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HOW PIGS INFLUENCE INDOOR AIR PROPERTIES IN INTENSIVE FARMING: PRACTICAL IMPLICATIONS – A REVIEW

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Abstract
Indoor environmental conditions in intensive pig farms are influenced by both the outdoor air temperature and humidity, and the heat, moisture and gas exchanges between the animal and the air. As ventilation rate in pig facilities is usually estimated in temperature, moisture and even CO_2 balances, estimation of heat losses or gains, and moisture and CO_2 production from the animal is needed, but the contribution of other sources of the barn, such as slurry or wet surfaces have also to be taken into account. Some recent studies have been conducted to update total heat and moisture production at farm level, showing that current, historical standards of latent heat transfer are consistently lower than those reported recently at facility level, for both adult and growing animals. Also, CO_2 production needs to be updated by including an estimation of its release from slurry. These new values will help with updating the standards for ventilation rate recommendations and design of the modern intensive pig buildings.

Key words: pigs, heat production, moisture production, carbon dioxide, ventilation rate

Heat losses and moisture and CO_2 production are important for housing design and climate control systems in pig production. For optimal health and production, the air surrounding the pig should fulfil certain requirements; however, those requirements often are not met, partly because the outdoor climate influences indoor air quality, and because of the effects of the livestock on the housing environment. Temperature and humidity are the main environmental factors that are influenced by pigs in facilities, although CO_2 and even NH_3 concentrations also are strongly affected by the pigs' activity and their use of the available space for behavioural activities and social interactions.

An understanding of the exchanges of heat, gas, and moisture between an animal and its environment is a critical step in identifying features of building design and environmental control strategies to achieve the optimum well-being of the animal. Therefore, it is important to understand the relationships between the factors that drive those exchanges and the implementation of barn design characteristics that favour optimal animal health and production. That said, season is a very important factor influencing indoor climate. In winter, low indoor air temperatures can be accompanied by high humidity and CO_2 concentrations; in summer, however, excessively high temperature is the most significant problem.

Both the interaction between the conditions on the outside and on the inside, and the interactions between the livestock, the ventilation system, and the building influence the indoor environmental conditions on pig farms. Those interactions can be modelled based on the steady-state balance equation for the sensible and latent heat and the carbon dioxide mass balance (Baxter, 1984; Pedersen et al., 1998; Schauberger et al., 2000; CIGR, 2002; Blanes and Pedersen, 2005), however, more precise assessments of heat, moisture, and CO_2 transfer from animals to the facility environment and their effects on estimates of air renewal, apparently are lacking.

The objective of this study was to examine the impacts of thermal, moisture, and gas exchanges between the pig and its surroundings in the most typical farm conditions and their implications for the implementation of environmental controls in commercial pig farms.

Heat production

Pigs are homeotherms; therefore, heat production and heat loss should be in balance. Feed intake or, more precisely, metabolizable energy (ME) intake, which can be calculated by subtracting the energy in urine from the digestive energy intake, is the main factor influencing heat production in pigs. Heat is produced because of various metabolic processes involved in maintenance and growth functions. Following Kielanowski (1965), ME is the sum of the energy for maintenance (ME_m) and the energy for production (ME_{prod}):

$$ME = ME_m + ME_{prod}$$

Energy for production is the energy required for fattening (protein and lipid deposition) in growing animals, for foetus and udder development and weight gain in pregnant sows, and for milk production in farrowing. ARC (1981) defines maintenance as "the requirement of nutrients for the continuity of vital processes within the body so that the net gain or loss of nutrients by the animal as a whole is zero". It reflects metabolic rate; i.e., heat production per unit time, expressed relative to body surface area. The surface areas of two bodies of similar shape and density but different size are in proportion to the two-thirds power of their weights (Kleiber, 1975). Thus, metabolic rate is proportional to body weight (BW); however, in terms of heat production, ME_m or total heat production (THP) is the sum of fasting heat production or basal metabolism (FHP), activity heat production (AHP), and the thermic effect of feeding (TEF) (van Milgen et al., 1997).

Apparently, genotype (or leanness) has a significant effect on FHP, because estimates are lower for obese Meishan barrows and higher for lean Pietrain boars (van Milgen et al., 1998). Those authors have also reported in growing pigs, that FHP of entire male pigs was higher than that of castrated pigs, which reflects the greater mass of viscera in entire animals (Quiniou and Noblet, 1995), which influences FHP (Koong et al., 1985; Pekas and Wray, 1991) because of the high energy requirements of the portal-drained viscera (Johnson et al., 1990). Therefore, heat production, particularly FHP, increases with an increase in lean tissue accretion rate. In recent decades, the genetic potential of pigs has improved considerably; however, in body composition, a reduction in lard yield and an increase in lean tissue have been the most significant changes. Tess et al. (1984) reported that a 2.1% increase in lean percentage was correlated with an 18.7% increase in FHP. In a 10-year period, Anderson (2002) detected those changes in fat and lean body content in four commercial breeds, showing a body lean tissue rate increase of 1.76 kg/114 kg (1.55%) over that decade (1991–2001), and therefore an increase of 14.6% of FHP in such period. In relation to the THP per day and for finishing pigs of 115 kg live weight, FHP or basal metabolism represents 62% and 51% for entire and castrated males, respectively (Labussière et al., 2013).

In a review, Brown-Brandl et al. (2004) reported that FHP in pigs has increased with the increase in lean tissue accretion of modern swine. Heat production at thermoneutrality was 17% higher between 1988 and 2002 than it was before 1988; however, after all experimental temperature conditions were included in the analysis, the increase in heat production ranged from 12% (90-kg pigs at 15ºC) to 35% (5-kg piglets at 35ºC), and the largest differences occurred at the highest temperatures. Data for latent heat production was unavailable for all mass ranges of pigs.

Another important component of the THP in swine is heat production caused by physical activity (AHP) because energy expenditure per hour of standing appears at least four times higher in pigs than it is in other domestic livestock species (Noblet et al., 1993). Taking into account the variation among different individuals, and that housing conditions can affect activity, the level of activity influences estimates of ME_m and THP (van Milgen and Noblet, 2003). Although various techniques have been used to measure physical activity, estimates of AHP in growing-finishing pigs have not differed appreciably among studies (200–250 kJ/kg $BW^{0.60}$ .d) (Quiniou et al., 2001), reflecting 15–16% of the THP for finishing pigs of 115 kg live weight, with no differences between entire and castrated males (Labussière et al., 2013).

The thermic effect of feeding (TEF) is the third component of THP, which is usually calculated as THP minus FHP and AHP (van Milgen and Noblet, 2000). Heat production from feed intake, digestion, and absorption is part of a short-term TEF, and processes such as hindgut fermentation and intermediary metabolism contribute to the long-term TEF. In finishing pigs of 115 kg live weight, TEF as a proportion of THP is lower for entire males (23%) than it is for castrated males (33%) (Labussière et al., 2013) because of the lower feed intake, higher protein deposition, and lower lipid deposition in entire pigs.

Heat exchange

Constant exchange of heat between the pig and its environment occurs because of the differences in temperature and humidity between the body core and the surroundings. As a homeothermic species, pigs mainly gain heat from their own metabolic activity. Therefore, as described above, the rate of metabolism is influenced by the level of food intake, but also is influenced by muscular activity. Although animals outdoors can gain substantial heat during the day by absorbing solar radiation (Cena, 1974), usually, indoors, this heat input is negligible. Heat loss to the environment occurs through two main routes: (1) non-evaporative heat transfer to the air and surrounding surfaces by convection, conduction, and thermal radiation exchange, mechanisms that are strongly influenced by the difference between the temperatures of the skin and the environment, and (2) evaporative heat transfer associated with the loss of water vapour from the body surface and, especially, from the respiratory system, which is influenced by the water vapour pressure difference between inhaled and exhaled air and by respiration volume.

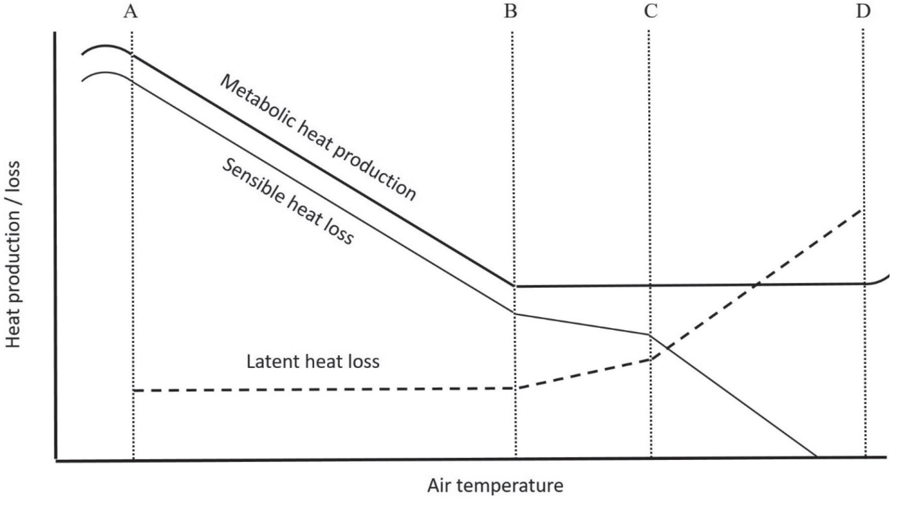

Figure 1. General concept of heat regulation in pigs (Mount, 1979). The symbols A to D are defined in text

A general relationship between the rate of metabolic heat production and air temperature was defined by Mount (1979) for specific levels of feed intake and activity (Figure 1). Under those conditions, zone AD of constant body temperature can be divided into two zones, AB and BD. Within zone AB, body temperature is kept constant through the regulation of THP. Below B (Lower Critical Temperature, LCT), to balance the rate at which heat is lost to its surroundings, the pig must increase its metabolic rate (heat production). Within that zone, heat production can be increased through shivering (shivering thermogenesis) or through the production of additional heat without shivering (non-shivering thermogenesis); e.g., through the mobilisation of fat reserves. Under farm conditions and, if feed is available, pigs that are exposed to temperatures below the LCT can increase their intake. Within zone AB, heat loss mainly occurs through non-evaporative routes. LCT is defined as the air temperature at which the heat emitted by an animal that has fully vasoconstricted skin, and skin and lungs that are losing minimal amounts of water vapour, equal to its heat production within the thermoneutral zone (Blaxter, 1989).

In zone BD, body temperature is kept constant through the regulation of heat loss (thermoneutral zone). Zone BC is the “comfort zone”, or the “zone of least thermoregulatory effort”. Within that zone, the metabolic rate is at the minimum and evaporative heat loss is slightly above the minimum. Ideally, to maximize production efficiency, the air temperature in a barn should be within the animal’s zone BC because the pigs will not have to invest additional energy (panting) to lose excess heat. If the air temperature exceeds LCT, there is a natural decrease in the proportion of metabolic heat that an animal loses through non-evaporative routes to the microclimate of the barn always within the thermoneutral zone, where metabolic rate is minimal and constant.

Although the definition of LCT appears straightforward, the concept of upper critical temperature (UCT) is less so. Bligh and Johnson (1973) defined UCT as the ambient temperature above which the thermoregulatory evaporative heat loss processes of a resting thermoregulating animal are recruited; however, this definition assumes that evaporative heat loss remains constant and is minimal within the thermoneutral zone, and that metabolic rate increases at some ambient temperature above UCT once evaporative heat loss reaches its summit value (Bligh, 1985). Thus, according to Mount (1974), the upper limit of the thermoneutral zone can refer either to the temperature above which evaporative heat loss rises markedly (C in Figure 1; evaporative critical temperature) or to the temperature (hyperthermic point) above which metabolic rate increases because of an increase in the core temperature of a resting thermoregulating animal (D in Figure 1; UCT). The latter definition is preferred in the literature (Yousef, 1985; Hahn and Hugh-Jones, 1989).

The situation presented in Figure 1, in which a constant level of feed intake is assumed, is only valid for a short period following a sudden increase in ambient temperature. In fact, during heat stress; e.g., at temperatures above point C, pigs will immediately reduce their feed intake. In particular, metabolic rate is reduced during prolonged exposure to high temperatures, which parallels reductions in food intake and thyroid activity (Clark and McArthur, 1994; Prunier et al., 1997). Huynh et al. (2005 b) described a sequence of the physiological changes that pigs experience when air temperature rises above point C. Specifically, modern pigs have high metabolism and, therefore, high heat production, and exhibit physiological signs of heat stress (significant increase in respiratory rate) as early as temperatures above 22ºC for group-housed growing pigs of 60 kg live weight fed *ad libitum*, although reductions in voluntary feed intake and increases in rectal temperature occurred at higher temperatures; 23.0–25.5ºC and 24.5–27.0ºC, respectively. Huynh et al. (2005 b) concluded that reductions in feed intake and increase in rectal temperature are reliable indicators of reduced performance in heat-stressed pigs.

Heat and moisture production rates in modern pigs

Total heat production (THP) can be partitioned into sensible heat production (SHP) and latent heat production (LHP) or moisture production (MP). Sensible heat mainly is lost from the animal’s body and often increases the barn temperature, while latent heat is dissipated through the animal’s breathing and evaporation from the skin, which increases the moisture content of the surrounding air. Rates of SHP and

MP from animals are important in the design of swine housing because they are used to calculate ventilation rates, which are used in the design of the climatisation system of the farm. Therefore, accurate and current values for those rates at house level are critical.

The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) and the American Society of Agricultural and Biological Engineers (ASABE) publish standards, which include heat and moisture production data for various species and weights of livestock (ASABE, 2012). For pigs, the ASABE Standards are based on studies conducted some decades ago by Bond et al. (1959) for growing-finishing pigs and gestation and lactation, and Ota et al. (1975) for nursery-age piglets. Recent studies, however, are lacking. As indicated above, some authors have suggested that heat production rates in modern swine are substantially higher than those reported in the standards because genetics, nutrition/feeding, and production methods have changed (Harmon et al., 1997; Brown-Brandl et al., 2004).

More recently, studies have been conducted to update THP and its partitioning into house-level LHP and house-level SHP. Traditional ASABE Standards are based on direct calorimetric studies of small groups of pigs or individual sows and litters in which there was no accumulation of manure in the chamber, which was cleaned daily. Although calorimetric studies have been useful for monitoring animal heat and moisture production, today, it is compulsory to account for facility and management impacts (stocking density, manure management, and the contribution of non-animal sources) in accurately estimating the heat and moisture production in modern pig facilities for the practical design and operation of climatisation systems. In addition, changes in the liveweight and metabolism of swine in recent decades have to be taken into account. Brown-Brandl et al. (2014) have provided, at calorimeter and facility levels, heat and moisture production data for all stages of modern swine production. Various stages were considered, including nursery piglets, growing pigs, early and late finishing pigs, gestating gilts, and farrowing sows. For 16 consecutive months, Stinn and Xin (2014) quantified the house-level latent and sensible heat at a modern 4300-sow breeding, gestation, and farrowing facility. In addition, they quantified the differences between daytime and night-time heat production, which were 30% (early gestation), 27% (late gestation), and 6% (lactation) lower at night than it was during the day.

Heat production rates at 20ºC reported by the ASABE Standards (ASABE, 2012), Brown-Brandl et al. (2014) for nursery and growing and finishing pigs, and Stinn and Xin (2014) for gestation and farrowing, are listed in Table 1, which includes other well-known sources of livestock heat production data at that temperature (CIGR and FAO). They are the most important sources of swine heat and moisture production to be used to calculate ventilation rate and therefore to optimise climatisation of modern pig farms.

The International Commission of Agricultural Engineering (CIGR) formed a working group on the climatisation of animal housing, which established guidelines for animal heat and moisture production for use in the design of ventilation and heating equipment. European standards for heat and moisture production are more based on CIGR equations. Their 1992 report was published in the CIGR Handbook (CIGR, 1999), which was updated in 2002 (CIGR, 2002). The CIGR predictive equations are based on the biological principles of heat loss. Each of those equations can be broken down into two parts: a calculation of maintenance requirements as a function of the metabolic body mass weight, and a calculation of heat dissipation resulting from production (growth in growing animals, and pregnancy and milk production in sows). Note that the CIGR report includes a correction for the calculation of total heat production that accounts for the effects of ambient temperature. For each degree >20ºC, the estimate of heat production is reduced 1.2%, and for each degree <20ºC, the estimate of heat production is increased 1.2%. Aarnink et al. (2016) noted that this linear temperature correction does not account for a thermo-neutral zone as proposed by Mount (1979) and confirmed by Huynh et al. (2005 b). The data of heat and moisture production reported by the FAO for pigs are also included in Table 1, although the primary sources of those data were not included in the report (Mrema et al., 2011).

Table 1. Summary of updated total heat production (THP), sensible heat production (SHP), and moisture production (MP) values for swine at different production stages. Modern data come from Brown-Brandl et al. (2014) (a) and Stinn and Xin (2014) (b), ASABE data from ASABE (2012) based on calorimetry studies, FAO data from Mrema et al. (2011) and CIGR data from CIGR (2002)

(a)

	Nursery				Growing				Finishing			
	Modern	ASABE	FAO	CIGR	Modern	ASABE	FAO	CIGR	Modern	ASABE	FAO	CIGR
Mass (kg)	16.7	17.5	20.0	20.0	34.0	40.0	40.0	40.0	117	100	90	100
THP (W/kg)	4.83	5.00	4.75	5.18	4.04	3.10	3.75	3.35	2.07	1.90	2.72	2.22
SHP (W/kg)	2.85	3.50	2.75	3.21	2.29	1.60	2.56	2.07	1.27	1.10	1.83	1.37
LHP (W/kg)	2.08	1.50	2.00	1.97	1.74	1.50	1.19	1.22	0.80	0.80	0.89	0.85
MP (g/h.kg)	3.06	2.20	2.94	2.90	2.56	2.20	1.75	1.79	1.18	1.18	1.31	1.25

(b)

	Gestation				Farrowing			
	Modern	ASABE	FAO	CIGR	Modern	ASABE	FAO	CIGR
Mass (kg)	204	200	180	200	175	177	180	180
THP (W/kg)	1.86	1.40	2.02	1.89	3.28	2.60	2.55	2.25
SHP (W/kg)	0.95	0.97	1.58	1.16	1.66	1.30	1.89	1.38
LHP (W/kg)	0.91	0.43	0.44	0.73	1.62	1.30	0.66	0.87
MP (g/h.kg)	1.34	0.63	0.65	1.07	2.38	1.91	0.97	1.28

The SHP at the facility level reported by Brown-Brandl et al. (2014) are similar to the current American standards based on calorimetric studies (ASABE, 2012), except the values for nursery piglets, but LHP values at the calorimeter level were less than those observed at farm level (Table 1). Thus, with the exception of the nursery stage, the current estimates of THP of modern pigs are higher than are the traditional standards. The THP data based on the CIGR equations (2002) and the FAO values reported by Mrema et al. (2011), are similar to the modern values, except those for farrowing sows, which have values that are, respectively, 46% and 29% lower than the values presented by Brown-Brandl et al. (2014). Values of LHP at the calorimeter level, however, were consistently lower than were those reported at facility level for adult animals (gestation and farrowing) and for growing pigs. Others have stated that estimates of latent heat loss at the housing level might be improved by distinguishing between the latent heat produced by the animals and the latent heat produced by evaporation from wet surfaces within the barn (Aarnink et al., 2016). Furthermore, taking into account that ventilation flow in barns usually is estimated based on an indirect method that uses, among other parameters, moisture balance (Blanes and Pedersen, 2005), the information in Table 1 clearly demonstrates that the recommendations for ventilation rates in pig farms should be updated. In general, historical recommendations that were based on old moisture production values clearly underestimate the need for moisture and temperature controls (Lu et al., 2017).

Heat losses

Thermal exchanges between an animal and its surroundings can be categorized into two main modes of energy exchange: sensible and latent.

Sensible heat exchange

Sensible heat exchange is thermal energy transfer that occurs because of a difference between temperatures. Although the core temperature of a pig is about 39.5ºC, the skin temperature of an adult or growing animal is slightly lower, and the temperatures of any surface or fluid in the surroundings that differ from these will lead to an exchange of thermal energy through sensible means. Sensible heat exchange occurs through conduction, mainly to the floor when the animal is lying down, convection to the air, and thermal radiation to various surfaces.

Conduction heat exchange involves the transfer of thermal energy from one object to another that are in contact. A pig's choice between standing or lying down, its lying posture, and the location of where it lays down can influence heat loss by conduction. Typically, pigs spend more time lying down if ambient temperatures are high (Huynh et al., 2005 a), primarily because standing increases the metabolic rate and heat production of a pig (van Milgen et al., 1998). In addition, the heat loss by conduction to the floor when the pig is lying down might be higher than the heat loss by convection to the air when the pig is standing, although the effect depends on the environmental circumstances (e.g., thermal conduction of the floor, air velocity). At high ambient temperatures, pigs tend to expose a larger area of their body to the floor by lying on their side and seeking a cool place for lying; e.g., a slatted vs. solid floor (Hacker et al., 1994; Aarnink et al., 2006).

Conduction heat transfer can be defined by the following equation:

$$Q = Ax \ \frac{T_H - T_C}{R}$$

where:

Q = total heat transmitted by conduction (W),

A = contact surface area (m^2),

$T_H - T_C$ = temperature difference between hot and cold surfaces in contact (ºC),

R = resistance to conduction heat flow = L/k (m^2. °C/W),

where:

L = path length that heat travels in the direction of heat flow (m), usually 3 cm,

k = thermal conductivity of the media heat travels through (W/m.ºC).

Thus, when calculating the transmittance of a roof or wall built with multiple materials, R is the sum of the resistances of the two materials involved in the process; i.e., the animal surface and the floor material. For the pig body, the conductivity coefficient for homeotherms is about 0.6 W/m.ºC (Blaxter, 1989).

In summer, a common problem is maintaining thermoneutrality in farrowing sow facilities when it is hot. A possible method for alleviating heat stress for the sow is the use of a cast-iron slatted floor, which has a conductivity of 50 W/m.ºC. Given an animal-floor contact surface area of 1 m^2, air and slatted-floor temperatures of 20ºC, and a sow surface temperature of 32ºC, the release of sensible heat via conduction of the sow will be:

$$R = \left(\frac{0.03(m)}{50 \ \frac{W}{m.\ ^\circ C}} \right) + \left(\frac{0.03(m)}{0.6 \ \frac{W}{m.\ ^\circ C}} \right) = 0.051\ m^2 \cdot {}^\circ C/W$$

$$Q = 1.0\ ([m]^2) \times \frac{(32 - 20)\ (^\circ C)}{0.051 (m^2 \cdot \frac{^\circ C}{W})} = 235\ W$$

To put those numbers into perspective, based on the data in Table 1, a 180-kg sow in a farrowing facility at an air temperature of 20ºC, will be able to release a maximum of 340 W of sensible heat. Thus, a cast-iron slatted floor can be very useful for alleviating heat stress when temperatures rise in summer. However, we have to consider that the temperature of the slatted floor will increase a short time after the sow lays down, and the thermal exchange will be reduced. Similarly, heat losses by conduction will be minimal in a polypropylene slatted floor, which has a thermal conductivity of 0.22 W/m.ºC:

$$R = \left(\frac{0.03(m)}{0.22 \frac{W}{m.\ ^\circ C}} \right) + \left(\frac{0.03(m)}{0.6 \ \frac{W}{m.\ ^\circ C}} \right) = 0.19\ m^2 \cdot {}^\circ C/W$$

$$Q = 1.0\ ([m]^2) \times \frac{(32 - 20)\ (°C)}{0.19\ (m^2 \cdot \frac{°C}{W})} = 63\ W$$

The key aspect of convection heat transfer is that the flow of energy is from one object, the animal surface, to a fluid (or vice versa), which mainly is influenced by the temperature difference between the fluid (typically, air in pig farming) and the animal surface. If the fluid under consideration is moving because of an external motive force (e.g., wind), the process is called ‘forced convection’. If the fluid is moving because of variations in fluid density only, the process is called ‘natural’ or ‘free’ convection.

Convection heat transfer from an animal’s surface can be defined by the following equation:

$$Q = h \times A \times (T_S - T_F)$$

where:

Q = sensible heat transferred by convection (W),

h = convective heat transfer coefficient ($W/m^2.°C$). It increases with an increase in airspeed, although at a diminished rate at high speed. Convective heat transfer coefficient has been measured experimentally by Holman (2002) for a sphere exposed to a moving airstream; i.e., 56 and 85 $W/m^2.°C$ for air velocities of 10 m/s and 20 m/s, respectively, and an ambient temperature of 20ºC. The value is much lower if the airspeed is near 0; e.g., 9 $W/m^2.°C$ for an air velocity of 0.5 m/s, which is the maximum level permitted in modern pig farming. Therefore, we can assume that convective heat transfer in an intensive pig facility, where airspeed is always <0.5 m/s, is about 7 $W/m^2.°C$, which is used in calculations for the transmittance of walls and roofs,

A = surface exposed to the thermal exchange (m^2). The body surface area can be calculated as $0.0734 \times LW^{0.656}$ (Swindle et al., 2012),

T_S = animal skin surface temperature (ºC),

T_F = fluid temperature surrounding the skin (ºC).

For example, based on the farrowing facility described above, with an air temperature of 20ºC and low airspeed, the convection heat transfer from a sow of 180 kg of live weight, with a skin surface temperature of 32ºC and an air temperature surrounding the skin of 26ºC ((32+20)/2), will be as follows:

$$Q = 7\ (W/m^2.°C) \times 2.2\ (m^2) \times (32–26)\ (°C) = 92\ W$$

An increase in airspeed or a reduction in air temperature will increase the heat loss by convection of the sow. Although, typically, airspeed inside intensive pig farms is low, external wind can influence significantly the indoor air temperature and, therefore, heat losses by convection (Forcada et al., 2014).

Radiation heat transfer involves the transfer of thermal energy from one surface to another because of a difference in temperatures and the area of surface exposed between objects. In pig farms, radiative heat losses depend on the temperature difference between the pig's skin and the surrounding materials, and on the skin area exposed to the construction. At high ambient temperatures, to increase convective and radiative heat losses, pigs try to increase the distance to other pigs.

The heat released by thermal radiation from an object at any temperature above absolute zero is defined by the Stefan-Boltzmann Law:

$$Q = A \times \varepsilon \times \sigma \times T^4$$

where:

Q = radiation heat released by an object at surface temperature T (W),

A = surface area (m^2),

σ = Stefan-Boltzmann constant: 5.67×10^{-8} ($W/m^2.K^4$),

ε = emissivity of a surface; range = 0-1 (dimensionless),

T = surface temperature (K).

At temperatures above absolute zero, all objects emit thermal radiation. Emissivity is defined as the ratio of the energy radiated from a surface to that radiated from a blackbody (a perfect emitter) at the same temperature and wavelength. It is a dimensionless number between 0 (for a perfect reflector) and 1 (for a perfect emitter). The emissivity of most building materials is between 0.75 and 0.97, except for metals (between 0.05 and 0.25).

At the same time that a given body or material emits radiant energy, however, it absorbs radiation from its environment because any surface that has a temperature above absolute zero radiates heat. Therefore, and according to Holman (2002), to measure the radiation heat transfer between the animal and the building, skin temperature and the temperatures of surrounding surfaces must be included, as follows:

$$Q = A \times \varepsilon \times \sigma \times (T_{SK}^4 - T_S^4)$$

where:

A = animal surface exposed to the thermal exchange (m^2). Can be calculated from Swindle et al. (2012): $0.0734 \times LW^{0.656}$,

ε = skin surface emissivity (= 0.90 for most animal surfaces at long-wave radiation) (Hoff, 2013),

T_{SK} = skin surface temperature of housed pig (K),

T_S = surface temperature of surrounding surfaces not touching a pig (K).

In the example calculation, for the farrowing facility described above, we assume that all of the surrounding surfaces to which the animal is exposed are at the same temperature. Radiation heat losses from a sow of 180 kg of live weight that has a skin temperature of 32ºC and the surrounding surfaces at 18ºC will be as follows:

$$Q = 2.2\ (m^2) \times 0.9 \times (5.67 \times 10^{-8})\ (W/m^2.K^4) \times (305^4 - 291^4)\ (K^4) = 166\ W$$

To put that value into perspective, this represents about 50% of the total sensible heat transferred by the lactating sow. Radiation heat losses are significant in large farm animals. A practical approach for improving the housing environment and reducing heat losses by radiation in intensive pig farms saving energy for heating if the case, is the use of polypropylene fabrics in winter in facilities for weaned piglets and growing pigs (Dolz et al., 2015).

Latent heat transfer

Although pigs lack active sweat glands, mainly because of the fat layer under the skin, evaporative heat loss is the most important means for the pig to lose heat at high ambient temperatures (Morrison et al., 1967; Hacker et al., 1994). Figure 1 (Mount, 1979) and other studies have shown that, with an increase in temperature, feed intake and sensible heat loss are reduced, and evaporative or latent heat loss increases (Huynh et al., 2007; Brown-Brandl et al., 2014), although the latter occurs sooner than does the decrease in voluntary feed intake (Huynh et al., 2005 b) and, apparently, is not strongly influenced by the humidity of the air (Huynh et al., 2007) (Figure 2). Therefore, some of the calculations for estimating the latent heat released by animals are based on the surrounding temperature. For example, the moisture production by 100-kg pigs can be calculated with the following formula, which is valid for temperatures between 5ºC and 30ºC (ASABE, 2012):

$$m = 4.2 \times 10^{-8} \times T^2 - 5.7 \times 10^{-7} \times T + 2.9 \times 10^{-5}$$

where:

m = moisture production (kg/s),

T = air temperature (ºC).

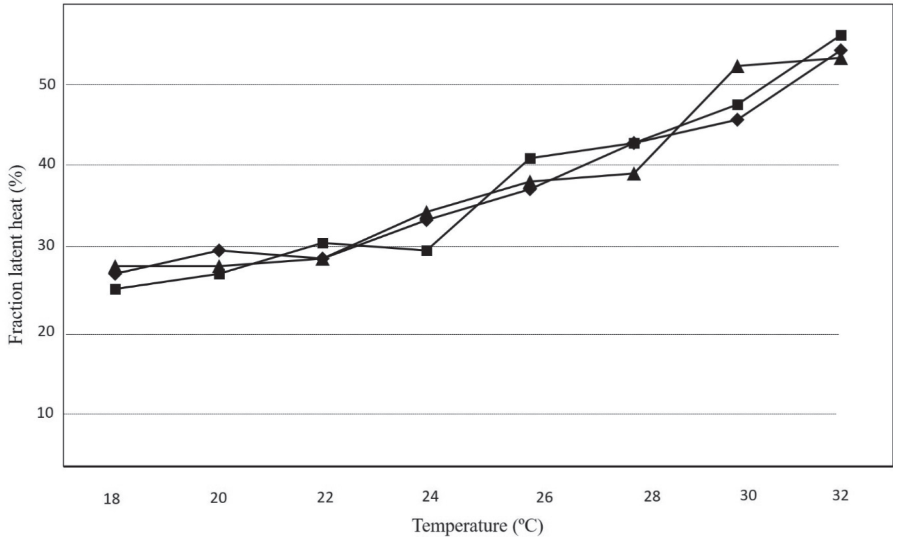

Figure 2. Fraction of latent heat in relation to total heat production at three different relative humidities (50% ♦; 65% ■; 80% ▲) and increasing ambient temperature. Adapted from Huynh et al. (2007)

In modern intensive farms, pigs depend largely on respiratory heat loss at high ambient temperatures. Typically, pigs in a non-heat stressed condition have a respiration rate of about 20–40 breaths/min (Eigenberg, 2002; Huynh et al., 2005 b); however, a heat-stressed pig can reach 80–100 (Eigenberg, 2002) or even 120 breaths/min (Huynh et al., 2005 b). Therefore, estimates of latent heat loss can be improved by calculating the respiration volume of the pigs depending on pig liveweight and ambient temperature. The respiration volume multiplied by the difference in water content between inhaled and exhaled air is the respiratory evaporation of water. For example, Huynh et al. (2005 b) reported the evaporated water volume in pigs of 65 kg live weight on the basis of air temperature and relative humidity, and respiration rate. Below 20ºC, the volume of water evaporated per pig was 76, 67, and 53.5 g/h for 50%, 65%, and 80% relative humidity, respectively. For each degree Celsius >20ºC, evaporated water increased by 4.8 g/h. Alternatively, evaporated water can be estimated based on respiration rate, which increases 0.6 g/h per each extra breath per minute above the basis of 30 breaths per minute of respiration rate at <20ºC.

In addition, if the pig skin is wetted, heat can evaporate at a very rapid rate (Ingram, 1965). In fact, to increase evaporative heat loss, especially when air temperature increases, pigs in confinement often wallow in their own urine and faeces. Wallowing becomes especially important at high humidity levels, when respiratory evaporation reaches its limit (Huynh et al., 2005 b). Therefore, estimates of latent heat loss at housing level might be improved by distinguishing between latent heat produced by the animals and latent heat produced by evaporation from wet surfaces within the barn, mainly the floor and the manure pit.

Carbon dioxide production

Carbon dioxide (CO_2) is one of the most important gaseous contaminants in intensive pig buildings, mainly because it is an important parameter for measuring indoor air quality, and a very useful tool for calculating minimum ventilation rate. Animal respiration and manure release and management are the two primary sources of CO_2 production in a pig housing facility.

Carbon dioxide produced through respiration is a function of energy metabolism rate, which is influenced by body weight, feeding level, diet composition, and animal activity (CIGR, 2002; Pedersen et al., 2008; Zong et al., 2014). In fact, CIGR (2002) estimated the production of respiratory CO_2 on the basis of body weight, level of production, and feed energy intake, which corresponded to 2.23, 3.68, 0.88, and 1.70 kg CO_2 per head and day for gestating and lactating sows, weaned piglets, and fattening pigs, respectively. For growing and fattening pigs, Philippe and Nicks (2014) proposed the following equation for estimating CO_2 exhalation (kg CO_2 per day) by pigs of 20–120 kg live weight from different models in the literature:

$$CO_2, pig = 0.136 \times LW^{0.573}$$

In manure, CO_2 originates from three sources: the rapid hydrolysis of urea into NH_3 and CO_2 catalyzed by the enzyme urease, and the anaerobic and aerobic degradation of organic matter (Philippe and Nicks, 2014). For liquid manure, which is typical in modern pig farms, anaerobic processes typically have been cited as the main source of CO_2 (Ni et al., 1999), although Moller et al. (2004) reported that aerobic and anaerobic processes are almost equally important at 20ºC, being the aerobic processes more important at low temperatures. In addition, crust formation at the surface of the slurry can lead to CH_4 oxidation into CO_2 as the CH_4 passes through the porous areas of the crust (Philippe and Nicks, 2014).

Some studies have reported that the levels of CO_2 released from manure are about 4–5% of the amount of CO_2 exhaled by animals (CIGR, 2002; Sousa and Pedersen, 2004; Dong et al., 2007), although others have reported amounts >10% of respiratory production (Philippe et al., 2007; Pedersen et al., 2008). Some contradictory results have been reported, however, particularly in studies carried out at the farm level. In such conditions Ni et al. (1999) found that emissions from manure were about 40% of the CO_2 released by exhalation. However, working in a fattening facility that had a partial ventilation pit that provided 10% of the maximum ventilation rate only, Zong et al. (2014) reported that the quantity of CO_2 released from manure was about 3% of total CO_2 production.

Therefore, to calculate the ventilation flow required in commercial pig farms on the basis of CO_2 production, studies have indicated clearly that, although manure is not the main source of CO_2 in pig facilities, CO_2 from slurry has to be taken into account. Pedersen et al. (1998) adopted a value of 0.185 m^3/h.hpu (total heat production unit equivalent to 1000 W at 20ºC), assuming that 4% of the total CO_2 production came from the slurry. Blanes and Pedersen (2005), however, reported that the value of 0.185 m^3/h.hpu should be updated to 0.201 m^3/h.hpu, which is a level of CO_2 production that is very similar to the 0.206 m^3/h.hpu recently reported by Zong et al. (2014).

Conclusions

In the present paper, some aspects of calculating heat production and losses and moisture and CO_2 production in pigs are discussed. The results from multiple sources were assessed for calculating ventilation rates. The main conclusion is that an update of the recommended ventilation rates usually adopted in the modern intensive pig farms is needed because they are based on heat, moisture, and gas levels that clearly underestimate the needs for environment control. Although sensible heat production has increased in the recent decades, estimates of heat losses do not seem to differ among the various sources evaluated, even though management and building and equipment materials are very important in regulating the heat exchanges between the animal and its environment. However, moisture production by swine should be revisited, and the estimates of latent heat loss in intensive pig farming might be improved by distinguishing between latent heat produced by the animals and latent heat produced by evaporation from wet surfaces within the building. In cold weather, moisture production standards based on calorimeter measurements only, seems to lead to an underestimation of the required ventilation rate, which may result in high relative humidity and, consequently, adversely affecting air quality and favouring the growth of microorganisms. In the same way, CO_2 production is also used to calculate the minimum ventilation rate; however, the current values need to include an estimate of the quantity of CO_2 released from slurry.

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