Modelling heat production and heat loss in growing-finishing pigs

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Abstract

The objective of this paper is to discuss some aspects of modelling heat production and heat losses in growing-finishing pigs. The main formulas from an existing, continuously updated, model (Anipro) are compared with existing formulas given by the CIGR working group on Climatization of Animal Houses (2002) and other formulas described in literature. The main conclusions from this comparison are: 1) the estimates of the metabolizable energy for maintenance varies substantially between different studies; this seems to be related to differences in animal activity levels during the studies and differences in genetics of the pigs; 2) the CIGR formulas for calculating heat production seems to be valid for modern pigs; the feeding levels, however, defined as n times maintenance, should be updated; 3) the Anipro and CIGR formulas for calculating evaporative heat losses are too simple and should be updated with a more fundamental approach, including not only ambient temperature, but also humidity level, respiration volume of the pigs, wetted areas inside the house, and air velocity.

Keywords: pigs, thermal regulation, climate condition, latent heat, sensible heat

Introduction

Accurate estimates of heat production and heat losses are important for housing design and climate control systems in pig production. Because pigs are homeothermic animals, heat production and heat loss should be balanced. For optimal production and health the climate surrounding the pig should fulfil certain requirements. These requirements often are not met, mainly because of too high ambient temperatures causing heat stress in pigs. Pigs have different strategies to influence heat production and heat losses. Heat production is mainly influenced by the feed intake. For regulating heat loss pigs have a variety of mechanisms. Heat can be lost through the following pathways: convection, conduction, radiation and evaporative heat loss. The heat losses through the first three mechanisms mainly depend on the temperature difference between the skin and the environment. Evaporative heat loss mainly depends on the water vapour pressure difference between inhaled and exhaled air and the respiration volume.

Mount (1979) formulated a general concept of thermo-regulation of pigs (figure 1). This concept is based on a certain level of feed intake. Within the temperature zone A - D pigs can keep their body temperature constant. Ambient temperatures below A cause body temperature to fall, while above D the body temperature rises. The zone A - D can be divided into zones A - B and B - D. Within zone A – B, body temperature is kept constant by regulation of heat production. Heat production within this zone can be increased by shivering (shivering thermogenesis) or by producing extra heat without shivering (non-shivering thermogenesis). In zone B - D body temperature is kept constant by regulation of heat loss. Point B is called the lower critical temperature, while point D is called the upper critical temperature. Zone B – C is called the comfort zone. According to Curtis (1983) this is the zone in which the pigs don’t need to invest extra energy (panting) to lose heat. In this case the lower temperature of the comfort zone equals the lower temperature of the thermo-neutral zone. The definition of the comfort zone is subject of debate. When it is defined as the zone in which the pigs feel comfortable, undesirable behavioral changes should also fall outside the comfort zone. Examples of undesirable behavioral changes are extreme huddling (affects the lower temperature of the comfort zone) and lying on the slatted floor instead of the solid (insulated) floor (affects the upper temperature of the comfort zone). During heat stress, so at temperatures above point D, pigs will directly drop their feed intake, so the situation given in Figure 1, assuming a constant feed intake, is only valid for a short term period after a sudden increase of ambient temperature.

Based on this general concept of Mount (1979) and based on formulas developed by Bruce and Clark (1979) and fundamental nutritional knowledge a heat balance model was developed. This model had its first versions already more than two decades ago (Van Ouwerkerk, 1999), and since then was continuously updated and extended. Within this paper some aspects of this heat balance model are described and discussed. Model calculations are compared with the formula proposed by the CIGR Working Group on Climatization of Animal Houses (CIGR, 2002).

The objective of this paper is to discuss some aspects of modelling heat production and heat losses in growing-finishing pigs. The main formulas used within the model are compared with existing formula given by the CIGR working group (2002) and other formula described in literature.

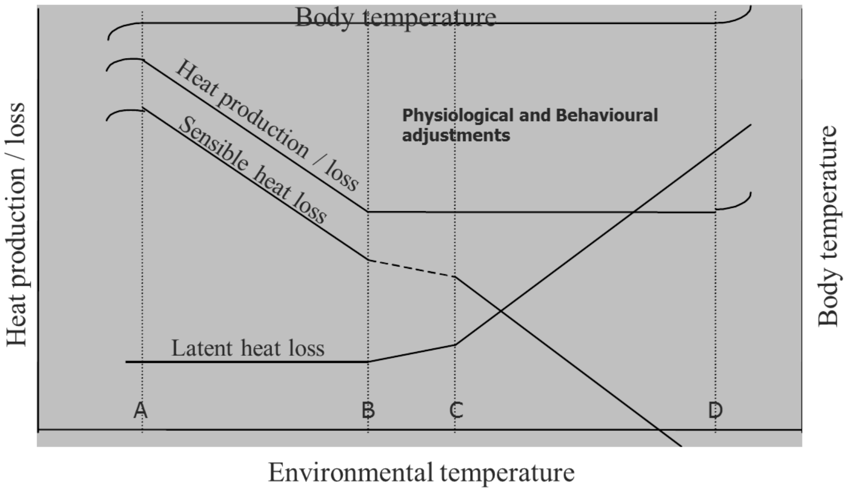

Figure 1. General concept of heat regulation in pigs (Mount, 1979). The different environmental temperature zones are defined as follows: A – D constant body temperature; A – B extra heat produced for constant body temperature; B – C comfort zone; B – D thermo-neutral zone.

Heat production

Heat production of pigs is mainly determined by their feed intake, more precise by their metabolizable energy (ME) intake, which can be calculated by subtracting the energy in urine from the digestible energy intake. According Kielanowski (1965) ME is the sum of the energy for maintenance (ME_m) and the energy for production (ME_{prod}):

$$ME = ME_m + ME_{prod} \quad (1)$$

Energy for animal activity is part of the metabolizable energy for maintenance. Animal activity can vary substantially between different animals and may be affected by housing conditions (Van Milgen & Noblet, 2003). That might be at least part of the reason that different studies resulted in different estimates of the required energy for maintenance depending on pig live weight (W). Some of these studies are the following:

Metz et al. (1986):

$$ME_m = -0.00134 \cdot W + 0.5525 \cdot W^{0.75} \quad (2)$$

Van Milgen and Noblet (2003):

$$ME_m = a * W^{0.60} \quad (3)$$

According these authors ‘a’ ranges between 0.85 and 1.00, mainly depending on the level of animal activity.

Proposed equation by the CIGR Working Group (CIGR, 2002) (recalculated from Watt to MJ/d):

$$ME_m = 0.4398 * W^{0.75} \quad (4)$$

Fowler et al. (2013):

$$ME_m = 0.641 * W^{0.66} \quad (5)$$

In figure 2 the calculated metabolizable energy for maintenance in growing-finishing pigs in the weight range of 20 – 120 kg is given. The figure shows quite some differences between the different formulas. The difference between max versus min values varies between 45% higher for pigs of 20 kg to 32% higher for pigs of 120 kg. While ME_m covers between 30 to 50% of total ME intake of pigs (CIGR, 2002), this potential error in estimation of the metabolizable energy cannot be ignored. The CIGR formula is quite well in the range of recently developed formula by Fowler et al (2013) and Van Milgen and Noblet (2003) for the lower coefficient (a = 0.85). In the Anipro model we use the equation of Van Milgen and Noblet (2003) with a = 0.85.

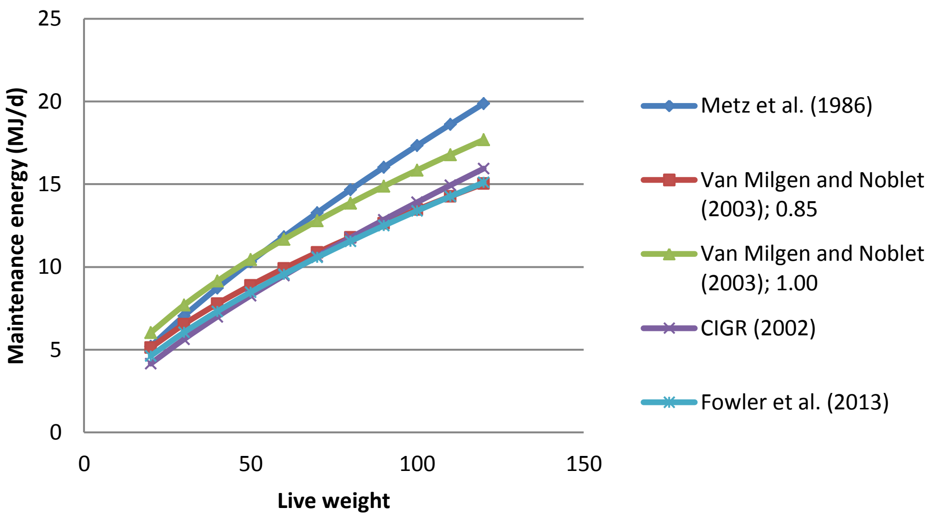

Figure 2. Estimated required energy for maintenance in relation to live weight of growing-finishing pigs in different studies. In the study of Van Milgen and Noblet, the regression coefficient can vary between 0.85 and 1 (see formula 3).

The metabolizable energy for production can be determined as follows Kielanowski (1965):

$$ME_{prod} = \frac{E_P}{k_P}.GP + \frac{E_L}{k_L}.GL \quad (6)$$

Where: ME_{prod} is the metabolizable energy for production (MJ/d)
E_P is energy in protein (MJ/kg)
E_L is energy in fat (MJ/kg)
k_P is the efficiency of protein retention, the remaining is converted to heat (MJ/MJ)
k_L is the efficiency of fat retention, the remaining is converted to heat (MJ/MJ)
GP is the protein retention (kg/d)
GL is the fat retention (kg/d)

The energy density of lipid is higher than of protein (39.8 vs. 23.8), but the efficiency for lipid deposition is also higher (0.80 vs. 0.60) (Van Milgen & Noblet, 2003). Overall approx. 50 MJ ME is needed to deposit 1 kg of fat and 40 MJ to deposit 1 kg of protein.

The Anipro model calculates the energy balance and the mass balance. For the mass balance the different retentions in the body are calculated (water, ash, protein, fat). De Lange et al. (2003) gave the following relationship between body protein mass and body water mass:

$$GW_{total} = 5.5513 * GP_{total}{}^{0.8592} \quad (7)$$

Where: GW_{total} is the total mass of body water (kg)
GP_{total} is the total mass of body protein (kg)

And the following relationship between gut fill and live weight:

$$GF_{total} = 0.227 * W^{0.612} \quad (8)$$

Where: GF_{total} is the total amount of gut fill (kg)
W is animal live weight (kg)

According De Lange et al. (2003) the ash retention varies between 18.6 and 21.0% of the protein retention. In Anipro we use the mean value of 20%.

In the Anipro model the starting weight and end weight of the pigs and the total feed intake and the feed composition (including digestibility coefficients of the components) are input in the model. The patterns of growth and feed intake are described by Gompertz curves. From these inputs and the formulas described above, the total heat production and the protein and fat retention can be estimated. This estimation of total heat production was compared with the calculation reported by the CIGR Working Group on Climatization of Animal Houses (2002):

$$Q_{total} = ME_m + (1 - k_Y) \cdot (ME - ME_m) \quad (9)$$

Where: Q_{total} is the total heat production (MJ/d)
k_Y is the efficiency of protein and lipid retention, the remaining is converted to heat (MJ/MJ)

k_Y can be estimated as follows (CIGR, 2002):

$$k_Y = 0.47 + 0.003 * W \quad (10)$$

In fact k_Y is the combination of k_P and k_L, as given in equation 6. In the CIGR report (2002) ME intake is calculated as n times maintenance. This n is given in a table in this report for different average growth rates of the pigs. Within the CIGR report a correction for the total heat production is made depending on the ambient temperature. For every degree Celsius above 20°C the heat production is reduced by 1.2% and for every degree Celsius below 20°C the heat production is raised by 1.2%. This linear temperature correction ignores the existence of a thermo-neutral zone as proposed by Mount (1979) and confirmed in other studies, e.g. Huynh et al. (2005b).

The Anipro and the CIGR calculation methods were compared within a study in which the different input variables were determined to calculate total heat production (figure 3). Figure 3 shows that the two methods of calculating total heat production gave quite similar results. The fluctuations of the CIGR-line is caused by the temperature correction of the heat production within the CIGR formula. The feeding level varied from 2.96 times ME_m at the start to 2.33 at the end of the growing period. These values of n are considerably lower than the ones given within Table 2.1 of the CIGR Report for similar growth rates (CIGR, 2002). This is probably caused by the large genetic improvement of the pigs in the last decades, giving leaner pigs who can convert energy in the diet more efficient into live weight gain. Furthermore, Brown-Brandl et al. (2014) found a large increase in fasting heat production of 50-kg and 100-kg pigs since 1936. The fasting heat production is closely related to ME_m, so this can also be an important reason for the decrease in feeding level defined as n times ME_m.

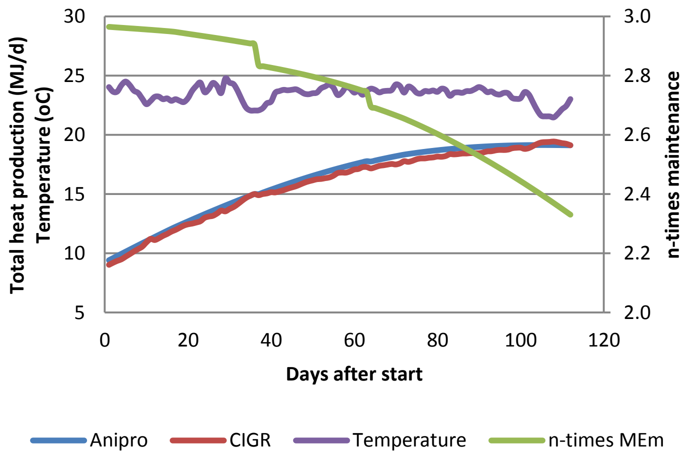

Figure 3. Comparison between the Anipro (described in this paper) and CIGR (CIGR, 2002) methods for determining total heat production in dependence of live weight of growing-finishing pigs. The room temperature and the feeding level (n-times maintenance) are also given. The weight range was 26 – 125 kg, average feed intake 2.25 kg/d, and daily gain 891 g/d.

Heat loss

Bruce and Clark (1979) were the first researchers making a comprehensive model on heat losses in pigs, in combination with heat production, to determine the lower critical temperature. This model was also used in the models of Turnpenny et al. (Turnpenny et al., 2000a; Turnpenny et al., 2000b). Heat loss can be divided into sensible and latent heat loss. The sensible heat loss will only be described qualitatively here. The latent heat loss will be described in more detail.

3.1 Sensible heat loss

Sensible heat loss is the sum of the heat lost by conduction, mainly to the floor when lying, by convection to the air, and by radiation to different construction surfaces. Heat lost by conduction can be influenced by the pig by choosing between standing or lying, by their lying posture and by choosing their lying location. Pigs generally are more lying at higher ambient temperatures (Huynh et al., 2005a). This seems mainly caused by the fact that standing increases the metabolic rate and the heat production of a pig (Van Milgen et al., 1998). Furthermore, the heat loss by conduction to the floor when lying might be higher than the heat loss by convection of the same skin area to the air when standing, but this will largely depend on the environmental circumstances (e.g. conduction of the floor, air velocity). Generally, however, it is observed that pigs expose a larger area of their body to the floor by lying fully laterally at high ambient temperatures. At high ambient temperatures pigs will also seek for a cool place for lying. In modern pig housing systems the slatted floor is generally the coolest place to lie down. In different studies the shift in lying behaviour from solid to slatted floor at increasing ambient temperatures have been demonstrated (Aarnink et al., 2006; Hacker et al., 1994; Randall et al., 1983). Heat loss by conduction is also influenced by the thermal resistances of the tissue and the skin of the pig. This, however, is an autonomous physiological process.

Heat loss by convection is mainly influenced by the temperature difference between skin and air, by the air velocity and by the skin area exposed to the air. The skin temperature is determined by the ambient temperature, air velocity, and by the thermal resistances of the tissue and skin. The area exposed to the air can be influenced by altering the contact area with other pigs. Radiative heat loss mainly depends on the temperature difference between pigs' skin and the surrounding construction and on the skin area exposed to this construction. At high ambient temperatures pigs try to increase the distance to other pigs to increase convective and radiative heat loss. Also conductive heat loss is generally increased at higher lying distances between pigs. The concrete floor does not only loose heat in vertical direction, but also in horizontal direction. This horizontal heat loss from the floor is influenced by the lying distance between pigs (Bruce & Clark, 1979).

3.2 Latent heat loss

In different studies it was shown that with increasing temperature feed intake and total heat production decrease and evaporative or latent heat loss increases (Brown-Brandl et al., 2014; Huynh et al., 2005b). As also shown in the figure of Mount (1979) (figure 1), with increasing temperature sensible heat loss decreases and latent heat loss increases. Evaporative heat can be lost by respiration and by the skin. While pigs cannot sweat (Ingram, 1965), they are largely depending on respiratory heat loss at high ambient temperatures in confinement. In the wild, however, pigs have the ability to wallow in the mud (Bracke, 2011); this can considerably increase evaporative heat loss (Ingram, 1965). In confinement pigs are often wallowing in their own urine to increase evaporative heat loss (Huynh et al., 2004). Wallowing especially becomes important at high humidity levels, when respiratory evaporation reaches its limits (Bracke, 2011; Huynh et al., 2004).

Latent heat loss from the animal (animal level) can be calculated with the following formula:

$$Q_{latent} = f_{l\_a} \cdot Q_{total} \tag{11}$$

Where: Q_{latent} is the latent heat loss (MJ/d)
f_{l_a} is the fraction of the total heat lost as latent heat at animal level (-)
Q_{total} is the total heat production (MJ/d)

Based on experimental data from literature, Aarnink et al. (1992) developed the following equation for f_{l_a}:

$$f_{l\_a} = 0.10 + 3.54 \cdot 10^{-7} \cdot {T_i}^4 \tag{12}$$

Where: f_{l_a} is the fraction of total heat lost as latent heat at animal level (-)
T_i is the ambient temperature (^oC)

These equations (11 and 12), included within the Anipro model, are a rather simple way to calculate evaporative heat loss and water evaporation from growing-finishing pigs. It does, for instance, not account for effect of humidity level. Figure 4 shows that the pattern of the calculated fraction of latent heat loss (with formula 12) is somewhat different from the measured fraction in the study of Huynh et al. (2005b) at different humidity levels. The data of Huynh et al. (2005b) show a clear effect of humidity level on the fraction of total heat that is lost as latent heat. This effect is probably mainly caused by differences in vapour pressure of inhaled air. At higher humidity levels less water can be evaporated per m^3 of inhaled air. Figure 4 also shows that within the normal temperature range (20 – 26 °C) in houses for growing-finishing pigs in the Netherlands the predicted values are in the same ranges as measured by Huynh et al. (2005b). At higher temperatures the calculated values are higher than the measured values. Prediction of latent heat loss can be improved by calculating the respiration volume of the pigs depending on pig live weight and ambient temperature. This respiration volume multiplied with the difference in water content between inhaled and exhaled air will give the respiratory evaporation of water. Knowledge, however, is lacking about the respiration volume and also about the temperature and water content of exhaled air. The temperature and water content of exhaled air might be related to the respiration rate and whether the pig is panting or not.

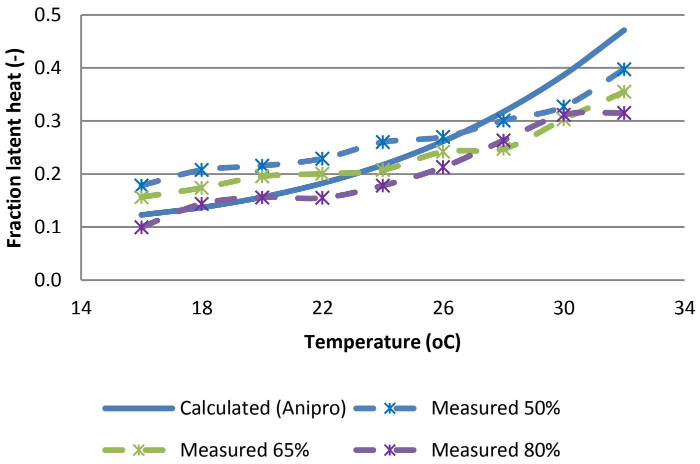

Figure 4. Comparison between calculated (Anipro; formula 12) and measured fraction of latent heat. In the study of Huynh et al. (2005b) the evaporative and total heat loss were determined at 3 relative humidity levels (50%, 65%, 80%). Data points are mean values of 4 groups of 10 pigs. Mean pig weight was 65.4 kg.

In animal houses water is evaporated by the animals, but also from wet surfaces of the floor, manure pit and wet feed. Streum and Feenstra (1980) developed the following formula for determining total latent heat loss from the pig house (housing level) (f_{l_h}):

$$f_{l\_h} = 0.20 + 1.85 \cdot 10^{-7} \cdot (T_i + 10)^4 \quad (13)$$

Where: f_{l_h} is the fraction of total heat lost as latent heat at housing level (-)

The CIGR Working Group (2002) proposed the following formula for calculating the sensible heat loss per heat producing unit (hpu = 1000 Watt heat production at 20°C):

$$Q_{sensible\_hpu} = 0.62 \cdot [1000 + 12 \cdot (20 - T_i)] - 1.15 \cdot 10^{-7} \cdot {T_i}^6 \quad (14)$$

Where: $Q_{sensible\_hpu}$ is the sensible heat loss per heat producing unit (W/hpu)

In figure 5 a comparison is made between the formulas of Streum and Feenstra (1980) and CIGR (2002) for calculating the water evaporation during a growing-finishing period. Both formulas are compared with measured values. Figure 5 shows that both formulas are over predicting the water evaporation a bit for this situation. The prediction of latent heat loss at housing level could be improved by separating between latent heat produced by the animals and latent heat produced by evaporation from wet surfaces within the house. When open heating systems are used the water evaporated from these systems should be included, as well. Mass transfer coefficients for water evaporation from the floor and for water evaporation from the manure pit should be determined. The mass transfer coefficient is mainly related to the air velocity above the wet surface. The water evaporation from wet surfaces can be calculated with the following general formula:

$$Evap_{surface} = k_{evap\_surface} \cdot (p_{surface} - p_{air}) \cdot A \quad (15)$$

Where: $Evap_{surface}$ is the water evaporation from the wet surface (kg/d)
$k_{evap\_surface}$ is the mass transfer coefficient (kg/(m^2.kPa.d)
$p_{surface}$ is the water vapour pressure of the wet surface (kPa)
p_{air} is the water vapour pressure of the air above the wet surface (kPa)
A is the area of the wet surface (m^2)

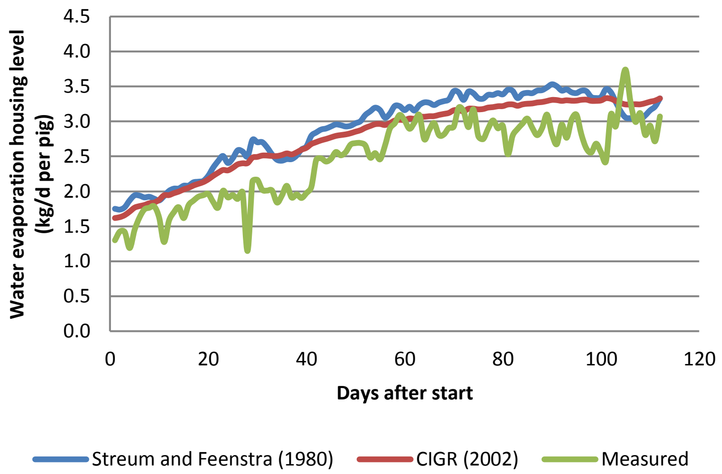

Figure 5. Water evaporation from a room for growing-finishing pigs. Model calculations based on Streum and Feenstra (1980) and (CIGR, 2002), compared with measured values (in the same room and growing period as shown in figure 3).

Conclusions

In this paper some aspects of calculating heat production and heat losses in growing finishing pigs are discussed. Results of a comprehensive model that is being developed (Anipro) were compared with results from formula given by the CIGR Working Group on Climatization of Animal Houses (CIGR, 2002) and with values measured in animal studies. The following can be concluded from this study:

- The estimates of the metabolizable energy for maintenance vary substantially between different studies. This seems to be related to differences in animal activity levels during the studies and differences in genetics of the pigs.
- The CIGR (2002) formula for calculating heat production seems to be valid for modern pigs. The table with feeding levels related to average growth rates, however, should be updated.
- The existing formula in Anipro and CIGR for calculating evaporative heat losses from the pigs themselves and the total from the house are too simple, with only a relation with ambient temperature. The approach should be more fundamental with factors involved like humidity levels, respiration volume of the pigs, wetted areas inside the house, air velocity.

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