decreasing die hole diameter on pellet quality has been recently reported (Cerrate *et al*.,

2009; Miladinovic and Svihus, 2010). Wood (1987) reported a linear relationship (r = 0.89) between pellet length and durability. It seems that using small diameter die holes through increasing, and possibly uniformly distributed, starch gelatinisation, and longer pellet lengths through decreasing the number of sensitive breaks (Löwe, 2005), may have an additive effect on pellet quality. Findings from Chapters 7 and 8 clearly showed that moisture addition and pellet size (diameter and length) manipulations can be considered as possible strategies to generate high physical quality pellets under low conditioning temperatures.

9.12. How can the broiler industry benefit from high physical quality pellets produced at low conditioning temperatures?

The effect of pelleting on feed efficiency is thought to be mediated largely through increasing energy available for production by reducing the feed energy used for ingestion and maintenance (Nir *et al.*, 1994). It has been shown that pelleted diets contain approximately 30% more productive energy than mash diets (Reddy *et al.*, 1962). A recent study by Latshaw and Moritz (2009) showed that broilers fed pellets decreased their heat increment and utilised more of the feed energy for productive purposes than those fed mash. Data reported in Chapter 7 showed that pellet quality improvements, due to pellet binder or/and moisture addition to diets conditioned at 60 ℃ had no effect on growth responses, whereas improved pellet quality due to pellet binder addition to the diet conditioned at 90 ℃ resulted in better broiler growth during starter and whole trial periods and better feed intake and feed per gain during starter period. Results reported in Chapter 8 are similar to the findings of the previous trial (Chapter 7) that showed greater pellet durability and hardness in both grower and finisher diets with 3-mm diameter and 6-mm length pellets, compared to those with 3-mm diameter and 3-mm length, had no positive effect on broiler performance. It appears that similar AME values observed in diets conditioned at 60 ℃ in Chapter 7 and, diets with 3-mm diameter and 3-mm length and diets with 3-mm diameter and 6-mm length in Chapter 8, do not leave any room for higher pellet quality to further improve bird performance. The improved performance parameters due to higher pellet quality achieved by pellet binder addition in diets conditioned at 90 ℃ (Chapter 7), which were determined to have lower AME values, lend further support to this thesis. Therefore, if higher pellet quality can offset lowered dietary AME resulting from application of higher conditioning temperature (Chapter 7), it is reasonable to assume that by

producing high physical quality pellets under conditioning temperatures which are not detrimental to nutrient digestibility and AME, the potential of higher pellet quality to offset the energy dilution (Moritz *et al.*, 2003) can be favourably used to reduce dietary energy content. It seems that high pellet quality may be used as a non-nutritional factor to meet a portion of the birds' energy requirements, if high physical quality pellets can be manufactured at low conditioning temperatures.

9.13.   Do we really need high conditioning temperatures?

The need to reduce potential levels of feed-borne pathogens such as salmonella and campylobacter for feed safety and to achieve high pellet quality has led to the application of relatively high conditioning temperatures during conventional pelleting processes. As discussed in Chapter 2, there are several strategies which can be employed to improve the physical quality of the pellets, instead of applying high conditioning temperatures. The findings of the last two studies (Chapters 7 and 8) also illustrated that pre-conditioning moisture addition in the form of water, and to lesser extent pellet binder addition (Chapter 7), and using small diameter die holes and longer pellet lengths (Chapter 8) can create high quality pellets under low conditioning temperature (60 ℃). More research is still required to identify and evaluate other possible approaches to manufacture high quality pellets at low conditioning temperatures. As demonstrated in this thesis, this aim can be readily achieved. The only remaining concern is the need to eliminate salmonella in feed, which is thought to require high-temperature heat treatment. Published data on the effects of conditioning temperature on optimal feed decontamination are contradictory. It has been suggested that temperatures greater than 80 ℃ (Veldman *et al.*, 1995) to 85 ℃ (Jones and Richardson, 2004) during conditioning are required to ensure salmonella-free feed. According to Peisker (2006), growth of salmonella and other microorganisms takes place in the range of 5-55 ℃, with salmonella having highest growth rate at 35-38 ℃. The growth of bacteria stops and they are killed when the temperature exceeds 60 ℃. Despite the controversy regarding the optimal conditioning temperature for manufacturing pathogen-free feed, there is no doubt that higher temperatures have a marked impact on the hygienic status of the feed. However, it should be noted that the temperature is not the only factor required for eliminating salmonella and that heating time and moisture content are also important. McCapes *et al.* (1989) suggested that a combination of 85.7 ℃ conditioning temperature, 4.1 min heating time and 145 g/kg

moisture was required in pelleting process to be 100% effective against salmonella and E. coli. In conventional pelleting operations, these temperature and moisture conditions are achievable, but the retention time of the mash inside the conditioner is usually far less than the time they suggested.

By comparing pelleting temperatures with salmonella contamination rates at the exit of three different pellet mills, Jones and Richardson (2004) suggested that applying high temperatures during pelleting does not guarantee salmonella elimination and that the sanitising effects of pelleting can be negatively affected by dust contamination around the pellet mill. Heat-treated feed may also be re-contaminated during transport and delivery. However, the biggest disadvantage of using higher conditioning temperatures to control salmonella is the potential detrimental effects on nutrient availabity.

According to Creswell and Bedford (2006), the move towards higher temperatures to sterilise feed can increase intestinal viscosity in birds fed diets based on viscous grains and lead to excessive growth of gut microflora. These effects can unwittingly make the bird more susceptible to other infections such as necrotic enteritis.

New techniques have been developed to protect exogenous enzymes and synthetic vitamins commonly added to the broiler diets by improving their thermostability. The need for these costly techniques will be eliminated if high temperatures during the conditioning process are avoided. Therefore, considering the ever-increasing cost of feed ingredients and the negative impact of high conditioning temperature *per se* on nutrient availability and feed efficiency, there is an urgent need to find new approaches of improving feed hygiene which are not detrimental to feed nutrients.

9.14.   Summary and main conclusions

The work reported in this thesis investigated the factors contributing to the variable influence of pelleting on broiler performance. Factors examined included grain type, conditioning temperature, pellet die, nutrient digestibility, feed form and pellet quality. Possible strategies to manufacture high physical quality pellets under low conditioning temperature were also studied.

The major finding of this research was that the balance between the negative effect of high conditioning temperatures on nutrient availability and the positive effect on pellet quality is relevant in determining broiler performance. Increasing the

conditioning temperature from 60 to 90 ℃ *per se* adversely influenced nutrient digestibility and broiler performance. However, when the high-temperature conditioned diets are pelleted, the better pellet quality obtained at high conditioning temperatures may (or may not) overcome the negative effect on nutrient availability. The probability and magnitude of this balance between nutrient availability and pellet quality are critical in determining the actual performance of broilers. These data suggest the possibility for high physical quality of pellet to be used as a non-nutritional factor to meet a fraction of the birds' energy requirements, if better pellets in terms of nutritional and physical quality, are manufactured. Future research is required to determine the degree of probable contribution of high physical pellet quality to the dietary energy.

Under the conventional pelleting process, which uses high conditioning temperatures, good pellet quality is obtained at the expense of nutritional quality. Negative effects of high conditioning temperatures on the nutrient availability of pelleted diets have not been clearly delineated previously due to the combined effects of conditioning and pelleting when investigating pelleted diets, or have been neglected due to concerns regarding physical pellet quality and feed safety. The work reported in this thesis also showed that pre-conditioning addition of moisture and using a small diameter die hole and longer pellet length can effectively address physical pellet quality concerns even at low conditioning temperatures. However, further research is warranted to find other possible solutions to manufacture good quality pellets at low conditioning temperatures. Heat treatment is currently thought to be the most practical method to achieve satisfying levels of feed safety, but a continued search for other methods which are not detrimental to feed nutrients and bird performance must be undertaken.

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