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David Renaudeau, Hélène Gilbert, Jean Noblet

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Feed efficiency in swine

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9. Effect of climatic environment on feed efficiency in swine

D. Renaudeau¹, H. Gilbert², and J. Noblet³

¹INRA, UR143, Animal Production Unit, F-97170 Petit Bourg, France

²INRA, UMR 444, Cell Genetics Laboratory, F-31326 Toulouse, France

³INRA, UMR 1348, Physiology, Environment and Genetics for the Animal and Livestock Systems, F-35590 Rennes, France

Abstract

Since feed costs comprise about 60 to 70% of the total costs of production, efforts to reduce feed costs is then a major preoccupation for increasing competitiveness of the pig industry. Understanding the factors that affect feed conversion in pigs can enable producer to more effectively combine various inputs in order to achieve a low feeding cost. There are many factors involved in reaching good feed efficiency including genetic, diet, feed, management, housing and environment. Temperature is the single most important environmental factor affecting the global farm feed efficiency. In *ad libitum* fed animals, changes in metabolic heat production are essential mechanisms to maintain body temperature within a physiologically safe range under cold or heat stress. These adjustments have direct consequences on energy intake and/or maintenance requirements which in turn could reduce energy efficiency as conversion of feed to tissue or other products. However, the low level of performance related to a thermal challenge can also be attributed to a direct effect of ambient temperature (independent of feed intake) on reproductive physiology, health, and energy metabolism. Finally, thermal stress could also be a major cause of pig mortality at birth, during the nursing period or thereafter, and could predispose pigs to mortality or morbidity by other causes (starvation, diseases, etc.). High mortality rates in nursing piglets or in finishing pigs have a significant impact on overall farm feed efficiency. The chapter describes how climatic environment impacts feed efficiency in pigs and reviews solutions that can be used in order to attenuate the effect of environmental temperature on feed efficiency.

Introduction

In pig production, 50 to 70% of the total production costs are due to feed expenses. The reduction of feeding costs is then a major preoccupation for increasing competitiveness of the pig industry, especially when cost of feedstuffs shows dramatic augmentations and (or) fluctuations. Thus, feed efficiency is an important determinant of profitability for swine producers and small increments/deteriorations in this trait can have a major economic impact. The overall feed efficiency of a pig farm is a complex trait which combines the sow's feed utilization to produce piglets and the pig's feed utilization to produce meat during the growing-finishing phase. As a consequence, feed efficiency depends upon a lot of factors such as (1) nutritional factors (the quantity, the composition, and the digestibility of feed), (2) animal factors (breed, sex, age, body weight), and (3) environmental factors (management, health and climate). Climatic factors can be considered as one of the main limiting environmental factors of feed efficiency both in reproductive sows and in growing pigs. The increasing concerns on production losses due to thermal cold or heat stress is justified not only for the coolest and the hottest periods of the year in temperate countries but

also in tropical areas where pig production has dramatically increased over the past 2 decades (Renaudeau *et al.*, 2008).

After some general considerations, this chapter will describe the effects of thermal stress on feed efficiency and the main strategies available for reducing the impact of climatic factors on feed efficiency.

General aspects

Feed efficiency

In farrow-to-finish farms, the overall feed efficiency is based on the total amount of purchased feeds required for producing one kilogram of marketed carcass. This calculation must consider the feed efficiency in the sow herd by measuring the sow feed per year or the sow feed per kilogram of litter weight produced at weaning and the feed efficiency in growing-finishing phase by measuring the amount of feed provided to the pig between weaning and slaughter per kilogram of carcass weight produced.

The total amount of feed required for a reproductive sow for producing piglets mainly depends on the feeding level during the gestation and lactation period and the duration of the non productive periods, i.e. days when a sow is neither pregnant nor lactating. These days include the interval between the weaning to effective service between successive litters, the time from when the sow enters the herd until she becomes pregnant, and the time when the sow is weaned at her last litter until the day she is culled and removed from the herd. On the other hand, the amount of litter BW produced at weaning is directly connected to the litter size at birth, to the piglet mortality rate and the litter growth rate during the lactation period. These parameters are generally related to sow prolificacy and her ability to produce milk. Sow and piglet performance is affected by numerous factors related to the sow's characteristics (breed, parity, sanitary status, body condition) and/or environmental factors (feed composition, housing system, climatic environment). Among these latter factors, there is now clear evidence that thermal environment (cold/heat) is one of the main factor influencing a sow's productivity.

As a large proportion of feed input (about 75 to 80% of total feed purchased) is utilized during the growing-finishing phase in a traditional farrow-to-finish pig production system, feed efficiency during this period is an important determinant of profitability for swine producers. Feed efficiency in growing finishing pigs can be evaluated by measuring the feed conversion ratio (FCR) which defines the feed requirement in kg per kg body weight (BW) gain. From a practical point of view, FCR can be expressed with the following relationship:

$$FCR = (ME_i/[ME])/([RE]/[E_{ADG}])$$

where ME_i , RE , $[ME]$ and $[E_{ADG}]$ correspond to daily ME intake, daily energy gain, diet energy content (Mcal ME/kg) and energy content of BW gain (Mcal/kg), respectively.

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As the amount of RE depends both on the amount of ME above maintenance ($ME_i - MEM$) and the partial efficiency of its utilization for growth (k_g), FCR can also be expressed as follows (Henry and Noblet, 1986; Noblet *et al.*, 1994b):

$$FCR = (1/[ME]) \times (1/k_g) \times [E]_{ADG} \times (FL/[FL - 1])$$

where FL is the feeding level (ME_i as a multiple of maintenance requirement).

This equation shows the well-known effects of energy density and energy content of BW gain (or body composition) on FCR. But it also indicates that FCR is reduced with increased FL and according to a curvilinear relationship with a sharp increase of FCR at energy intakes close to the maintenance level and a small decrease at very high feed intakes. A reduced FCR can then be achieved by raising the ME intake and/or by reducing the maintenance requirement (MEM). However, according to the curvilinear relationship between FL and $[E]_{ADG}$, the reduction of FCR with the increase of FL is attenuated, especially when ME_i increases above ME required for maximal protein deposition. Under *ad libitum* conditions and if adequate feed is used, it is assumed that climatic factors, especially hot climatic conditions, have small effects on intake (kg) (D. Renaudeau, unpublished results). Therefore, the effects of climatic conditions on FCR should be envisaged according to both their effects on body composition and feed intake relative to the maintenance energy requirements.

Thermoregulation and energy utilization

Pigs are homeothermic animals as they can maintain body temperature within narrow limits under varying environmental thermal conditions by balancing heat loss and heat production (HP). The relationships between ambient temperature (T_a) and the balance between heat loss and heat production is schematically illustrated in Figure 1. According to Mount *et al.* (1974), the thermoneutral zone is defined as the T_a range above which, at a fixed level of energy intake, heat production is minimal and constant. The lower and upper limits of the thermoneutral zone are called the lower (LCT) and upper (UCT) critical temperatures, respectively. In thermoneutral conditions, heat production is related to the utilization of metabolisable energy (ME) for maintenance and productive processes. At maintenance, total ME intake is converted into heat as the energy retention is nil. The contribution of maintenance HP to total body HP varies with the level of production averaging 70 to 72% in the growing pig (Noblet *et al.*, 1999), 90 to 92% in the pregnant sow (Noblet *et al.*, 1997), and 65% in the lactating sow (Noblet and Etienne, 1987). Heat associated with the productive processes results from the synthesis of new tissues (muscle and fat tissues, fetal tissues, milk) from ME above maintenance. The amount of heat generated for tissue deposition depends on the partition of ME into protein and lipids synthesis and on the biochemical origin of nutrients used for meeting the requirements. In fact, the energetic efficiency (net energy to ME ratio) for protein deposition is lower than for lipid deposition (60 vs. 80%; Van Milgen *et al.*, 2000) and the efficiency of utilization of ME for NE (k_g) varies with dietary characteristics: the k_g value is higher for starch (82%) and fat (90%) than for crude protein (CP; 60%) or dietary fiber (60%) (Noblet *et al.*, 1994a). In other words, the amount of HP that will be dissipated in the environment will be higher in high CP or fiber diets than in high starch or fat diets. These variations in thermic effect of diet (TEF) are used to formulate diets adapted to different T_a situations (see below).

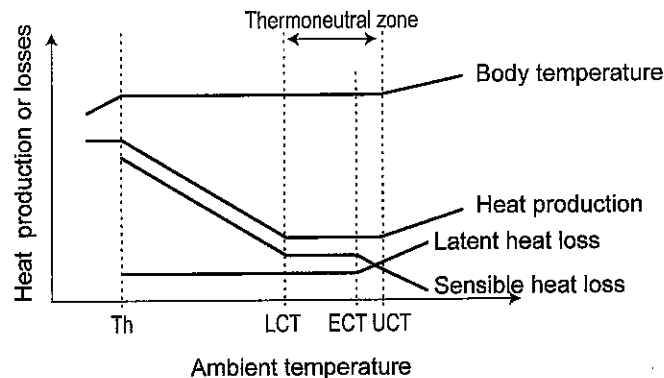


Figure 1. Diagrammatic representation of the relation between heat production or heat losses and body temperature as affected by ambient temperature (adapted from Mount et al., 1974). T_h , LCT, ECT, and UCT are threshold temperatures for hypothermia, lower, evaporative and upper critical temperatures, respectively.

Ambient temperature affects both total heat loss and the partition between latent (evaporative) and sensible heat loss. In thermoneutral conditions, body temperature is maintained constant through some adjustments in heat losses. Between the LCT and the evaporative critical temperature (ECT), sensible heat loss is predominant. This loss mainly depends on the thermal gradient between the animal surface and the contacting surface (surrounding air for radiation and convection, and the floor or other animals for conduction). In both cases, the body surface area that is in contact with the surrounding environment also plays a crucial role in heat loss process. Below LCT, the sensible heat losses increase as a consequence of the increased thermal gradient between animal surface and surrounding environment, and the only way for the animal to maintain homeothermy is to increase the rate of heat production. The maintenance of a high metabolic rate below LCT is closely dependent on both availability of energy substrate (body reserves, energy intake) and the ability of the animal to utilize these substrates as an energy source (Le Dividich *et al.*, 1998). When T_a is below the hypothermia threshold, the summit metabolic rate is reached and the animal cannot compensate for the high rate of heat loss, so body temperature falls and sooner or later, the body temperature decreases and the animal dies (Curtis, 1983).

Above the ECT, the increase in T_a makes sensible heat transfer less effective because of the reduction of the required minimal thermal gradient between the skin and the surrounding environment. Due to the fact that the pig has relatively few functional sweat glands, the major component of the increase in evaporative heat loss is through increased respiratory rate. Skin evaporation can also occur by passive processes, especially when the pig can have access to a wallow. The efficiency of both respiratory and skin evaporative heat loss depends on the vapor pressure gradient between the animal and the environment. As a consequence, in tropical humid climates, the evaporative heat losses are less efficient, which accentuates the effect of heat stress on pig performance. When T_a increases above the UCT, the pig can no longer control its body temperature. Therefore, the increase in body temperature causes an increase in the metabolic rate

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(due to the Van't Hoff effect) which causes an increase in HP which in turn results in a further increase in body temperature until the lethal temperature is reached (Curtis, 1983). For instance, the lethal rectal temperature for a 50 kg BW pigs is about 42 °C on average, but it is variable between animals (Figure 2).

For the purpose of animal production, the determination of the lower and upper limits of the thermoneutral zone is of major importance because this zone represents the temperature range over which the efficiency of energy utilization is maximum and the energy available for tissue deposition is optimal. Little information exists on the thermoneutral zone in pigs, especially for UCT values (Table 1). In contrast, studies on LCT are well documented. It depends on many factors, including animal factors (breed, body weight, physiological stage, thermal insulation), management factors (feeding level, group size), and environmental factors (relative humidity, air movement, radiant heat, floor type, sanitary status) (Close and Clark, 1981; Noblet *et al.*, 2001). In general, LCT decreases as the body weight and the thermal insulation increase or when the feeding level is increased.

In the following parts of this chapter, the term 'thermal stress' will refer to thermal conditions for which T_a is lower than LCT or higher than UCT.

Consequences of thermal stress on feed efficiency

Physiological and metabolic adjustments resulting from the thermoregulatory responses to a thermal stress have negative consequences on pig productivity and health. In *ad libitum* fed animals, changes in metabolic heat production (HP) are essential mechanisms to maintain body temperature within a physiologically safe range under cold or heat stress. These changes have direct consequences on energy intake and/or maintenance requirements which in turn could reduce energy efficiency as conversion of feed to tissue or product. However, the low level of performance related to a thermal challenge can also be attributed to a direct effect of T_a

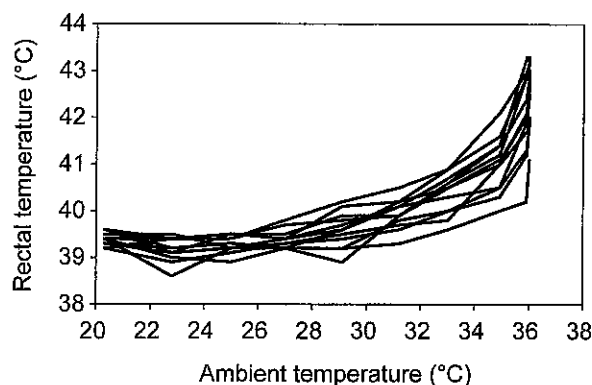


Figure 2. Change in body temperature from thermoneutrality to lethal ambient temperature in 50 kg BW Large White pigs housed in individual crates (D. Renaudeau, unpublished results).

Table 1. Values of critical temperature according to the physiological stage and the housing conditions.

Class of pigs	Housing	Age/BW	Critical temperature (°C)			
			Th	LCT	ECT	UCT
Newborn piglets	individually	1 d	13 ¹	34 ¹	-	-
	individually	2 d	10 ¹	30 ¹		31-33 ²
	group	2 d	-	26 ³		
Nursing piglets	group	3-4 kg	-	20 ³		
Weaned piglets	individually	28 d	-	30 ⁴		
	group	28 d	-	27 ⁵		
Growing/finishing pigs	individually	20 kg	-	19 ⁶	28 ⁷	30 ⁶
	group	20 kg	-	17 ⁶		
	individually	60 kg	-	18 ⁶	26-27 ^{8,9}	29 ⁶
	group	60 kg	-	16 ⁶	25 ¹⁰	
	individually	100 kg	-	17 ⁶	24 ¹¹	29 ⁶
	group	100 kg	-	15 ⁶		
Pregnant sows	individually	-	-	21 ^{12,13}		30 ²
	group	-	-	14 ¹³		30 ²
Lactating sows	individually	-	-	12 ¹⁴	25 ¹⁵	27 ¹⁵
Boars	individually	-	-	20 ¹⁶	-	-

¹ Berthon *et al.* (1994), ² Holmes and Close (1977), ³ Kovacs and Rafai (1973), ⁴ Rinaldo and Le Dividich (1991), ⁵ Le Dividich *et al.* (1980), ⁶ Adapted from Holmes and Close (1977) for an average ME intake equal to $\times 2.5$ ME for maintenance, ⁷ Ingram (1964), ⁸ Brown-Brandl *et al.* (2001), ⁹ Renaudeau *et al.* (2007), ¹⁰ Huynh *et al.* (2005), ¹¹ Comberg *et al.* (1972), ¹² Noblet *et al.* (1989), ¹³ Geuyen *et al.* (1984), ¹⁴ Black *et al.* (1993), ¹⁵ Quiniou and Noblet (1999), ¹⁶ Kemp *et al.* (1989).

(independent of feed intake) on reproductive physiology, health, and energy metabolism. Finally, thermal stress could also be a major cause of pig mortality at birth, during the nursing period or thereafter, and could predispose pigs to mortality or morbidity by other causes (starvation, diseases, etc.). High mortality rates in nursing piglets or in finishing pigs have a significant impact on overall farm feed efficiency.

Young pigs

It is well established that pre-weaning mortality has serious economic impact on a sow's feed efficiency. Currently, up to 20% of live born piglets do not survive from the onset of farrowing to weaning at 28-d age and this proportion tends to increase with hyper prolific sows (Le Dividich, 2006). Piglet mortality comprises stillbirths and live-born piglets that die before weaning. Stillborn piglets represent 5 to 7% of total born and die during farrowing or immediately after farrowing as a result of asphyxiation or soon after birth since they have been weakened by the birth process (Herpin *et al.*, 1996). During the last two decades, the number of stillborn piglets

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has increased with selection for litter size, limiting the effectiveness of selection for this trait (Canario *et al.*, 2006). From a survey conducted in Belgium, when T_a in the farrowing room exceeds 22 °C at the time of parturition, the risk of stillbirth increases significantly (Figure 3). Similar results were reported in tropical areas (Yang *et al.*, 1996; Renaudeau *et al.*, 2003b). The related prolonged farrowing duration at high T_a would explain the increased number of stillbirths. However, appropriate supervision of births and provision of assistance to weaker piglets could help to save many pigs (Herpin *et al.*, 1996).

Many reports have been conducted to examine the causes of pre-weaning mortality (Le Dividich, 2006). Crushing by the sow, starvation, infection or abnormalities are immediate causes of mortality with, in most surveys, crushing by the sow and starvation being more frequent (Varley, 1995). Pre-weaning mortality increases with litter size, lighter pigs being at a particular risk (Herpin *et al.*, 2002). At birth, the piglet experiences a dramatic change in the T_a of its new surroundings. In comparison with the homeostatic temperature in the sow uterus (38 to 40 °C), the piglets are usually born into a much cooler environment (20 to 22 °C) (Kammersgaard *et al.*, 2011). In addition, the ability of the piglet to conserve heat is very limited because the piglet is virtually hairless, devoid of subcutaneous fat, and wet with fetal fluids. Although a warm environment is usually provided in the farrowing pen using various heat systems, the piglets are relatively unable to detect it during the first day. In practice, as the T_a of the farrowing room is much lower than its LCT and close to the temperature for which the metabolic rate is maximal, the newborn piglet experiences a dramatic period of cold stress until it displays an efficient thermoregulatory response consisting essentially in the ability to locate itself in the heated area or close to the udder, to huddle, and to consume sufficient amounts of colostrum and milk (Le Dividich *et al.*, 1998). The maintenance of a high metabolic rate during this period of cold stress is closely dependent on both the availability of energy substrate and the ability of the newborn pig to utilize these energy sources. The requirement for energy is met by mobilization of energy body reserves (glycogen and fat) and by colostrum ingestion. As the fat content of newborn piglet is very low when compared to most other mammalian newborns (Mellor and

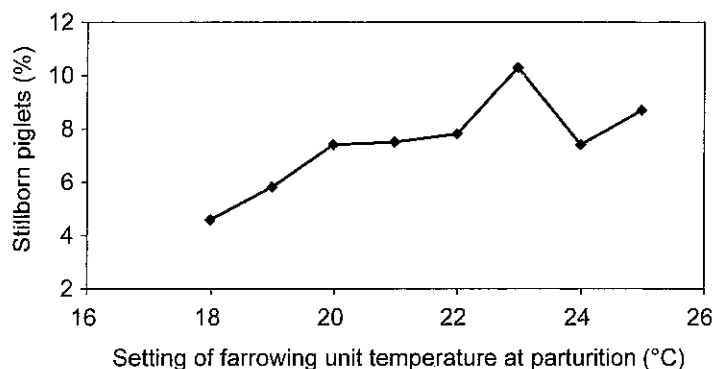


Figure 3. Effect of farrowing unit ambient temperature at parturition on the mean percentage of stillborn piglets (adapted from Vanderhaeghe *et al.*, 2010).

Cockburn, 1986), most of the energy from the body reserves is derived from glycogen stored in the liver and skeletal muscles. As the depletion rate of the glycogen reserves is rapid after birth, colostrum rapidly becomes the main source of energy for thermoregulation. The thermogenic importance of colostrum is illustrated by Noblet and Le Dividich (1981) who reported a positive relationship between metabolic heat production and the amount of colostrum intake by piglets kept at 18 °C during the first day postpartum. The colostrum intake is 27% lower at 18 to 20 °C compared to that at 30 to 31 °C (Le Dividich and Noblet, 1981) with detrimental consequences on the acquisition of passive immunity and energy supply for sustaining a high metabolic rate. However, factors related to the piglet such as low birth weight and poor vitality also influence the consumption of colostrum and therefore they are crucial for piglet survival. Noblet *et al.* (2001) summarized the complex etiology of piglet mortality and the central role of cold stress on this analysis in Figure 4.

From 2 days of age to weaning, the improvement of piglet's thermal insulation, related to the increase in peripheral fat accretion, reduces the LCT and decreases its susceptibility to cold stress. In addition, in the presence of a supplemental heat source in the farrowing pen, the piglet fully expresses its thermoregulatory behavior with a reduced metabolic extra-thermoregulatory heat demand (Noblet *et al.*, 2001). During the nursing period, piglet BW gain is mainly related to sow milk production and, to a lesser extent, on the amount of additional feed (solid/liquid) intake (Pluske *et al.*, 1995).

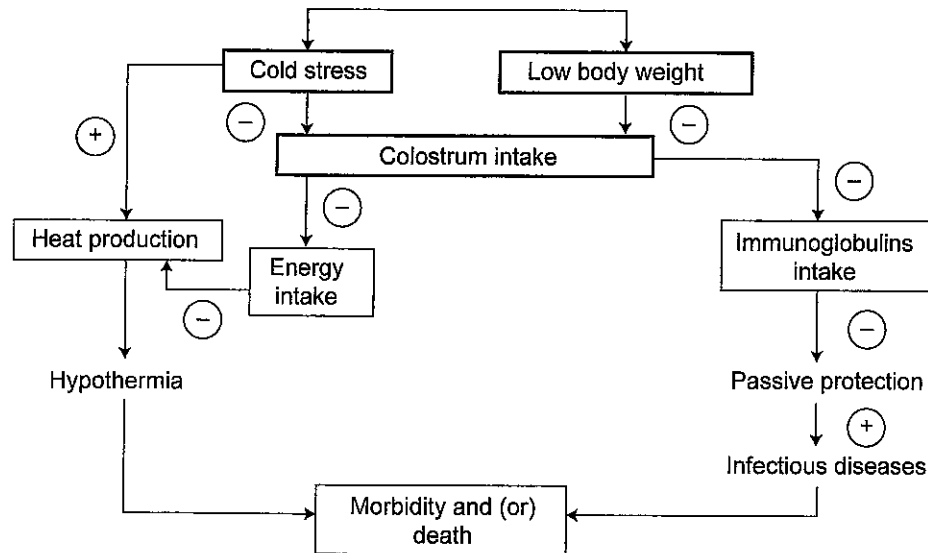


Figure 4. Representation of the possible effects of cold stress and low birth weight on the health of the neonatal pig (Noblet *et al.*, 2001).

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Post-weaning, and growing-finishing pigs

The period following weaning between 3 and 4 weeks of age is characterized by rapid changes in environmental components of the piglets in relation to changes in feed intake and feed composition, metabolism, and tissue thermal insulation (Le Dividich and Herpin, 1994). This period is an important time in the life of the pig, one which has significant impact on future performance (Tokach *et al.*, 1992). Under most commercial situations, weaning results in simultaneous stress including separation from the sow and mixing of the litters, changes in housing and climatic environment and in diets. This feeding transition is generally associated with a critical period of underfeeding leading to reduced feed efficiency and growth rate. The related low feeding level elevates the newly-weaned pig's thermal requirements (Le Dividich, 1999). On average, the LCT is about 26 to 28 °C during the first week post weaning and it decreases down to 23-24 °C in the second week post weaning (Close, 1987). This means that after the critical period corresponding to about the first two weeks after weaning, T_a can be reduced by 2 to 3 °C/week until the temperature to be maintained in the finishing house is reached. During this period, the pig is to some extent able to compensate for a suboptimum environment by increasing its voluntary feed intake.

In growing-finishing pigs fed nutritionally adequate diets, feed efficiency mainly depends on the level of feed or energy intake, the maintenance requirement, and the efficiency with which ME above maintenance is used for growth. Changing feed intake is an efficient strategy used by the animal to cope with changes in T_a . These variations in energy intake have direct and indirect effects on energy deposition.

In *ad libitum* feeding conditions, pigs adjust their energy intake to compensate for the effect of changes in T_a . In practice, changes in energy intake vary according to the duration and the intensity of the thermal challenge. For example, when pigs are challenged with a chronic thermal stress, changes in feed intake occur within the 3 to 6 days after the onset of the cold or the hot thermal challenge (Verhagen *et al.*, 1988; Renaudeau *et al.*, 2010). According to a quantitative analysis of data published in the literature, our results show a curvilinear decrease in feed intake with an increase in T_a (Figure 5). For a 50 kg BW pig, feed intake decreases at a rate of 8 g/d/°C from 16 to 24 °C and then at a rate of 46 g/d/°C from 24 to 32 °C. Over the same T_a range, feed intake is reduced by 30 and 70 g/d/°C, respectively for a 75 kg BW pig. In addition, the threshold temperature at which feed consumption starts to decrease is reduced when BW increases (Renaudeau *et al.*, 2011b). This larger susceptibility in heavier pigs is mainly related to a lower ability to dissipate heat (lower surface area-to-mass ratio, high backfat thickness). In our meta-analysis approach, we pointed out that a large variability existed among studies regarding the effect of T_a on feed intake. As suggested by Le Dividich *et al.* (1998), this high variability is explained by numerous factors including breed, degree of body fatness, diet composition, sanitary status, and other climatic factors (humidity, draught, etc.). In addition, pre-experimental rearing conditions and their potential related effects on the animal response to heat stress during the experimental period could be an additional source of variation. Differences in the experimental protocol between studies (e.g. duration of acclimation period to temperature, treatment before the experimental period) could also explain some of this variability. Under practical housing conditions and especially under tropical conditions where buildings are often semi-opened, pigs

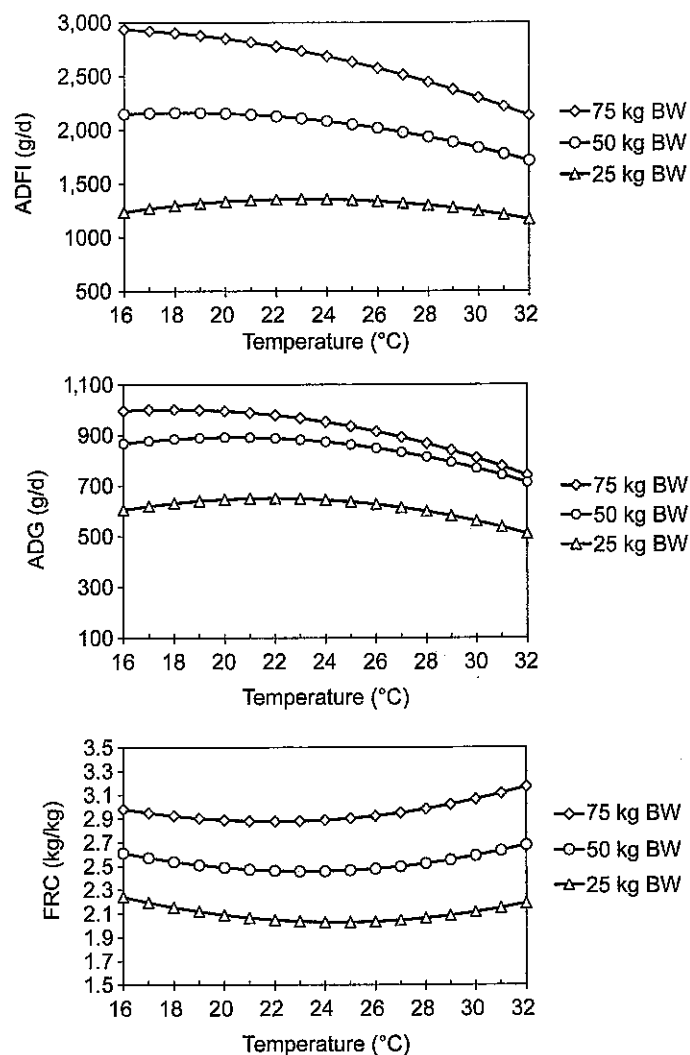


Figure 5. Effect of ambient temperature and pig BW on daily feed intake (ADFI, g/d), average daily gain (ADG, g/d) and feed conversion ratio (FRC, kg feed/kg gain) (adapted from Renaudeau *et al.*, 2011).

are usually subjected to fluctuations in T_a within a day or over successive days. Consequently, the application of results collected in closely controlled and constant environments may be inappropriate when applied to variable T_a conditions. In fact, some evidence shows that pigs are partially capable of maintaining feed consumption when exposed to a cycling diurnal T_a challenge. For example, pigs maintained in a hot, cyclic T_a , partially shift their feeding activity to the cooler periods of the day to minimize the detrimental effect of high T_a on feed intake (Feddes *et al.*, 1988; Renaudeau *et al.*, 2006). However, in growing-finishing pigs, the extra feed consumed during the cooler period

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of the day can compensate for the reduced feed intake during the hot periods of the day as long as the temperature variation does not exceed $\pm 1.5^\circ\text{C}$ (Quiniou *et al.*, 2000a).

As shown for feed intake, responses of ADG and FCR to T_a are curvilinear and they are both strongly affected by pig BW (Figure 5). According to Rinaldo and Le Dividich (1991) and Nienaber *et al.* (1987), the T_a range for which the ADG is maximal is 15 to 25 $^\circ\text{C}$ in young pigs and 10 to 20 $^\circ\text{C}$ in growing-finishing pigs, respectively (Figure 6). The corresponding values for a minimal FCR are 25 to 30 $^\circ\text{C}$, and 20 to 25 $^\circ\text{C}$, respectively. Under cold conditions, the ADG and FCR decrease at rates of 8 g/d/ $^\circ\text{C}$ and 0.040/ $^\circ\text{C}$ from 18.5 to 12.0 $^\circ\text{C}$ in young pigs and 5 g/d/ $^\circ\text{C}$ and 0.052/ $^\circ\text{C}$ from 15 to 5 $^\circ\text{C}$ in growing finishing pigs (Figure 6). In addition, under cold conditions, the energy content of the BW gain ($[E]_{\text{gain}}$) remains constant in young pigs between 25 and 15 $^\circ\text{C}$ (Rinaldo and Le Dividich, 1991) whereas it increases +22 kcal/kg/ $^\circ\text{C}$ for growing finishing

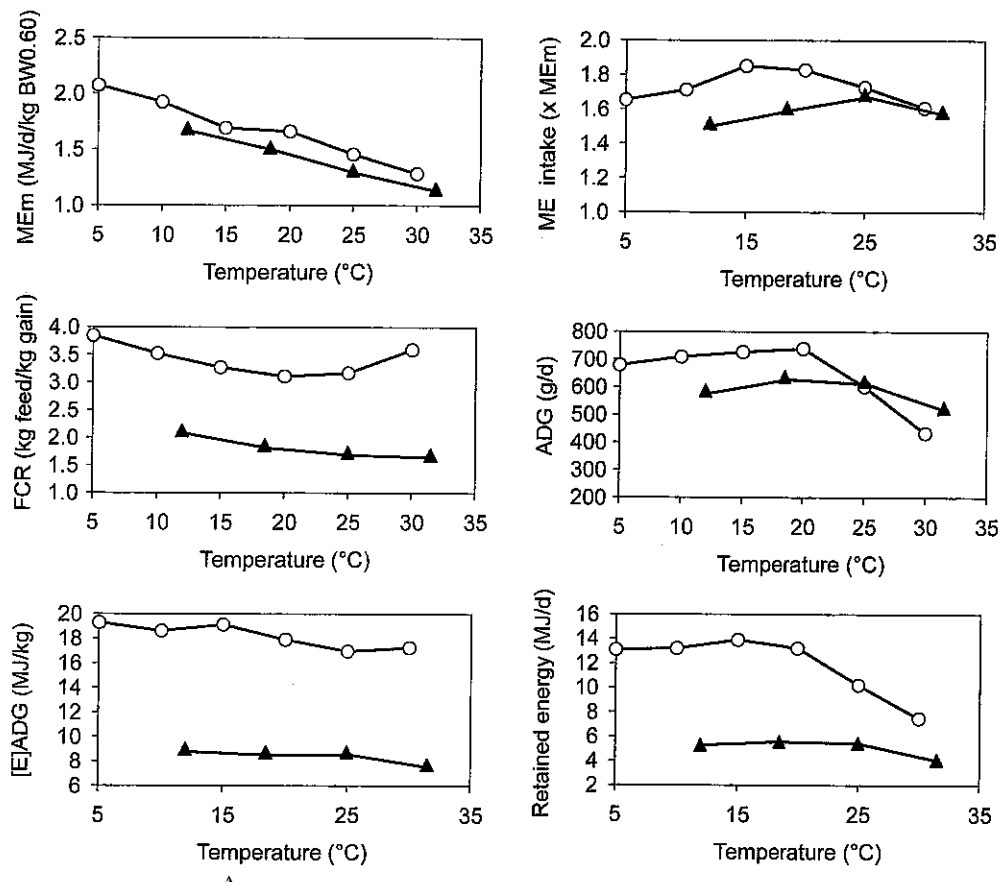


Figure 6. Effect of T_a on energy intake ($\text{ME} \times \text{MEm}$), feed conversion ratio (FCR, kg feed/kg gain) and average daily gain (ADG, g/d) in 20 kg-pigs (▲) and in 65 kg-pigs (○) (Nienaber *et al.*, 1987; Rinaldo and Dividich, 1991).

pigs between 20 and 5 °C (Nienaber and Hahn, 1987) in relation with an increase of carcass fatness (Figure 6). Whatever the physiological stage, the reduction of FCR at low Ta is mainly the consequence of a reduction of the feeding level, expressed as a multiple of MEM and the use of a fraction of the energy intake for thermoregulation. The effect of the feeding level on FCR may be emphasized by the increase of $[E]_{\text{gain}}$ especially in heavier animals.

At a Ta higher than the optimal range, ADG decreases primarily as a result of a severe decline in feed intake. The increase of FCR in hot conditions ($T_a > 24$ to 25 °C) depends on both the Ta level and the pig BW (Figures 5 and 6). From 24 to 32 °C, the rates of increase in FCR average 0.020 and 0.035/°C in 25 and 75 kg BW pigs, respectively (Figure 5). This increase is not linear and is significant only for extreme Ta (>30 °C). This increased FCR reflects a reduced proportion of ME intake available for tissue growth, which is mainly explained by the strong reduction of ME intake rather than an increase in MEM which is not markedly changed. In fact, the slight decrease of MEM at high Ta is more a consequence of the reduced feed intake (Koong *et al.*, 1985; De Lange *et al.*, 2002; Labussière *et al.*, 2011) than a direct effect of the high Ta. Under *ad libitum* feeding, elevated Ta does not markedly reduce body fatness and $[E]_{\text{gain}}$ (as feed restriction will do at normal Ta) which emphasizes the negative effect of high Ta on FCR.

Pregnant sows

There is no evidence that cold conditions impair the normal course of pregnancy in the sow. However, pregnant sows are often exposed to a Ta lower than their LCT which can compromise the building of body reserves, unless feeding level is increased. From a compilation of literature, Noblet *et al.* (1997) showed that the daily increment of heat production with Ta reduction varies with many factors (housing conditions, floor type, feeding level, etc.). These latter authors reported that the daily heat increment ranges from 2 to 2.5 kcal/°C·kg BW^{-0.75} in group housed sows or in sows close to the LCT or at high feeding levels to 3.6 to 4.3 kcal/°C·kg BW^{-0.75} in individually-housed sows or at low Ta. For the latter case, it can then be calculated that the amount of feed required to compensate for the increase in heat production is about 60 to 80 g/d/°C for a 220 kg BW sow fed a standard diet.

In pigs, a certain degree of seasonality of reproduction has been reported in many countries. Major manifestations of seasonal infertility in sows include delayed onset of puberty, a prolonged weaning to estrus interval and a reduced proportion of mated sows that farrow. Numerous studies have highlighted the multi-factorial nature of seasonal infertility problem in sows. They are partly explained by reduced semen quality of the boar (Wettmann *et al.*, 1976; Suriyasomboon *et al.*, 2004). However, changes in the photoperiod and/or thermal challenges occurring during the mating period or in the early gestation period (Edwards *et al.*, 1968) or the extent to which maternal body reserves are mobilized during the preceding lactation period (Prunier *et al.*, 2003) also affect reproductive performance. Logically, summer infertility and the related increase in the number of non-productive days have a direct negative consequence on the amount of feed given to pregnant sows per born piglets. In addition, severe heat stress may also result in significant embryo (Wildt *et al.*, 1975) and fetal mortality (Omtvedt *et al.*, 1971), and may emphasize the deterioration of feed efficiency in pregnant sows during the hottest periods of the year.

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Lactating sows

According to its low LCT (15 to 18 °C), cold is not a problem for lactating sows. In contrast, high T_a is much more problematic for lactating sows which have a high metabolic rate related to milk production. The reduction in HP under hot conditions is mainly achieved by a decrease in feed intake. The average rate of ME reduction is 645 kcal/d/°C (Figure 7). However, as shown for growing pigs, the effect of heat stress on feed consumption becomes more pronounced as the T_a increases (Quiniou and Noblet, 1999). Concomitantly, the amount of nutrients and energy available for milk synthesis is reduced with a negative consequence on the litter growth rate (-50 g/d/°C on average; Figure 7) and the litter BW at weaning. In thermoneutral T_a , the energy requirement for milk production generally exceeds feed intake capacity, especially in modern hyper prolific sows. Consequently, the mobilization of body reserves is inevitable to compensate for the energy deficit. On average, the marginal rate of rise in maternal BW loss is 0.046 kg/°C (Figure 7). Sows losing excessive amounts of body weight have a prolonged weaning to estrus intervals. Under thermal stress, the energy deficit and occurrence of reproductive failure are accentuated, especially in young sows (Prunier *et al.*, 1996). Variation in milk production in hot conditions is mainly explained by reduced feed consumption. However, direct effects of heat stress on milk production and on the mobilization of body reserves have also been reported in primiparous (Messias de Bragança *et al.*, 1998) and multiparous sows (Renaudeau *et al.*, 2003a).

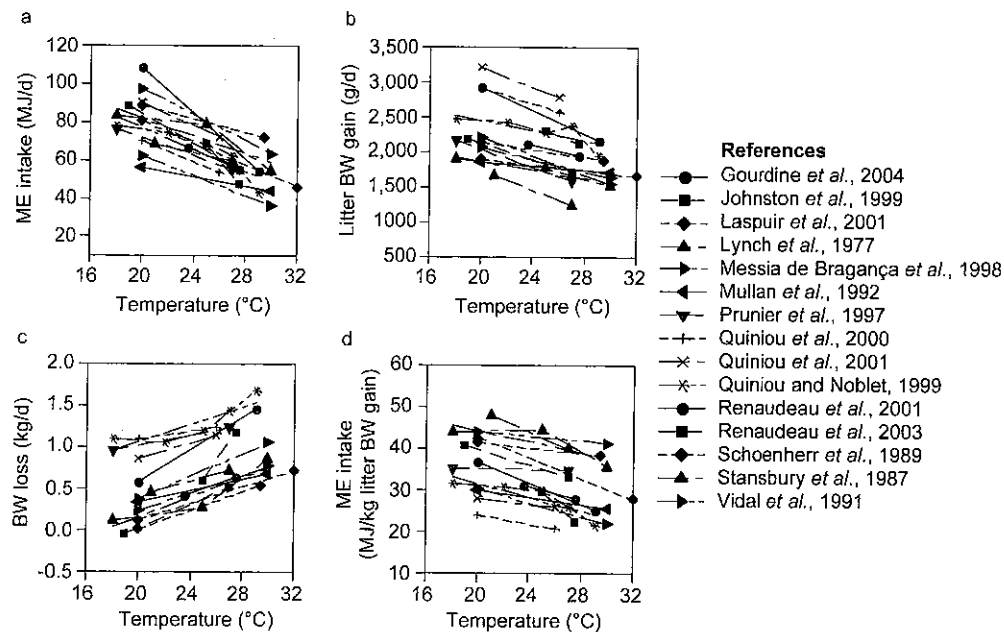


Figure 7. Compilation of the literature data on the effects of elevated ambient temperature on sow performance during lactation: (a) metabolizable energy intake (MJ/d), (b) litter body weight (g/d), (c) body weight loss (kg/d), and (d) metabolizable energy intake (MJ/kg litter BW gain) (adapted from Renaudeau, 2008).

Total feed efficiency for milk production, defined as the ME requirement per unit of litter BW gain, declines when T_a increases (Figure 7). This reduction of the apparent efficiency of ME utilization for milk production could be explained to some extent by an increase in the relative importance of MEm requirement compared to the total ME intake in hot conditions. In addition, heat stress during lactation may also decrease feed efficiency in pregnant sows by increasing the weaning to oestrus interval and/or in the growing-finishing phase by decreasing piglet BW at weaning.

Strategies for alleviating the effects of thermal stress on feed efficiency

In cold or hot conditions, solutions for improving feed efficiency can be classified into three groups; those promoting a higher energy intake, those decreasing the maintenance requirement and especially extra energy requirement for thermoregulation, and those decreasing the direct effect of thermal stress on pig metabolism, physiology, and health.

Changes in diet composition

Some evidence shows an interaction between dietary energy content and T_a on pig metabolism and performance. In growing pigs, TEF is higher in high fiber diets as compared to high starch diets in thermoneutral conditions, whereas, it is similar for both diets in cold conditions (Noblet *et al.*, 1985). Similar results are reported in pregnant sows (Noblet *et al.*, 1989). From these results, the efficiency of ME for energy retention is independent of T_a level for high energy diets but it increases at low T_a for low energy density diets. In fact, TEF of high fiber diets is partly used to meet the pig's elevated maintenance needs in cold whereas it is likely lost or wasted in pigs housed in T_a higher than LCT. In other words, high heat increment diets could be useful in cold conditions because HP related to feed utilization can minimize the amount of the other nutrients or tissues that must be used for extra thermoregulatory HP. Quite logically, in a cold environment, FCR is similar in growing finishing pigs fed high fiber diets compared to those fed high energy corn-soybean meal diets (Coffey *et al.*, 1982). On the other hand, the introduction of fiber rich ingredients in diets has negative consequences on FCR and growth rate under warm conditions.

Pregnant sows are more frequently exposed to cold stress than growing pigs, especially when they are individually housed. The contribution of dietary fiber to net supply of energy is much greater in breeding sows than in growing pigs in connection with a higher ability to digest it (Noblet and Le Goff, 2001) and the energy value of fiber rich ingredients is higher at low T_a (Noblet *et al.*, 1989). These results are clearly in favor of the use of and the economic interest in high fiber ingredients in pregnant sows exposed to cold conditions.

Few studies have been done to test the effect of high fiber diets on lactating sows in hot conditions. According to Schoenherr *et al.* (1989), the inclusion of 48% of wheat bran in lactation aggravates the effect of thermal heat stress on sow performance. In this study, the efficiency of utilization of ME intake for milk production at 32 °C was reduced in the high fiber diet in comparison with the basal corn-soybean meal diet (8.0 vs. 6.6 Mcal ME/kg litter BW gain). In contrast, in tropical-humid conditions (26.3 °C and 89% RH on average), we showed that a high fiber diet (36% wheat bran) improved the sow's milk production but had negative effects on the mobilization of maternal body reserves (Renaudeau *et al.*, 2003b).

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In contrast to high fiber diets, low heat increment diets in hot conditions can reduce the amount of HP to be dissipated, increase the portion of energy available for tissue synthesis and global feed efficiency. Some trials were carried out to evaluate the performance of growing-finishing pigs reared under low or high Ta conditions and fed high fat diets. In these studies, the economic value of dietary fat was not only estimated from the impact on fat addition on the amount of feed required per unit of gain, but also on the days required to reach market weight and the pig's carcass merit (fat and lean content). It has been demonstrated that the effects of dietary energy density on FCR depends on the Ta level and to a lesser extent on the BW. In cold conditions, each extra 100 kcal increase in dietary ME content results in a decline of FCR of about 0.10 kg feed/kg gain whereas it remains constant when expressed as Mcal ME intake/kg gain (10.5 Mcal ME/kg gain on average; Coffey *et al.*, 1982; Stahly and Cromwell, 1979). In these studies, pigs tended to adjust their voluntary feed intake to the diet energy density for maintaining a constant level of ME intake and then were not markedly improved which can practically limit the economic interest of fat supplementation in cold conditions. In hot conditions, the response of FCR to dietary fat supplementation in growing-finishing pigs is rather similar to that in cold conditions (-0.12/100 Kcal ME on average; Stahly and Cromwell, 1979; Stahly *et al.*, 1981; Katsumata *et al.*, 1996; Spencer *et al.*, 2001). However, dietary fat supplementation at high Ta improved growth performance in growing and in finishing pigs. In hot conditions, high energy diets are better tolerated because these (1) are associated with a reduced TEF, which must be dissipated to the environment and (2) they result in higher energy intake (especially in finishing pigs), which counterbalances to some extent the reduction in feed intake occurring in warm conditions. At thermoneutrality or at high Ta, pigs fed high fat diets are generally fatter than pigs fed control diets and this effect depends on the level of fat supplementation (Stahly and Cromwell, 1979; Stahly *et al.*, 1981; Katsumata *et al.*, 1996; Spencer *et al.*, 2001). This high adiposity is mainly related to an excess of energy relative to protein intake. However, body fat deposition is more strongly affected by level of ME intake at high Ta than at thermoneutrality (Katsumata *et al.*, 1996). This result is partly explained by the large increase in ME intake at elevated Ta. However, using a pair-feeding experimental design, Le Bellego *et al.* (2001) demonstrated that maximal protein deposition rate can be limited by a direct effect of high Ta and they suggested that the increase in energy intake in hot conditions by dietary manipulations benefits mainly or more to the lipid than to the protein deposition and increases carcass fatness.

The response to high dietary fat addition- diets has also been studied in heat stressed lactating sows but to a lesser extent. When high-fat diets were used without an increase in CP or essential amino acids (AA) to maintain a constant protein/ME ratio, the BW loss during lactation and the milk yield were not affected by the dietary treatment (McGlone *et al.*, 1988). In contrast, when the diet was correctly balanced for protein or lysine to ME ratio, the increase in diet nutrient density in heat stressed sows improved litter BW gain, via an increase in milk-fat content, but it did not limit the mobilization of body reserves (Dove and Haydon, 1994; Quiniou *et al.*, 2000b; Schoenherr *et al.*, 1989). However, the magnitude of these effects seems to be dependent on the rate of dietary fat in the diet.

The utilization of low heat increment diets based on a reduction of dietary crude protein level has been tested both in growing pigs and in lactating sows in order to attenuate the effect of high Ta on voluntary feed intake and performance. As reviewed by Renaudeau *et al.* (2008), the

utilization of low CP diets at high ambient temperature moderately improves energy intake in hot conditions; the effect seems to be significant only in finishing pigs (Spencer *et al.*, 2001). In lactating sows, the results show great variability. In response to a reduced protein level from 16.8 to 14.3%, Quiniou and Noblet (1999) did not report any improvement in performance of lactating sows housed at 29 °C. Johnston *et al.* (1999) observed an increase in litter BW gain (+60 g/d) in the hot season for mixed parity sows fed a low CP diet (13.7 vs. 16.5%). In this study, the increase in daily weight gain of the litter was attributed to an increase in the mobilization of sow body reserves due to a probable imbalance of some essential AA (threonine, tryptophan, and valine) in the LP diet. In experiments in which essential AA supplies were kept constant and adequately balanced, heat stressed sows fed low CP diets tended to consume more energy and mobilize fewer body reserves (Renaudeau *et al.*, 2001; Silva *et al.*, 2009a).

Other feeding strategies

With respect to the postnatal management of the piglet, provision of an early intake of colostrum or milk replacer for all the piglets or only to the weak, light, and latter born piglets could be useful to promote survival especially at low Ta. A variety of energy compounds including glucose, lactose, and lipids have been tested as energy supplements for neonatal pigs with little success (Noblet *et al.*, 2001). For example, providing supplemental energy as oral doses of corn oil during the 48 h post partum did not significantly improve pre-weaning mortality (Pettigrew *et al.*, 1986).

The growth of nursing piglets is directly dependent on the ability of the sow to produce milk. As mentioned above, milk yield is reduced in heat stressed sows which lowers the litter BW gain. To supplement milk production, producers can provide piglets with creep feed or starter diets based predominately on cereals and various sources of animal proteins. At thermoneutrality, creep feed intake is generally low and highly variable among the litters within each study and between each study (see review of Pluske *et al.*, 1995). When offered during the last week of lactation, the amount of creep feed consumed before weaning by nursing piglets was higher when sows were kept in hot conditions (Renaudeau and Noblet, 2001). This higher intake was interpreted as an adaptation to compensate for insufficient milk production by the heat-stressed sows. Moreover, Azain *et al.* (1996) showed that providing litters with a milk substitute during the warm season is more effective in improving litter BW gain than during the cool season (+38 vs. +10%). In addition, it has been shown that supplying milk replacer to piglets during periods of heat stress could attenuate the maternal BW loss and improve post-weaning reproductive performance (Spencer *et al.*, 2003). These results suggest that the provisioning of supplemental feed or milk substitutes can attenuate the reduced growth rate of nursing piglets during heat stress and have a subsequent positive effect on post weaning growth performance. However, these practices need to be economically evaluated in regard to the high cost of these types of substitutes.

Water is an essential nutrient for livestock, especially during a thermal stress. Water intake during heat stress is a limiting factor for survival and performance since water has a fundamental role in the heat exchange system required for temperature regulation and maintenance of water balance (Mroz *et al.*, 1995). Whatever the physiological stage, water restriction enhances the negative effect of thermal stress on animal performance and especially on FCR (Nienaber and Hahn, 1984; Leibbrandt *et al.*, 2001). In hot conditions, water losses increase (evaporation by panting)

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and water ingested in feed and generated by metabolism is reduced. Consequently, drinking water consumption has to increase to meet the requirements of a heat-stressed animal. In warm climates, a key husbandry practice is to provide an abundant clean source of drinking water close to the feeding area. Moreover, in many high temperature regions, drinking water provided to pigs is often warm. Some studies demonstrated that providing chilled water would improve animal performance by reducing body temperature through absorbed heat energy (West, 2003; Jeon *et al.*, 2006). However, it must be considered that most animals are limited in chilled water consumption. According to Jeon *et al.* (2006), chilled water (22 to 15 °C) can provide sufficient cooling to allow lactating sows to increase their feed intake (+40%) and milk production (+20%) during heat stress.

Environmental modifications

A broad spectrum of environmental and technical solutions can be used to temper the effects of high or low T_a on feed efficiency in pigs. Whatever the climate, in order to reduce the effect of T_a on FCR, approaches leading to reduce the extra energy expenses for thermoregulation and/or to increase energy intake must be favoured. Classically, these approaches can be divided in two groups, those modifying the climatic environment to prevent or limit the degree of heat/cold stress to which the animals are exposed or those enhancing/decreasing heat exchanges between the animal and the environment (Renaudeau *et al.*, 2011a). Basically, the decision on the degree to modify the animal environment depends upon the cost of providing improved performance compared with the value of improved performance. In other words, the merit of maximizing feed efficiency from an environment standpoint may be questionable according to the relative price of feed versus energy.

Maintaining the T_a at or higher than the LCT during the 7 to 14 d period following weaning helps to avoid loss of excessive body fat and hence limits the reduction of thermal insulation and cold stress and associated consequences of weaning on health (diarrhoea) and on performance (post weaning growth lag) (Le Dividich *et al.*, 1998). Thereafter, once regular feed intake is established, T_a can be reduced by about 2 to 3 °C until the T_a to be maintained in the finishing house is reached (Noblet *et al.*, 2001). During this period, a moderate reduction of T_a does not have marked detrimental effects on growth performance because the pig is generally able to compensate for the extra energy requirement for thermoregulation by increasing its voluntary feed intake (Rinaldo and Dividich, 1991). The related increase in FCR and the associated economic loss can be avoided by maintaining the post weaning house at an optimal T_a . In practice, especially during the winter season in temperate climates, a high amount of heating in weaning houses is required to maintain T_a within the thermoneutral zone and the cost of providing this improved environment has to be considered. Several ways of reducing the heating requirement while maintaining piglet performance at acceptable levels have been investigated. As reviewed by Le Dividich and Herpin (1994), these solutions include the provision of a microenvironment and/or the reduction in nocturnal temperature. The creation of a microenvironment within the post-weaning crate is considered the simplest way to save heating costs. For example, hovers and covers are effective devices to reduce draughts and to capture heat generated by the piglets. According to Shelton and Brumm (1984), pigs subjected to these energy management techniques generally performed similar to, or better than, pig housed at recommended air temperatures. The reduction in

nocturnal temperature is based on the fact that the pig displayed marked circadian variation in its metabolic rate; its LCT is lower during the night time than during the daytime (Van Der Hel *et al.*, 1984). Compared with a constant T_a , a 4 to 10 °C reduction in nocturnal T_a did not affect pig performance but it decreased heating costs by 16 to 35% (Brumm *et al.*, 1985; Brumm and Shelton, 1988; Brumm and Shelton, 1991; Nienaber and Hahn, 1989). However, pigs on the reduced nocturnal treatment where the reduction in T_a was higher than 8 °C tended to have a higher incidence and severity of scouring. In some cases, the reduced nocturnal temperature can deteriorate FCR due to an increase in feed intake, especially during the night (Rinaldo, 1989).

When compared with post weaning pigs, growing-finishing pigs allowed *ad libitum* access to feed are less sensitive to cold T_a . Once the other climatic parameters (draughts, relative humidity) are controlled, the effect of T_a on FCR can be alleviated by providing supplemental heat to the building. However, this can be costly and is not practical in cases using lower-cost open-front housing systems. In this situation, providing wind protection for the pigs on three sides and dry bedding (straw, wood shavings, or other similar materials) in the sleeping area are adequate to prevent cold stress.

From an economical point of view, heat stress is a greater problem for growing-finishing pigs than is cold stress because of its negative effects on both FCR and growth rate. As the group size can influence critical temperatures (Close and Clark, 1981), the number of pigs per pen should be reduced with the aim to increase the minimum floor space allowed to the pigs. One of the most effective methods to promote heat losses under high T_a involves the addition of water to the skin with or without supplemental air flow to increase the rate of evaporation of the additional water. Water evaporation occurs by absorbing heat directly from the body of the animal and also by absorbing water to the surrounding air. The efficiency of these systems depends on the magnitude of thermal stress, the pig BW and the conditions of the water application (Renaudeau *et al.*, 2011a). The interval between wettings, the duration of water application, and the amount of supplied water per wetting need to be considered to maximize evaporative heat losses. With sprinklers operating intermittently (1 min on and 14 min off) below 29.5 °C and continuously above 29.5 °C, feed intake and average daily gain were improved by 13% in heat stressed finishing pigs (Nichols *et al.*, 1987). In that study, the reduction of water flow rate from 1.6 to 0.8 l/pig/h did not change the performance of the spray cooling system. The advantage of wetting finishing pigs during heat stress is supported by the results presented in Table 2. Whatever the wetting system, the growth performance was improved when compared to the control group. The experiment shows that the intermittent wetting system is more effective than continuous fogging system and the effect of intermittent sprinkling on voluntary feed intake were large enough to improve FCR. In fact, for evaporative cooling to be valuable, water must be applied intermittently to permit time for evaporation of the moisture at the skin surface. This rate of evaporation can be improved by providing supplemental air flow (Turner *et al.*, 1997).

As described before, the thermal requirement of lactating sows differs from that of suckling piglets. In practice, T_a in the farrowing barn is kept at a compromise between the requirement of the sow and the piglets. This means that T_a is too low for the litter, especially during the first days following the farrowing, and too high for the sows. This thermal dilemma is accentuated either in cold or in heat stress situations. For avoiding this problem, two microclimates have

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Table 2. Effects of the cooling system on growth performance in finishing pigs (initial BW=51 kg) during summer (adapted from Nichols *et al.*, 1979).

	Cooling system		
	Control	Fogger ¹	Sprinkler ²
No. of pigs	40	40	40
Feed intake (kg/d)	1.95	2.21	2.36
Average daily gain (kg/d)	0.521	0.580	0.698
FCR (kg/kg) ³	3.75	3.84	3.39

¹ System that generated low volume, small droplet nozzles and operated continuously when Ta exceeded 26.7 °C.

² System that generated high volume, large droplet nozzles and operated intermittently (1 min on followed by 29 min off) when Ta exceeded 26.7 °C

³ FRC = feed conversion ratio.

to be used to cool the sows without detrimental effects on piglet's well-being and/or to warm piglets without causing heat stress in sows. An infrared lamp located over the creep area and/or a heated floor are the most common methods used to provide a thermal environment suitable for the newborn piglet (Kuhn, 1990). However, the provision of an adequate environment must take into account the behaviour of the newborn piglet. During the first days of life, the newborn prefers to lie close to the sow udder rather than in the heat area which increases the risk of being crushed by the sow (Hrupka *et al.*, 1998). To avoid this problem, a movable infrared lamp is placed at the rear of the sow during parturition to avoid excessive changes in the piglet's body temperature. Thereafter, the lamp is used to direct the piglet away from the zone of the sow and attract them progressively towards the heating device (heating lamp or map) in the creep area. Covering the creep area was found to be effective in reducing heat losses in piglets. Because of the high susceptibility of the lactating sows to high Ta, a lot of alternatives were tested in order to increase heat exchange between the animal and the environment. Provision of supplemental fresh air directly on the sow's head and neck ('snout cooler') was found to be an efficient way to improve performance under heat stress. At 30 °C, the average daily feed intake was increased by 25 to 35% when snout coolers were used to cool the sow (McGlone *et al.*, 1988; Stansbury *et al.*, 1987). In these latter studies, voluntary feed intake and milk production were also increased by 24% and 19% by using a drip cooling method based on the application of a water drip for 3 min every 10 min. As previously described, the reduction of energy intake in heat stressed animals is mainly related to the inability to dissipate sufficient body heat to the environment. As the lactating sow spends about 85 to 90% of the day resting (Renaudeau *et al.*, 2002), most of the time a large part of its body is in contact with the floor. Thus, cooling the floor under the sow in the farrowing crate should increase the dissipation of sow's body heat by conduction (Table 3). It is interesting to note that the benefit of a floor cooling system for milk production seems to be higher than for feed intake. This result also confirms the direct effect of high Ta on mammary gland metabolism. Finally, use of the floor cooling system did not reduce piglet mortality; it has been suggested that the surface temperature was not low enough to keep the piglet away (Wagenberg *et al.*, 2006).

Table 3. Effect of floor cooling system on performance of lactating sows and their litter¹.

Reference	Treatment	No. of sows	ADFI (kg/d)	BW loss (g/d)	LBWg (kg/d)	WEI (d)
Wagenberg <i>et al.</i> (2006) ²	control	29	4.90	1,060	2.52	—
	cool	29	5.50	943	2.93	—
Silva <i>et al.</i> (2006) ³	control	20	5.60	276	1.70	4.3
	cool	20	6.47	-133	2.17	3.9
Silva <i>et al.</i> (2009b) ⁴	control	14	4.71	580	1.96	5.7
	cool	15	5.48	328	2.57	4.0

¹ Abbreviations used: ADFI = average daily feed intake; BW loss = maternal BW loss during the whole lactation period; LBWg = litter BW gain during lactation; WEI = weaning to estrus interval.

² Study performed in Netherlands with an average Ta on 24 °C

³ Study performed in Brazil with an average Ta on 23.5 °C

⁴ Study performed in Brazil with an average Ta on 25.5 °C

Genetic strategies

Whatever the physiological stage, the depressed effect of thermal stress on FCR cannot be totally eliminated by management solutions. Moreover, most of these practices are not economically or technically feasible in all livestock production systems. As a consequence, selection for pigs able to maintain a low FCR whatever the Ta, if successful, could be the most cost-effective method for mitigating the effects of thermal stress on FCR.

In growing pigs, an important part (60-70%) of voluntary feed consumption can be explained by maintenance and production requirements (Dekkers and Gilbert, 2010). The remaining variation, referred to as residual feed consumption (RFC), may be used for direct selection of feed efficiency without any change in production. In practice, RFC of individual growing pigs can be estimated as the residual of a multiple linear regression for feed intake that includes growth rate and body composition (backfat thickness or carcass lean content) as covariates to account for production requirements, along with metabolic BW to account for maintenance requirements (Mrode and Kennedy, 1993). As far as we know, only two selection experiments for RFC have been conducted in growing pigs, one at INRA (Gilbert *et al.*, 2007) and the other one at Iowa State University (Cai *et al.*, 2008), both in purebred Large White/Yorkshire pigs. Details on the selections designs have been given by Gilbert *et al.* (2007) and Cai *et al.* (2008). The selection on RFC has shown to be effective in creating lines of pigs having different feed intake levels but a rather similar growth potential. Among others, individual variations in RFC can reflect differences in digestion and/or metabolic utilization of feed which includes differences in heat production and/or in body composition. From a comparison of two divergent lines with a low (RFC-) or a high RFC (RFC+) over 4 generations of selection from the INRA experiment, it has been shown that digestibility of a conventional cereals-soybean meal-diet did not differ between the two lines (Barea *et al.*, 2010). However, the efficiency of ME utilization for growth was higher in RFC- than in RFC+ pigs, in connection to a reduced total HP (9% reduction in RFC- pigs compared to RFC+ pigs;

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Table 4). This difference is mainly due to a reduced basal metabolic rate and, to a lesser extent, lower physical activity (9% reduction in RFC- pigs; Table 4). According to the importance of HP on thermoregulatory responses, selection for RFC is assumed to be able to change the ability of the pig to cope with thermal stress. We have tested this hypothesis through two experiments conducted at INRA by exposing pigs to a thermal heat stress in which they were exposed to 24 °C (thermoneutrality) during one week and, thereafter, to a constant high Ta (30 or 32 °C) for 2 or 3 weeks. A first experiment was designed to determine the effect of selection for RFC on energy utilization during a thermal heat acclimation period, in pigs individually housed in respiration chambers for a 28 d period. As expected, feed intake and total HP were significantly reduced under thermal stress (Figure 8). However, these changes were not significantly affected by line. From data obtained in a second experiment on a larger number of pigs, we found that pigs with a low RFC tended to have a greater ADG (+50 g/d) and a lower FCR (-0.40) at 30 °C when compared to pig with a high RFC (Figure 9). These preliminary results would suggest that the selection for RFC could improve the capacity of pigs to cope with heat stress. However, further studies are required to validate these results in growing pigs under practical conditions such as those encountered in tropical areas, and to identify the correlated effects of selection for FCR on the ability of other physiological stages (piglets, lactating sows) to tolerate cold or hot conditions.

Conclusion

Thermal stress negatively impacts the global feed efficiency on a pig farm by changing the energy intake and the metabolic utilization of energy for tissue deposition, by reducing the overall productivity of sows, and/or by increasing the mortality rate whatever the physiological stages. This lower feed efficiency, when combined with other direct and indirect losses of production related to climate effects, results in very important economic impacts on the pig industry. Current and past research has resulted in significant improvements in pig management in cold and hot conditions. This chapter provides a non exhaustive review of the strategies available to alleviate

Table 4. Effect of a divergent selection for the residual feed consumption (RFC) on energy balance (kcal/kg of BW^{0.60}/d) in growing pigs (adapted from Barea et al. 2010).

	RFC+	RFC-
No. of pigs	12	12
Average BW (kg)	60.4	60.0
ME intake	668 ^a	622 ^b
Heat production (HP)		
Fasting HP	202 ^a	184 ^b
Activity HP	60 ^a	52 ^b
TEF ¹	94	93
Total	352 ^a	332 ^b

^{a,b} Rows with different superscript are significantly different ($P < 0.05$).

¹ TEF = thermic effect of feeding.

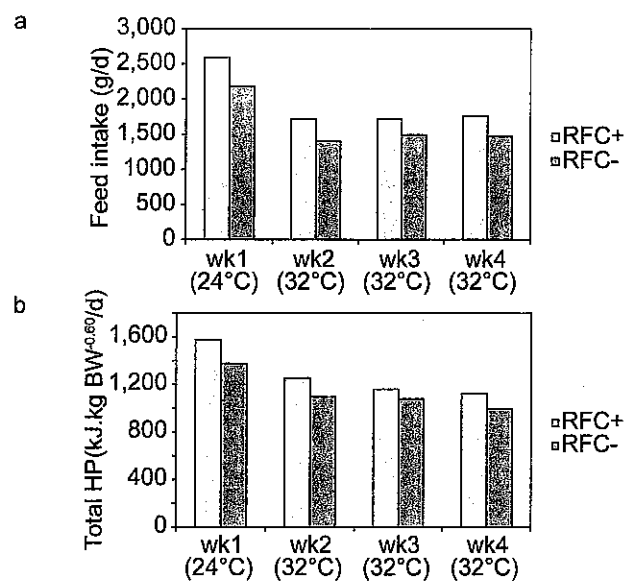


Figure 8. Effects of the line and the duration of exposure to 32 °C on (a) feed intake and (b) total heat production (HP) in growing pigs. Pigs (5/line) were kept at 24 °C for 7 days and thereafter at 32 °C for 21 days (Renaudeau, Frances, Dubois, Gilbert, Noblet, unpublished results).

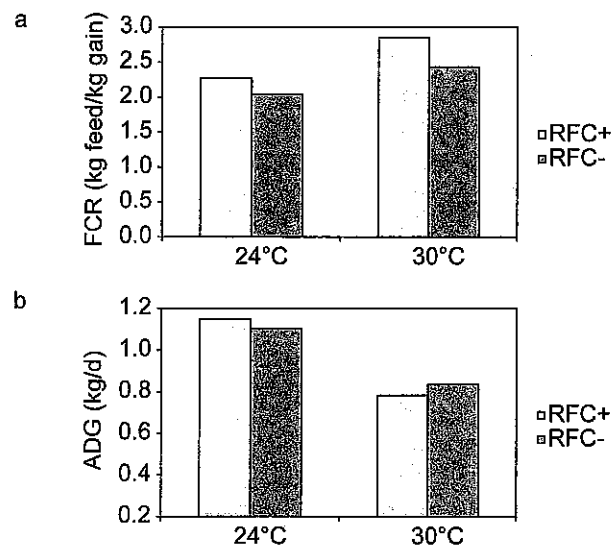


Figure 9. Effect of line and ambient temperature on (a) average daily BW gain (ADG) and (b) feed conversion ratio (FCR) in growing pigs. Pigs (17 RFC+ and to 19 RFC-) were kept at 24 °C for 7 days and thereafter at 30 °C for 14 days (Campos, Renaudeau, Gilbert, Noblet, unpublished results).

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the effects of T_a changes on feed efficiency and, more generally, on pig performance. Maximizing production levels and the feed efficiency of pig farms is important but economic considerations largely determine the level of environmental or feeding manipulations used to cope with thermal stress. In the future, efforts have to be developed to select animals with high production efficiency and optimal heat tolerance.

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