Chapter 2

Effective Temperature for Poultry and Pigs in Hot Climate

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Additional information is available at the end of the chapter

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Abstract

Existing knowledge on the relative significance of air temperature, humidity, and velocity in a hot environment for housed pigs and poultry is reviewed and synthesized in an effective temperature (ET) equation. The suggested unit has an easily perceivable scale where ET is equal to air temperature if the relative humidity is 50% and the air velocity is 0.2 ms^{-1}. The included method to determine the relative significance of air temperature and humidity is similar to the way it is done in the Temperature Humidity Index. Several authors have suggested different Thermal Humidity Indices for different categories of animals, but this chapter found no evidence that the relative importance of temperature and humidity is different for pigs than for poultry or for large than small ones. The suggested ET equation includes a separate velocity term, which assumes that the chill effect is proportional to the **air** velocity or to the square root of the **air** velocity and that the chill effect declines linearly with increased **air** temperature until it becomes insignificant as the **air** temperature approaches the animal body temperature.

Keywords: effective temperature, heat stress, thermal humidity index, air velocity, poultry and pig production

1. Introduction

Hot climate has a direct negative effect on productivity and animal welfare in livestock production. Addressing these negative consequences requires access to a variety of technical solutions that can influence one or more of the air physical parameters in the animal zone. The technical solutions involve approaches such as increased ventilation, air conditioning, air recirculation and insulation and may influence climate parameters such as air temperature, velocity, humidity, and conditions for radiation heat exchange. Optimal use of the available approaches presumes knowledge on how the animals respond to changed thermal environment and how the different air physical parameters contribute to protect animals from heat stress.

Fifty years ago, Beckett [1] suggested an effective temperature (ET) for swine to express the combined influence of air temperature and humidity and defined the effective temperature to be equal to room temperature if the relative humidity was 50%. An air velocity of 0.2 m/s is often used as a reference level for draught-free condition, and therefore, we assess that it will be relatively easy to relate to an effective temperature (ET) that is equal to air temperature if the air velocity is equal to 0.2 m/s.

A long tradition exists for using a combination of dry-bulb and wet-bulb temperature to calculate indices expressing the combined effect of air temperature and air humidity [2]. These indices are given different names but can generally be written in the form of Eq. (1). The Temperature Humidity Index, THI (°C), is the most frequently used name for these indices when they are applied to farm animals, and numerous authors [3–9] have suggested the use of THI to express the relative significance of air temperature and humidity on heat stress among confined pigs and poultry

$$THI = at_{db} + (1 - a)t_{wb} \tag{1}$$

where a is the weighting of dry-bulb temperature; t_{db} is the dry-bulb temperature (°C); t_{wb} is the wet-bulb temperature (°C).

The sole difference between THI and the effective temperature [1] is that THI is equal to the air temperature if the relative humidity in air is equal to 100%, where the effective temperature is equal to air temperature if the relative humidity is 50%. For certain value of a (in Eq. (1)), the effective temperature at the air velocity of 0.2 m/s $\left(ET_{v=0.2}\left(^{\circ}\mathrm{C}\right)\right)$ with approximation can be calculated as THI plus a linear function of air temperature as it appears in Eq. (2)

$$ET_{v=0.2} = THI + bt_{db} + f \tag{2}$$

where b and f are constants depending on a in Eq. (1).

The general procedure used to determine the a-value in Eq. (1) is to expose animals to different combinations of air temperature and humidity and determine which a-value results in the best correlation between THI and measured response variables, which can be physiological parameters [3–9] or production parameters [10]. The resulting a-values differ from study to study, and if more response variables are included in the same study, the a-value may be different for the different response variables [4–6, 8]. Most frequently, reported a-values lie in the interval between 0.6 and 0.9, and normally it appears that the a-values have to differ considerably from the value that resulted in the best correlation before it significantly degrades the correlation between the parameters used and THI. From a practical point of view, it is naturally most convenient to use the same a-value for all of the categories of animals included, and therefore in this study we investigate to which extent the use of a common a-value agrees with reported studies. An initial review of reported studies led us to the assumption that 0.75 would be an appropriate level for a common a-value. In this study, we inquire the validity of using a common a-value of 0.75 by comparing the correlation coefficient at the a-value that best reflects data with the correlation coefficient at $a = 0.75$.

At $a = 0.75$, the constants b and f in Eq. (2) was calculated to be 0.042 and 0.70, respectively, and Eq. (2) can then be rewritten as

$$ET_{v=0.2} = THI + 0.042t_{db} + 0.70 \tag{3}$$

After the insertion of Eq. (1) in Eq. (2), $ET_{(v\ =\ 0.2)}$ can be calculated as

$$ET_{v=0.2} = 0.794t_{db} + 0.25t_{wb} + 0.70 \tag{4}$$

Tao and Xin [9] developed a Temperature-Humidity-Velocity-Index (THVI) for market-size broilers based on measured body temperature increase for 90 min of exposure to 18 different heat-stress conditions. The conditions include three levels of air temperatures (35, 38, and 41°C), two levels of dew-point temperatures (19.4 and 26.1°C), and three levels of air velocities (0.2, 0.7, and 1.2 m/s).

The authors defined THVI as shown in Eq. (5)

$$THVI = (0.85t_{db} + 0.15t_{wb})v^{-0.058}(0.2 \leq v \geq 1.2) \tag{5}$$

where v is the air velocity, m/s.

The equation predicts the effect of an increased air velocity at an increased air temperature without considering the animal body temperature, and therefore it does not reflect that the convective chill effect of an increased air velocity must decline as air temperature approaches the animal body temperature.

Our preliminary examination of the data reported by Tao and Xin [9] indicated that it would be more adequate to assume a decreased influence of the air velocity when the air temperature approaches the animal body core temperature. This relationship prompted us to suggest an equation structure that treats the influence of the air velocity as an additional term to Eq. (2) as it appears in Eq. (6)

$$ET = ET_{v=0.2} - c(d - t_{db})(v^e - 0.2^e) \tag{6}$$

where c is a constant that may depend on animal species, sizes, and animal density; d is the temperature where ET no longer can be reduced by increased air velocity (°C); e is a constant that controls the influence of velocity.

In the study, the data presented by Simmons et al. [11] and Dozier et al. [12] indicate a linear influence of velocity corresponding to $e = 1$ in Eq. (6). An alternative assumption of a square-root relationship of velocity is supported by results reported by Uwagawa et al. [13] and by heat transfer theory where the Nusselts number is frequently assumed to be proportional to the square root of the Reynolds number [14]. The aim of this chapter is to review literature to identify data that can be used for parameter estimation and for validation of Eq. (6) and to uncover the limitations for the equations and the need for using **different** parameters for **different** species, animal density, or body weights.

2. Methods and results

The suggested effective temperature equation was developed from a review of published studies on how pigs and poultry react when exposed to various combinations of air temperature, humidity, and air velocity.

2.1. Combined effect of air temperature and air humidity

2.1.1. Pigs

Beckett [1] based the "swine-effective temperature" on a partitional heat loss diagram for a 67-kg growing pig and presented a graph to illustrate the combined influences of air temperature and humidity. From the mentioned graph, we read the swine-effective temperature for nine combinations of air temperature (29.4, 32.2, and 35.0°C) and relative humidities (25, 50, and 75%) and tested which a-value in Eq. (1) resulted in the best correlation between the effective temperature and Eq. (1). The best correlation was found for $a = 0.88$, and the correlation coefficient was as high as 0.995. Unfortunately, the author did not indicate how well heat loss data were reflected in the presented graphs.

Ingram [3] exposed four pigs aged 10–12 weeks to each of six different combinations of dry- and wet-bulb temperatures (t_{db}, °C/t_{wb}, °C: 32/22, 32/27, 36/23, 36/32, 40/26, and 40/36) and measured the rectal temperature every 5 min for up to 70 min after the exposure began. The author plotted the results against an effective temperature equivalent to THI in Eq. (1) for $a = 0.15$, 0.35, and 0.65. The visual results were that the correlation was best in the graph where $a = 0.65$, but no correlation coefficients were mentioned. A comparison of the included three graphs indicates that an increase in the a-value from 0.65 to 0.75 would have only a limited influence on the correlation between the rectal temperature increase and THI.

Roller and Goldman [4] exposed 26 barrows weighing 76–119 kg to heat exposure for 3 h. Two pigs were tested at one of 13 combinations of dry-bulb temperatures (34.4–42.8°C) and dew-point temperatures (17.7–31.1°C), and rectal temperature, **respiration rate, pulse rate,** and ambient temperatures (dry-bulb and wet-bulb) were measured. Data were examined to determine which relative influence of wet-bulb temperature (1-a) in Eq. (1) resulted in the best correlation with results. According to a graph presented by the authors, the best correlation coefficient ($r = 0.88$) was found when the rectal temperature increase after 3 h of heat exposure was used as the response variable, and this correlation coefficient was found at a-value of 0.68. Including the effect of respiration rate increase and the results after 2 h of exposure, the authors concluded that THI using $a = 0.75$ would be the most precise for a single indicator of thermal environment imposed.

2.1.2. Broilers

As mentioned in Section 1, Tao and Xin [9] develop a Temperature-Humidity-Velocity-Index (THVI) based on body temperature increase at broilers exposed to warm conditions at different dew points and air velocities. The authors used Eq. (1) to state the relative significance of air temperature and humidity and found that $a = 0.85$ best represented their data. However, a graph presented in their article indicates a very limited influence of "*a*" in the interval from 0.7 to 1.0. Purswell et al. [10] presented similar relationships. Their study concerned live performance of broilers maintained at three different dry-bulb temperatures (15, 21, and 27°C) and three different relative humidities (50, 65, and 80% RH) **from days 49 to 63 of age.** The authors used regression analysis to demonstrate a quadratic relationship between THI and live performance parameters, where THI was based on $a = 0.85$. Successively, we used their reported data to determine the significance of varying the *a*-value in these analyses. The result was a very limited influence of *a* in the interval from $a = 0.6$ to 1.0.

2.1.3. Laying hens

Egbunike [5] conducted a study using 68 Harco birds that were 10 months old at natural humid tropical environmental conditions. The daily dry and wet temperatures during the study period ranged from 25.4 to 33.3°C and from 20.6 to 22.2°C, respectively. The respiratory rates and rectal temperatures were measured at 2-h levels from 08:00 to 16:00. The correlation coefficients between measurements and Eq. (1) were calculated for each of eleven 0.1 interval of "*a*" between 0.0 and 1.0 in Eq. (1). The best agreement (correlation coefficient = 0.71) was found for respiratory rate at $a = 0.6$. The correlation coefficient would be reduced from 0.71 to 0.69 if "*a*" was increased from 0.6 to 0.75. For rectal temperature, the best agreement (correlation coefficient = 0.69) was found for $a = 0.5$, and using $a = 0.75$, the correlation coefficient was reduced to 0.66.

Zulowich [6] measured 10 different physiological parameters (mainly related to respiration rate and rectal temperature) for laying hens individually exposed for 5 h to five different air temperatures (30, 32, 34, 36, and 38°C) at two different relative air humidities (50 and 90% RH). The author used the measurement to calculate the correlation coefficient for the linear relationship between the physical parameters and THI at *a*-values between 0.1 and 0.9. The result showed that the highest correlation coefficient was at very different *a*-values for the included physiological parameters; however, the *a*-value had a limited influence on the correlation coefficient.

2.1.4. Turkeys

Xin et al. [7] subjected 15–16-week-old turkeys to acute heat exposures of three different dry-bulb temperatures (32, 36, and 40°C) and two different wet-bulb temperatures at each of the dry-bulb temperatures. The authors found a significant increase in the total heat production with heat load which correlated best ($r = 0.98$) with THI at $a = 0.74$.

Brown-Brandl et al. [8] determined the *a*-value in Eq. (1) for tom turkeys at 6, 10, 15, and 20 weeks of ages based on the measurement of four different physiological responses (body temperature, CO_2 production, moisture production, and heart rate). Thirteen birds in each age group were individually exposed to temperatures between 23 and 40°C in combination with relative humidities between 40 and 90%, and response surface methodology was applied to use fewer birds than a conventional design would demand. The resulting weighting of dry-bulb temperature (a) was between 0.10 and 0.99 and the belonging R^2-values ranged from 0.004 to 0.81. **In addition,** the result did not indicate any systematic influence of bird ages, and the large difference between the values indicates that the results have a limited utility in the assessment of using a common a-value in Eq. (1).

2.1.5. Overview over a-values and correlation coefficients

Table 1 shows an overview of cases where it was possible to state a-values that best reflected the used data and the correlation coefficient for how well the data were reflected at that a-value and at a = 0.75. The table is organized, so the investigations that resulted in the highest correlation coefficient are mentioned first, and the investigations where the correlation coefficient was below 0.6 are not included. It appears that the a-value that best reflected data was between 0.50 and 0.90 and that the correlation coefficient at a = 0.75 was nearly as high as for the a-value that reflected the data best.

[Ref]	Species	Response variable	a-Value	Correlation coefficient
[9]	Broiler	Body temperature increase after 1.5 h of heat exposure	0.85	0.99 (0.99)
[7]	Turkeys	Total heat production after 3.5 h of heat exp.	0.74	0.98 (0.98)
[10]	Broilers	Feed intake	0.90	0.98 (0.98)
		Body weight gain	0.80	0.97 (0.97)
		Feed conversion	0.75	0.90 (0.90)
[4]	Pigs	Rectal temp. increase after 3 h heat exposure	0.68	0.88 (0.86)
[6]	Hens	Maximum rectal temp. after 5 h heat exp.	0.55	0.83 (0.83)
		Respiratory rate after 5 h heat exposure	0.85	0.79 (0.79)
		Time with heat exposure before rectal temperature reaches 44.5°C	0.70	0.73(0.73)
[4]	Pigs	Rectal temp. increase after 2 h of heat exp.	0.80	0.72 (0.71)
[6]	Hens	Respiration rate increase at exposure to natural warm condition	0.60	0.71 (0.69)
		Body temperature increase at exposure to natural warm condition	0.50	0.69 (0.66)
[4]	Pigs	Respiration rate increase after 3 h heat exp.	0.70	0.63 (0.63)
[6]	Hens	Number of times the resp. rate crossed 100 m^{-1} at 5 h heat exp.	0.90	0.63 (0.63)
		Time for hen to reach her maximum respiratory rate at heat exp.	0.62	0.62 (0.61)

The figures in brackets show the correlation coefficient at a = 0.75.

Table 1. Overview of studies where it is possible to state the a-value (in Eq. (1)) that best reflects the used data and the correlation coefficient for how well the data are reflected at that a-value and at a = 0.75.

2.2. Combined effect of air temperature, humidity and velocity

2.2.1. Broilers

Tao and Xin [9] provided data on the average body temperature rise for the four broilers included in each of the 18 temperature treatments mentioned in Section 1. We used these 18 observations to determine which values for the parameters c and d in Eq. (7) resulted in the best agreement between predicted values and data assuming either a linear or a square-root dependency with velocity (e = 1 or 0.5). The best quadratic correlation (r-square value of 0.97) was obtained at c = 0.7, d = 43°C, and e = 0.5

$$ET = 0.794t_{db} + 0.25t_{wb} + 0.70 - c(d - t_{db})(v^e - 0.2^e) \tag{7}$$

Figure 1 compares the measured body temperature rise with prediction by the equation presented by Tao and Xin [9] (Eq. (5)) or by Eq. (7), at c = 0.7, d = 43°C, and e = 0.5. It shows that Eq. (7) significantly improves the agreement compared to Eq. (5), especially at high heat load.

As it appears from **Figure 1**, the body temperature for broilers exposed to the warmest conditions was elevated by approximately 4°C during the experiment which may explain why the parameter d (in Eq. (7)) is found to be a few degrees above the normal body temperature for broilers.

In order to determine the maximum body temperature increase, Tao and Xin [9] continued the 18 treatments for at least 3 h or until at least one of the four broilers included in each treatment died. Circles in **Figure 1** indicate treatments where at least one of the four birds died. Using Eq. (7), no animals died unless they were exposed to an ET above 35°C, and at least one of the four birds used in each treatment died if they were exposed to ET above 35°C.

If the assumed dependence of velocity is changed from a square-root relationship (e = 0.5) to a linear relationship (e = 1), then the best reflection of the data presented by Tao and Xin [9] will be at c = 0.31 and d = 44°C, and the R-square value is reduced from 0.97 to 0.96. This small reduction indicates that an assumed linear relationship with velocity reflects the data almost as well as an assumed square-root relationship.

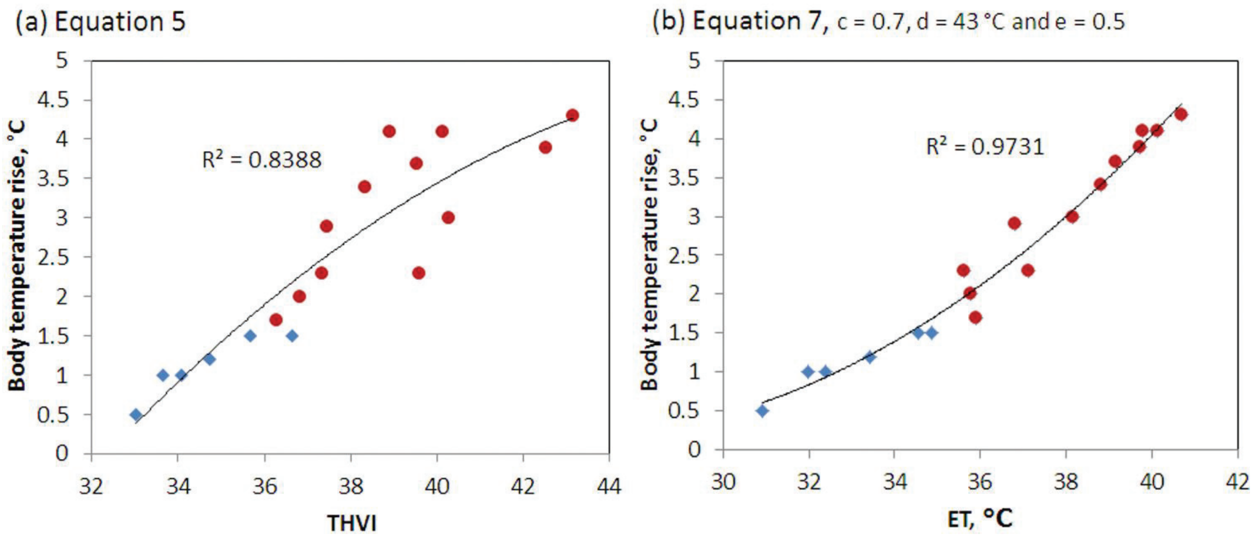

Figure 1. Comparison of measured and predicted body temperature rise for broilers exposed to 18 different combinations of dry-bulb temperature, dew-point temperature, and air velocity as a function of (a) THVI (Eq. (5)) and (b) ET (Eq. (7)).

Simmons et al. [11] measured heat loss from groups of broiler chickens subjected to various air speeds (1, 1.5, 2, 2.5, and 3 m/s) and ambient temperatures (29, 32, and 35°C). The measurements were conducted in a wind tunnel where groups of either 500 five weeks old birds or 400 six weeks old birds, were exposed to each of the 15 treatments for 60 min including a 30-min period permitting the broilers to react to the air speed setting and a 30-min measurement period. **The air velocity was measured** in an unobstructed section at the exit of the wind tunnel. The sensible heat loss was measured as the heat increase across the bird section, and similarly, the latent heat estimation was based on the measured increase of air humidity across the bird section. The authors modeled the measured heat losses as a second-order polynomial of the air velocity for each ambient temperature level, each heat loss type (sensible and latent), and each bird age, and found R^2-values of 0.73–0.96 for the agreements between data and the models. The estimated values generated by the models show a negative sensible heat loss at an ambient temperature of 35°C at air velocities up to 2.5 m/s. This is an unlikely result because it would require that the surface temperature should have been below the ambient temperature and that disagree with Uwagawe et al. [13], that for laying hens and the same ambient temperature measured skin temperatures between 37.4 and 40.2°C. The negative sensible heat loss at 35°C found by Simmons et al. [11] may be due to evaporation of water from litter in the wind tunnel and consequently the underestimation of sensible heat loss and corresponding overestimation of latent heat loss. The estimated negative sensible heat loss at relatively low temperatures makes values predicted by the models unsuitable for estimations of the parameters in Eq. (7).

The two studies of Yahav et al. [15, 16] report the growth performance for fast-growing male Cobb chickens raised for 4 weeks in battery brooders in a temperature-controlled room at 26°C. From 5–7 weeks, the birds were housed in individual cages and subjected to air temperature of 35°C and 60% relative humidity. Each trial included four groups of 60 birds exposed to different air velocities. The authors mentioned that the air velocities were maintained at ±0.25 m/s, but did not provide further information on how the velocities were measured. Reported results show that both the body weight and feed intake increased with the air velocity until the air velocity reached 1.5 or 2 m/s; however, above 2 m/s both parameters decreased with the air velocity. Yahav et al. [16] also measured body temperature and found a significantly higher body temperature among the birds exposed to the air velocity of 3 m/s than among those exposed to 2 m/s. The authors suggested that the body water balance is the main reason for the deterioration in the bird performance at an increased air velocity and that broilers might be unable to drink sufficient amount of water under extreme hot conditions.

For individually kept chickens, these results indicate that the assumption of the influence of the air velocity used in Eq. (7) fails for the air velocity larger than 1.5 or 2.0 m/s. Yahav et al. [15] mentions that the bird density may play a role for the found influence of an increasing air velocity from 2 to 3 m/s. For animals kept in pens at higher density, "radiation and conductance among the birds may increase heat load, and the high density may prevent ventilation of unfeathered areas such as the shanks, which are major structures for sensible heat loss, and thus efficient convection may be prevented" [15].

Simmons et al. [11] and Dozier et al. [12, 17] measured the growth performance of male broiler chickens kept in flocks of 53 birds at a diurnal temperature cycle. Simmons et al. [11] exposed the birds to air temperatures of 25–30–25°C over 24 h (sine curve) with dew point maintained at a constant temperature of 23°C at different air velocities. The reported results for the birds from the 5th to the 7th week of life are reproduced in **Figure 2**.

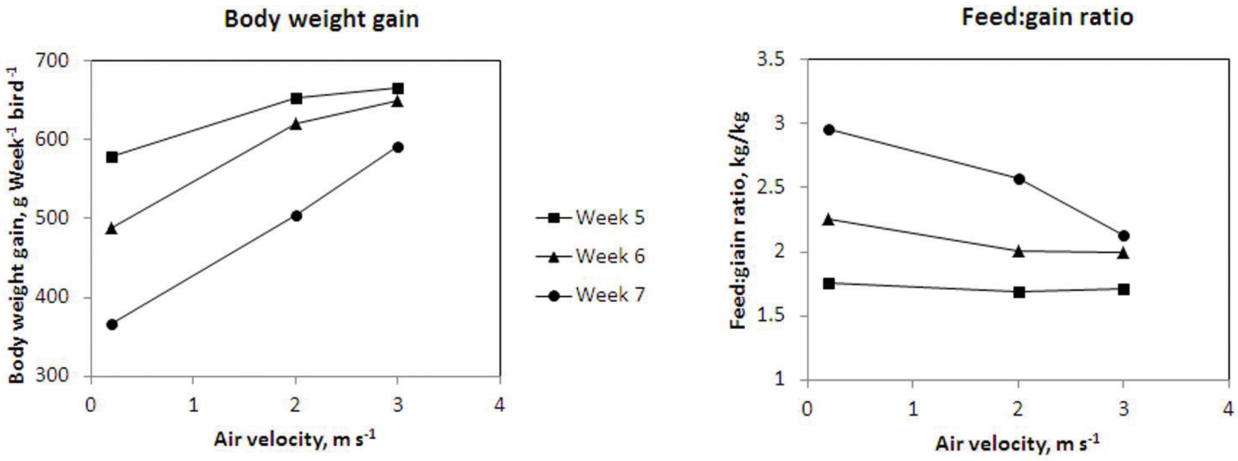

Figure 2. Body weight gain and feed conversion ratio during weeks 5–7 for broilers maintained at different air velocities at air temperatures controlled between 25 and 30°C in a 24-h sine curve and at a constant **dew point** of 23°C (based on the data by Simmons et al. [11]).

For both body weight gain and feed conversion ratio, **Figure 2** indicates a tendency to a reduced influence of the air velocity at an increased air velocity for birds at 5 and 6 weeks of age, but this tendency is not seen for birds at 7 weeks. A possible explanation can be that the younger birds already are close to their optimal production condition at an air velocity of 2 m/s and therefore they will experience a minor benefit due to further increase in the air velocity.

Dozier et al. [17] used a more extreme diurnal cyclic air temperature of 25–35–25°C (dew-point temperature still at 23°C) and reported measured body weight gain and feed conversion rate during weeks 5–7 as shown in **Figure 3**.

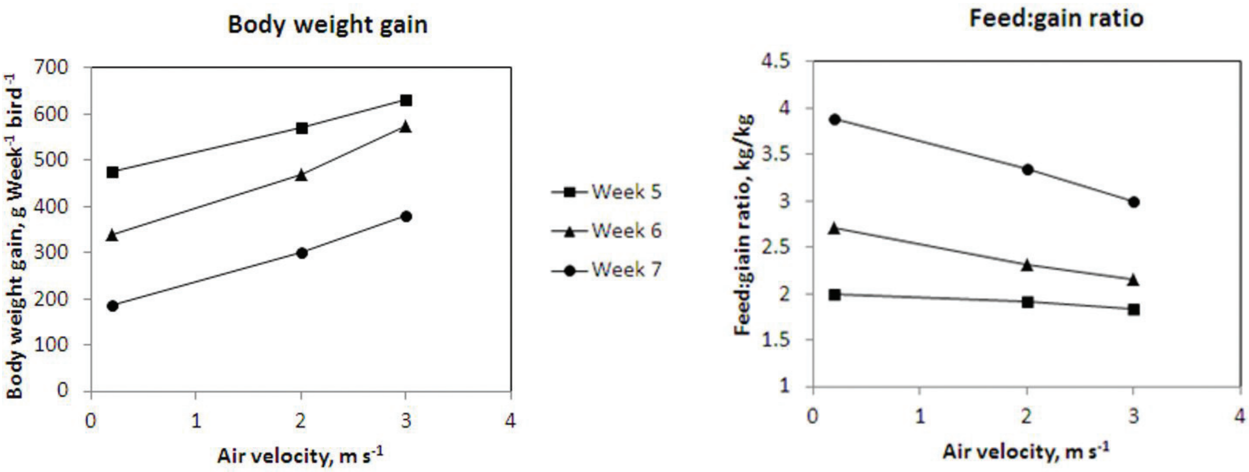

Figure 3. Body weight gain and feed conversion ratio during weeks 5–7 for broilers maintained at different air velocities at air temperatures controlled between 25 and 35°C in a 24-h cycle and at a constant dew point of 23°C [17].

The results consistently show that a linear influence of the air velocity may be valid for flocks of broilers at least up to an air velocity of 3 m/s.

In the absence of further data sets suitable for validation of Eq. (7), we tried to model the relative body weight gain reduction as a function of ET using data from different studies. This includes measurements in groups maintained at different air velocities and the same air temperature or maintained at different temperatures and the same air velocity. In that effort, we defined the relative body weight gain reduction (RBWR, % $°C^{-1}$) at a certain ET (°C) as

$$RBWR = \frac{(BWG_{Low\ \ ET} - BWG_{High\ \ ET}) \times 100}{0.5(BWG_{Low\,ET} + BWG_{High\ \ ET})\,0.5(Low\ \ ET + High\ \ ET)} \quad (8)$$

where *Low ET* is the ET at the condition for measurement with low heat load (°C); *High ET* is the ET at the condition for measurement with high heat load (°C); $BWG_{Low}\ ET$ is the body weight gain at low ET (g day^{-1} $bird^{-1}$); $BWG_{High}\ ET$ is the body weight gain at high ET (g day^{-1} $bird^{-1}$).

In addition, we assumed that the calculated RBWR was valid for ET = 0.5 (*Low ET* + *High ET*) and calculated relations between ET and RBWR for different values of *c* and *d* in Eq. (7) assuming either a linear or a square-root relationship with velocity. The best agreement with a quadratic model was found for a linear relationship with velocity (*e* = 1) and *c* = 0.15, *d* = 41, see **Figure 4**.

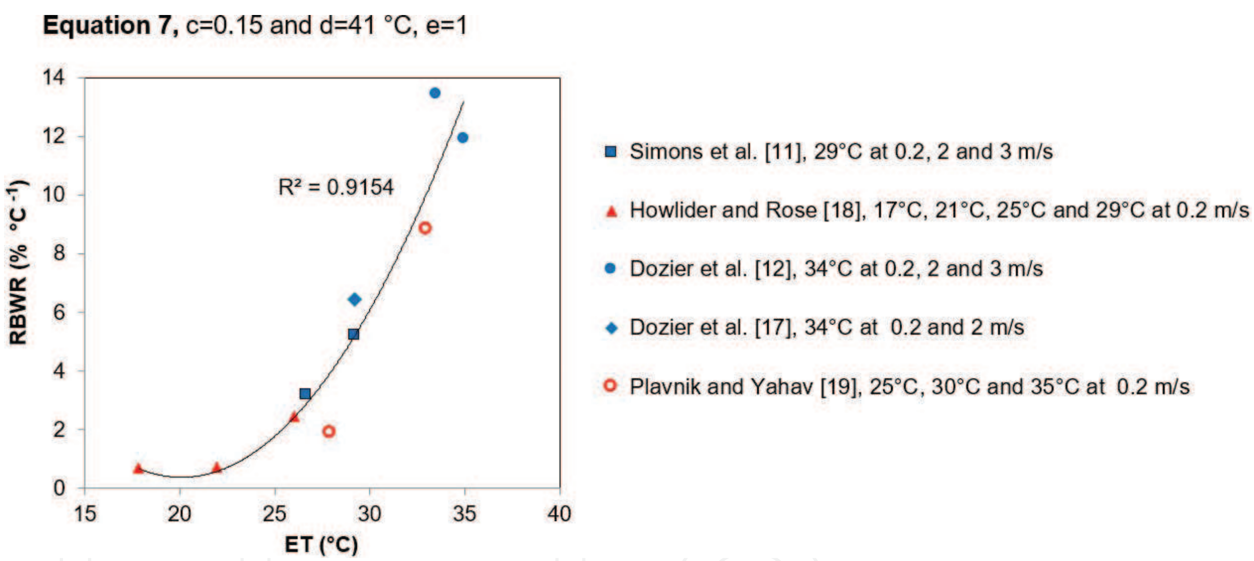

Figure 4. Relative body weight gain reduction (RBWR) for flocks of 22–56-day-old broilers maintained at different ETs calculated by Eq. (7).

The figure includes data from two studies [18, 19] comparing the body weight gain for flocks of broilers exposed to different air temperature treatments at the same air velocity and three studies [11, 12, 17] comparing the body weight gain for flocks of broilers exposed to different air velocities at the same air temperature treatment.

The study conducted by Howlider and Rose [18] included broiler chickens kept in 12 pens of 40 birds at each of four constant temperature levels (17, 21, 25, and 29°C) in the period from 22 to 49 days of age. Unfortunately, the authors did not report air velocity and air humidity during the study period. To identify a possible assumption for humidity to calculate ET, we investigated how the parameters *c* and *d* depended on two widely different assumptions—either a relative humidity of 50% or a dew point of 10°C. The two assumptions resulted in nearly identical values for the two parameters, and therefore, we assessed that both assumptions would be acceptable and decided to use the relative humidity of 50%, for the data presented by Howlider and Rose [18]. The authors provided separate weight gain data for male and female chickens, and it shows that males grew 20% faster than females, but a temperature increase from 17 to 29°C reduced the weight gain by 15% for both genders. This similar effect of increased temperature justifies that **Figure 4** includes studies with both genders as well as studies with males only.

The study by Plavnik and Yahav [19] included four groups of six male Cobb chickens exposed to each of four different temperature treatments during 6–8 weeks of age. The temperature treatment included three constant temperature levels (25, 30, and 35°C) and one treatment where the chickens were exposed to a diurnal cyclic temperature of **12 h at 25°C and 12 h at 35°C**. Compared with the cyclic temperature treatment, the body weight gain was increased to 63% at the constant 25°C treatment and decreased to 6% at the constant 35°C treatment. This indicates that the cyclic temperature treatment is comparable with a constant temperature that is only marginally lower than the temperature in the warmest part of the cycle. We utilized this relationship to assume that other studies involving cyclic temperatures [11, 12, 17] could be treated as studies where temperature was 1°C below the temperature in the warmest part of the cycle.

Dozier et al. [12] measured the growth of male broilers exposed to either still air or air velocity of 2 m/s from 28 to 49 days of age at a 25:30°C diurnal cyclic temperature conditions corresponding to those used by Simmons et al. [11] and Dozier et al. [17]. To investigate the significance of the abovementioned temperature assumption, we conducted additional calculations assuming temperatures either 0 or 2°C below the temperature in the warmest part of the cycle. This calculation did not change the parameters that resulted in the best agreement, but using the same temperature as in the warmest period resulted in slightly better agreement.

The articles that included different air velocities [11, 12, 17] do not provide detailed information on how the stated air velocities were measured, but apparently they are all conducted in the same wind tunnel facility and there is no indications of differences in velocity measurement procedures between the three studies.

The same articles report weekly weight gain data showing that the influence of velocity increases with age. Therefore, it is a source of uncertainty that has been necessary to incorporate studies that include different age intervals as shown in **Figure 4**, but **no measurements indicate** that the relative influence of temperature and velocity is affected by age.

If the assumed dependency of velocity is changed from a linear relationship ($e = 1$) to a square-root relationship ($e = 0.5$), then the R-square value for the best agreement between RBWR and ET is reduced from 0.92 to 0.72.

2.2.2. *Laying hens*

Uwagawa et al. [13] measured the effect of the air velocity and temperature on skin temperatures (at comb, shank, and wattle) for 78-week-old laying hens exposed to different air temperatures (10, 15, 20, 25, 30, and 35°C) and different air velocities (0, 1, 2, and 4 m/s), but no information about the air humidity was provided. The birds were individually exposed to the environment for 1.5 h before a 30-min measure period. We used the average of reported skin temperatures measured at comp, shank, and wattle to determine the values of c and d in Eq. (7)

that resulted in the best quadratic relationship with ET assuming either a linear or a square-root relationship with velocity. To investigate the significance of the lack of information on the air humidity, we made the calculation with two widely different assumptions, either that all measurements were conducted at 50% RH or that they all were conducted at dew-point temperature of 8°C. The latter causes a decrease in relative humidity from 87 to 18% for the temperature increase from 10 to 35°C. For both assumptions, the best correlation was found for a square-root relationship with velocity (*r*-square values of 0.99) at $c = 0.15$ and $d = 44$ (**Figure 5**).

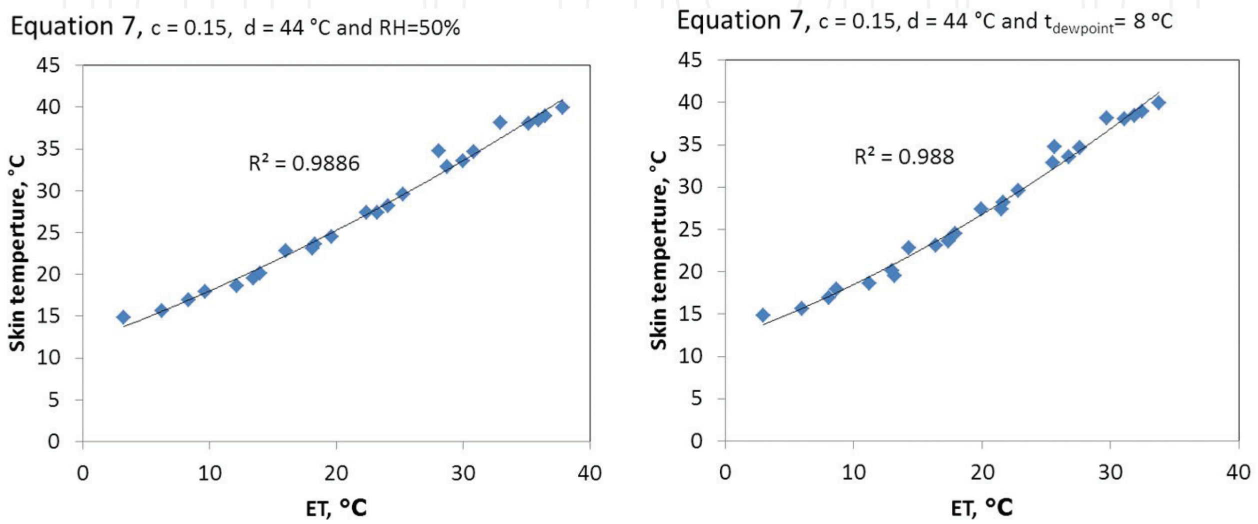

Figure 5. Skin temperature at different ETs calculated by Eq. (7) assuming $c = 0.15$, $d = 44$°C, and $e = 0.5$. Data originate from the study by Uwagawa et al. [13] and include exposure to different ambient temperatures (10, 15, 20, 25, 30, and 35°C) and different air velocities (0, 1, 2, and 4 m/s). The left-hand graph assumes a constant air humidity of 50% RH and the right-hand graph assumes a constant dew-point temperature of 8°C.

If the assumed dependency of velocity is changed from a square-root relationship ($e = 0.5$) to a linear relationship ($e = 1$), then the *R*-square value for best reflection of the data presented by Uwagawe et al. [13] is reduced from 0.99 to 0.97.

2.2.3. Pigs

Mount and Ingram [20] 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 measurements were conducted with a heat flow disc [21] 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 a stream of air vertically into the cage and the air speed was measured at 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 close to 0.08, 0.35, 0.60, and 1.00 m/s for each of five ambient temperatures (35, 30, 25, 20, and 15°C). Unfortunately, the authors did not provide information about air humidity and, therefore, we also in this case investigated the significance of different humidity assumptions. As in the former case, the parameters c and d in Eq. (7) that best reflected the measurements were unaffected of whether the relative humidity or the dew point was assumed to be constant. For all three weight ranges, the best correlations were found for a square-root relationship with velocity (R^2 between 0.91 and 0.98) at $c = 1.0$ and $d = 42$) (**Figure 6**). A linear relationship with velocity resulted in the best agreement with measurements at $c = 0.8$ and $d = 42$ and the r-square value was between 0.89 and 0.96 for the three weight ranges.

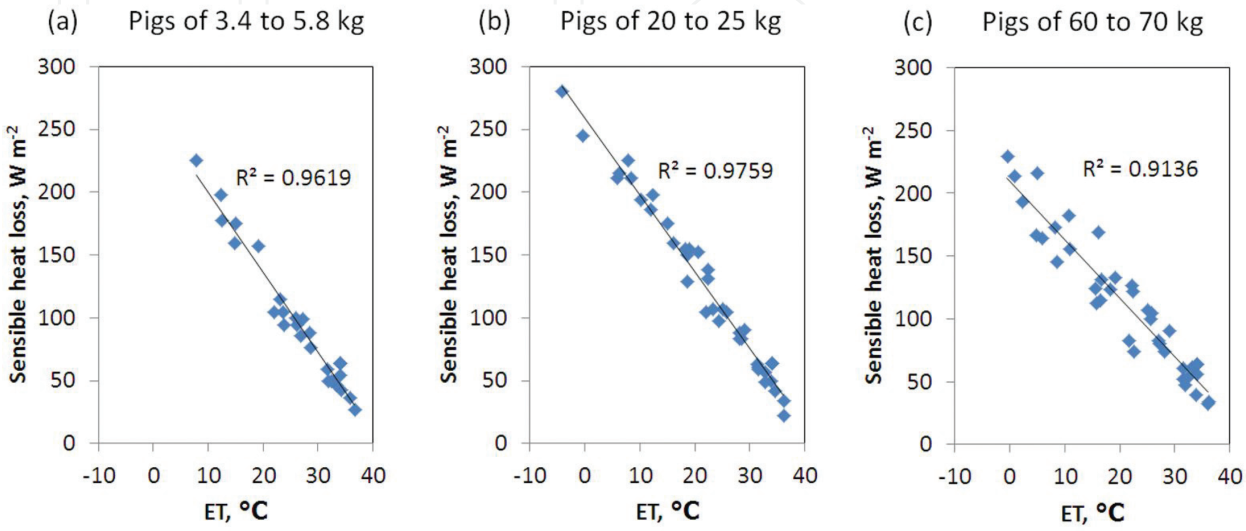

Figure 6. Sensible heat loss for pigs at different ETs calculated by Eq. (7) assuming $c = 1$, $d = 42°C$, 50% RH, and a square-root relationship with measurement. Data originate from mount and Ingram [20] and include exposure to different ambient temperatures (15, 20, 25, 30, and 35°C) at different air speeds (close to 0.08, 0.35, 0.60, and 1.00 m/s). The three graphs represent different weight ranges.

Massabie and Granier [22] 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 the air velocity. The authors inform 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 7** show that the ceiling fan increased the daily weight gain, but simultaneously it increased the feed conversion ratio.

The results presented in **Figure 7** indicate that the negative influence of increased temperature on daily gain begins at approximately 20°C without the air velocity and at a higher temperature if the pigs are exposed to the air velocity. At 28°C, the effect of the air velocity (an increase from 0.2 to 1.07 ms^{-1}) is equivalent to an approximately 5°C lower temperature without the air velocity. For the feed conversion ratio, the effect of velocity is equivalent to an approximately 3° lower temperature without the air velocity. These figures can be compared with the estimated influence of the air velocity on ET. Using Eq. (7) and assuming $t_{db} = 28°C$ and $t_{wb} = 23°C$, we calculated that an increase of an air velocity from 0.2 to 1.07 ms^{-1} can reduce the ET by approximately 4°C if $c = 0.42$ and $d = 39°C$. This calculation was based on an assumed linear relationship with velocity, but since data included only two levels of velocity it is equally

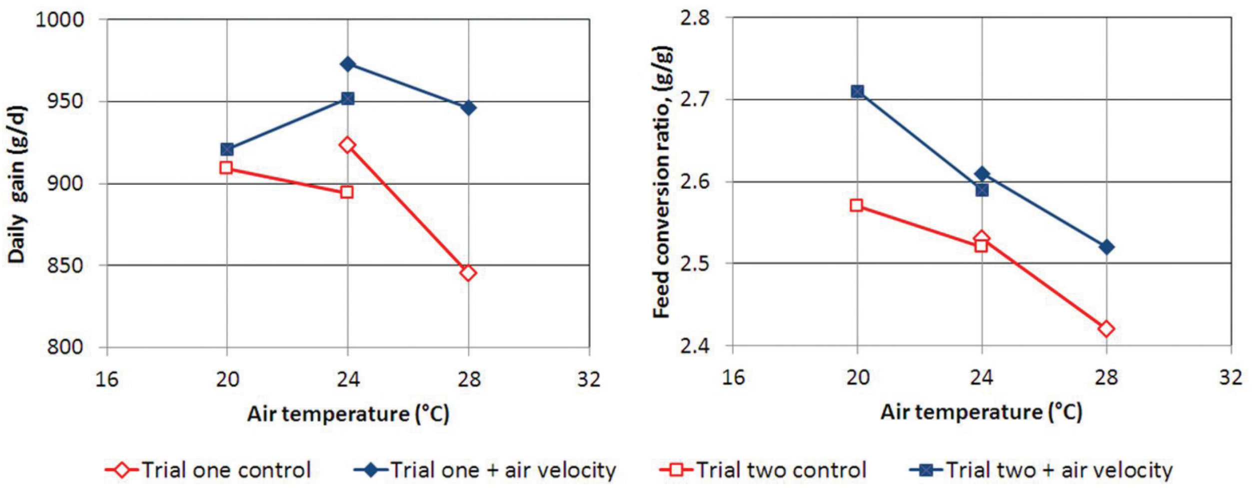

Figure 7. Daily weight gain (left-hand graph) and feed conversion ratio (right-hand graph) for finishing pigs maintained at different air temperatures with and without a ceiling fan to increase the air velocity from 0.56 to 1.3 ms^{-1} during the growth period (results reported by Massabie and Granier [22]).

relevant to assume a square-root relationship with velocity and that the assumption would change the parameter c to 0.62.

3. Discussion

Data from several studies [4, 6, 7, 9, 10] confirm that the THI calculated as Eq. (1) is an operational way to express the relative significance of air temperature and air humidity. The relative significance of the two parameters has been determined by analyzing which value of "a" provides the best agreement between a response parameter and the THI. **Table 1** includes 15 cases where a response variable was correlated to THI, and it appears that a-values between 0.55 and 0.90 best agreed with the used data. The cases include growing pigs, broilers, hens, and turkeys, and response variables included respiratory rate, body temperature, heat production, and performance results. As it appears from **Table 1**, the correlation coefficient in all 15 cases was nearly equally large at a = 0.75 as it was at the a-value that best reflected the data. Generally, the chapter shows that an a-value needs to differ relatively much from the value that best reflects the data before the correlation significantly degrades.

The work by Brown-Brandl et al. [8] regarding tom turkeys is the sole study that includes data systematically divided into animals at different ages, but the results are ambiguous and, therefore, not suitable to indicate how practical a-values should depend on the age of the animals. It is notable that Egbunike [5] found an a-value of equal magnitude in natural humid tropical environmental condition at relatively low heat load (t_{db} range from 25 to 33°C) as Roller and Goldman [4], Ingram [3], Tao and Xin [9], and Xin et al. [7] found at acute exposure to severe heat load (t_{db} range from 32 to 43°C). **Based on this, our assessment** is that the works we have reviewed do not include results that require or justify the use of different a-values for pigs or poultry, for large or for small animals, for different animal density, or for mild or severe heat load. We assess that an a-value of 0.75 is valid as a common applicable value.

The study by Tao and Xin [1] was the sole work found in this chapter that systematically investigated the combined influence of air temperature, air humidity, and air velocity. They proposed a THVI equation (Eq. 5) by extending the THI model with a correction factor ($v^{-0.058}$) to include the influence of the air velocity. Analyses in this chapter show that THVI overpredicts the influence of the air velocity if the air temperature approaches the animal body temperature. The data provided by Tao and Xin [1], however, support the assumption that the effect of increased velocity declines if the air temperature approaches the animal body temperature, which is the case in Eq. (7), and analyses in this study showed that the data provided by Tao and Xin [1] correlated remarkably well with Eq. (7).

Unfortunately, the article on skin temperature in laying hens [13] and the article on sensible heat loss from pigs [20] provide no information on air humidity. However, analyses in this study showed that data from both Uwagawa et al. [13] and Mount and Ingram [20] correlated very well with Eq. (7) at widely different assumptions for the air humidity.

For all three [9, 13, 20] a square-root relationship with velocity ($e = 0.5$) correlated slightly better with Eq. (7) than a linear relationship with velocity ($e = 1$). These studies all concern short-term exposure of individual animals to different thermal environments.

For broilers in flocks, other studies [11, 12, 18] indicate that it might be valid to assume a linear influence of the air velocity up to at least 3.0 m/s. The difference might be because the animals give shelter to each other and, therefore, reduce the effect of the air velocity. This hypothesis also explains why we found smaller influence of velocity ($c = 0.15$ instead of $c = 0.31$ at $e = 1$) in the analyses of body weight gain reduction for flocks of broilers. Provided that the velocity represents the velocity above the animals, the increase in animal density will increase the sheltering and consequently decrease the velocity among the animals, and an adjustment of the c-values appears to be an appropriate way to compensate for this relationship.

The study by Uwagawa et al. [13] on skin temperatures in laying hens indicated that Eq. (7) might be valid in a range of temperature of 10–35°C and air velocity of 0.2–4 m/s. As it was the case for the data presented by Tao and Xin [9] and by Mount and Ingram [20], a square-root relationship with velocity reflected the data slightly better than a linear dependency, which supports the choice of the square-root dependency in the estimation of ET for individually kept animals.

Tao and Xin [9] exposed the animals to thermal condition that increased their body temperature with up to about 4°C and that may explain why calculated parameter d was above the normal temperature for broilers. Correspondingly, the data by Uwagawa et al. [13] and by Mount and Ingram [20] included treatments with high temperatures and low air velocities that may have increased the animal body temperature and therefore explains why the parameter d also calculated from these data was above the normal temperature for the included animals. The data used for broilers in flock resulted in a d-value similar to the normal body temperature for broilers (40.6–43.0°C [23]) which matches the milder thermal load the animals in the included studies were exposed to.

As for broilers, the studies on pigs [20, 22] indicated a larger influence of velocity for individually kept animals than those kept in groups, which as mentioned for broilers can be explained by those group-housed animals that give shelter to each other.

The estimated influence of velocity (parameter *c* in Eq. (7)) was generally larger for pigs than for broilers, but these results may possibly be explained by the difference in used test facilities and methods to determine the air velocity.

The studies on individually kept animals [9, 13, 20] confirm the validity of the velocity term in Eq. (7), but, unfortunately, the used experimental conditions were widely different from animal production. Determinations of the parameters *c*, *d*, and *e* for practical use require data obtained from conditions corresponding to animal production. The included studies on broilers in flocks [11, 12, 17] are all conducted in an experimental wind tunnel, which, to some extent, are similar to commercial tunnel-ventilated broiler houses, although there are large differences in the tunnel scale and in the number of animals. The experimental condition used in the study on group-housed pigs [22] could possibly be implemented in pig production, but the uncertainty on how the air velocity was determined in this study limits the possibilities of exploiting the results.

Unfortunately, we did not find other studies to validate Eq. (7) or to estimate the parameters *c*, *d*, and *e* for other categories of pigs and poultry than broilers and finishing pigs kept in groups. But nevertheless, we assess that Eq. (7) is a valid way to express knowledge on the relative significance of air temperature, humidity, and velocity at high heat load for pigs and poultry. However, it is acknowledged that the influence of the air velocity is determined based on a very limited amount of data. Therefore, it is likely that future studies will generate more knowledge that improves estimations of the parameter in—and possibly also the structure of—the model for ET estimation and furthermore establishes parameters adapted to different species, different age groups, or different production levels.

4. Conclusions

Existing knowledge on the relative significance of air temperature, humidity, and velocity in the thermal environment for housed pigs and poultry is reviewed and synthesized in an ET equation (Eq. (7)) with an easily understandable scale, where ET is equal to air temperature if the relative humidity is 50% and the air velocity is 0.2 ms^{-1}. The suggested ET equation treats the relative significance of air temperature and humidity in the same way as the frequently used THI equation (Eq. (1)). Analyses of reported data suitable to determine the relative weighting of the dry-bulb temperature (*a* in Eq. (1)) in poultry and pigs show that the weighting with the best correlation with data differs a great deal, but the correlations are in all cases nearly equally good if a weighting corresponding to $a = 0.75$ is used. Consequently, a common *a*-value of 0.75 is used in the further development of the ET equation for broilers and pigs.

The dependence of velocity is treated as an additional term in the suggested ET equation. This term is assumed to be proportional to the difference between the animal body temperature and the room air temperature, and reported data were analyzed to determine whether a linear or a square-root relationship with velocity best reflected the data. Data from studies on body temperature increase of broilers [9], on skin temperature of laying hens [13], and on sensible heat loss of pigs [20] individually exposed to different thermal environment agreed well with the ET equation, and the agreement was slightly better with a square-root dependence of velocity than with a linear dependence.

The data from studies of animal groups are less clear, but indicated that the wind shading among the animals reduces the effect of the air velocity (the parameter c in Eq. (7)). For broilers in flocks, a linear dependency of velocity reflected data better than a square-root dependency.

Future studies on the influence of the air velocity may generate results that enable improvements of the ET equation and possibly generate different versions of the equation to deal with different species, age groups, and production levels. However, presently the proposed model and parameters might be useful in the assessment of the relative influence of air temperature, air humidity, and air velocity for groups of broilers or finishing pigs.

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