Heat and moisture production in growing-finishing pigs and broilers

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Abstract: Heat and moisture production are important parameters for designing ventilation and climate control systems in livestock housing. In 2002 a report was published of the CIGR Section II Working Group on Climatization of Animal Houses 'Heat and moisture production at animal and house levels' with formula to calculate heat and moisture production for different livestock categories. The objective of this paper is to discuss these CIGR formula for growing-finishing pigs and broilers. Results from calculated heat and moisture production with the relatively simple formula in the CIGR report were compared with results from a more comprehensive model. From this comparison the following conclusions were drawn: 1) The relatively simple CIGR formula to calculate total heat production of growing-finishing pigs give similar results as the comprehensive model in which protein and fat retention are calculated, and seems therefore sufficient accurate. Only the table to calculate metabolizable energy needs to be updated, because of genetic improvement of the pigs in the last decades. 2) To calculate total heat production for growing-finishing pigs a linear correction factor is used for indoor temperature. Although this does not fit with the concept of a thermo-neutral zone, this could be done without large error. 3) Calculation of moisture production in growing-finishing pigs can be improved by separating moisture production from the pigs and moisture production from the rest of the house. This, more fundamental approach for determining moisture production, is needed to be able to accurately calculate moisture production under less average conditions. 4) The CIGR equation to calculate total heat production of broilers is too simple, while it is not related to the main variable determining heat production, the ME intake. 5) The CIGR formula to calculate moisture production of broilers should not only depend on indoor temperature, but also on live weight of the birds. Similar as for pigs, it is also suggested to separate moisture production from the animals and moisture production from the rest of the house.

Keywords: heat production, moisture production, sensible heat, latent heat, pigs, poultry

1. Introduction

Heat and moisture production are important parameters for designing ventilation and climate control systems in livestock housing. In 2002 a report was published of the CIGR Section II Working Group on Climatization of Animal Houses 'Heat and moisture production at animal and house levels' (CIGR, 2002). Within that report formula are given to calculate total heat production from animals for the different livestock categories and how to correct the heat production for indoor temperature. The CIGR report also gives formula how to partition total heat loss between sensible and latent heat, from which moisture production can be calculated. Within this paper it is discussed how these formula could be improved for growing-finishing pigs and broilers.

Animals have different strategies to influence heat production. While pigs and poultry are homeothermic animals heat loss should equal heat production. Heat production is mainly influenced by the feed intake, or more accurate the intake of metabolizable energy. 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 is lost from the skin and from respiration. Evaporative heat lost from the skin depends on the wetted area of the skin, with water from sweat or external water, the water vapor pressure difference between skin and environment, and vapor mass transfer coefficient, mainly depending on air velocity (Bruce and Clark, 1979; Fialho et al., 2004b). Evaporative heat loss from respiration mainly depends on the water vapor pressure difference between inhaled and exhaled air and the respiration volume.

Mount (1979) formulated a general concept of thermo-regulation of homeothermic animals (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. 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 Mount (1979) this is the zone in which animals don't need to invest extra energy for thermo-regulation. The width of the thermo-neutral zone and the comfort zone varies between species and can be influenced by different environmental factors that influences heat loss, e.g. air velocity, radiation, conduction to the floor, wetting of the skin. From point C to point D heat loss is shifted from sensible to latent, causing a significant increase in water evaporation from the animal. At housing level, generally a part of the sensible heat is converted to latent heat by evaporation from wet surfaces (floors, manure pit, moist bedding material).

The objective of this paper is to discuss the present CIGR formula to calculate heat and moisture production for growing-finishing pigs and broilers, with the background of the theory described in former paragraph. In this paper we will focus on daily average heat and moisture productions, so we will not go into diurnal variations, although those variations cannot be fully ignored when designing ventilation and climate control systems (Pedersen et al., 2015).

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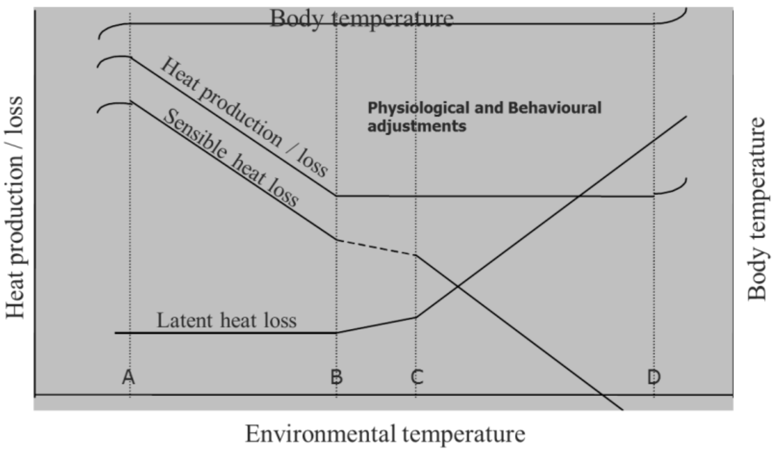

Figure 1. General concept of heat regulation in homeothermic animals (Mount, 1979). The different environmental temperature zones are defined as follows: A – D constant body temperature; A – B extra heat produced for constant body temperature; B – C comfort zone; B – D thermo-neutral zone.

2. Growing-finishing pigs

Heat production

Within the report of the CIGR Working Group on Climatization of Animal Houses (2002) the following formula is given to calculate total heat production:

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

Where: Q_{total} is the total heat production (W); ME_m is energy for maintenance (W); k_Y is the efficiency of protein and lipid retention, the remaining is converted to heat (W/W); ME is the intake of metabolizable energy (W).

In formula 1 ME_m, k_Y, and ME are estimated as follows (CIGR, 2002):

$$ME_m = 5.09 * W^{0.75} \quad (2)$$

$$k_Y = 0.47 + 0.003 * W \quad (3)$$

$$ME = n * ME_m \quad (4)$$

Where: W is pig live weight (kg);

There is a difference in efficiency of energy retention in protein and fat. Overall approx. 50 MJ ME is needed to deposit 1 kg of fat and 40 MJ to deposit 1 kg of protein, of which approx. 10 and 16 MJ is released as heat (Van Milgen and Noblet, 2003). Therefore it would be more accurate when k_Y would directly depend on the amount of protein and fat retention in the body, and not on animal weight. It is rather difficult, however, to calculate the amount of protein and fat retention. Within the Anipro model (Aarnink et al., 2016a) the protein and fat retentions are calculated, but the objective of that model is also to determine excretion levels of nitrogen, making the estimation of nitrogen retention in protein deposition more important. Furthermore, in a direct comparison between the two methods very similar heat productions were calculated (Aarnink et al., 2016a). Within the CIGR report (2002) a table is given for the feeding level, given as n times maintenance energy, depending on the growth rate and live weight of the pigs. This table should be updated, because of genetic improvement of the pigs in the last decades (Aarnink et al., 2016a). Pigs have become leaner and convert energy in the diet more efficiently 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. The best approach, however, is depending on the available input data. It would be more simple just to use the daily feed intake and the metabolizable energy per kg of feed as input variables. Within the Anipro model we use the total feed intake during the whole growing period as input. With a Gompertz curve we estimate the feed intake at a certain day of the growing period. The same is done with the live weight of the animals, when start and final weights are input variables.

Within the CIGR report (2002) a correction is made for heat production depending on the indoor temperature. For every degree Celsius above 20° heat production is lowered with 1.2% and for every degree Celsius below 20° heat production is raised with 1.2%. This linear correction ignores the existence of a thermo-neutral zone, but as is shown in the report the error assuming linearity is rather small and estimates were even better than in previous reports in which the thermo-neutral zone was incorporated. From this approach, however, it should not be concluded that the concept of thermo-neutrality does not exist. As an example, in figure 2 all the data are given that were measured within the study of Huynh et al. (2005), but with some extra (virtual) data points added below temperatures of 16°C. This figure shows that the concept of thermo-neutrality can exist in combination with a linear correction factor for temperature, without large error.

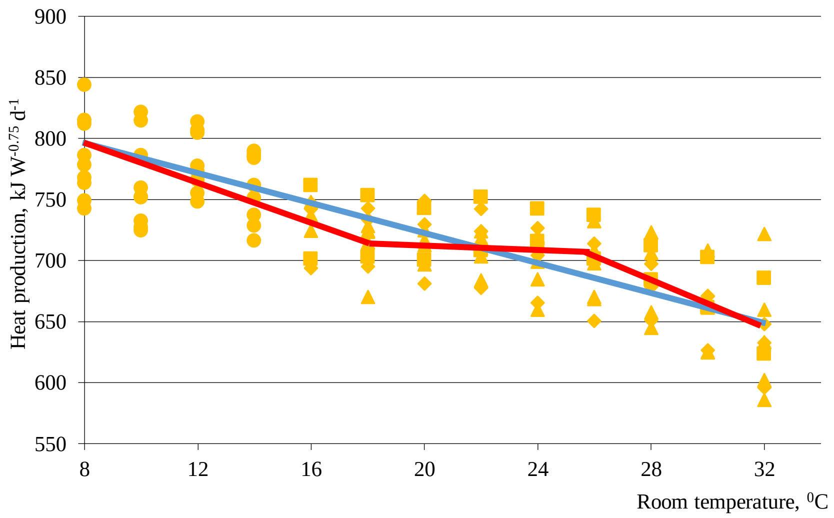

Figure 2. Linear correction of total heat production in pigs and the concept of thermo-neutrality. Data points from study of Huynh et al. (2005), but some extra data points with similar variation as the measured points are given for temperatures below 16°C.

Moisture production

In the CIGR report (2002) latent heat production at housing level is calculated by subtracting the sensible heat production from the total heat production. Sensible heat production is calculated as follows:

$$Q_{sensible} = [0.62 \cdot (1000 + 12 \cdot (20 - T_i) - 1.15 \cdot 10^{-7} \cdot {T_i}^6] \cdot \frac{Q_{total}}{1000} \qquad (5)$$

Where: $Q_{sensible}$ is sensible heat production (W); Q_{total} is total heat production (corrected for temperature, W) ; T_i is room temperature (°C)

Moisture production is calculated by dividing latent heat by the evaporative heat of water. This calculation procedure is very useful under average circumstances (average pig weight, typical Northern European housing conditions). However, there are two main imperfections in this calculation procedure for moisture production: 1) there is no separation made between animal and housing level; 2) there is no effect of animal weight included.

Housing conditions can be very different between and within countries and between and within different climate regions. This will cause a large difference in moisture production within the house, mainly because of differences in wet area per animal and differences in evaporation per m^2 wetted area, caused e.g. by differences in humidity levels and air speed. Therefore it is proposed to calculate moisture production from the house, excluding animals and open heating systems, as follows:

$$evap_{wet\_area} = k\_evap_{wet\_area} \cdot (p_{wet\_area} - p_{air}) \cdot A_{wet\_area} \tag{6}$$

Where: $evap_{wet\_area}$ is the water evaporation from wet areas inside the animal house (kg/d); $k\_evap_{wet\_area}$ evaporation coefficient (kg/(m^2.kPa.d)); p_{wet_area} is the vapor pressure of the wet area (kPa); p_{air} is the vapor pressure of the air (kPa)

This equation can be used for different kinds of wet area, e.g. wetted floor, manure surface of the pit, bedded areas. We assume that the vapor pressure of wet areas equals 100%. The vapor pressure can be calculated with formula from the ASHRAE Handbook of Fundamentals (ASHRAE, 2009). According Beeking et al. (1994) the evaporation coefficient is linearly related with the square root of the air velocity above the wet surface:

$$k\_evap_{wet\_area} = b_{k\_evap} \cdot \sqrt{v_{surface}} \tag{7}$$

Where: b_{k_evap} is a linear regression coefficient; $v_{surface}$ is air velocity above the wet surface (m/s)

For a partially slatted house a b_{kevap} for wet floor and wet pit areas of 7.69 was estimated (Aarnink et al., 2018). The temperature of the evaporating surface, needed for calculating the vapor pressure difference, and air velocity above the evaporating surface could be input in the model or be calculated from relationships with respectively room temperature and ventilation rate.

To calculate moisture production at animal level the following equation was developed to determine the fraction of latent heat from the total heat production (Aarnink et al., 1992):

$$f_{l\_a} = 0.10 + 3.54 \cdot 10^{-7} \cdot T_i^{\,4} \tag{8}$$

Where: f_{l_a} is the fraction of total heat lost as latent heat at animal level (-); T_i is room temperature (°C)

In Aarnink et al. (2016a) it was shown that within the temperature range, typical for Dutch pig housing conditions, simulated moisture production was in the same range as measured moisture production. Outside this range, however, differences increased. A problem with former calculation is that no account is taken of the humidity level. Results of

Huynh et al. (2005) clearly show an effect of humidity level on the fraction of latent heat. Moisture calculations at animal level could therefore be improved by following a more fundamental approach, as described in the next paragraphs.

The evaporation from the skin can be determined by the wet area, the vapor mass transfer coefficient and the difference in water vapor pressure between the wet skin and the air. By multiplying this value with the specific latent heat (J g^{-1}) the heat loss from the skin can be determined:

$$Q_{e\_s} = A_{ws} \cdot k_{ws} \cdot (p_{ws} - p_{wa}) \cdot L \quad (9)$$

where: Q_{e_s} is evaporative heat loss from the skin (W); A_{ws} is the wet skin area exposed to air (m^2); k_{ws} is the vapor mass transfer coefficient = $6.28 \cdot 10^{-6} \cdot (15.7 \cdot v^{0.6}/W^{0.13})$ (g s^{-1} m^{-2} Pa^{-1}), (Bruce and Clark, 1979; Fialho et al., 2004b); p_{ws} is water vapor pressure of the wet skin surface (Pa); p_{wa} is water vapor pressure of the air (Pa); L is the specific latent heat = 2425 (J g^{-1}).

The wet skin area is input in the model. Although pigs do not sweat, there is some diffusion of water from the body to the skin. This minimum value equals a wet skin area of 4% of the total surface (McArthur, 1987; Fialho et al., 2004a). Water vapor pressures can be calculated with formula from the ASHRAE (2009).

The heat loss from respiration is calculated from the respiration rate, the tidal volume, the specific density of air and the enthalpy difference between exhaled and inspired air:

$$Q_r = r_r \cdot V_r \cdot \rho_{air} \cdot (\Delta H_{out} - \Delta H_{in}) \quad (10)$$

where: Q_r is heat loss (mainly evaporative) from respiration (W); r_r is respiration rate (s^{-1}); V_r is respiration (tidal) volume of exhaled air (m^3); ρ_{air} is density of exhaled air (kg m^{-3}); ΔH_{out} enthalpy of exhaled air (J kg^{-1}); ΔH_{in} enthalpy of inhaled air (J kg^{-1}); r_r and V_r were determined from data of Huynh et al. (2005). ρ_{air}, ΔH_{out}, and ΔH_{in} are calculated from formula of ASHRAE (2009).

In figure 3 the calculated evaporation from respiration is compared with measured data from Huynh et al. (2005), depending on the ambient temperature. This figure shows that at the higher temperatures the calculated data are in good agreement with measured data, at the lower temperatures, however, calculated data seem to be overestimated. Furthermore, the figure shows that differences in evaporation between the different humidity groups seem to be larger in practice than calculated.

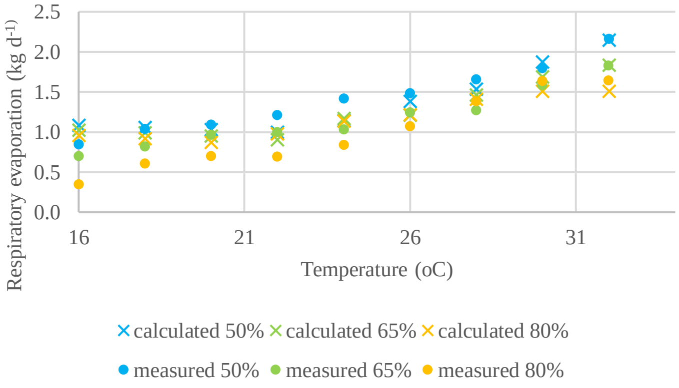

Figure 3. Calculated and measured evaporation from respiration depending on ambient temperature at different relative humidity levels (50, 65, and 85%).

3. Broilers

Heat production

Within the report of the CIGR Working Group (2002) the following formula is given to calculate total heat production of broilers:

$$Q_{total} = 10.62 \cdot W^{0.75} \tag{11}$$

Where: Q_{total} is the total heat production (W); W is live weight (kg)

This is a very simple equation only depending on broilers' live weight. While the main determining variable for heat production 'ME intake' is not in this equation, calculated results might largely deviate from real values in practice. For broilers a similar heat production model was developed as for growing-finishing pigs, but with other parameter values. Parameters to calculate required energy to deposit 1 kg of fat and protein are, according Lopez and Leeson (2008), 46 and 36 MJ, respectively. This is including the energy in the fat and protein itself. The same authors reported the following formula to calculate the energy necessary for maintenance:

$$ME_m = 155.3\ W^{0.66} \cdot \frac{4.184}{1000} \tag{12}$$

Where: ME_m is metabolic energy for maintenance (MJ/d); W is live weight; 4.184/1000 is the conversion factor from kcal to MJ

With Gompertz curves the live weight and feed intake at each day during the growing period are calculated, with start and final weight and total feed intake as input variables. Calculations with this model and with the CIGR model (2002) were compared with results from measured heat productions in climate controlled respiration chambers with *ad libitum* fed broilers (Ellen et al., 2015) (figure 4). This figure shows that the calculated heat production with the CIGR equation is higher than measured in the whole calculated range, on average 11.3% higher. This is a bit surprising, while we might expect, similar as in pigs, that due to genetic improvement with higher growth rates, the CIGR formula would underestimate heat production levels. The new model was on average 2.9% higher than measured, but calculated heat production were clearly overestimated at the start and a bit underestimated at the end of the growing period. This might be caused by a lower required maintenance energy per kg metabolic weight ($W^{0.66}$; equation 12) at early age when compared to later ages (Plavnik and Hurwitz, 1985).

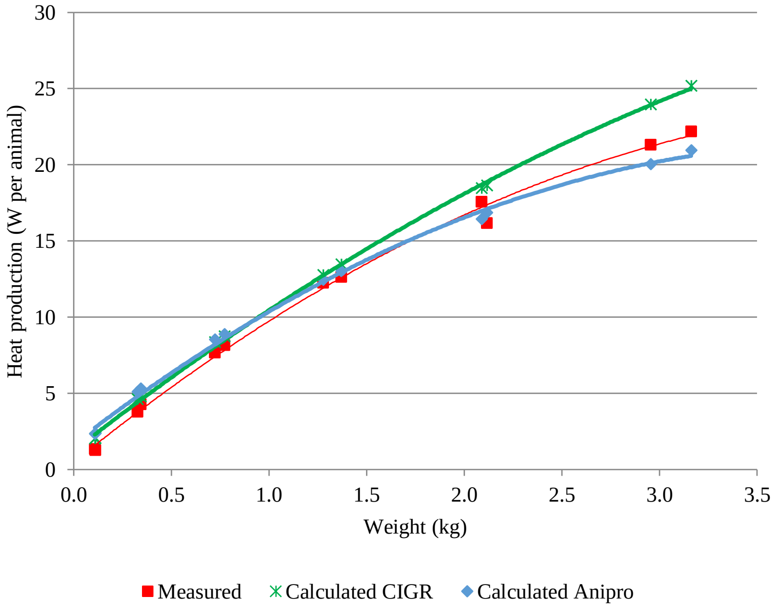

Figure 4. Measured heat production in respiration chambers (Ellen et al., 2015) and calculated heat production with the CIGR equation and with the new (Anipro) model.

Moisture production

For broilers the latent heat production is calculated in a similar way as for growing-finishing by subtracting the sensible heat production from the total heat production. Sensible heat production is calculated as follows (CIGR, 2002):

$$Q_{sensible} = [0.61 \cdot (1000 + 20 \cdot (20 - T_i) - 0.228 \cdot T_i{}^2] \cdot \frac{Q_{total}}{1000} \qquad (13)$$

Where: $Q_{sensible}$ is sensible heat production (W); Q_{total} is total heat production (corrected for temperature, W) ; T_i is room temperature (°C)

Moisture production is calculated by dividing latent heat by the evaporative heat of water. Similar as for growing-finishing pigs, this calculation of heat production has two omissions: 1) there is no separation between moisture produced by the animals and moisture produced in the rest of the house; 2) no effect of animal weight is included.

For calculating moisture production from the animals and from the rest of the house we used a similar approach as in growing-finishing pigs. Evaporation from wet (bedded) areas (kg/d) is calculated with equation 6. An adapted empirical equation from Beeking et al. (1994) is used to calculate k_{evap}:

$$k_{evap} = a_{k_{evap}} + b_{k_{evap}} \cdot \sqrt{v} \cdot \left(\frac{(Litter_{W\%} - 16)}{0,03} + 21\right) \qquad (14)$$

Where: k_{Evap} is evaporation coefficient (kg m^{-2} kPa^{-1} d^{-1})); a_{k_Evap} is a constant; b_{k_Evap} is a regression coefficient; v is air velocity above evaporating surface (m/s); $Litter_{W\%}$ is water content of bedding material (%)

From calibration on the water content of the bedding the following parameter estimates were made: a_{k_Evap} = 0.25 and

$b_{k\_Evap} = 1.31 \times 10^{-4}$ (Aarnink et al., 2016b).

Water evaporation at animal level is not fully worked out yet. Figure 5 gives the results of a study in which mass balances of broilers have been measured (Aarnink et al., 2016b). In this study the water evaporation from the broilers was determined by subtracting the water retention (calculated from N retention) and the amount of water in fresh faeces from the total water intake (drinking water + feed water) plus the amount of metabolic water. From this water evaporation the amount of latent heat loss was calculated. Then the fraction (f_{Qs}) of sensible heat loss was calculated from the calculated total heat loss. Based on these data a polynomial function was fitted and used in the new model to calculate f_{Qs} at animal level. For simplicity also a constant level of f_{Qs} during the growing period of 0.67 might be assumed. This value, but also the values of the polynomial curve, are only valid for the situation that the broilers are housed within their thermo-neutral zone. At higher temperatures less sensible heat and more latent heat will be lost. Figure 5 also shows the calculated f_{Qs} with the CIGR formula and the new model at housing level. A large deviation between these two calculations can be observed, especially during the first weeks of the growing period. This seems to be mainly caused by the fact that animal live weight is not included in the CIGR formula. At the start of the growing period high temperatures are set in the broiler house. The measured temperature is also given in figure 5. The temperature in this study decreased from 33.4ºC at the start to 19.3ºC at the end of the growing period. These temperatures are set to keep the broilers within their thermo-neutral zone. Within the thermo-neutral zone broilers don't need to evaporate a lot of water to loose heat. Therefore it is suggested to calculate f_{Qs} not only depending on temperature but also on live weight.

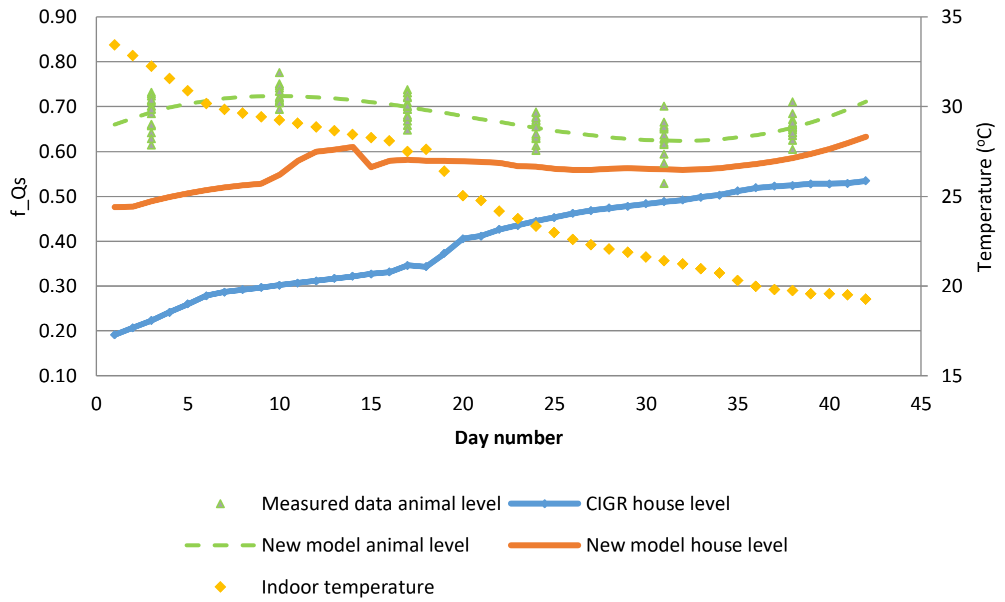

Figure 5. Calculated fraction of sensible heat (f_{Qs}) with CIGR equation and with the new model (animal and house level), 'measured' f_{Qs} at animal level and the indoor temperature.

4. Conclusions

Within this paper the different CIGR formula to calculate heat and moisture production in growing-finishing pigs and broilers are discussed. The following conclusions can be drawn:

- The relatively simple CIGR formula to calculate total heat production of growing-finishing pigs give similar results as a more comprehensive model in which protein and fat retention are calculated, and seems therefore sufficient accurate. Only the table to calculate metabolizable energy needs to be updated, because of genetic improvement of the pigs in the last decades.
- To calculate total heat production for growing-finishing pigs a linear correction factor is used for indoor temperature. Although this does not fit with the concept of a thermo-neutral zone, this could be done without large error.
- Calculation of moisture production in growing-finishing pigs can be improved by separating moisture production from the pigs and moisture production from the rest of the house. This, more fundamental approach for determining moisture production, is needed to be able to accurately calculate moisture production under less average conditions.
- The CIGR formula to calculate total heat production of broilers is too simple, while it is not depending on the main variable determining heat production, the ME intake.
- The CIGR formula to calculate moisture production of broilers should not only depend on indoor temperature, but also on live weight of the birds. Similar as for pigs, it is also suggested to separate moisture production from the animals and moisture production from the rest of the house.

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