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Modeling skin temperature to assess the effect of air velocity to mitigate heat stress among growing pigs

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ABSTRACT. ***It is generally accepted that increased air velocity can help to mitigate heat stress in livestock housing, however, it is not fully clear how much it helps and significant uncertainties exists when the air temperature approaches the animal body temperature. This study aims to develop a skin temperature model to generated data for determining the potential effect of air velocity to mitigate heat stress among growing pigs housed in warm environment. The model calculates the skin temperature as function of body temperature, air temperature and the resistances for heat transfer from the body to the skin and from the skin to the surroundings. The latter is modelled as the united resistance for convection, radiation and evaporation. The model considers that the thermal heat load affects the tissue resistance, the body temperature and the evaporation from the skin, which is managed by modeling the tissue resistance, the body temperature and evaporation from the skin as functions of the skin temperature. The results indicate that the combination of an air temperature of 24 °C and an air velocity 0.2 m/s results in the same skin temperature as the combinations of 27 °C and 0.6 m/s, and of 30 °C and 1.9 m/s.***

Keywords. ***Effect of air velocity Effective temperature, Heat stress, Pigs, Skin temperature.***

Introduction

It is generally accepted that increased air velocity can help to mitigate heat stress in livestock housing, however, it is not fully clear how much it helps and significant uncertainties exists when the air temperature approaches the animal body temperature. To reduce these uncertainties especially for growing and finishing pigs Bjerg et al (2016a) developed an effective temperature (ET) equation to assess the integrated effect of temperature, humidity, velocity and turbulence. Their work indicated that the effects of humidity and turbulence were of minor significance and therefore in this work we ignored these effects, whereas the ET equation can be written as:

$$ET = t_{ambient} + c(d - t_{ambient})(v^e - 0.2^e) \qquad (1)$$

where $t_{ambient}$ = ambient temperature (°C), v = air velocity magnitude (m s^{-1}), c = a constant that represents the significance of velocity, d = a constant that represents the temperature where increased air velocity no longer provides any chill effect (°C) and e = a constant that represents the power of velocity.

Bjerg et al (2016b) reviewed the literature on the effect of air velocity on the heat stress-related responses from the animals and found a single study (Mount and Ingram, 1965) conducted with live animals that could be utilized to determine value of the three constants in Eq. 1. In that study, the authors measured the effect of ambient temperature and air velocity on sensible heat loss from two pigs in each of three different weight ranges (3.4-5.8, 20-25 and 60-70 kg). The experiments were conducted with a heat flux sensor (Hatfield, 1950) strapped to the dorsal thorax of the pigs, while they were individually kept in a cage with closed sides. Above the cage, a variable speed fan directed airflow vertically downward into the cage and the air speed were measured 5-10 cm above the heat flow disc. Body temperatures, environmental temperatures and heat loss were measured every 5 min, until four readings had indicated that a steady state had been reached. The measurements were conducted at air speed of 0.08, 0.35, 0.60 and 1.00 m/s for each of five ambient temperatures (35, 30, 25, 20 and 15 °C). Bjerg et al. (2016a) investigated which values of the constants in Eq. (1) that caused the best agreement between the effective temperature and the measured sensible heat loss. The result was that c=-1, d=42 °C and e=0.66 agreed well for all three weight ranges (see Figure 1) and there were no indications that using different values for the different weight ranges would cause significant improvement.

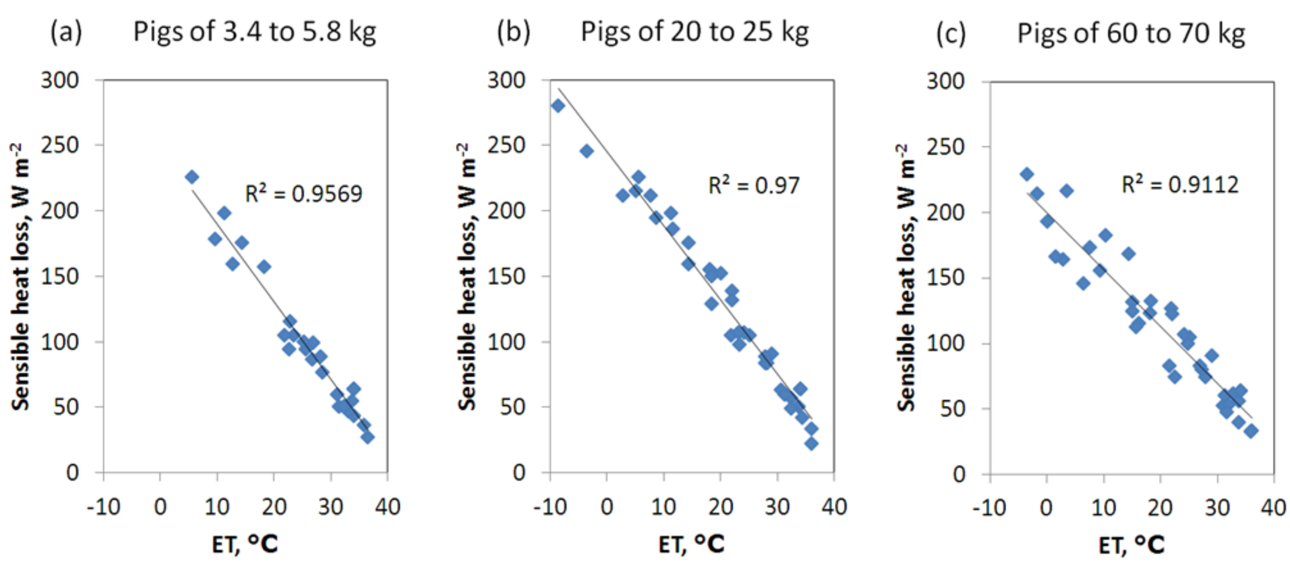

Figure 1. Sensible heat loss for pigs at different ET (Eq. 1) assuming c = -1.0, d = 42 °C and e=0.66. Data originates from Mount and Ingram (1965) and includes exposure to different ambient temperatures (15, 20, 25, 30 and 35 °C) at different air speed (close to 0.08, 0.35, 0.60 and 1.00 m/s). The three graphs represent different weight ranges.

Massabie and Granier (2001) measured production performance for finishing pigs kept in groups of six animals (0.67 m^2/animal) at air temperatures of 20, 24 and 28 °C, with and without ceiling fans located above the partitions between each second pen generating downward air streams to increase air velocity. The authors informed that the air velocity was increased from 0.56 to 1.3 ms^{-1} during the growth period, but provides no information on how the air velocity was measured. A time weighted average velocity of 1.07 ms^{-1} can be calculated from a step curve reported by the authors. Reported results illustrated in Figure 2 show that the ceiling fan increased the daily weight gain, and simultaneously it increased the feed conversion ratio.

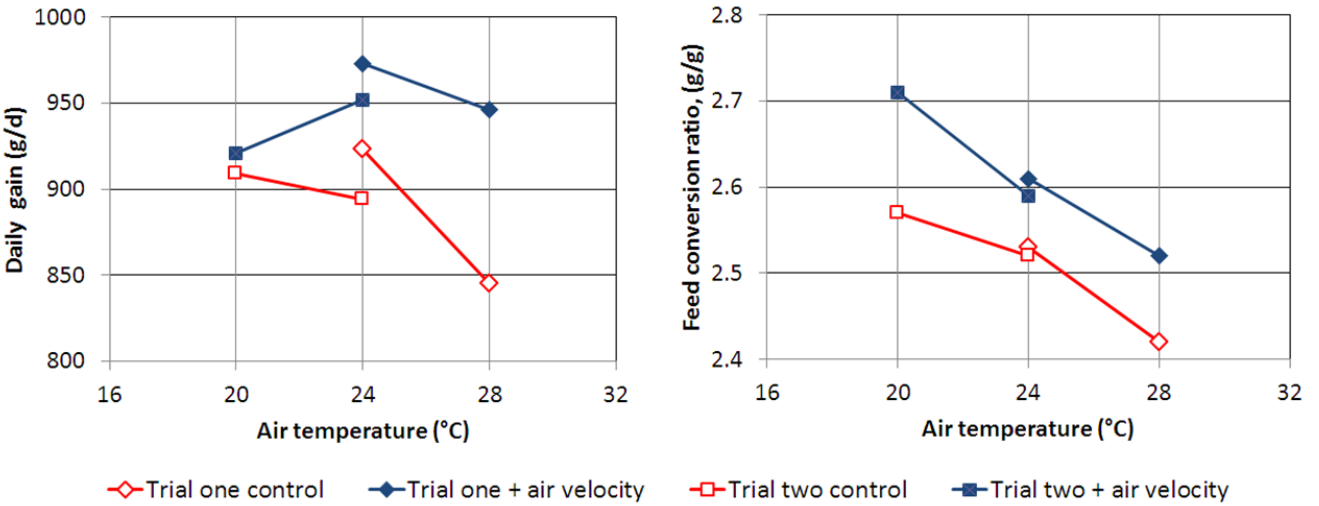

Figure 2. Daily weight gain (left hand graph) and feed conversion ratio (right hand graph) for finishing pigs kept at different air temperatures with and without a ceiling fan to increase air velocity from 0.56 to 1.3 ms^{-1} during the growth period (results reported by Massabie and Granier (2001)).

The results presented in Fig 2 indicate that the negative influence of increased temperature on daily gain begins at approximately 20 °C without air velocity and at a higher temperature if the pigs are exposed to the air velocity. At 28 °C the effect of air velocity (increase from 0.2 ms^{-1} to 1.07 ms^{-1}) is equivalent to an approximately 5 °C lower temperature without air velocity. For the feed conversion ratio, the effect of velocity is equivalent to an approximately 3 °C lower temperature without air velocity. These effects of increased air velocities are only 50 and 30 %, respectively, of the effect estimated by Eq 1. if the parameters determine from the data provide by Mount and Ingram (1965) (c = -1.0, d = 42 °C, e=0.66) are used. However, adjustment of the parameter e to 0.26 and 0.14 respectively, would make Eq 1. agree with the results presented by Massabie and Granier (2001).

Unfortunately, we found no additional studies on the effect of air velocity to mitigate heat stress useful for validation of Eq. 1. Therefore, the aim of this study was to procure alternative data for validation of Eq. 1, by review of published recommendations on air velocity as method to mitigate heat stress among growing pigs and by development of a model to simulate a heat stress related response.

Existing recommendations on air velocity as method to mitigate heat stress among growing pigs

Mount (1975) described a method to assess the thermal environment in relation to pig production. The method where based on a property referred to as Equivalent Standardized Environmental Temperature, and the approach was to adjust the air temperature by Equivalent Standardized Environmental Temperature variation caused by e.g. increased air velocity (see table 1).

Table 1. Equivalent Temperature variation caused by increased air velocity, (Modified after Mount (1975)).

Air velocity, m s^{-1}	Temperature variation, °C
Still air	0
0.2	-4
0.5	-7
1.5	-10

The relationship where estimated from a work by Burton and Edholm (1955) that reported data on how the resistance against heat transfer from a human body surface declined at increased air velocity. Unfortunately Mount (1975) did not reported all the required assumption used to calculated the values in table 1. However, the author indicated that the property was intend to be used for conditions near the lower critical temperature and therefor it occurs reasonable that he did not found it necessary to indicate how the values were affected by the air temperature. In addition, he mentioned that the values are probably not appropriately used outside the weight limits of about 20-50 kg. The figures are reproduced frequently in newer recommendations (Chambers, 2002; Meyer 2002; Barker, 2004), without the limitations mentioned by Mount (1975) and without referring to any specific air temperature. Assuming that the values are valid at ambient temperature around 20 °C the chill effect mentioned in table 1 is around 50 % of the values calculated by Eq 1 (assuming c = -1.0, d = 42 °C and e=0.66). The data in table 1 correlates well (R^2 = 0.99) with Eq. 1 at c = -0.4, d = 42 °C and e=0.4.

Bottcher et al. (2001) presented a table (Figure 3) including figures for wind chill and effective temperature at increased temperature and velocity. Unfortunately, the authors did not indicate how the figures was generated. It appears that it is valid for pigs of 48 lbs in housing with pad evaporative cooling, but it is not clear how the cooling should effect the results. The effective temperature mentioned in the table correlates best (R^2=0.98) with Eq. 1 at c = -0.37, d = 44 °C and e=1.5.

Finishing Windchill Effect Based on Building 40' wide x 7'6" ceiling
Pig Weight = 48 lbs. With Pad Evaporative Cooling

	Number or Fans		Actual	Tunnel Vel.	Wind Chill	Effective Temp.
Temperature	48"	36"	C.F.M.	FPM	Deg F.	Deg F.
70	Time		2534.4	0		70
74	1		23000	30	2	72
78	1	1	34000	106	6	72
81	1	2	45000	141	8	73
84	2	2	68000	213	13	71
87	3	2	91000	284	17	70

Figure 3. Wind chill and effective temperature at increased temperature and velocity for pigs of 48 lbs housed in pad evaporative cooled units (table presented by Bottcher et al.,2001).

Hoff et al (1993) developed an effective environmental temperature (EET) for newborn piglets to describe the thermal environment by incorporating the mean radiant temperature, dry-bulb temperature and air velocity near the newborn. The EET was based on an assumed constant heat transfer resistance from the core to surface (0.033 °C m^{-2} W^{-1}) and on the assumption that the evaporative and conductive heat loss was insignificant. The article includes a table with estimated EET at different thermal conditions. Values in that table for dry-bulb temperatures between 10 and 35 °C, velocities between 0.12 to 0.72 m s^{-1}, and mean radiant temperatures equal dry bulb agrees very well (R^2>0.999) with Eq. 1 at c = -1.0, d = 42 °C and e=0.32.

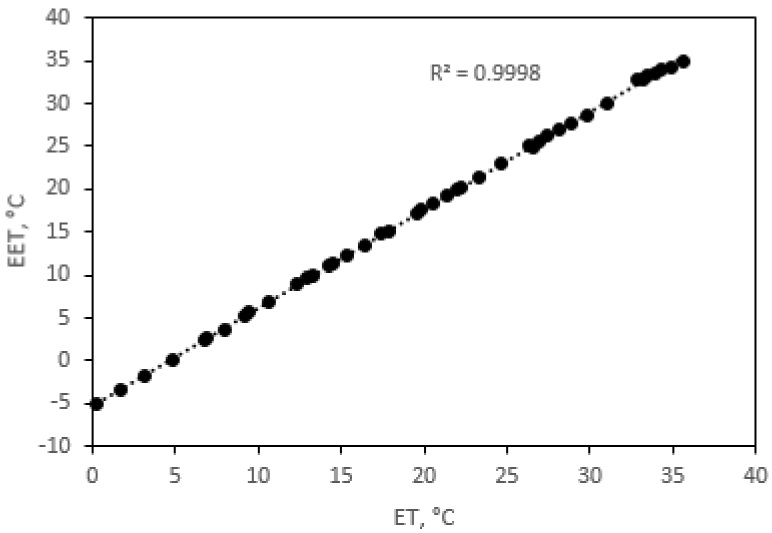

Figure 4. Effective environment temperature (EET) for newborn piglets (Hoff et al., (1993) compared with ET (Eq. 1) assuming c = -1.0, d = 42 °C and e=0.32.

In an earlier publication, Hoff (1978) presented curves for EET for pigs of 20, 50 and 100 kg at ambient temperature between 5 and 35 °C at velocities from 0.11 to 1.9 m s^{-1}. Read values from these curves are in Figure 5 compared with ET values calculated by Eq. 1 (assuming c = -1.0, d = 42 °C) where the constant e is adjusted to obtain the best correlation within each pig weight. It appears from that ETT correlates very well with ET (R^2≥0.999) if e is set to 0.14, 0.12 and 0.10

for pigs of 20, 50 and 100 kg, respectively.

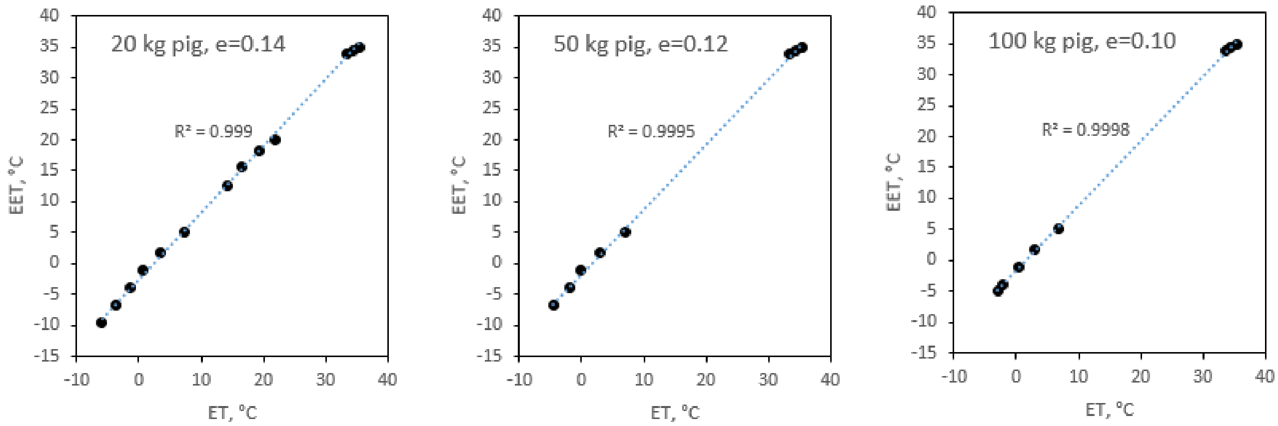

Figure 4. ETT for pigs at 3 different weights (Hoff et al., 1993) compared with ET (Eq. 4) assuming c = -1.0, d = 42 °C.

Unfortunately, Hoff (1978) did not provide details on how the mentioned curves were developed, and therefore it is e.g. unclear whether the assumption mentioned in relation to the newborn pigs also are used in the calculation for the larger pigs.

Development of a model to simulate a heat stress related response.

Heat stress is related to several physiological parameter as heart rate, respiratory rate, body temperature and skin temperature. Among these, skin temperature has the advantage that it is affected by thermal conditions both at high and lower heat load, and therefore it occurs most relevant to investigate the possibility to model the skin temperature.

The skin temperature (t_{skin},°C) is related to body temperature (t_{body},°C) ambient temperature (t,°C) tissue resistance (R_{tissue}, °C m^{-2} W^{-1}), and resistance from the skin to the surroundings (R_{sour}, °C m^{-2} W^{-1}) as illustrated in Figure 5 and can be calculated as:

$$t_{skin} = t_{body} - \frac{(t_{body} - t_{ambient}) \times R_{tissue}}{R_{tissue} + R_{sour}} \qquad (2)$$

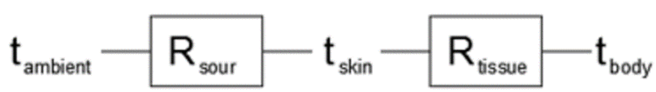

Figure 5. Model of the connections between body temperature (t_{body},°C), tissue resistance (R_{tissue}, °C m^2 W^{-1}), skin temperature (t_{skin},°C), resistance from the skin to the surroundings (R_{sour}, °C m^{-2} W^{-1}) and ambient temperature ($t_{ambient}$,°C).

The resistance from the skin to the surrounding can be calculated as the united resistance for convection (R_{conv}), radiation (R_{rad}) and evaporation (R_{evap}) (all with the unit of °C m^2 W^{-1}).

$$R_{sour} = \frac{1}{\frac{1}{R_{conv}} + \frac{1}{R_{rad}} + \frac{1}{R_{evap}}} \qquad (3)$$

Consequently, a model to calculate the skin temperature from the ambient temperature and the air velocity requires knowledge about R_{conv}, R_{rad}, R_{evop}, T_{tissue} and the body temperature.

Resistances for convection and radiation.

Bruce and Clark (1979) developed a deterministic model for heat production of growing pigs below their lower critical temperature. The included expression for the convective and radiant resistance (Eq. 4 and 5) may also be valid at higher ambient temperatures.

$$R_{conv} = 0.064 \frac{m^{0.13}}{v^{0.6}} \qquad (4)$$

$$R_{rad} = 0.019 \qquad (5)$$

where m = the weight of the pig (kg).

Bruce and Clark (1979) ignored the evaporative heat released from the skin, which might be reasonable at low ambient temperature but questionable at high temperature.

Resistance for evaporation

The potential effect of increased air velocity on skin evaporation is depended on the amount of water that can be transferred to the skin surface, and on whether moist are present on the skin surface. If no moist is present on the skin surface then the ability to transfer moist to the skin will control the evaporation, and under such circumstances, either velocity or humidity will affect the evaporation.

Morrison et al. (1967) measured skin and lung moisture loss for two 90 kg gilts. The animals were individually placed in a chamber with an air velocity of 0.025 m/s. At 70 % RH the authors found that the skin moisture loss increased from 23 to 53 g pig^{-1} h^{-1} when temperature increased from 15.5 to 29.4 °C. At high temperature the highest skin moisture loss was found at 70 % RH, however, an increase of RH to 90% caused only a very small decrease in skin moisture loss, see figure 6. The results that a high skin moisture loss can be obtained even at high RH (90 %) and low air velocity (0.025 m s^{-1}) indicates that the process is controlled by a limited moisture transport to the skin surface, which agrees with that the authors informs that "*no moisture was observed on the skin*". The results also indicate that the skin moisture loss remain at a low level at moderate heat load, and increase to a higher level at high as heat load.

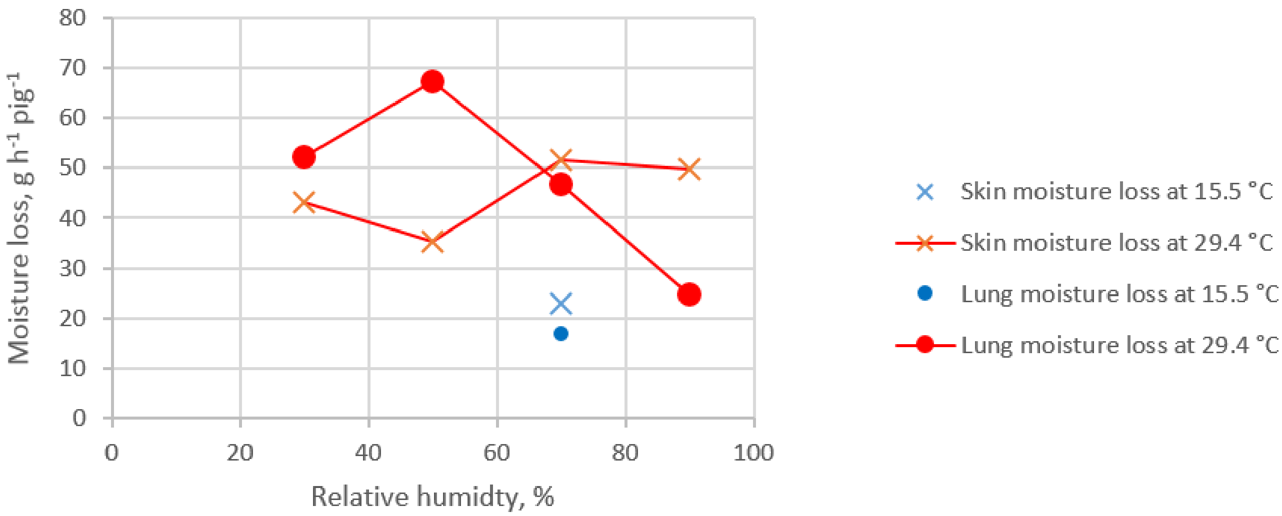

Figure 6. Skin and lung moisture loss for gilts of 90 kg (data from Morrison et al (1967))

A relationship between skin moisture loss and skin temperature is useful to model the skin temperature. Moreover, even though, Morrison et al. (1967) did not report the skin temperature their measured relationship between skin moisture loss and respirations frequency (figure 7) may be utilized if it is linked to a relationship between respiration rate and skin temperature reported by Huynh et al. (2005). The line shown in Figure 7 illustrate the possible assumption that the skin moisture loss is maintained at 13 g m^{-2} as long the long the respiration frequency is below 40 breath min^{-1}, and that it, thereafter, increases linearly with the respiration rate until it reaches a new constant level of 30 g m^{-2} at 130 breath min^{-1}.

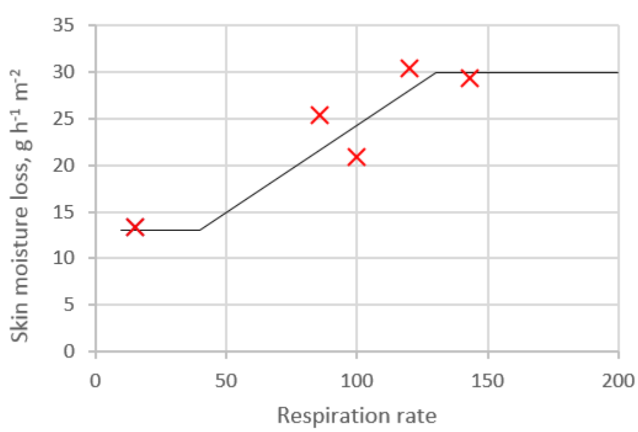

Figure 7. Skin moisture loss as function of respiration rate for gilts of 90 kg (data from Morrison et al (1967))

Huynh et al. (2005) studied the effect of room temperatures on respiration rate, skin temperature and rectal temperature. In their study, groups of 10 pig (62 kg) were exposed to increased ambient temperature from 16 to 32 °C where the room temperature was raised 2 °C each day, the air velocity where approximately 0.2 m s^{-2} and the RH where held constant. At 50 % RH they found that the respiration rate was 33 breath min^{-1} and unaffected by air temperature up to 23.4 °C. Above that level respirations rate increased linearly with room temperature, where 1 °C increased temperature increased respiration rate by 15 breath min^{-1}. The skin temperature was 33.3 °C at room temperature of 16 °C, and increased linearly with 0.25 °C for each degree increase of room temperature. These relations can justify the assumption that respiration increases with skin temperature (60 breath min^{-1} $°C^{-1}$) if skin temperature is above 35.2 °C and constant (33 breath min^{-1}) below this level. Combining this relationship with the relationship illustrated by the line in figure 7 leads to the assumption that evaporative heat loss from the skin (Q_{evap}, W m^{-2}) can be modelled as

$$Q_{evap} = \begin{cases} 9 & t_{skin} \leq 35.2 \\ 7.3333 t_{skin} - 249.3 & 35.2 < t_{skin} < 36.7 \\ 20 & t_{skin} \geq 36.7 \end{cases} \qquad (6)$$

Subsequently, R_{evap} can be calculated as

$$R_{evap} = \frac{t_{skin} - t_{ambient}}{Q_{evap}} \qquad (7)$$

Body temperature

The study by Huynh et al. (2005) also indicates that rectal temperature is unaffected by skin temperature as long skin temperature is below a certain level and that it increases linearly with skin temperatures above this level. Their reported results for pigs kept at 50 % RH is utilized to develop following relationship:

$$t_{body} = \begin{cases} 39.3 & t_{skin} \leq 36.0 \\ 0.56 t_{skin} + 19.14 & t_{skin} > 36.0 \end{cases} \qquad (8)$$

Tissue resistance

Tissue resistance can be estimated from knowledge about how the thermal environment affects skin temperature, body temperature and the heat release from the skin (Q, W m^{-2}).

$$R_{tissue} = \frac{t_{body} - t_{skin}}{Q} \qquad (9)$$

In addition, the heat release can be calculated as:

$$Q = \frac{t_{skin} - t_{ambiant}}{R_{sour}} \qquad (10)$$

The study by Huynh et al. (2005) includes relationships between skin temperature and ambient temperature and between body temperature and ambient temperature for pigs of 62 kg at air velocity of 0.2 m s^{-1}, see Figure 8.

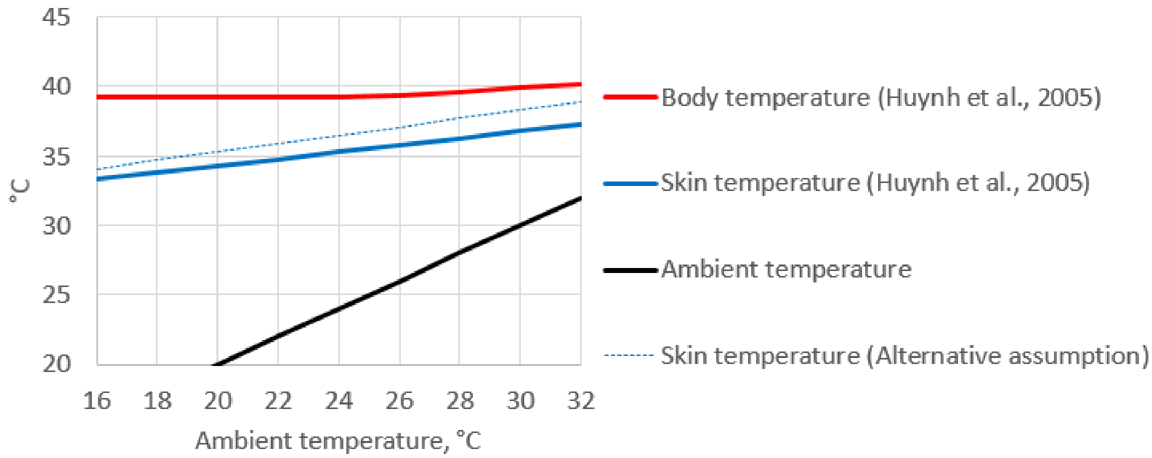

Figure 8. Body temperature and skin temperature as function of ambient temperature for pigs of 62 kg kept at 50 % RH and air velocity of 0.2 m s^{-1}.

We assume that the relationship between tissue resistance and skin temperature determined at one air velocity, also are valid at other air velocities, and therefore we used the curves in Figure 8 to estimate this relationship. The results are shown as the black dots in Figure 9, and it appear that the tissue resistance is independent of skin temperature up to a skin temperature of 35.2 °C where the evaporation begins to increase, which involves a reduction of the evaporation resistance. The body temperature begins to increase at a skin temperature of 36 °C, which causes an increase of the estimated tissue resistance at increased skin temperature above that level. Subsequently equation 11 was used to model the relation between skin temperature and the tissue resistance.

$$R_{tissue} = \begin{cases} 0.037 & t_{skin} \leq 35.3 \\ 0.0056599 t_{skin}^2 - 0.2636 t_{skin} + 4.7813 & t_{skin} > 35.3 \end{cases} \quad (11)$$

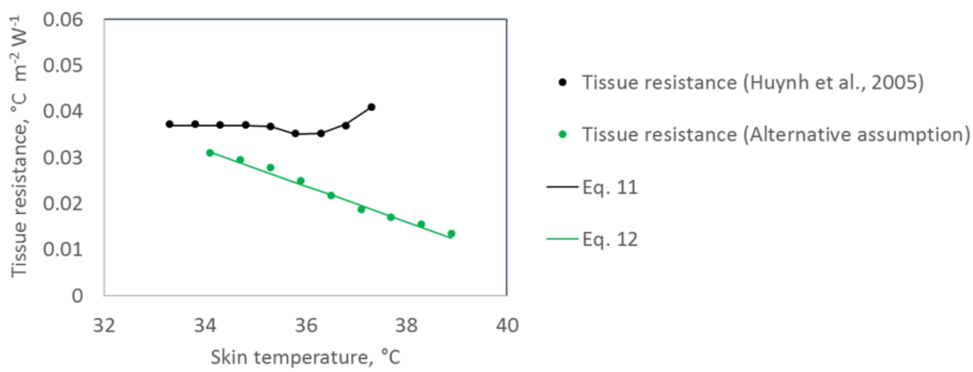

Figure 9. Tissue resistance as function of skin temperature.

The relationship derived by these results disagrees with the expectation that the vasodilation increases at increased temperature, however, it is immediately difficult to assess to which extend the relationship between tissue resistance and skin temperature influence effect of air velocity on the skin temperature. Therefore, we constructed an alternative relationship between ambient temperature and skin temperature (the dotted line in Figure 8) which gives following relationship between skin temperature and body temperature:

$$t_{body} = \begin{cases} 39.3 & t_{skin} \leq 37.3 \\ 0.42 t_{skin} + 23.65 & t_{skin} > 37.3 \end{cases} \quad (12)$$

This alternative relationship for estimation of the tissue resistance results in a nearly linearly decline at increased velocity, see Figure 9, and the relationship can be modelled as Eq. 13.

$$R_{tissue} = -0.0039 t_{skin} + 0.1642 \quad (13)$$

Results

The skin temperature was calculated in an iterative sequence as illustrated in Figure 10, and results from five levels of ambient temperatures and five levels of air velocity are presented in table 2.

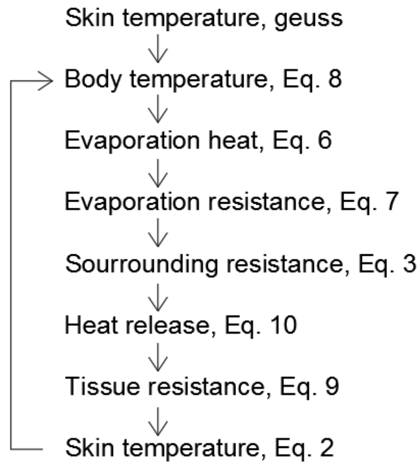

Figure 10. Sequence for estimation of skin temperature.

Table 2. Two dataset generated by calculating skin temperatures at 5 levels of ambient temperature and 5 levels of air velocity for two different assumption for skin temperature at 0.2 m s^{-1}, see Figure 8.

Data set		1					2				
Skin temperature at 0.2 m/s		As Huynh et al. (2005)					Alternative assumption				
Body temperature		Eq. 8					Eq. 12				
Tissue resistance		Eq. 11					Eq. 13				
Air velocity, m s^{-1}		0.2	0.5	1.0	2.0	3.0	0.2	0.5	1.0	2.0	3.0
Ambient temperature, °C:	20	34.3	33.4	32.4	31.1	30.3	35.5	34.0	32.2	29.9	28.5
	24	35.2	34.5	33.8	32.8	32.1	36.5	35.7	34.6	32.9	31.8
	28	36.4	35.8	35.1	34.4	33.9	37.7	36.8	36.2	35.3	34.6
	32	37.4	37.0	36.7	36.2	35.8	39.1	38.5	37.8	37.0	36.6
	36	38.5	38.3	38.1	37.9	37.7	40.0	39.8	39.6	39.2	38.9

Both data set mentioned in table 2 agrees well with Eq. 1 at c=1 and d=42, e=0.28 (R^2=0.996), see Figure 11, however an even better agreement with data set 1 (R^2=0.998) was obtained at e=0.23. For data set 2 an insignificant better correlation was obtained at e=0.29.

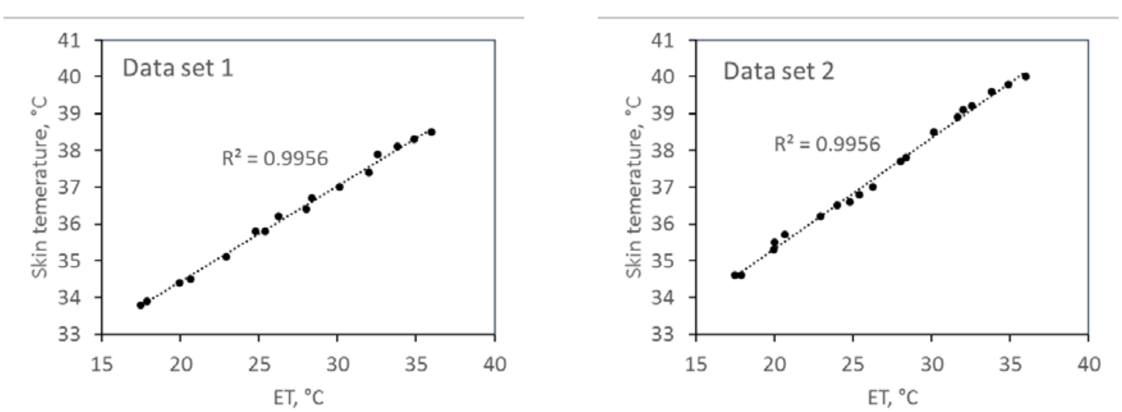

Figure 11. Estimated skin temperature as function of ET for the two data set mentioned in Table 2 (c=-1, d=42 and 2=0.28).

Discussion and conclusions

The developed skin temperature model and all investigated data from literature agreed with the general formulation of Eq. 1. The use of c=-1 and d=42 °C in Eq.1 agreed with all data except the recommendations provided by Bottcher et al. (2001) and by Mount and Ingram (1965). Unfortunately, these authors give so limited information that it is impossible to explain the deviations, however the recommendation provided by Bottcher et al. (2001) cause that the effect of increased velocity increases at higher air velocity (because e>1), which disagrees with any expectations based on air physical relationships.

Table 1 summaries the studies providing data agreeing with c=-1 and d=42 °C in Eq. 1. It appears that the estimated e-values differ considerably between the different dataset, and it is immediately difficult to derive a single value that best reflects how air velocity mitigate heat stress. The data provided by Mount and Ingram, (1965) has the advantage that it includes data from live animals exposed to a broad variation of different air velocities and temperatures. A disadvantage of these data is that the response – the sensible heat loss at short time exposure to a combination of velocity and temperature - may be a debatable measure for heat stress. The high value of e estimated from these data may possibly be associated with the short time exposure to the treatment, where the individually kept animal has limited options for adaption to the environment. Oppose to that the production performance for groups of pigs included in the data by Massabie and Granier (2001) is more direct link to heat stress, but this study is basically limited to one observation only. This study, also, illustrates that the chosen response – in the particularly study daily gain or feed conversion – may be important for the estimated effect of velocity. However, it is not straightforward to assess to which extend the difference in the responses can explain the difference in the estimated e-values between the different studies mentioned in figure 4. The data derived from the study on modeling of EET for new born piglets (Hoff et al.,1993) includes the limitations that it does not consider that tissue resistances and evaporation from the skin may be influenced by the ambient thermal conditions. The data on EET for larger pigs (Hoff, 1978) is difficult to assess due to lack of information on how it is established.

Table 3. Values of the constant e in studies providing data that agrees with Eq. 1 assuming c=-1 and d=42 °C

Study	Methods	Response	Correlation with ET, R^2	e
Mount and Ingram, (1965).	Experiment with short time exposure to combination of different combination ambient temperature air velocities.	Sensible heat loss for pig of		
		3.4-5.8 kg	0.96	0.66
		20-25 kg	0.97	0.66
		60-70 kg	0.91	0.66
Massabie and Granier (2001)	Production performance study with group housed finisher pigs.	Daily gain	-	0.26
		Feed conversion ratio	-	0.14
Hoff et al. (1993)	Modeling of effective environmental temperature (EET).	EET for new born piglets	0.999	0.32
Hoff (1978)	Modeling of effective environmental temperature	EET for pigs of		
		20 kg	0.999	0.14
		50 kg	0.999	0.12
		100 kg	0.999	0.10
This study	Modeling skin temperature	Skin temperature		
		data set 1 (see Table 2)	0.998	0.23
		data set 2 (see Table 2)	0.996	0.29

The data from modelling of skin temperature generated in this study includes an attempt to consider that evaporative heat release from the skin and the tissue resistance is affected the thermal environment. The value of e estimated from these data is in the same order of magnitude as indicated for effect on daily gain estimated from the data provide by Massabie and Granier (2001). Therefore, we assess that the current knowledge indicates that the e-value should be around 0.25 when Eq. 1 is used to predict the chill. Thereof following values are presented in table 4.

Table 4. Chill effect of velocity calculated by Eq. 1, assuming c=-1, d=42 °C and e=0.25.

		Air velocity, m s^{-1}				
		0.2	0.5	1.0	2.0	3.0
Ambient temperature, °C:	20	0	4	7	11	14
	24	0	3	6	9	12
	28	0	2	5	7	9
	32	0	2	3	5	6
	36	0	1	2	3	4

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