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ORIGINAL PAPER

Mean surface temperature prediction models for broiler chickens—a study of sensible heat flow

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Abstract Body surface temperature can be used to evaluate thermal equilibrium in animals. The bodies of broiler chickens, like those of all birds, are partially covered by feathers. Thus, the heat flow at the boundary layer between broilers' bodies and the environment differs between feathered and featherless areas. The aim of this investigation was to use linear regression models incorporating environmental parameters and age to predict the surface temperatures of the feathered and featherless areas of broiler chickens. The trial was conducted in a climate chamber, and 576 broilers were distributed in two groups. In the first trial, 288 broilers were monitored after exposure to comfortable or stressful conditions during a 6-week rearing period. Another 288 broilers were measured under the same conditions to test the predictive power of the models. Sensible heat flow was calculated, and for the regions covered by feathers, sensible heat flow was predicted based on the estimated surface temperatures. The surface temperatures of the feathered and featherless areas can be predicted based on air, black globe or operative temperatures. According to the sensible heat flow model, the broilers' ability to maintain thermal equilibrium by convection and radiation decreased during the rearing period. Sensible heat flow estimated based on estimated surface temperatures can be used to predict animal responses to comfortable and stressful conditions.

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Introduction

Surface temperature is used widely as a parameter to evaluate the comfort or thermal stress of broiler chickens (Malheiros et al. 2000; Shinder et al. 2007; Cangar et al. 2008). In birds, variations in body surface temperature are related directly to peripheral blood flow, which can indicate that animals are actively attempting to maintain their core body temperature.

Increasing surface temperatures correspond to increased blood flow near the body surface and heat loss through sensible routes. In contrast, decreases in blood flow are related to peripheral vasoconstriction. This phenomenon is observed when a chicken is experiencing thermoneutral or cold stress conditions. Skin surface temperature is an important evaluable parameter that varies rapidly with environmental changes and can be used to indicate changes in peripheral blood flow and heat exchange. The contributions of different body regions to the maintenance of thermal equilibrium have been studied widely (Richards 1971; Malheiros et al. 2000; Shinder et al. 2007). However, additional information regarding the contributions of different body regions during the rearing period is needed. Furthermore, it is unknown whether different strains exhibit distinct surface temperature profiles under comfortable and thermally stressful conditions. According to Yahav et al. (2004), the quantification of heat losses from different body regions is necessary to estimate the sensible heat exchange of broilers with their surroundings. Therefore, models that predict the mean surface temperatures of birds based on the temperatures of their conservative and responsive vasomotor regions, such as the foot and comb, are important. These models could be used to estimate the sensible heat exchanges that occur through radiation and convection.

Models and methods that can be applied easily to practically predict the mean surface temperature of broilers are lacking. Such models and methods could also be used to calculate sensible heat exchange. The model proposed by Richards (1971) was used in a study in which poultry temperature was measured with surgically implanted thermoresistors and thermocouples. Although the model was applied to feather temperatures (e.g., Malheiros et al. 2000), the temperature measurements were conducted on poultry skin. Skin temperature is always higher than feather temperature; thus, the temperatures in this latter study were underestimated. In addition, broiler surface temperature varies with age (Richards 1970). Thus, models that consider bird development on a weekly or daily basis during the rearing period are needed.

The objectives of this research were as follows: to determine the sensible heat flow between broiler surface and the environment during the rearing period, under both comfortable and stressful conditions; to use multiple linear regression models to calculate the surface temperatures of broilers based on environmental measurements; and to use another databank to test the prediction of sensible heat flow based on the estimated surface temperature models.

Materials and methods

This research was conducted in a climate chamber (2.25 m× 3.75 m) obtained from the Ambience Research Nucleus of the Biosystems Engineering Department at the "Superior School of Agriculture Luiz de Queiroz—University of São Paulo" located in Piracicaba city (22° 42′S, 47° 38′W; altitude 546 m). Two broiler chicken strains (Cobb and Avian) were exposed to comfortable and stressful conditions. During their first days of life, broilers are more sensitive to low air temperatures and should be raised at environmental temperatures of approximately 32 °C–35 °C. Lower temperatures can increase the incidence of hypothermia and ascites (Mickelberry et al. 1966; Maxwell and Robertson 1998, cited in Malheiros et al. 2000). As they grow, birds become more vulnerable to high temperatures, and air temperatures above 32 °C are considered to represent a stressful condition (Cooper and Washburn 1998). The experimental conditions for the climate chamber control were pre-established based on these observations; these conditions are described in Table 1.

A total of 576 broilers were analyzed during the trial, distributed in two groups of 288 birds. One group was used to establish linear regression models to predict body surface temperature, and the other group was used to test the predictive power of these models. To develop the linear regression models to predict body surface temperatures, 48 broiler chickens per week were analyzed, giving a total of 288 broiler chickens in the 6 weeks of the rearing period. The birds were divided into four flocks of 12 animals each on a weekly basis. Each group contained six birds from each strain as an experimental unit. The birds were analyzed for the first 4 days of each week. All of the birds were exposed to both comfortable and stressful conditions. The same amount of data (from 288 broilers) was measured to test the predictive power of the proposed models. The birds were distributed into two pens of 1 m^2 (one strain per pen) at a density of 12 birds m^{-2}. The groups were homogeneous, with gender distributed randomly in each of the studied flocks. The birds were raised in a conventional facility and were transferred to a climate chamber during the evaluation days. Water and food were available ad libitum. Inside the chamber, the air temperature, relative humidity and black globe temperature were measured at 10 min intervals by a data logger (Hobo, http://www.onsetcomp.com/). The wind speed was kept constant at 0.5 m s^{-1} throughout the experimental period.

The birds were exposed to different environmental conditions for 30 or 60 min to establish stress and for 60 min to establish comfort. The stress exposure duration influences the thermal sensations experienced by the animals and their physiological responses. The durations of exposure to the

Table 1 Environmental condition variables [air temperature (T_a), black globe temperature (T_g), operative temperature (T_o) and relative humidity (RH)] corresponding to comfortable and stressful conditions during the 6-week broiler chicken rearing period

Week of rearing period	Comfortable condition				Stressful condition			
	T_a (°C)	T_g (°C)	T_o (°C)	RH (%)	T_a (°C)	T_g (°C)	T_o (°C)	RH (%)
1st	33.8	34.0	33.9	50	29.3	29.6	29.6	60
2nd	30.9	31.1	31.1	60	24.6	25.1	25.1	70
3rd	27.5	27.9	27.8	70	36.7	36.9	36.9	50
4th	25.3	22.3	22.5	70	35.6	35.7	35.7	50
5th	22.8	23.3	23.3	70	34.7	34.9	34.8	60
6th	22.2	23.0	23.0	70	34.3	34.3	34.2	50

stressful condition were selected based on a study by Yanagi Jr et al. (2001), which used a minimum exposure time of 20 min. In this case, it was assumed that a period of 20 min was required for the birds to achieve stable thermoregulatory processes.

The exposure time was also based on the previous report by Richards (1971), who documented surface temperature measurements of birds after at least 30 min.

The body temperatures of the birds were measured with an infrared thermometer (Fluke 566, http://www.fluke.com) at the end of the exposure times in the chamber. Five body regions were selected for evaluation, including the back, wing and head (feathered areas) and the foot and comb (featherless areas).

A cluster analysis was used to identify the proximity of the different body regions. This analysis was used to determine whether the surface temperatures of the bodies could be modelled with a unique model and whether it was necessary to distinguish between feathered and featherless areas. The distances between each pair of body regions were calculated using the procCLUSTER nearest neighbour estimation in SAS (2009) software. A dendrogram was used to clearly distinguish the studied body regions [procTREE in SAS (2009)].

A previously described model was adopted to determine the sensible heat exchange per unit of body surface area between the broilers and the environment (Maia et al. 2005). For the feathered body areas, this model was based on temperature differences between the animal surface and the operative temperature (Eq. 5). The operative temperature accounts for the relationship between the air and mean radiant temperatures and the boundary layer resistance to convection and long wave radiation. The model is represented by the following equation:

$$G_s = \frac{\rho\ c_p}{r_o}(T_s - T_o) \tag{1}$$

where G_s is the sensible heat exchange between the broiler and the environment (W m^{-2}), ρ is the air density (g m^{-3}), c_p is the air specific heat (J g^{-1} K^{-1}), r_o is the resistance of the boundary layer to the sensible flow (m s^{-1}), T_s is the body surface temperature (K) and T_o is the operative temperature (K) (a combination of the mean radiant and air temperatures).

The resistance of the boundary layer to sensible heat flow was calculated by considering the long-wave radiation and convection flows occurring in parallel, as described by the following equation:

$$r_o = \frac{r_h\ r_l}{r_h + r_l} \tag{2}$$

where r_h is the boundary layer resistance to convective flow (s m^{-1}) and r_l is the boundary layer resistance to long wave radiation flow (s m^{-1}). These parameters are defined in the following equations:

$$r_h = \frac{\rho\ c_p d_b}{k\ \ Nu} \tag{3}$$

$$r_l = \frac{\rho\ c_p}{\varepsilon_s \sigma \left(T_s + \overline{T_R}\right)\left(T_s^2 + \overline{T_R^2}\right)} \tag{4}$$

where d_b is the average diameter of the body of the broilers (m) that was calculated with the equation proposed by Mitchell (1930), k is the air thermal conductivity (W m^{-1} °C^{-1}), Nu is the dimensionless Nusselt number, ε_s is the emissivity of the skin [0.98 in the calculation for the featherless body regions, which is the value recommended for biological tissues (Steketee 1973), and 0.94 for the calculation of the feathered areas (Malheiros et al. 2000)], σ is the Stefan-Boltzmann constant (5.67051 × 10^{-8}, W m^{-2} K^{-4}) and $\overline{T_R}$ is the mean radiant temperature (K).

The operative temperature (T_o, K) is calculated as follows:

$$T_o = \frac{r_h \overline{T}_R + r_l T_A}{r_l + r_h} \tag{5}$$

where T_A is the air temperature (K).

Dimensionless numbers were calculated as shown in Table 2 by assuming the birds to have the geometric shape of a sphere.

To test the predictive power of the model, the simulated data from the linear regression models of the feathered areas and featherless areas were compared to the measured values using the mean square deviation (MSD) as described in Kobayashi and Salam (2000).

$$MSD = SDSD + LCS + SB \tag{6}$$

where SDSD is the difference in the magnitude of fluctuation between the simulated and measured values, LCS is the lack of positive correlation weighted by the standard deviation and SB is the bias of the simulation for the measurements.

Results

To define the models used for body surface temperature prediction, a cluster analysis was performed to determine the distances between each of the studied areas. The resulting dendrogram indicated a clear difference between the body temperatures of the feathered and featherless regions, independently of the week of the rearing period. Therefore, two clusters were defined based on the minimum distances between regions with different body temperatures. The first cluster consisted of the wing, back and head, and the second cluster consisted of the foot and the comb. Based on these

Table 2 Dimensionless numbers of sensible heat flow in bodies modelled as spheres. All properties were measured at the ambient (air) temperature (T_A)

Number	Equation[a]
Nusselt (Nu) – natural convection	$2+\frac{\left\{0.589(Gr\ \ \mathrm{Pr})^{\frac{1}{4}}\right\}}{\left\{1+\left(\frac{0.469}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right\}^{\frac{4}{9}}}$
Nusselt (Nu) – forced convection	$2+\left\{0.4\left(\mathrm{Re}^{\frac{1}{2}}\right)+\left(0.06\ \ \mathrm{Re}^{\frac{2}{3}}\right)\right\}\left(\mathrm{Pr}^{0.4}\right)$
Grashof (Gr)	$\frac{g\ \ d_b^3(T_s-T_A)}{v^2 T_A}$
Reynolds (Re)	$\nu\ d_b\ V^{-1}$
Prandtl (Pr)	$\rho c_p v k^{-1}$

[a] Where ν is the kinematic viscosity of the air ($m^2\ s^{-1}$), d_b is the diameter of the body (m), V is the wind speed ($m\ s^{-1}$) and g is the acceleration due to gravity for a given location ($m\ s^{-2}$)

observations, distinct linear regression models were proposed for feathered and featherless areas.

A correlation analysis indicated that surface temperatures of the body regions were highly dependent on air temperature, mean radiant temperature, relative humidity and black globe temperature, with values of 0.83 ($P<0.0001$), 0.79 ($P<0.0001$), −0.75 ($P<0.0001$) and 0.82 ($P<0.0001$), respectively. The surface temperatures did not differ between the Cobb and Avian strains ($P=0.1099$).

Thus, linear regression models incorporating the day of the rearing period (from 1 to 42), the air, operative and black globe temperatures and the relative humidity were proposed. The models for the feathered and featherless regions are shown in Tables 3 and 4, respectively. In addition, the coefficients of determination (adjusted R^2) for the models are presented in Tables 3 and 4.

To test the predictive power of the models, the simulated data from the linear regression models of the feathered areas (Table 3) and featherless areas (Table 4) were compared to the measured values via calculation of the mean square deviation (MSD). The MSD results for the feathered and featherless body regions are shown in Figs. 1 and 2, respectively. The three models developed for the feathered body regions presented low values for SB, and the model based on the air temperature showed a lower SDSD, and consequently a lower MSD, than the models based on the operative and black globe temperatures. The two models tested for the featherless body regions also presented lower SB values and similar values of SDSD, but the LCS was higher than that in the model based on the air temperature, which also presented the highest MSD.

Table 4 Linear regression models to predict the estimated surface temperatures (T_s, °C) of the featherless body regions across environmental conditions and age. Data are presented with the respective coefficients of determination

Environmental variable	Linear regression model	R^2 adjusted
Air temperature (T_a, °C)	T_s=20.63+0.005 day+0.53 T_a−0.084RH	0.74
Operative temperature (T_o, °C)	T_s=24.25+0.081 day+0.46 T_o−0.109RH	0.72
Black globe temperature (T_g, °C)	T_s=25.01+0.082 day+0.45 T_g−0.115RH	0.72

The coefficients of correlation between the temperatures of the feathered regions and the temperatures predicted by the linear regression models were 0.91 ($P<0.0001$) for the air temperature and 0.90 ($P<0.0001$) for the operative and the black globe temperatures. Moreover, the relative humidity and air temperature were highly negatively correlated (−0.91; $P<0.0001$), indicating that the surface temperature estimates based on air temperature and relative humidity provide similar results.

Therefore, the following equation can be used to estimate the black globe temperature (T_G, °C) as a function of air temperature (T_A, °C) (for facilities with any heat source):

$$\mathrm{Tg} = 0.08907 + (1.007\mathrm{T_A}) \quad (7)$$

The sensible heat flow per unit of body surface area between broilers and the environment was calculated for the 6-week trial condition rearing period as a function of the differences between the feathered surfaces (wing, head and back) and the operative temperature (Fig. 3). Sensible heat flow did not differ between strains ($P=0.7428$), and the general mean was 69 W m^{-2}. Sensible heat flow differed for the weeks of the rearing period in decreasing order ($P<0.0001$). A higher flow was observed in the 1st and 2nd weeks of the rearing period (72 W m^{-2} and 108 W m^{-2}, respectively). The flow decreased over the subsequent 4-weeks, and a mean of 53 W m^{-2} was observed in the 6th week of the rearing period.

Table 3 Linear regression models for the prediction of surface temperature (T_s, °C). Equations were constructed based on the environmental variables of the feathered regions and the age during the rearing period and are presented with their respective coefficients of determination

Environmental variable	Linear regression model	R^2 adjusted
Air temperature (T_a, °C)	T_s=16.93+0.007 day+0.60 T_a−0.009RH	0.68
Operative temperature (T_o, °C)	T_s=19.22+0.009 day+0.55 T_o−0.024RH	0.67
Black globe temperature (T_g, °C)	T_s=19.91+0.010 day+0.54 T_g−0.030RH	0.67

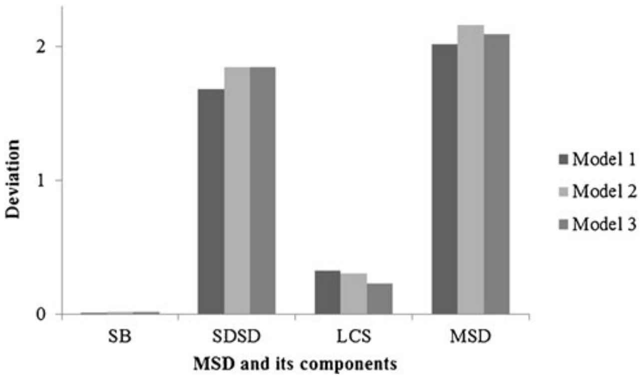

Fig. 1 Comparisons between the mean square deviation (MSD) and its components, the lack of correlation weighted by the standard deviation (LCS), the squared difference between the standard deviations (SDSD) and the squared bias for the linear regression models for feathered body regions as a function of the following parameters: air temperature, relative humidity and broiler age (Model 1); operative temperature, relative humidity and broiler age (Model 2); and black globe temperature, relative humidity and broiler age (Model 3)

The total sensible heat loss during the rearing period as a function of the experimental condition (comfortable or stress for 30 and 60 min) is shown in Fig. 4. Broilers exhibit a higher sensible heat loss through convection and radiation under comfortable conditions than under stressful conditions ($P<0.0001$). Means of 91 W m^{-2} and 58 W m^{-2} were observed under comfortable and stressful conditions, respectively.

From the proposed linear regression model incorporating the air temperature and the age of the broilers during their rearing period, sensible heat flow can be estimated (G_{sest}) by Eq. (8) below. These models also consider the age of the chicken (day of life) because this is intrinsically related to the live weight of the animal and is more easily measured in the field.

$$G_{sest} = \frac{\rho \ c_p}{r_o}\{(16.93 + 0.007\text{day} + 0.60T_A - 0.009RH) - T_o\} \quad (8)$$

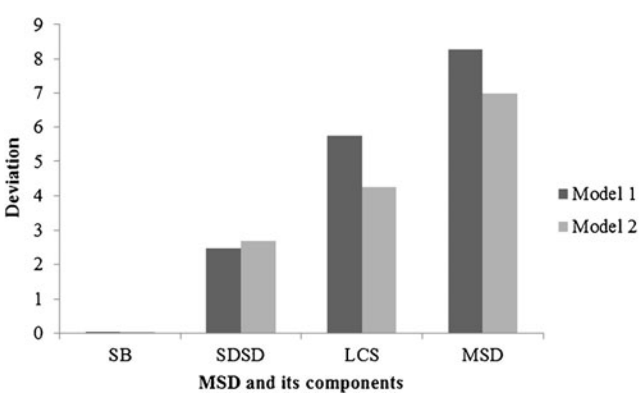

Fig. 2 Comparisons between the MSD and its components, the lack of correlation weighted by the LCS, SDSD and the squared bias for the linear regression models of featherless body regions as a function of the following parameters: air temperature, relative humidity and broiler age (Model 1); black globe temperature, relative humidity and broiler age (Model 2)

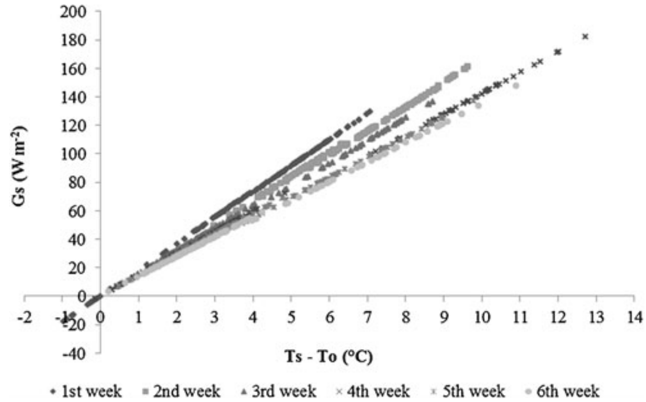

Fig. 3 Sensible heat flow (W m^{-2}) of broiler chickens throughout the 6-week rearing period as a function of the difference between the feathered body region temperature (T_s) and the operative environment temperature (T_o)

The correlation coefficient between the estimated (G_{sest}) and the measured (G_s) sensible heat flow of the feathered regions was 0.86 ($P<0.0001$). Thus, the proposed model can be considered reliable and useful under both field and practical conditions.

Discussion and conclusions

A difference in surface temperature between the feathered and featherless body regions was observed, as has been well described in the literature (Richards 1971; Malheiros et al. 2000; Shinder et al. 2007). However, in this study, a difference between the feathered and featherless areas was also observed at the beginning of the rearing period. Broilers acquire thermoregulatory maturity during the early postnatal development (Tzschentke 2007), at approximately 10 days post-hatching (Moraes et al. 2003). We speculated that the

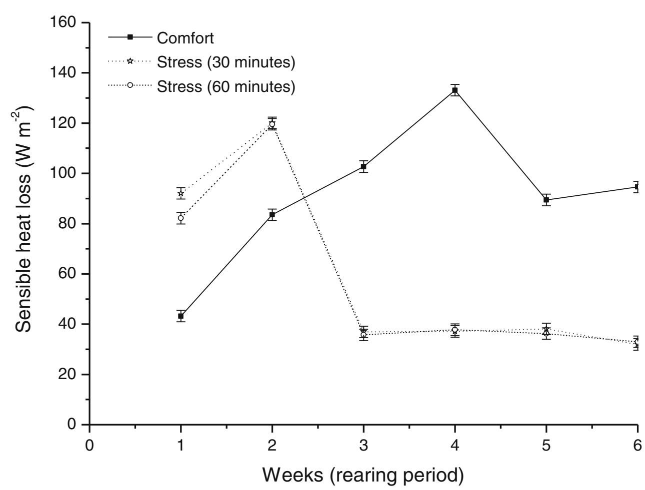

Fig. 4 Total sensible heat loss (W m^{-2}) of broiler chickens throughout the 6-week rearing period under comfortable and stressful conditions (exposure for 30 and 60 min)

immaturity of the thermoregulatory mechanisms might lead to a lack of distinction between feathered and featherless body areas within the first 2 weeks of the rearing period, but this was not observed. Rather, our results indicate that the models used to predict broiler surface temperature must consider the differences between the feathered and featherless areas throughout the entire rearing period.

Thus, measurement of the mean surface temperature of poultry bodies is essentially meaningless. Instead, a clear distinction between feathered and featherless areas and their individual contributions to heat flow must be considered. In addition, the sensible heat flow varies between the feathered and featherless regions of the body and needs to be distinguished. Few studies have described the contributions of different body surface regions to heat flow (Yahav et al. 2005; Shinder et al. 2007). The first results regarding the contribution of featherless and feathered areas, considering the legs as a responsive vasomotor organ and the face as a conservative vasomotor organ, were reported by Shinder et al. (2007). Yahav et al. (2005) described differences in the surface temperatures of many body areas (comb, wattles, face, legs, toes, neck, body and wings). However, some adjustments of the geometries of these areas must be performed in further studies.

The high correlation coefficients between the surface temperatures of the birds and environmental variables confirms that air temperature, relative humidity and wind speed are the main factors that affect broiler performance (Giloh et al. 2012). However, wind speed was not included in our regression models because it was kept constant at 0.5 m s^{-1} throughout the rearing period in our trials. In addition to wind speed (Dozier et al. 2005), air temperature has a major influence on the maintenance of body temperature of broilers (Yahav et al. 2009).

Therefore, the linear regression models included the environmental variables and the day of the rearing period (from 1 to 42); age is an important factor that affects broiler surface temperature (Cangar et al. 2008). To establish the linear regression models, all tested variables were included in the initial model. Simpler models were also generated, and the best models were selected based on the adjusted R^2 values. Thus, three linear regressions were proposed to model feathered and featherless body regions. Each model presented the same adjusted R^2 as the model incorporating all variables. Estimated models included one environmental variable (air, operative or black globe temperature), relative humidity and broiler age.

To test the predictive power of the models, the simulated data from the linear regression models of the feathered and featherless areas were compared to the measured values using the mean square deviation (MSD). The surface temperature of the featherless body regions was better predicted by model 2 (smaller MSD). The small SB value in model 2 also suggests that this model more accurately predicts surface temperature and shows a closer relationship between measured and predicted values. This result demonstrates the importance of considering the black globe temperature of the environment. The application of the black globe temperature-based model can be useful during the starter phase of birds. During this phase, long-wave radiant heat sources are commonly used to warm the broilers, and the quantification of this effect is important. The linear regression model based on the black globe temperature is also the most appropriate model for use in open facilities.

The surface temperature of the feathered areas can be measured by any of the three models (the calculated MSD values were similar). Furthermore, the mean values that were predicted by the three regression models were close to the observed values (as observed through the SB values). Using this model, the surface temperatures of the poultry can be estimated easily based on simple measurements in the field. Air temperatures strongly affect broiler response (Yahav et al. 2009; Horowitz 1998). Because air temperatures and broiler response are correlated, the air temperature can be used to predict the temperatures of feathered body regions. This method is particularly useful for situations in which adequate instruments, such as infrared cameras or infrared thermometers, are unavailable.

Nääs et al. (2010) developed two functions to predict the temperature of feathered and featherless body areas of broilers. However, this model can be applied only to birds on the 42nd day of the rearing period, which greatly limits its practical application. The model described by Richards (1971) has also been used to predict skin surface temperature. Other authors (Malheiros et al. 2000; Nascimento et al. 2011) used this model to estimate the temperature of feathered regions, but this model underestimated the actual values. In addition, in the model proposed by Richards, the temperatures of several body areas must be measured (back, head, wing and foot) with adequate instrumentation, which could be limiting under field conditions.

Thermal sensitivity to high temperatures increases with the live weight of the animal (Lin et al. 2005). The surface temperature of a bird is determined by the heat loss from the body core to the skin. In addition, this temperature is modulated by the rate of heat loss, which depends on blood flow from the inside to the outside of the body (Lin et al. 2005). Richards (1973) affirms that this temperature depends on the internal and external insulation of the birds, which can cause the high flow resistance that was observed from weeks three to six of the rearing period.

The difference between the feathered body region temperature and the operative temperature was higher when the birds were exposed to comfortable conditions. In addition, the majority of the heat loss occurred through sensible pathways. Furthermore, the difference between the feathered body region temperature and the operative temperature decreased under stressful conditions. In this case, evaporative mechanisms (mainly respiratory evaporation) assumed a more important role in maintaining thermal equilibrium. This result can be observed indirectly as an accentuated increase in the respiration rate of the broilers (Nascimento et al. 2012).

Wathes and Clark (1981) report that the sensible heat flow in poultry increases with age from 1 to 9 days, remains constant until 21 days and then decreases considerably until 42 days of age. In this trial, the broilers exhibited different heat flow under comfortable and stressful conditions. In addition, it was observed that even 30 min of exposure to a stressful condition resulted in a decrease in sensible heat flow. This result was related to the higher broiler area-to-volume proportion in the first days of life, which leads to greater losses of heat through the body surface. The development of feathers during the rearing period increases the heat stress susceptibility of the animal by elevating its temperature. Aerts and Berckmans (2004) verified that a decrease in sensible heat flow occurred after 25 days of life and that minor flow was observed during the later stages of the lifecycle. These trends were also observed in our study.

We believe that these findings could be helpful in estimating sensible heat flow in broilers under field and experimental conditions. The surface temperatures of feathered and featherless areas of chickens during the rearing period can be predicted based on environmental parameters and the age of the chicken. Broilers have a higher sensitivity to thermal stress in later life stages, and this phenomenon is reflected by the estimation of sensible heat flow.

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