

# Heat stress and feeding strategies in meat-type chickens

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Heat stress can induce hyperthermia in poultry. A reduction in heat load can be achieved by increasing the possibilities for dissipation, decreasing the level of heat production or by changing the thermal production pattern within a day. Strategies to reduce the negative effects of heat stress can be based on a specific feeding strategy, such as restricted feeding. Feed that is offered long enough before a hot period can ameliorate the harmful effects of high temperature. Another strategy may be to use choice feeding from different feed ingredients, rich in protein or in energy. With such self-selection, the chicken may adjust its intake of individual components, allowing the bird to optimise the heat load associated with the metabolism of the ingested nutrients. Additional promising strategies involve offering a choice between feeds with a different feed particle size or structure. A large particle size contributes to the development of the gastro-intestinal tract (GIT), especially the gizzard and the caeca. A large gizzard will maximize the grinding process and potentially ease digestion down the GIT, thereby reducing heat production associated with digestive processing. Also wet feeding may be profitable under heat stress conditions as well. Feeding wet diets may facilitate an increased water intake and larger particle sizes can limit water excretion in droppings, resulting in more water being available for evaporation during panting, hence cooling the bird. In conclusion, these feeding strategies may help to reduce heat production peaks, facilitate evaporative activity and/or decreases the heat load, resulting in beneficial effects on performance and health of the bird kept in more tropical areas worldwide.

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**Keywords:** high temperature; self-selection; wet feed; broiler; particle size; gastrointestinal tract

## Introduction

In Western European countries, meat-type birds are mostly kept in confined systems in temperate zones. These chickens have been selected for a high growth rate for decades

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(Havenstein *et al.*, 2003), and have high feed intakes and thus high metabolic rates. In addition, they are able to regulate their heat balance relatively well and do not spend much energy on activity. In many other parts of the world, however, particularly in warm tropical and subtropical regions as well as in the southern part of Europe, poultry are more likely to be kept in semi-intensive outdoor systems. In these systems, high ambient temperatures can have detrimental effects on production efficiency. A high ambient temperature (HT) is known to depress growth rate and reduce meat yield of commercial broilers (Cahaner and Leenstra, 1992; Yalcin *et al.*, 1997). Apart from inducing a high mortality rate, decreased feed intake and decreased body weight gain, HT seems to negatively affect intestinal development (Mitchell and Carlisle, 1992; Garriga *et al.*, 2006). At HT, broilers showed disturbance in the acid-base balance and increasing respiratory rate can lead to a respiratory alkalosis (Borges *et al.*, 2007).

In nature, when chickens are exposed to HT, they may use water to splash their combs and wattles in order to increase evaporative cooling from these surfaces (Dawson and Whittow, 2000). Birds may use sand baths to dissipate the heat from the body, move to a shaded area or seek a micro-environment that avoids extremely high environmental temperatures. They can also express their normal behaviour such as foraging, thereby ingesting those ingredients that avoid excessive heat loads while being ingested and metabolised. On the other hand, heat-stressed chickens tend to distance themselves from each other, pant, and often stand with their wings drooped and lifted slightly from the body to maximize heat loss (Etches *et al.*, 2008).

Birds can increase the flux of heat from the tissues to the environment by behavioural changes. Under HT conditions, the animal will apply physiological, anatomical and behavioural mechanisms aimed at facilitating heat loss to, or minimising heat gain from the environment (Etches *et al.*, 2008). Therefore, poultry farmers in regions with high temperatures must find ways to apply management and feeding strategies to facilitate these coping mechanisms. Unfortunately, there are only few scientific studies that report on birds under heat stress in extensively managed systems, such as in tropical countries.

A solution for the prevention of heat stress requires a multifactorial approach and may include genetics (Gowe and Fairfull, 2008), housing (Yahav *et al.*, 2004), thermal conditioning (Yahav and McMurtry, 2001), and feeding and nutrition (Balnave and Mutisari Abdoellah, 1990; Moritz *et al.*, 2001; Uni *et al.*, 2001; De Basilio *et al.*, 2003; Zarate *et al.*, 2003a; 2003b; Balnave and Brake, 2005; Ahmad and Sarwar, 2006; Dagher, 2008a). Recently, Lin *et al.* (2006) reviewed potential strategies to combat heat stress, including the use of Naked neck genes, thermal conditioning and the provision of certain micronutrients (vitamins and minerals).

This review will focus on the daily heat production patterns, as a result of changes in feeding management (diurnal feeding patterns, self-selection, coarse particle and wet feeding) in meat-type chickens to alleviate heat stress.

## **Effect of HT on heat production and heat loss**

Developments in the genetic selection of meat-type birds has led to rapid growth and a high metabolic rate, which is accompanied by a higher heat production level due to increased feed intake (Havenstein *et al.*, 2003). Birds are homeothermic and able to maintain body temperature within a narrow range (Yahav *et al.*, 2005). When the ambient temperature is high (Yahav, 2009), the bird has less ability to dissipate heat.

The body temperature of domestic chickens is within a narrow range that is reflected by an upper and lower limit of a circadian rhythm in deep body temperature (Etches *et al.*,

2008). When exposed to a hot environment or by performing vigorous physical activity or both, body temperature can rise. This occurs when heat cannot be dissipated within a short time. Conversely, when birds are exposed to a cold environment, heat is lost from the body and, unless the heat is compensated by extra metabolism, body temperature will decline until the bird is unable to survive and dies. These effects comprise the concept of the thermo-neutral zone (TNZ), with lower and upper critical temperatures (Mount, 1979).

There is a large variation in the ideal temperature range for different classes and age-groups of poultry. This is due to variation in type of birds and in aspects of the environment. As for the optimum temperature range, what is ideal for heat exchange may not be optimal for production such as for growth, egg mass or for feed efficiency. The overall optimum range is mainly dependent on the relative market value of the product produced, in proportion to feed costs. As the ratio of price of feed to gain increases, the best temperature is the one which provides the lowest ratio (Daghir, 2008b).

#### HEAT PRODUCTION AS A RESULT OF FEED INTAKE

Thermo-neutral heat production (HP) at a given intake and ambient temperature determines the range of the comfort zone for an animal. In growing birds, maintenance metabolism is a large part of HP. HP from maintenance will be higher if an animal exerts physical activity in order to gather food and water (Gous and Morris, 2005). Foraging related activities need more energy (Andersson *et al.*, 2001) and increase total heat production. The form of feed which is offered can influence the energy expenditure related to feed consumption activity. The time spent for eating a meal in pelleted form was reduced to one third compared to mash diets. Eating a pellet diet instead of a mash diet saves about 6% energy (Gous and Morris, 2005), which could be beneficial at HT.

HP is the result of the heat produced due to energy use associated with digestion processes and the absorption and utilization of nutrients. Together these processes are part of the heat increment caused by feed consumption. It has been shown that heat stress may decrease digestibility of dry matter, protein, and carbohydrates, whereas fat digestibility was relatively unaffected (Puvadolpirod and Thaxton, 2000b).

Broiler HP is particularly high because of high growth rate, mediated by high feed consumption. The inefficiency of conversion of feed above maintenance into protein and lipid is about 20 to 25%. Wiernusz (1998) estimated that about 60% of total ME intake is lost as heat (maintenance plus 25 to 30% of the ME above maintenance). If feed intake diminishes at HT this means that HP from feed above maintenance decreases, as does total HP. In addition, HP normally increases with an increase in total protein accretion (MacLeod, 1997).

HP in broilers is dependent on genetics (Buys *et al.*, 1999). Lines selected for fast growth accompanied with a low FCR have lower HP compared to those selected either for slow growth with a low FCR or slow growth with a high FCR. Fast growing birds may have problems with its respiratory and/or cardio-vascular system due to increased metabolic demands. This is shown by a higher  $p\text{CO}_2$  and lower  $p\text{O}_2$  in their venous blood as compared to slow growing lines, indicating a lower  $\text{O}_2$  and  $\text{CO}_2$  carrying capacity, leading to a lower HP.

HP over a 24 h period is not constant and depends on the activity pattern of the animal over the day. Extra HP due to feed intake should preferably not be generated during the hottest period of the day. Broiler chickens kept in intensive, temperature controlled, dark houses experience no particular hot period. However, with a natural day light scheme

(such as in extensive tropical poultry systems), this may not be achievable as it is dark during the coolest period of the day when feed intake will not occur.

A circadian variation in HP of growing broilers, maintained at different feed intake levels and ambient temperatures with a 23L:1D lighting pattern, is shown in *Figures 1 and 2*. *Figure 1* shows that HP tends to decrease until the 1-h dark period (00.30 h). HP rates in the fed groups were similar at 10.30 h and then decreased linearly until 00.30 h. HP decreased significantly with decreasing feed intake. This shows that regulated feeding may change the pattern of circadian variation in HP rate. In *Figure 2*, a clear negative relationship between ambient temperature and HP rate is demonstrated.

The primary consequence of heat stress is that animals will reduce feed intake progressively while ambient temperature increases (May and Lott, 1992). This lower feed intake (energy intake) will reduce HP of the chicken.

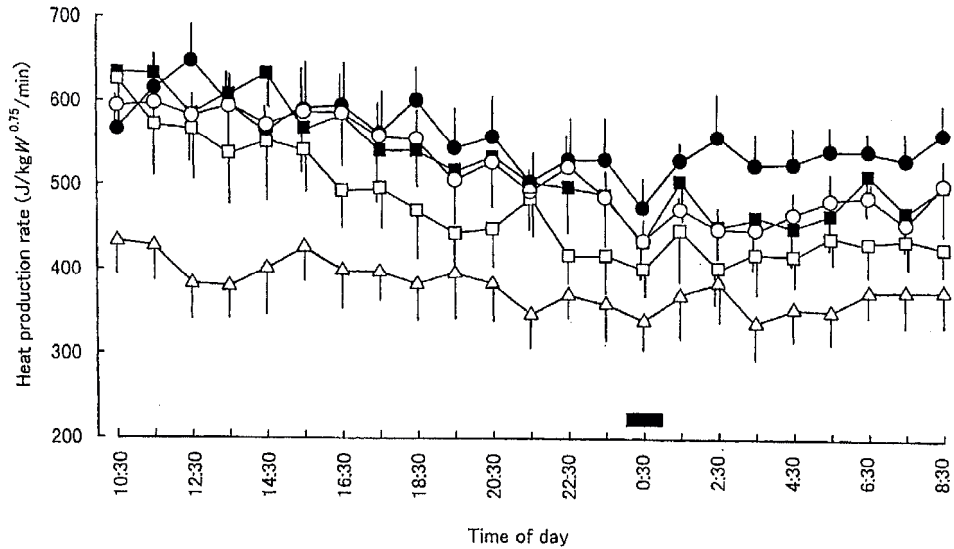


Figure 1 Pattern of circadian variation in HP rates of growing broilers given free access to feed (●), 75% of ad lib intake (○), 50% of ad lib intake (■), 25% of ad lib intake (□) and no feed at all 0% (Δ). The black horizontal bar represents the dark period and vertical bars are SEM of 5 birds (Koh and MacLeod, 1999a).

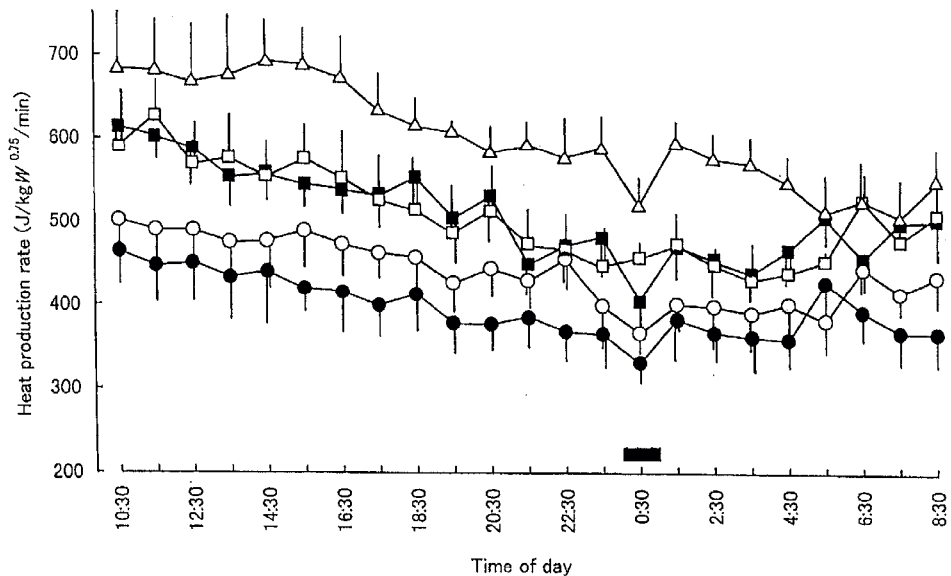


Figure 2 Pattern of circadian variation in HP rates of growing broilers maintained at 14°C ( $\Delta$ ), 17°C ( $\square$ ), 22°C ( $\blacksquare$ ), 27°C ( $\circ$ ) and 32°C ( $\bullet$ ). The black horizontal bar represent the dark period and vertical bars are SEM of 5 birds (Koh and MacLeod, 1999a).

#### HEAT LOSS BY SENSIBLE AND EVAPORATIVE HEAT DISSIPATION

At relatively low temperatures, heat is dissipated through sensible heat loss (SHL) and is emitted by radiation, conduction and convection (Yahav *et al.*, 2005). SHL can be dissipated when ambient and/or wall and floor temperatures are below the fowl's surface temperature (Hilman *et al.*, 1985; Etches *et al.*, 2008). Radiative heat transfer can occur between the bird and its environment if the surface temperature of the bird is different from that of the surrounding surface or in open air. Convection occurs by giving off heat to the surrounding air from comb, wattles, face, legs, toes, neck, body and wings (Yahav *et al.*, 2005). SHL from the comb and wattles represents 34% of the total SHL at 35°C (Hilman *et al.*, 1985). In addition, heat loss by convection plus radiation ( $Q_t$ ) can increase considerably with increasing air velocity. Air velocity also exposes the skin more and thus may increase radiant losses. The SHL by  $Q_t$ , expressed as a percentage of energy expended for maintenance, reaches a level of about 45% in broilers subjected to 3.0 m/s air velocity (Yahav *et al.*, 2004). Therefore, SHL can play a major role in heat loss to the environment. Exposure to high ambient temperatures enhances blood flow in the chicken foot due to the opening of arteriovenous anastomoses (Hilman *et al.*, 1985), which can facilitate conductive heat loss.

An increase in body temperature above the regulated range may lead to a cascade of thermoregulatory events that may be lethal if body temperature cannot be maintained within certain limits (Yahav *et al.*, 2005). If ambient temperature rises, heat dissipation is shifted from non-evaporation towards more evaporation (of moisture) at higher temperatures (Etches *et al.*, 2008). In the bird, heat is mainly dissipated through an increased respiration (called 'panting') (Marder and Arad, 1989) but also via cutaneous evaporative mechanisms (Ophir *et al.*, 2002).

At the high end of the TNZ, heat loss through panting can account for 60% of the total

heat loss (Etches *et al.*, 2008) and even up to 80% at very high temperatures (32°C) (Ahmad and Sarwar, 2006). Evaporative heat loss is associated with loss of water and dehydration can occur. Sufficient water intake will facilitate this type of heat loss and contribute to thermo-tolerance at higher ambient temperatures (Yahav *et al.*, 2005).

### **Effect of HT on feed intake, water intake, body weight, physiology and GIT development**

A high ambient temperature is a relative term especially since each animal has its own upper threshold of what is experienced as the comfort zone. When the ambient temperature exceeds the animal's thermo-neutral zone, the animal experiences heat stress. The ambient temperature at which this happens also depends upon the RH and air velocity (Veldkamp *et al.*, 2002). A high ambient temperature affects feed and water intake, respiration rate, body temperature, heterophil/lymphocyte (H/L) ratio and GIT development.

#### **FEED INTAKE**

Poultry production efficiency is affected by ambient temperatures and humidity (Wiernusz, 1998). Feed intake by broilers is reduced at high temperature HT (NRC, 1994; Cheng *et al.*, 1997). An increase in the ambient housing temperature from 21.1 to 32.2°C caused a drop in feed intake of about 9.5% per bird/day from the first week to the sixth week of age. When ambient temperature rose from 32.2 to 37.8°C, it caused a further drop in feed intake of 9.9% per bird/day, as compared to 21.1°C (North and Bell, 1990).

#### **WATER INTAKE**

High ambient temperatures will increase water intake. Chickens drink four times more at 38°C (North and Bell, 1990), as compared to 21°C. The latest data showed that water consumption increases about 7% for each 1°C above 21°C (NRC, 1994). Stimulation of water intake may benefit the bird by facilitating the evaporation mechanism (Belay and Teeter, 1993) which helps cooling (Ahmad *et al.*, 2005). Thus water is involved in many aspects of poultry metabolism including body temperature control, digestion processes, absorption of feed and transport of nutrients. Water consumption during heat stress depends on the amount of feed consumed. Birds that received feed 1 h before heat exposure had a larger increase in water consumption during the heat exposure period compared to birds that did not receive feed prior to heat exposure (Lott, 1991).

Furthermore, water consumption in low-high and high-low temperature cycles was affected by drinker types (bell versus nipple; *Table 1*) and the height of the nipple above the bird (*Table 2*). Data were summarised for 24 h periods that began and ended at a low temperature. At each age, daily water consumption was significantly lower for birds with nipple drinkers than for birds with bell drinkers. In particular, this difference was most pronounced during the quarters of the day that temperature was highest (29.4-35-29.4°C) (*Table 1*). Daily water consumption was largest for birds with bell drinkers, intermediate for birds with low nipple drinkers and lowest for birds with high nipple drinkers (*Table 2*). Average water consumption over 3 d (54 to 56 d of age) in birds with a bell drinker increased with increasing temperature, but consumption from a nipple drinker decreased surprisingly with increasing temperature (May *et al.*, 1997).

In the study of May and Lott (1992), they reported that an increased water consumption at 24-35-24°C cyclic temperature was accompanied by a decreased feed consumption. It is clear that a depressed feed consumption results in lower body weight gain.

**Table 1** Effect of drinker type and high cyclic temperature on water consumption by broilers (May *et al.*, 1997).

Age (d)	Drinker type	Daily consumption	Quarterly water consumption during cyclic temperature interval <sup>1</sup>			
			23.9 to 29.4°C	29.4 to 35°C	35 to 29.4°C	29.4 to 23.9°C
21	Bell	27.2 <sup>a</sup>	23.6 <sup>a</sup>	32.4 <sup>a</sup>	27.8 <sup>a</sup>	25.0 <sup>a</sup>
	Nipple	24.8 <sup>b</sup>	23.3 <sup>a</sup>	25.7 <sup>b</sup>	24.7 <sup>b</sup>	25.5 <sup>a</sup>
28	Bell	26.0 <sup>a</sup>	25.8 <sup>a</sup>	31.1 <sup>a</sup>	28.3 <sup>a</sup>	18.9 <sup>a</sup>
	Nipple	21.2 <sup>b</sup>	20.1 <sup>b</sup>	21.3 <sup>b</sup>	23.5 <sup>b</sup>	20.1 <sup>a</sup>
35	Bell	22.5 <sup>a</sup>	22.1 <sup>a</sup>	28.4 <sup>a</sup>	24.5 <sup>a</sup>	15.1 <sup>a</sup>
	Nipple	17.1 <sup>b</sup>	17.5 <sup>b</sup>	14.3 <sup>b</sup>	20.9 <sup>b</sup>	15.7 <sup>a</sup>
42	Bell	23.0 <sup>a</sup>	21.8 <sup>a</sup>	30.6 <sup>a</sup>	26.1 <sup>a</sup>	13.4 <sup>a</sup>
	Nipple	14.2 <sup>b</sup>	17.5 <sup>a</sup>	12.3 <sup>b</sup>	12.7 <sup>b</sup>	14.3 <sup>a</sup>
49	Bell	19.0 <sup>a</sup>	17.2 <sup>a</sup>	24.6 <sup>a</sup>	23.1 <sup>a</sup>	11.0 <sup>a</sup>
	Nipple	13.5 <sup>b</sup>	15.4 <sup>a</sup>	9.4 <sup>b</sup>	16.0 <sup>b</sup>	13.3 <sup>a</sup>

<sup>a-b</sup>Means within an age and within daily consumption or quarterly consumption with no common subscript differ significantly ( $P<0.05$ ).

<sup>1</sup>Consumption is given as percentage of body weight per day. Quarterly consumption is presented as the consumption per quarter times four.

**Table 2** Effect of nipple height and high cyclic temperature on water consumption by broilers (May *et al.*, 1997).

Drinker type	Daily consumption	Quarterly water consumption during cyclic temperature interval <sup>1</sup>			
		23.9 to 29.4°C	29.4 to 35°C	35 to 29.4°C	29.4 to 23.9°C
Bell	16.9 <sup>a</sup>	17.6 <sup>a</sup>	20.5 <sup>a</sup>	18.1 <sup>a</sup>	11.5 <sup>a</sup>
Nipple-high <sup>2</sup>	11.2 <sup>c</sup>	13.1 <sup>b</sup>	8.0 <sup>c</sup>	10.0 <sup>c</sup>	13.7 <sup>a</sup>
Nipple-low <sup>3</sup>	14.7 <sup>b</sup>	17.2 <sup>a</sup>	12.7 <sup>b</sup>	15.1 <sup>a</sup>	13.8 <sup>a</sup>

<sup>a-c</sup>Means within daily consumption or quarterly consumption with no common subscript differ significantly ( $P<0.05$ ).

<sup>1</sup>Consumption is given as percentage of body weight per day. Quarterly consumption is presented as the consumption per quarter times four.

<sup>2</sup>High nipple drinkers were at a height that forced the broilers to extend their necks to reach the nipple.

<sup>3</sup>Low nipple drinkers were at approximately the height of the back of the broilers.

## BODY WEIGHT

Broilers that were subjected to high temperature (HT) gained less than those subjected to normal temperature (NT). Body weight of broilers at six weeks of age was decreased by about 14.3% and 21.2% at 32.2°C and 37.8°C, respectively (North and Bell, 1990) and even up to 34% at 32.2°C as compared to 21.1°C (Cheng *et al.*, 1997). There have been few studies on the combined effects of temperature and RH in relation to BW. It is generally accepted that high humidity aggravates the detrimental effects of a high temperature. A bell-shaped response function of BW gain to RH was observed in five to eight-week-old broiler chickens in response to various RH levels with a maximum BW at 60 to 65% RH, both at 30 and 28°C (Yahav, 2000).

## BODY TEMPERATURE AND RESPIRATION RATE

Male turkeys (Waibel and MacLeod, 1995) and broilers (Yahav, 2000; De Basilio *et al.*, 2003) raised under high ambient temperatures show an increased body temperature and respiration rate. Broilers maintained at 10°C above TNZ had the highest core body temperature (CBT) compared to the other temperature treatments (40.1 vs. an average of



39.9°C, respectively;  $P < 0.001$ ). CBT was influenced by gender and crude protein level in the diet. Protein level did not affect CBT of males but CBT was significantly elevated (0.07°C) in females on the higher protein level (Zuidhof *et al.*, 2010). The higher CBT can be derived from three reasons. Firstly is the lower surface per BW. The male has a lower surface area per BW because they are normally bigger than female. So, heavy birds may suffer more at HT if they have the same HP per BW. Secondly is the efficiency in protein deposition. Males deposit protein more efficient than females. This means that males use less CP for lipid deposition than females, therefore males produce less heat. Thirdly if FCR is higher, CBT is higher because more HP is produced.

Respiration rate is dependent on the age of the bird, ambient temperature and RH. At 20 weeks of age, respiration rate in turkeys was increased from 195 breaths per minute at 25°C to 230 breaths per minute at 32°C. The increase in respiration rate was more pronounced when RH is high (Brown-Brandl *et al.*, 1997). This finding is in line with reports by Yahav (2000) who found that the rate of panting estimated from blood pH and  $p\text{CO}_2$  was higher in chickens exposed to 30°C than to 28°C.

#### HETEROPHIL/LYMPHOCYTE RATIO

This ratio is affected by a number of stressors such as high ambient temperature and can be used as an indicator of heat stress (Gross and Siegel, 1983; Puvadolpirod and Thaxton, 2000a). A high ratio is negatively correlated with BW and positively correlated with mortality (Puvadolpirod and Thaxton, 2000a; Al-Murrani *et al.*, 2006).

#### GASTROINTESTINAL TRACT DEVELOPMENT

Gastrointestinal tract (GIT) development can be influenced by heat stress also. GIT development, as indicated by total wet and dry weights of the whole small intestine, were reduced by about 22 and 23%, respectively, in birds kept at 35°C compared to those kept at 22°C. Moreover, the size of the absorptive surface was reduced as indicated by villus height by about 19% ( $P < 0.001$ ) in birds maintained at 35°C (762  $\mu\text{m}$ ) compared to those kept at 22°C (938  $\mu\text{m}$ ) per unit length of jejunum for 14 d (Mitchell and Carlisle, 1992). In terms of intestinal development, birds exposed to HT and RH (30°C and 70%) showed a 27.2% reduction in fresh weight of jejunum and a 3.8% reduction in jejunum length compared to birds exposed to a low temperature and RH (20°C and 50%) (Garriga *et al.*, 2006). The decrease in jejunum weight was mainly attributed to the effect of the reduced intake with high ambient temperature because restrictedly pair-fed birds showed similar values to the control birds. This indicates that high temperature reduces intestinal weight concurrent to lower feed intake. Furthermore, the decrease in intestinal weight and villus height may be influenced by the reduction in  $T_3$  production (Mitchell and Carlisle, 1992; Garriga *et al.*, 2006) under heat stress, because thyroid hormones stimulate the growth of the intestines (Levin, 1994; McNabb, 2007). Therefore, functional hypothyroidism mediates the reduction in jejunal mass and villus height in heat stressed birds (Garriga *et al.*, 2006).

### **Effect of HT on energy and protein requirements**

It appears that birds under HT conditions have a preference for nutrients that will result in less HP at a given physiological status of the birds. Accordingly, they will adjust their production level.



## ENERGY REQUIREMENTS

The advantages of using a high-energy diet for broilers by adding fat in feeding programs for high ambient temperatures are well documented (Daghir, 2008b). Adding fat (5%) at 31°C improved feed intake in laying hens by about 17%, whereas at 10-18°C it improved feed intake by only 4.5% (Daghir, 2008a). Compared to either protein or carbohydrates, fat gives less heat production because dietary fat used for deposition has a lower heat increment than protein or carbohydrates (Musharaf and Latshaw, 1999). However, a significant additional weight response to additional energy (like extra fat) occurred only with an adequate amino acid (lysine) level in the diet (McNaughton and Reece, 1984). On the other hand, digestibility of energy, protein and fat in diets with a high energy to protein ratio was reduced during a two week exposure to 32°C in six week old male broilers. So, high quality oil and protein sources with a high digestibility should be used (Bonnet *et al.*, 1997).

Male broilers housed at ambient temperatures ranging from 21.1°C to 35°C and fed grower diets containing either 12.7 or 13.4 MJ ME/kg with five different levels of CP and amino acids showed that feeding high energy diets across all temperatures significantly improved feed conversions and a better protein utilisation (Cheng *et al.*, 1997). This means that high level energy densities may be required under hot conditions to reduce the heat load (Balnave and Brake, 2005), and less heat will need to be lost via panting.

The energy requirement for maintenance (MEM) at different temperatures can be derived from linear regression of energy retention on ME intake at each temperature. When MEM was estimated, the requirements were 157.8, 112.1, and 127.2 kcal of ME/kg of  $W^{0.75}/d$  for chickens reared at 13, 23, and 32°C, respectively. Temperature had a quadratic effect on MEM with a minimum MEM near 26°C:  $MEM = W^{0.75} (307.87 + 15.63 T + 0.31 T^2)$  (Sakomura *et al.*, 2005). The quadratic effect of temperature on MEM implies that the MEM requirement is increased at HT. This estimation suggests that metabolism of the birds changes when they are reared above or below their TNZ in order to dissipate heat or increase heat production.

Adaptive changes in feed intake and energy expenditure over the long-term contribute to homeostatic control of body energy stores and maintaining a constant BW. In addition to meeting immediate energy demands, feed intake can be adjusted to ensure that energy and nutrients are stored in anticipation of periods of high demand or feed shortage (Richards and Proszkowiec-Weglarz, 2007). Therefore, it is a challenge to estimate the energy requirement at HT.

The estimate of average efficiency of total energy use of different nutrients for various body functions is given in *Table 3*. Each nutrient has its own ATP potential. So when starch and lipids are used for maintenance about the same amount of ME can be used as ATP and this means the same amount of heat is produced per calorific value of the nutrient when used for maintenance. If fatty acids are used as an energy supply for activity, than about 66% of the calorific value of fatty acids can be converted into ATP and the rest (34%) is lost as waste heat. If the body produces fat, it does not need to make many changes to fatty acids and it will deposit about 90% of the calorific value of these into fat and with 10% resulting in 'waste' heat. When protein is used for ATP more heat is produced per calorific value (42%). It is clear that lipid is deposited with a high efficiency. So in that case only a small part of the calorific value of lipid is lost as heat. Therefore, a high energy diet with relatively high fat content gives less heat load per energy unit after digestion. Animals will deposit a part of the dietary fat directly as body fat. In this case, not many changes are needed to convert fatty acids into body lipids. Dietary protein has to be hydrolysed first to amino acids (AAs) and peptides. From these AAs, body protein can be made if the intake pattern is balanced. So if the dietary amino acid pattern matches the protein needed for accretion, not many changes are needed and

this will cost energy. Synthesis of body fat from fatty acids does not require additional changes or energy compared to synthesising body fat from *e.g.* carbohydrates. In addition, the body does not store much carbohydrate. So carbohydrate molecules have to be transformed before they can be used for fat synthesis or for ATP, and several metabolic changes occur when they are used for lipid synthesis.

**Table 3 Biochemical efficiency of absorbed nutrients for ATP and for lipid synthesis (Black, 1995).**

Nutrients	Calorific value (kJ/g)	ATP production (%)	Lipid synthesis (%)
Fatty acids	39.8	66	90
Starch	17.7	68	74
Protein	23.8	58	53

### PROTEIN AND AMINO ACID REQUIREMENTS

Dietary protein has received considerable attention in relation to heat stress, because its catabolism is associated with higher heat production when compared to that of fats and carbohydrates in birds under TNZ conditions (see also *Table 3*).

Raising the protein level of a diet above NRC (1994) recommendations did not improve performance at 33°C (Cheng *et al.*, 1997). Low protein diets had negative effects on broiler performance when ambient temperature was high. This is clear because lower feed intake results in reducing intake of amino acids and further results in a poor feed efficiency and poor BW gain (Alleman and Leclercq, 1997). Broiler chickens exposed to acute heat stress (36.4 and 40.0°C) had reduced plasma amino acid concentrations. The most significant change was seen at 40°C compared to lower temperatures (Tabiri *et al.*, 2000). These authors speculated that changes in plasma Trp/LNAA (large neutral amino acid, sum of isoleucine, leucine, valine, tyrosine and phenylalanine) ratio and in Tyr may be related to a reduced feed intake and to altered thyroid function. Both phenomena are usually measured in heat stressed birds.

Under heat stress conditions, broilers aged 21 to 49 days should be fed diets that contain between 90 to 100% of the NRC (1994) recommended levels of amino acids and protein in diets containing 13.4 MJ ME/kg (Cheng *et al.*, 1999). According to Cheng *et al.* (1999), nutritionists should not compensate for a decreased intake in hot temperatures by increasing the concentration of protein and amino acids. So the final effect on performance then depends on the amounts of 'ideal protein'. The ideal amino acids pattern is not similar among species as shown in *Table 4*. Relative to lysine, the chicken requires more methionine+cystine, threonine and less leucine than the turkey and the pig. The ideal amino acid balance for broilers may vary somewhat with ambient temperature. This is logical, as the amino acid part of the diet that is used for maintenance or growth changes due to metabolic stress (Moughan, 1999; Moughan and Fuller, 2003). They concluded that if intake is reduced the overall pattern needed will more closely resemble the maintenance pattern.

**Table 4 Estimated ideal protein ratio for a starting hen turkey, broiler chicken and pig, expressed as a percentage of the lysine requirement (Firman and Boling, 1998).**

Amino Acid	Turkeys	Broiler Chickens	Pigs
Lysine	100	100	100
Methionine+Cystine	59	72	60
Threonine	55	67	65
Valine	76	77	68

Table 4 Continued

Amino Acid	Turkeys	Broiler Chickens	Pigs
Arginine	105	105	NA <sup>1</sup>
Histidine	36	31	32
Isoleucine	69	67	60
Leucine	124	100	111
Phenylalanine+Tyrosine	105	105	95
Tryptophan	16	16	18

<sup>1</sup>NA = not available

At 31°C, broilers on low sodium chloride diets had an improved FCR at similar feed intakes and numerically higher BW on a 1.36 Arg:Lys ratio diet compared to a 1.10 Arg:Lys ratio (Brake *et al.*, 1998). These authors showed a beneficial effect of an increased Arg:Lys ratio at HT. However, others reported that an increased level of lysine in broilers (Mendes *et al.*, 1997) or Arg:Lys ratio in turkeys (Veldkamp *et al.*, 2000) was unable to improve weight gain and breast meat yield, or attenuate the adverse effects of heat stress.

Raising the protein level at HT without raising the level of essential amino acids such as lysine, will not help very much in overcoming the reduction in BW gain and feed conversion efficiency (Ait-Tahar and Picard, 1987). However, an increased dietary lysine concentration appears necessary to compensate partly for the reduced feed intake (Corzo *et al.*, 2003). Improvements were found in intake and growth by feeding broilers with 2-hydroxy-4-(methylthio) butanoic acid (HMB), but not with DL-methionine (Chen *et al.*, 2003). Amino acid supplementation had a minimum effect on heat production (Zarate *et al.*, 2003a). Moughan (1999) stated that the ideal amino acid pattern for maintenance is not the same as the ideal amino acid pattern for growth.

## Feeding strategies to combat heat stress

Heat stress can only be reduced by feeding strategies if the animal produces less heat and/or loses more heat. A lower HP can be realised by *e.g.* a reduced heat increment, catabolism of fewer nutrients above requirements or more efficient nutrient digestion. More heat loss can be realised through water evaporation from the body. The possible ways to combat heat stress by feeding strategies are applying diurnal feeding patterns, self-selection strategies, feeding coarser diets and wet feeding.

### DIURNAL FEEDING PATTERNS

As the production cycle shortens due to improvements in genetic selection and nutrition, the implementation of restricted feed at HT may not produce a better performance, but could reduce the adverse effect of HT.

Early growth restriction induced by feed restriction cannot completely compensate for the adverse effect of high ambient temperature on performance, nor can high ambient temperatures recover the beneficial effect of an early growth restriction in improving feed efficiency and reducing fattening (Plavnik and Yahav, 1998). Others have reported that feed withdrawal two hours before the hottest period of the day improved feed conversion and lowered mortality without affecting BW (Yalcin *et al.*, 2001). Furthermore, chickens fed less for 2 h prior to a hot period of the day gained 2.8% more and showed a lower H/L ratio than heat stressed bird fed *ad libitum* (Yalcin *et al.*, 2003). This means that feed restriction during the heat stress period can reduce the harmful effects of HT.

Feed withdrawal during the warmest part of the day (09:00 to 16:00 h) was compared

with the distribution of ground corn during 09:00 to 16:00 h and commercial feed consumed ad libitum. The broilers were exposed to tropical conditions from 28 to 42 d (averaged  $T_a = 25^\circ\text{C}$ ; RH = 72%). From 16:00 to 09:00 h, continuous light was provided in the poultry house and all chickens received a commercial diet. Results showed that both feed withdrawal and corn distribution during the day period reduced growth and deteriorated feed conversion. However, the body temperature ( $T_b$ ) in birds on the control diet was higher than of those fed both limited feed and corn (Lozano *et al.*, 2006). Separate feeding of a high protein fraction (16:00 to 09:00 h) and an energy-rich fraction (09:00 to 16:00 h) at diurnally cyclic temperatures of  $26^\circ\text{C}$  (16:00 to 09:00 h) and  $30^\circ\text{C}$  (09:00 to 16:00 h) compared with a control diet show that growth and feed efficiency were slightly reduced (-4%) by separate feeding. However, during the thermal challenge period at the age of 34 d of  $36 \pm 2^\circ\text{C}$  and 40 to 58% RH for 7 h,  $T_b$  was reduced by separate feeding (De Basilio *et al.*, 2001). Certainly the gap between two feeds is important with regard to its influence on performance at HT. It can certainly help to reduce heat stress as shown by the lower  $T_b$ .

Feed withdrawal between 10:00 to 16:00 h during the day from weeks five to six or in week six was compared with control feeding with the same feed on broilers reared under natural summer conditions. BW and daily weight gain were higher in the feed withdrawal groups during week six. Feed withdrawal during weeks five to six produced the lowest body weight and daily weight gain. However,  $T_b$  was lower in the feed withdrawal treatment (Özkan *et al.*, 2003). Because total feed intake and feed conversion ratio by 6 h feed withdrawal during the seven days before market age did not affect slaughter weight, it can be suggested that feed withdrawal during the hot period of the day can be used to alleviate heat stress.

Broiler breeders responded to a restricted feed intake by a reduction in HP resulting in a reduced BW gain. The reduced metabolic rate per unit of weight was associated with a thermoregulatory advantage at high ambient temperature (MacLeod *et al.*, 1993). Reducing weight gain by restricted feeding resulted in a longer growing period and delay in marketing age. Therefore, during a heat stress period, the producer has to balance the benefits of a faster growth rate and a greater risk of mortality.

Feed intake at different levels of feed restriction under various environmental temperatures is shown in *Figure 3* (Koh and MacLeod, 1999b). The HP in relation to feed intake and ambient temperature is shown in *Figure 4* (Koh and MacLeod, 1999a). HP data were calculated for each combination of temperature and feed intake. When HP ( $\text{kJ/kg W}^{0.75}/14 \text{ h}$ ) was calculated at each combinations, HP significantly decreased with a decreasing feed intake and increasing ambient temperature.

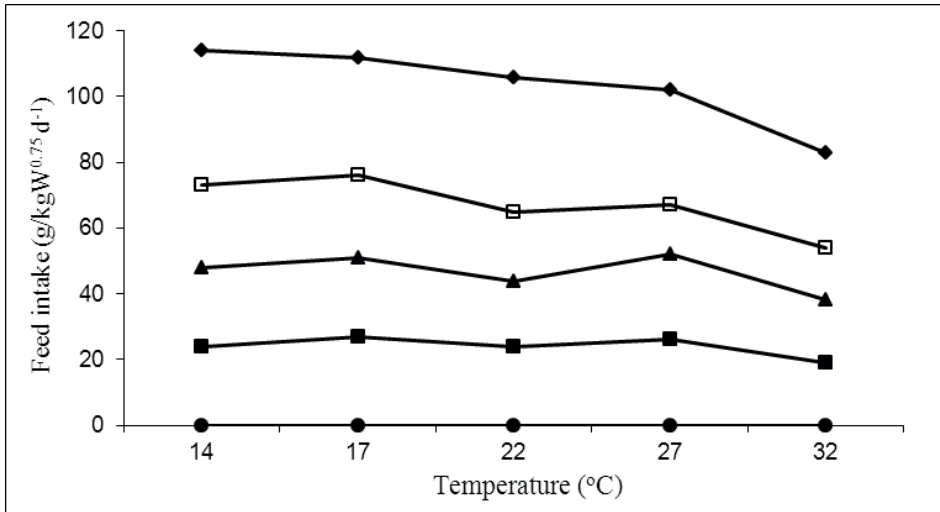


Figure 3 Feed intake at different ambient temperatures of growing broilers provided feed ad lib (♦), 75% of ad lib (□), 50% of ad lib (▲), 25% of ad lib (■) and no feed 0% (●) (Koh and MacLeod, 1999b).

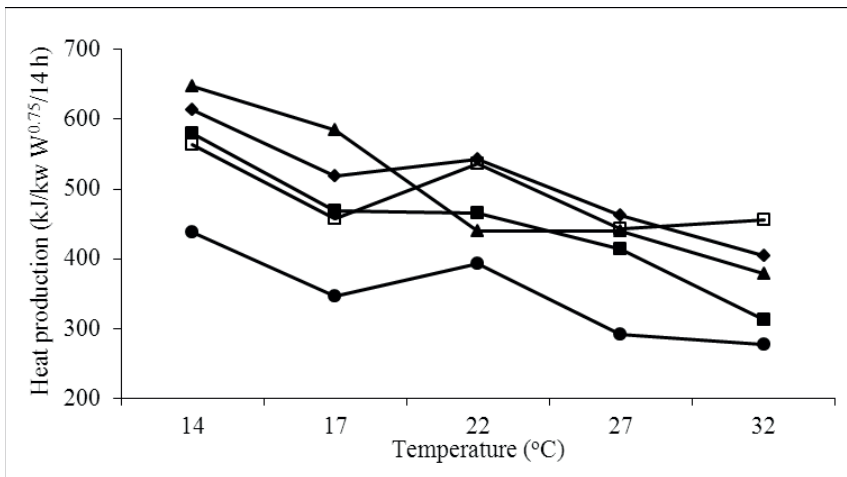


Figure 4 Heat production in relation to ambient temperature and feed intake level of growing broilers provided feed ad lib (♦), 75% of ad lib (□), 50% of ad lib (▲), 25% of ad lib (■) and no feed 0% (●) (Koh and MacLeod, 1999a).

### SELF-SELECTION

A direct measure of separate regulation of protein and energy intake can be made with self-selection feeding. There is evidence that both wild and domesticated fowl are able to adjust their nutrient intake by selecting from various feed ingredients that match their physiological requirements (Hughes, 1984; Yo *et al.*, 1998). Self-selection could allow the bird to meet their daily cyclic requirements for nutrients more effectively compared to offering a complete diet. For example, during hot cyclic periods, the birds may prefer to

change energy intake from the hot (afternoon) to the cooler periods (morning) in order to reduce heat production during the hottest part of the day. In this way they can fulfil their energy demands throughout the entire 24h-period of the day. Information concerning the ability of chickens to separately regulate their consumption protein and energy under heat stress is still limited, certainly for village chickens kept under tropical climate condition. Factors that influence dietary choice by chickens include genotype, chronological age, physiological state, ambient temperature, health status, stress and prior experiences (Forbes and Shariatmadari, 1994).

Some researchers have reported an improved (Gabriel *et al.*, 2003), similar (Rose *et al.*, 1995) or decreased (Amerah and Ravindran, 2008) growth performance of chickens under HT conditions after subjecting them to choice feeding (with wheat). Feeding additional pea meal did not give differences in performance with control feed, so the response depends on feed ingredients (McNeill *et al.*, 2004).

From choice feeding studies, a broiler at HT (cycling diurnally between 25 and 35°C) prefers to consume less protein and more energy compared to a complete diet (Sinurat and Balnave, 1986). Japanese quail preferred to eat more energy and less protein if they were offered a choice as compared to a single complete diet when housed between 20°C and 35°C (MacLeod and Dabutha, 1997). This response of birds at HT is probably caused by them trying to avoid the increased risk of heat increment from protein conversion associated with HT. Indeed, high fat diets (5%) reduced the detrimental effect of heat stress in broilers raised at 29 to 36°C (Ghazalah *et al.*, 2008). These results agree with Veldkamp *et al.* (2002), who concluded that turkeys modulate their feed intake when exposed to HT in relation to caloric diet density.

In a hot environment, self-selection means that animals can select a diet and optimise the heat load associated with metabolism. It may enable the bird to more precisely balance nutrient intake against its requirements. This has been particularly evident in laying hens with increased egg mass output when a high energy, complete diet was fed with an additional protein concentrate in a hot climate (Balnave and Mutisari Abdoellah, 1990).

The effect of choice feeding on performance seems to be determined by the age of birds when the choice is offered for the first time. BW of choice-fed chickens under tropical conditions from 1 to 42 d of age and from 8 to 42 d of age was lower at 35 and 42 d. When chickens changed from a complete diet to choice feeding from 22 to 42 d and from 36 to 42 d, their BW at 42 d did not differ from those that had received the control diet (Yo *et al.*, 1998). The lower BW of choice-fed birds was presumably due to a dramatic decline in the level of protein concentrate consumed during 1 to 42 d period (control fed birds: 16.3 g/kg, choice fed birds: 13.8 g/kg).

The length of exposure to heat stress can affect the response of birds to diets varying in dietary protein. Gonzalez-Esquerra and Leeson (2005) fed broilers two levels of dietary protein (CP 10% and 30%) in a choice feeding experiment and compared them with a single diet with 26% CP with the same ME at 1. NT (23°C at 21 d), 2. acute heat stress (AHS; sudden temperature increase to 29.4°C at 21 d) and 3. chronic heat stress (CHS; gradually temperature increase to 29.4°C at 7 d). Result from 28 to 42 d of age showed that feed intake was 25% and 27% lower and BW gain was 19% and 23% lower at AHS and CHS respectively as compared to NT. Within temperature, the choice fed birds consumed 25.4, 24.9 and 26.6% at NT, AHS and CHS, respectively. However, BW gain of choice fed birds was 14%, 2% and 7% lower than single diet fed birds at NT, AHS and CHS, respectively. The small differences in BW gain between choice and control fed birds under heat stress reflects adaptation mechanisms to balance energy to CP intake ratios, as a means to avoid excessive heat load. The effect of choice feeding



may depend on ingredient quality, since some contribute less to a balanced intake of nutrients, due to differences in palatability or particle sizes (Cruz *et al.*, 2005).

Yo *et al.* (1997) concluded that physical form of feed offered is an important factor to be considered in a choice feeding system. They fed whole, cracked or ground corn associated with a protein concentrate (pellet or mash) to broilers at tropical climate conditions with temperatures varying between  $23.6 \pm 1.3$  and  $29.2 \pm 1.8^\circ\text{C}$ . Results showed that birds fed on whole corn had a lower intake (73.3 g/d) than those fed cracked (87.1 g/d) or ground corn (84.1 g/d). Presenting the protein concentrate as a pellet resulted in a higher intake (40.1 g/d) and a higher proportion of concentrate in the selected diet (33.0%) than feeding it as a mash (33.4 g/d and 29.6%), respectively. When corn was fed as whole grain, the intake of the protein concentrate in the self-selected diet was higher (35.1%) than if corn was fed cracked (29.3%) or ground (29.1%). Although none of the diets affected BW, FCR was lower for the diets with the large particle sizes.

In a choice feeding situation, physical appearance can have an effect on development of GIT. The birds that chose whole wheat had increased development of the upper part of the GIT (Gabriel *et al.*, 2003). Research shows that the inclusion of whole wheat or the use of a coarse mash (larger particle sizes) is associated with heavier gizzards. This resulted in an increase in total transit time in the GIT due to a longer retention time in the gizzard (Banfield *et al.*, 2002; Plavnik *et al.*, 2002; Hetland *et al.*, 2004; Amerah *et al.*, 2007). There is no relationship between the volume of ingesta in the gizzard and the mass of the empty gizzard nor between maximal gizzard length and width with dietary treatment (Amerah *et al.*, 2007). A large muscular gizzard will maximize the grinding capacities of the gastrointestinal tract (Kwakkel *et al.*, 1997) which may increase the digestive capacity and in this way contribute to better performance. The coarse diet increases the chemical (pepsin in the proventriculus) and physical (gizzard muscle) functionality of the upper part of the digestive tract and, consequently, feed intake and BW gain will increase (Kho, 2007).

The advantage of choice feeding is that birds are able to adjust their nutrient intake over the day by selecting from various feed ingredients to match their physiological requirements. This may be of particular interest for birds kept under tropical conditions. However, the results of a choice feeding strategy could be potentially affected by properties such as particle size, the initial age from when the choice was offered, the quality of protein and energy sources and the level of CP. The economic advantages of choice feeding could include a reduction of feed costs because mixing ingredients would be no longer necessary and formulations less crucial. To summarise, a self-selection feeding strategy appears relevant for poultry farmers, perhaps even large producers, in high temperature zones in both developing and developed countries.

## COARSE PARTICLE

It is unknown whether a change from a fine to a coarsely ground diet for broilers under HT may assist digestive function and therefore reduce heat generated by such processes. However, water excretion in droppings is negatively related to the proportion of coarse particles as shown by the regression relating water excretion to food intake by coarse particles. This relationship is due to increased retention time of coarse particles in the GIT (Carré *et al.*, 2002). Therefore, coarse diets may allow more water to be reabsorbed from the GIT compared to fine diets. If more water is available from metabolism, heat loss through evaporation of moisture during panting may be facilitated. On the other hand, more heat loss via evaporative cooling emphasises the importance of increasing water consumption in heat stressed broilers. Coarsely ground diet may help to dissipate the heat load under HT conditions.

## WET FEEDING

Changes in feed management such as adding water to the feed are well known for their positive effects on performance of birds. This strategy has been particularly evident in broilers at NT because it improves feed intake, weight gain and/or feed conversion ratio and weight of the GIT compared to birds on dry feed (Yasar and Forbes, 2000; Moritz *et al.*, 2001; Shariatmadari and Forbes, 2005; Khoa, 2007). In addition, a higher rate of passage through the GIT with wet feeding has been suggested because the weight of digesta in the whole digestive tract of birds was less while feed intake was higher (Yasar and Forbes, 2000).

The improvements in digestive efficiency with wet feeding are thought to come from a heavier empty weight, a longer full gut length and increased gut wall thickness in some parts of the digestive tract (Yasar and Forbes, 2000). Viscosity of digesta was significantly reduced by wet feeding and this may indicate a faster passage rate of digesta. Moreover, a thicker gut wall may improve digestive function (Yasar and Forbes, 2000). Adding water to the feed reduces digesta viscosity to a similar extent and stimulates pre-digestion and absorption possibly due to a faster penetration of digestive enzymes into feed particles than with the ingestion of dry food. As a result, nutrient digestibility may increase.

In addition to the dilution of dry feed by water, the inclusion of exogenous enzymes to the wet feed may have an extra potential effect for absorption. It may increase substrate accessibility by enzymes thereby also enhancing the absorption of nutrients. Acidified feed with Calprona AL® (Khoa, 2007) or fungal origin (Yasar and Forbes, 2000) had some additional effect to watering the diet in terms of feed intake, BW gain and FCR. However, using yeast (*Saccharomyces cerevisiae*) to a wet diet resulted in a heavier BW and similar FCR than those fed on a dry diet with yeast or feed without yeast in dry and wet form (Afsharmanesh *et al.*, 2010). The different results of these studies are probably due to the differences in enzyme activity. Yeast has been traditionally used as a growth promoter in poultry and other animal diets and to stimulate micro-organisms capable of modifying the gastrointestinal environment to improve health status and performance. The improvement of performance is thought to be mediated by alterations of the intestinal flora e.g. the increase of the growth of non-pathogenic facultative anaerobic and gram positive bacteria. These can form lactic acid and hydrogen peroxide and may suppress the growth of intestinal pathogens. It may well be that the enhancement of digestion and the utilization of nutrients works in this way (Afsharmanesh *et al.*, 2010).

Three studies into wet feeding and its effect on laying performance at HT have been reviewed by Lin *et al.* (2006). They reported that the increased performance by wet feeding may be the result of an elevated dry matter (DM) intake at HT. In this way, egg production and egg weight can be improved under HT conditions (Lin *et al.*, 2006). In broilers, only a few studies are available. Water addition to diets fed to broilers housed at HT contributed to an increase in feed intake, live weight, better feed efficiency, higher weights of heart, crop, and abdominal fat (Awojobi and Meshioye, 2001; Kutlu, 2001; Awojobi *et al.*, 2009). Empty gizzard weights were higher in broilers fed a wet diet (two parts of water to one part of feed) without drinking water (Awojobi *et al.*, 2009). This study gave the opposite results to the higher gizzard weights in broilers fed dry diet seen in the first reported study by Awojobi and Meshioye (2001). The most optimal water to feed ratio was 1:1 for feed conversion efficiency and carcass weight in finishing broilers (Awojobi *et al.*, 2009). Wet feeding is desirable not only during hot weather conditions, but also during the rainy season in a tropical climate (Awojobi and Meshioye, 2001). It can be speculated that high feed intake of birds housed in HT conditions with wet feeding is enabled by the cooling effects of fresh water or wetted feed. In addition, extra water in the body in association with a high DM intake can help to reduce Tb. Extra water for

metabolism will facilitate heat loss by evaporation. With wet feeding, the feed is already soaked to stimulate pre-digestion and absorption, ready for gastric and intestinal digestion (Khoa, 2007). The contribution to the digestive process before the feed arrives in the crop could be more important than any digestion occurring in the crop itself.

## **Conclusions**

Heat stress induces hyperthermia and reducing heat load can be achieved by increasing heat dissipation and/or decreasing heat production. In a hot environment, the bird reduces feed intake and increases water intake, which can result in a shortage of nutrients such as protein, amino acids and energy. Overall, heat stress will affect the performance of the chicken.

The use of a high fat diet for optimal broiler performance is suggested for warm regions because high fat generate less heat increment per unit of energy than high carbohydrate diets. This only applies if an adequate level of essential amino acids (lysine) is provided. However, increased lysine or Arg:Lys ratio at HT was not able to improve growth rates and reduce the adverse effects of heat stress.

Predicting the optimal energy and protein content in a diet for meat-type chickens (both native and exotic birds) under hot conditions has not been studied in great detail. Therefore there is a challenge of accurately defining the optimal nutrient contents in the diet of birds kept in hot ambient temperatures. This may be done by self-selection feeding practises.

Another promising strategy to increase performance in heat stress conditions is water addition to the feed in combination with adjusting the particle size to promote GIT development. A well-developed gizzard and longer small intestine will enhance the grinding capacity, potentially improve digestion and provide a larger area for absorption. Larger particle sizes allow more water for metabolism and dissipate more heat through panting activity. Wet feeding increases voluntary feed intake, increases development of some parts of the GIT, and reduces digesta viscosity. Therefore, together with wet feeding, large particle diets should maintain litter quality and may cool the chickens, improving welfare. Further research should include the native chicken kept by many farmers in rural areas under hot tropical temperatures and RH cycling.

## **References**

- AFSHARMANESH, M., BARANI, M. and SILVERSIDES, F.G. (2010) Evaluation of wet-feeding wheat-based diets containing *Saccharomyces cerevisiae* to broiler chickens. *British poultry science* **51**: 776-783.
- AHMAD, T., SARWAR, M., MAHR-UN-NISA, AHSAN-UL-HAQ and ZIA-UL-HASAN (2005) Influence of varying sources of dietary electrolytes on the performance of broilers reared in a high temperature environment *Animal feed science and technology* **20**: 277-298.
- AHMAD, T. and SARWAR, M. (2006) Dietry electrolyte balance: implications in heat stressed broiler. *World's Poultry Science Journal* **62**: 638-653.
- AIT-TAHAR, N. and PICARD, M. (1987) Influence of ambient temperature on protein requirements of broilers. *Research Note, INRA Laboratoire de Recherches Avicoles, Nouzilly, France*, pp. 1-12.
- AL-MURRANI, W.K., AL-RAWI, A.J., AL-HADITHI, M.F. and AL-TIKRITI, B. (2006) Association between heterophil/lymphocyte ratio, a marker of 'resistance' to stress, and some production and fitness traits in chickens. *British Poultry Science* **47**: 443-448.
- ALLEMAN, F. and LECLERCQ, B. (1997) Effect of dietary protein and environmental temperature on growth performance and water consumption of male broiler chickens. *British Poultry Science* **38**: 607-610.
- AMERAH, A.M., LENTLE, R.G. and RAVINDRAN, V. (2007) Influence of feed form on gizzard morphology and particle size spectra of duodenal digesta in broiler chickens. *Journal of Poultry Science* **44**: 175-181.

- AMERAH, A.M. and RAVINDRAN, V. (2008) Influence of method of whole-wheat feeding on the performance, digestive tract development and carcass traits of broiler chickens. *Animal Feed Science and Technology* **147**: 326-339.
- ANDERSSON, M., NORDIN, E. and JENSEN, P. (2001) Domestication effects on foraging strategies in fowl. *Applied Animal Behaviour Science* **72**: 51-62.
- AWOJOBI, H.A. and MESHIOYE, O.O. (2001) A comparison of wet mash and dry mash feeding for broiler finisher during wet season in the tropics. *Nigerian Journal of Animal Production* **28**: 143-146.
- AWOJOBI, H.A., OLUWOLE, B.O., ADEKUNMISI, A.A. and BURAIMO, R.A. (2009) Performance of finisher broilers fed wet mash with or without drinking water during wet season in the tropics. *International Journal of Poultry Science* **8**: 592-594.
- BALNAVE, D. and MUTISARI ABDOELLAH, T.M. (1990) Self-select feeding of commercial pullets using a complete layer diet and a separate protein concentrate at cool and hot temperature. *Australian Journal of Agricultural Research* **41**: 549-555.
- BALNAVE, D. and BRAKE, J. (2005) Nutrition and management of heat-stressed pullets and laying hens. *World's Poultry Science Journal* **61**: 399-406.
- BANFIELD, M.J., KWAKKEL, R.P. and FORBES, J.M. (2002) Effects of wheat structure and viscosity on coccidiosis in broiler chickens. *Animal Feed Science and Technology* **98**: 37-48.
- BELAY, T. and TEETER, R. (1993) Broiler water balance and thermobalance during thermoneutral and high ambient temperature exposure. *Poultry Science* **72**: 116-124.
- BLACK, J.L. (1995) Modelling energy metabolism in the pig - critical evaluation of a simple reference model, in: MOUGHAN, P.J., VERSTEGEN, M.W.A. & VISSER-REYNEVELD, M. (Eds) *Modelling Growth in the Pig*, Vol. pp. 87-102 (Wageningen Pers, Wageningen, The Netherlands).
- BONNET, S., GERAERT, P.A., LESSIRE, M., CARRE, B. and GUILLAUMIN, S. (1997) Effect of high ambient temperature on feed digestibility in broilers. *Poultry Science* **76**: 857-863.
- BORGES, S.A., FISCHER DA SILVA, A.V. and MAIORKA, A. (2007) Acid-base balance in broilers. *World's Poultry Science Journal* **63**: 73-81.
- BRAKE, J., BALNAVE, D. and DIBNER, J.J. (1998) Optimum dietary arginine:lysine ratio for broiler chickens is altered during heat stress in association with changes in intestinal uptake and dietary sodium chloride. *British Poultry Science* **39**: 639-647.
- BROWN-BRANDL, T.M., BECK, M.M., SCHULTE, D.D., PARKHURST, A.M. and DESHAZER, J.A. (1997) Physiological responses of tom turkeys to temperature and humidity change with age. *Journal of Thermal Biology* **22**: 43-52.
- BUYS, N., SCHEELE, C.W., KWAKERNAAK, C., VAN DER KLIS, J.D. and DECUYPERE, E. (1999) Performance and physiological variables in broiler chicken lines differing in susceptibility to the ascites syndrome: 1. Changes in blood gases as a function of ambient temperature. *British Poultry Science* **40**: 135-139.
- CAHANER, A. and LEENSTRA, F. (1992) Effects of high temperature on growth and efficiency of male and female broilers from lines selected for high weight gain, favorable food conversion and high or low fat content. *Poultry Science* **71**: 1237-1250.
- CARRÉ, B., IDI, A., MAISONNIER, S., MELCION, J.P., OURY, F.X., GOMEZ, J. and PLUCHARD, P. (2002) Relationships between digestibilities of food components and characteristics of wheats ( *Triticum aestivum* ) introduced as the only cereal source in a broiler chicken diet. *British poultry science* **43**: 404-415.
- CHEN, J., HAYAT, J., HUANG, B., BALNAVE, D. and BRAKE, J. (2003) Responses of broilers at moderate or high temperatures to dietary arginine:lysine ratio and source of supplemental methionine activity. *Australian Journal of Agricultural Research* **54**: 177-181.
- CHENG, T.K., HAMRE, M.L. and COON, C.N. (1997) Effect of environmental temperature, dietary protein, and energy levels on broiler performance. *Journal of Applied Poultry Research* **6**: 1-17.
- CHENG, T.K., HAMRE, M.L. and COON, C.N. (1999) Effect of constant and cyclic environmental temperatures, dietary protein, and amino acid levels on broiler performance. *Journal of Applied Poultry Research* **8**: 426-439.
- CORZO, A., MORAN, E.T. and HOEHLER, D. (2003) Lysine needs of summer-reared male broilers from six to eight weeks of age. *Poultry Science* **82**: 1602-1607.
- CRUZ, V.C., PEZZATO, A.C., PINHEIRO, D.F., GONCALVES, J.C. and SARTORI, J.R. (2005) Effect of free-choice feeding on the performance and ileal digestibility of nutrients in broilers. *Revista Brasileira de Ciência Avícola* **7**: 143-150.
- DAGHIR, N.J. (2008a) Broiler feeding and Management in Hot Climates, in: DAGHIR, N.J. (Ed.) *Poultry Production in Hot Climate*, Vol. pp. 227-260 (CAB International, Cromwell Press, Trowbridge).
- DAGHIR, N.J. (2008b) Nutrient requirements of poultry at high temperature, in: DAGHIR, N.J. (Ed.) *Poultry Production in Hot Climate*, Vol. pp. 133-160 (CAB International, Cromwell Press, Trowbridge).
- DAWSON, W.R. and WHITTOW, G.C. (2000) Regulation of Body Temperature, in: WHITTOW, G.C. (Ed.) *Sturkie's Avian Physiology*, Vol. pp. 343-390 (Academic Press, San Diego).

- DE BASILIO, V., VILARINO, M., YAHAV, S. and PICARD, M.** (2001) Early age thermal conditioning and a dual feeding program for male broilers challenged by heat stress. *Poultry Science* **80**: 29-36.
- DE BASILIO, V., REQUENA, F., LEON, A., VILARINO, M. and PICARD, M.** (2003) Early age thermal conditioning immediately reduces body temperature of broiler chicks in a tropical environment. *Poultry Science* **82**: 1235-1241.
- ETCHES, R.J., JOHN, T.M. and VERRINDER, G.A.M.** (2008) Behavioral, physiological, neuroendocrine and molecular responses to heat stress, in: DAGHIR, N.J. (Ed.) *Poultry Production in Hot Climates*, Vol. pp. 49-80 (CAB International, Cromwell Press, Trowbridge).
- FIRMAN, J.D. and BOLING, S.D.** (1998) Lysine: Ideal protein in turkeys. *Poultry Science* **77**: 105-110.
- FORBES, J.M. and SHARIATMADARI, F.** (1994) Diet selection for protein by poultry. *World's Poultry Science Journal* **50**: 7-24.
- GABRIEL, I., MALLETT, S., LECONTE, M., FORT, G. and NACIRI, M.** (2003) Effects of whole wheat feeding on the development of coccidial infection in broiler chickens. *Poultry Science* **82**: 1668-1676.
- GARRIGA, C., HUNTER, R.R., AMAT, C., PLANAS, J.M., MITCHELL, M.A. and MORETO, M.** (2006) Heat stress increases apical glucose transport in the chicken jejunum. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology* **290**: R195-201.
- GHAZALAH, A.A., ABD-ELSAMEE, M.O. and ALI, A.M.** (2008) Influence of dietary energy and poultry fat on the response of broiler chicks to heat therm. *International Journal of Poultry Science* **7**: 355-359.
- GONZALEZ-ESQUERRA, R. and LEESON, S.** (2005) Effects of acute versus chronic heat stress on broiler response to dietary protein. *Poultry Science* **84**: 1562-1569.
- GOUS, R.M. and MORRIS, T.R.** (2005) Nutritional interventions in alleviating the effects of high temperatures in broiler production. *World's Poultry Science Journal* **61**: 463-475.
- GOWE, R.S. and FAIRFULL, R.W.** (2008) Breeding for resistance to heat stress, in: DAGHIR, N.J. (Ed.) *Poultry Production in Hot Climates* Vol. pp. 13-29 (CAB International, Cromwell Press, Trowbridge).
- GROSS, W.B. and SIEGEL, H.S.** (1983) Evaluation of the heterophil/lymphocyte ratio as a measure of stress in chickens. *Avian Diseases* **27**: 972-979.
- HAVENSTEIN, G.B., FERKET, P.R. and QURESHI, M.A.** (2003) Growth, livability, and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. *Poultry Science* **82**: 1500-1508.
- HETLAND, H., CHOCT, M. and SVIHUS, B.** (2004) Role of insoluble non-starch polysaccharides in poultry nutrition. *World's Poultry Science Journal* **60**: 415-422.
- HILMAN, P.E., SCOTT, N.R. and VAN TIENHOVE, A.** (1985) Physiological responses and adaptations to hot and cold environments, in: YOUSEF, M.K. (Ed.) *Stress physiology in livestock*, Vol. III, pp. 1-72 (CRC Press, Inc., Boca Raton, Florida).
- HUGHES, B.O.** (1984) The principles underlying choice feeding behavior in fowls with special reference to production experiments. *World's Poultry Science Journal* **40**: 141-150.
- KHOA, M.A.** (2007) Wet and coarse diets in broiler nutrition: Development of the GI tract and performance. *PhD Thesis*. Wageningen University and Research Centre, Wageningen.
- KOH, K. and MACLEOD, M.G.** (1999a) Circadian variation in heat production and respiratory quotient in growing broilers maintained at different food intakes and ambient temperatures. *British Poultry Science* **40**: 353-356.
- KOH, K. and MACLEOD, M.G.** (1999b) Effects of ambient temperature on heat increment of feeding and energy retention in growing broilers maintained at different food intakes. *British Poultry Science* **40**: 511-516.
- KUTLU, H.R.** (2001) Influences of wet feeding and supplementation with ascorbic acid on performance and carcass composition of broiler chicks exposed to a high ambient temperature. *Archiv für Tierernährung* **54**: 127 - 139.
- KWAKKEL, R.P., VAN DER POEL, A.F.B. and WILLIAM, B.A.** (1997) Gut motility as affected by diets differing in particle size distribution: impact on bird health and feed processing. *Proceedings of the 16th Scientific Day of the Southern African Branch of the WPSA*, University of Pretoria, South Africa, pp. 80-84.
- LEVIN, R.J.** (1994) Digestion and absorption of carbohydrates - From molecules and membranes to humans. *American Journal of Clinical Nutrition* **59**: 690S.
- LIN, H., JIAO, H.C., BUYSE, J. and DECUYPERE, E.** (2006) Strategies for preventing heat stress in poultry. *World's Poultry Science Journal* **62**: 71-86.
- LOTT, B.D.** (1991) The effect of feed intake on body temperature and water consumption of male broilers during heat exposure. *Poultry Science* **70**: 756-759.
- LOZANO, C., DE BASILIO, V., OLIVEROS, I., ALVAREZ, R., COLINA, I., BASTIANELLI, D., YAHAV, S. and PICARD, M.** (2006) Is sequential feeding a suitable technique to compensate for the negative effects of a tropical climate in finishing broilers? *Animal Research* **55**: 71-76.
- MACLEOD, M.G.** (1997) Effects of amino acid balance and energy:protein ratio on energy and nitrogen metabolism in male broiler chickens. *British Poultry Science* **38**: 405-411.
- MACLEOD, M.G. and DABUTHA, L.A.** (1997) Diet selection by Japanese quail (*Coturnix coturnix japonica*) in relation to ambient temperature and metabolic rate. *British Poultry Science* **38**: 586-589.



- MACLEOD, M.G., SAVORY, C.J., MCCORQUODALE, C.C. and BOYD, A. (1993) Effects of long-term food restriction on energy expenditure and thermoregulation in broiler-breeder fowls (*Gallus domesticus*). *Comparative Biochemistry and Physiology Part A: Physiology* **106**: 221-225.
- MARDER, J. and ARAD, Z. (1989) Panting and acid-base regulation in heat stressed birds. *Comparative Biochemistry and Physiology Part A: Physiology* **94**: 395-400.
- MAY, J.D. and LOTT, B.D. (1992) Feed and water consumption patterns of broilers at high environmental temperatures. *Poultry Science* **71**: 331-336.
- MAY, J.D., LOTT, B.D. and SIMMONS, J.D. (1997) Water consumption by broilers in high cyclic temperatures: bell versus nipple waterers. *Poultry Science* **76**: 944-947.
- MCNABB, F.M.A. (2007) The Hypothalamic-Pituitary-Thyroid (HPT) Axis in Birds and Its Role in Bird Development and Reproduction. *Critical Reviews in Toxicology* **37**: 163-193.
- MCNAUGHTON, J.L. and REECE, F.N. (1984) Response of broiler chickens to dietary energy and lysine levels in a warm environment. *Poultry Science* **63**: 1170-1174.
- MCNEILL, L., BERNARD, K. and MACLEOD, M.G. (2004) Food intake, growth rate, food conversion and food choice in broilers fed on diets high in rapeseed meal and pea meal, with observations on sensory evaluation of the resulting poultry meat. *British Poultry Science* **45**: 519-523.
- MENDES, A.A., WATKINS, S.E., ENGLAND, J.A., SALEH, E.A., WALDROUP, A.L. and WALDROUP, P.W. (1997) Influence of dietary lysine levels and arginine:lysine ratios on performance of broilers exposed to heat or cold stress during the period of three to six weeks of age. *Poultry Science* **76**: 472-481.
- MITCHELL, M.A. and CARLISLE, A.J. (1992) The effects of chronic exposure to elevated environmental temperature on intestinal morphology and nutrient absorption in the domestic fowl (*Gallus domesticus*). *Comparative Biochemistry and Physiology Part A: Physiology* **101**: 137-142.
- MORITZ, J.S., BEYER, R.S., WILSON, K.J. and CRAMER, K.R. (2001) Effect of moisture addition at the mixer to a corn-soybean-based diet on broiler performance. *Journal of Applied Poultry Research* **10**: 347-353.
- MOUGHAN, J.P. (1999) Protein metabolism in the growing pig, in: KYRIAZAKIS, I. (Ed.) *A Quantitative Biology of the Pig*, Vol. pp. 299-332 (CAB International, Wallingford, UK).
- MOUGHAN, J.P. and FULLER, M.F. (2003) Modelling amino acid metabolism and the estimation of amino acid requirements, in: D'MELLO, J.P.F. (Ed.) *Amino Acid in Animal Nutrition*, Vol. pp. 187-202 (CAB International, Wallingford, UK).
- MOUNT, L.E. (1979) Adaptation to thermal environment: Man and his productive animals. Edward Arnold Limited, Thomson Litho Ltd, East Kilbride, Scotland.
- MUSHARAF, N.A. and LATSHAW, J.D. (1999) Heat increment as affected by protein and amino acid nutrition. *World's Poultry Science Journal* **55**: 233-240.
- NORTH, M.O. and BELL, D.D. (1990) Commercial chicken production manual. 4 ed. Chapman & Hall, New York.
- NRC (1994) Nutrient requirements of poultry. 9 ed. National Research Council.
- OPHIR, E., ARIEL, Y., MARDER, J. and HOROWITZ, M. (2002) Cutaneous blood flow in the pigeon *Columba livia*: Its possible relevance to cutaneous water evaporation. *The journal of experimental biology* **205**: 2627-2636.
- ÖZKAN, S., AKBAŞ, Y., ALTAN, Ö., ALTAN, A., AYHAN, V. and ÖZKAN, K. (2003) The effect of short-term fasting on performance traits and rectal temperature of broilers during the summer season. *British poultry science* **44**: 88-95.
- PLAVNIK, I. and YAHAV, S. (1998) Research notes: Effect of environmental temperature on broiler chickens subjected to growth restriction at an early age. *Poultry Science* **77**: 870-872.
- PLAVNIK, I., MACOVSKY, B. and SKLAN, D. (2002) Effect of feeding whole wheat on performance of broiler chickens. *Animal Feed Science and Technology* **96**: 229-236.
- PUVADOLPIROD, S. and THAXTON, J.P. (2000a) Model of physiological stress in chickens 1. Response parameters. *Poultry Science* **79**: 363-369.
- PUVADOLPIROD, S. and THAXTON, J.P. (2000b) Model of physiological stress in chickens 4. Digestion and metabolism. *Poultry Science* **79**: 383-390.
- RICHARDS, M.P. and PROSZKOWIEC-WEGLARZ, M. (2007) Mechanisms regulating feed intake, energy expenditure, and body weight in poultry. *Poultry Science* **86**: 1478-1490.
- ROSE, S.P., FIELDEN, M., FOOTE, W.R. and GARDIN, P. (1995) Sequential feeding of whole wheat to growing broiler chickens. *British Poultry Science* **36**: 97-111.
- SAKOMURA, N.K., LONGO, F.A., OVIEDO-RONDON, E.O., BOA-VIAGEM, C. and FERRAUDO, A. (2005) Modeling energy utilization and growth parameter description for broiler chickens. *Poultry Science* **84**: 1363-1369.
- SHARIATMADARI, F. and FORBES, J.M. (2005) Performance of broiler chickens given whey in the food and/or drinking water. *British Poultry Science* **46**: 498-505.
- SINURAT, A.P. and BALNAVE, D. (1986) Free-choice feeding of broilers at high temperatures. *British Poultry Science* **27**: 577-584.



- TABIRI, H.Y., SATO, K., TAKAHASHI, K., TOYOMIZU, M. and AKIBA, Y.** (2000) Effect of acute heat stress on plasma amino acids concentration of broiler chickens. *Japan Poultry Science* **37**: 86-94.
- UNI, Z., GAL-GARBER, O., GEYRA, A., SKLAN, D. and YAHAV, S.** (2001) Changes in growth and function of chick small intestine epithelium due to early thermal conditioning. *Poultry Science* **80**: 438-445.
- VELDKAMP, T., KWAKKEL, R.P., FERKET, P.R., NIXEY, C. and NOORDHUIZEN, J.P.** (2000) Interaction between ambient temperature and supplementation of synthetic amino acids on performance and carcass parameters in commercial male turkeys. *Poultry Science* **79**: 1472-1477.
- VELDKAMP, T., KWAKKEL, R.P., FERKET, P.R. and VERSTEGEN, M.W.A.** (2002) Impact of ambient temperature and age on dietary lysine and energy in turkey production. *World's Poultry Science Journal* **58**: 475-491.
- WAIBEL, P.E. and MACLEOD, M.G.** (1995) Effect of cycling temperature on growth, energy metabolism and nutrient retention of individual male turkeys. *British Poultry Science* **36**: 39-49.
- WIERNUSZ, C.J.** (1998) Nutritional therapies to optimize poultry production during high humidity and ambient temperature exposure. Pages 1-6. Technical News, Quarterly Publication of Cobb-Vantress, Incorporated, Arkansas
- YAHAV, S.** (2000) Relative humidity at moderate ambient temperatures: its effect on male broiler chickens and turkeys. *British Poultry Science* **41**: 94 - 100.
- YAHAV, S. and MCMURTRY, J.P.** (2001) Thermotolerance acquisition in broiler chickens by temperature conditioning early in life-the effect of timing and ambient temperature. *Poultry Science* **80**: 1662-1666.
- YAHAV, S., STRASCHNOW, A., LUGER, D., SHINDER, D., TANNY, J. and COHEN, S.** (2004) Ventilation, sensible heat loss, broiler energy, and water balance under harsh environmental conditions. *Poultry Science* **83**: 253-258.
- YAHAV, S., SHINDER, D., TANNY, J. and COHEN, S.** (2005) Sensible heat loss: the broilers paradox. *World's Poultry Science Journal* **61**: 419-434.
- YAHAV, S.** (2009) Alleviating heat stress in domestic fowl: different strategies. *World's Poultry Science Journal* **65**: 719-732.
- YALCIN, S., SETTAR, P., OZKAN, S. and CAHANER, A.** (1997) Comparative evaluation of three commercial broiler stocks in hot versus temperate climates. *Poultry Science* **76**: 921-929.
- YALCIN, S., OZKAN, S., TURKMUT, L. and SIEGEL, P.B.** (2001) Responses to heat stress in commercial and local broiler stocks. 1. Performance traits. *British Poultry Science* **42**: 149-152.
- YALCIN, S., OZKAN, S., CABUK, M. and SIEGEL, P.B.** (2003) Criteria for evaluating husbandry practices to alleviate heat stress in broilers. *Journal of Applied Poultry Research* **12**: 382-388.
- YASAR, S. and FORBES, J.M.** (2000) Enzyme supplementation of dry and wet wheat-based feeds for broiler chickens: performance and gut responses. *British Journal of Nutrition* **84**: 297-307.
- YO, T., SIEGEL, P.B., GUERIN, H. and PICARD, M.** (1997) Self-selection of dietary protein and energy by broilers grown under a tropical climate: effect of feed particle size on the feed choice. *Poultry Science* **76**: 1467-1473.
- YO, T., SIEGEL, P.B., FAURE, J.M. and PICARD, M.** (1998) Self-selection of dietary protein and energy by broilers grown under a tropical climate: adaptation when exposed to choice feeding at different ages. *Poultry Science* **77**: 502-508.
- ZARATE, A.J., MORAN Jr, E.T. and BURNHAM, D.J.** (2003a) Exceeding essential amino acid requirements and improving their balance as a means to minimize heat stress in broilers. *Journal of Applied Poultry Research* **12**: 37-44.
- ZARATE, A.J., MORAN Jr, E.T. and BURNHAM, D.J.** (2003b) Reducing crude protein and increasing limiting essential amino acid levels with summer-reared, slow-and fast-feathering broilers. *Journal of Applied Poultry Research* **12**: 160-168.
- ZUIDHOF, M.J., PISHNAMAZI, OUELLETTE, C.A., KORVER, D.R. and RENEMA, R.A.** (2010) Broiler nutrition: Optimizing genotype x environment interactions. *Proceedings of the Eastern Nutrition Conference*, Guelph, pp. 13.

