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Alternative form to obtain the black globe temperature from environmental variables

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Abstract. Reaching thermal comfort conditions of animals is essential to improve well-being and to obtain good productive performance. For that reason, farmers require tools to monitor the microclimatic situation inside the barn. Black Globe-Humidity Index (BGHI) acts as a producer management tool, assisting in the management of the thermal environment and in decision making how protect animals from heat stress. The objective of this work was to develop a mathematical model to estimate the black globe temperature starting from air temperature, relative humidity and air velocity. To reach this goal, data of air temperature and humidity were collected, with the aid of recording sensors. The black globe temperature was measured with a black copper globe thermometer and the air velocity was monitored with a hot wire anemometer. Data were analysed using a regression model to predict the black globe temperature as a function of the other variables monitored. The model was evaluated, based on the significance of the regression and the regression parameters, and the coefficient of determination (R^2). The model proved to be adequate for the estimation of the black globe temperature with $R^2 = 0.9166$ and the regression and its parameters being significant ($p < 0.05$). The percentage error of the model was low (approximately 2.2%). In conclusion, a high relation between the data estimated by the model with the data obtained by the standard black globe thermometer was demonstrated.

Key words: thermal comfort, black globe temperature, black globe-humidity index, animal housing.

The animal breeding system in the intensive form is increasing, because the food demand of the world population has grown significantly. Therefore, this breeding system stands out and attracts investments, since it presents high productivity when well operated (FAOSTAT, 2015). The climatic variations influence the animal metabolism and consequently can compromise the performance, affecting the profitability of the productive activity. In a breeding system, the animals should remain within their range of thermoneutrality and environmental thermal comfort conditions should be reached (Baêta & Souza, 2010), to avoid that climatic conditions can negatively influence production and well-being.

The four major environmental factors that influence effective temperature are: dry-bulb temperature, humidity, radiation and air movement.

Thermal comfort can be evaluated by means of thermal comfort indexes that integrate two or more microclimatic elements. A variety of indexes are used to predict comfort or discomfort of environmental conditions and then estimate the degree of heat stress affecting the animals (Herbut et al., 2018). Generally, the two environmental parameters considered have been air temperature and relative humidity. The most common index is the Temperature-Humidity Index (THI), which uses the dry-bulb temperature (Tdb) and the wet bulb temperature (Twb) to estimate the magnitude of heat stress (Thom, 1959).

The THI was studied by several researchers (Ingraham et al., 1979; Buffington et al., 1981; Gaughan et al., 2008) and used to evaluate the thermal comfort of animals of different species (Campos et al., 2001; Klosowski et al., 2002; Turco et al., 2008; Gantner et al., 2011; Herbut & Angrecka 2012). Because of the differences in sensitivity to ambient temperature and amount of moisture in the air among species, a range of equations for calculation of THI with different weightings of dry-bulb temperature (Tdb) and air moisture have been proposed.

The general equation to calculate THI can be expressed by the following equation (CIGR, 2006):

$$\mathrm{THI} = a\mathrm{Tdb} + b\mathrm{Twb} + c \qquad (1)$$

where Tdb is the dry-bulb temperature, Twb is the wet-bulb temperature, a, b, c are constants depending on species.

Dikmen & Hansen (2009) compared eight different THI indices to verify if rectal temperature of Holstein cows is related to THI and other environmental parameters. In particular two of the eight indexes showed a very high correlation with Tdb. As conclusion, for the authors, at a practical level, the predictive value of THI is only slightly better than Tdb alone and Tdb is nearly as good a predictor of rectal temperature of lactating Holsteins in a subtropical environment as THI.

Oliveira et al. (2017) argue that the evaluation of thermal comfort through the indexes is an important tool to help producers in the choice of thermal solutions inside a building.

Another important index used to evaluate the thermal environment and the stress conditions of the animals is based on the black globe temperature. In literature the index based on the black globe temperature is called black globe and humidity (BGHI) or wet-bulb globe temperature (WBGT). In any case, the index requires measuring the black globe temperature, using a black globe thermometer, a device consisting of a thin copper sphere (usually 0.15 m diameter), black painted with a temperature sensor in the centre. The black metal ball absorbs radiant heat, and raises the temperature inside. It gives indirect information about the contribution of radiation and wind speed (°C).

The WBGT is very popular due to its simplicity and ease of use in industry, sports and other areas to indicate the heat stress level for humans and animals (Brake & Bates, 2002; Dimiceli e al., 2011; Golbabaei et al., 2014; Vatani et al., 2015).

The Black Globe Humidity Index (BGHI) integrates dry-bulb temperature, humidity, net radiation, and air movement into a single value. BGHI is created by inserting the black globe temperature (instead of the dry-bulb temperature) in the THI equation.

The BGHI is a very precise indicator of the thermal comfort of the animal in comparison to the THI, in conditions of the external environment presenting high solar radiation or air velocity (Buffington et al., 1981). Consequently, BGHI is a more accurate indicator of animal comfort and production than the THI under heat-stressing environmental conditions when animals are exposed to incident solar radiation. Under conditions of little or moderate thermal radiation levels, BGHI and THI are about equally as effective as indicators of animal comfort.

The BGHI has some limitations. To calculate the index it is necessary to have the black globe temperature. However, the black globe temperature sensor can be costly and, to obtain an appropriate value of black globe temperature, it could be necessary to get measurements in different locations (Yanagi, 2006). So, a long time is required to measure the black globe temperature.

The BGHI can find several applications in animal housing. Collier et al. (2011) found that the effects of radiant heat load can be evaluated using the BGHI, developed by Buffington et al. (1981). Oliveira (1980) developed a model to estimate BGHI using data referred to edification (dimensions and thermal conductivity of the buildings materials) and climate (temperature, relative humidity, wind velocity, atmospheric pressure, and solar radiation). In this model, the incident overall solar radiation on the surface of the roof was estimated by the overall solar radiation measured by instruments and corrected to the surface of the roof.

Yanagi et al. (2011) developed a computer model to predict the black globe humidity index (BGHI) to simulate different resultant conditions in designing poultry buildings. The simulated BGHI values were compared to experimental measurements, obtained in a poultry facility at Viçosa (MG, Brazil), giving a mean deviation of 1.31%. The model was then used to predict BGHI values as affected by roof slopes and column heights.

Some studies have been carried out to solve the problem related to the acquisition of data concerning the black globe temperature. Although this temperature is one of the most common variables used for assessing heat stress, usually it is not reported in meteorological data. Turco et al. (2008) derived equations to estimate the black globe temperature based on meteorological data creating a statistical model.

Dimiceli et al. (2011) obtained a formula to estimate the black globe temperature using readily available data collected by the Weather Service. Recently Hajizadeh et al. (2017) carried out a study in Iran to develop a model to estimate the black globe temperature based on meteorological measurements, in order to calculate the occupational heat stress index in outdoor workplaces.

The aim of this work was to develop a mathematical model to estimate the black globe temperature (T_{gn}) starting from air temperature (T_{ar}), relative humidity (RH) and air velocity (V_{ar}), which are easier to obtain.

MATERIALS AND METHODS

Data Acquisition

The climatic data for the development of the mathematical model of black globe temperature estimation were collected in the experimental area of the Centre for Research in Ambience and Engineering of Agroindustrial Systems (AMBIAGRO, lat 20°46’15” long 42°52’21”) belonging to the Federal University of Viçosa.

Data were collected for three consecutive days at one hour intervals. The air temperature and relative humidity data were collected with the aid of recording sensors (Onset Computer Corp, model Hobo, U12-013; temperature range: -20 °C to 70 °C, accuracy ± 0.35 °C; humidity range: 5% to 95% RH, accuracy: ± 2.5%, USA). The black globe temperature was measured by a temperature probe housed inside a black copper globe (Homis Control and Instrumentation, model TGD – 1,000; temperature range: 0 °C to 50 °C with accuracy ± 0.6 °C, Brazil) and the air velocity was monitored with a hot wire anemometer (SKILL-TEC, model sktafq-01; air velocity 0.4 a 30 m s^{-1}, accuracy 0.1 m s^{-1}, Brazil).

Statistical analysis

The data collected were analysed using a multiple linear regression model:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i \tag{2}$$

where Y_i – response in the ith test; β_0, β_1, β_2 and β_3 – parameters of the model; X_{i1}, X_{i2} and X_{i3} – values of predictor variables in the ith test; ε_i – error term.

The black globe temperature was then estimated as a function of the variables collected (air temperature – Tar, relative humidity – RH, air velocity – Var) and their interaction. The evaluation of the model was performed, based on the significance of the regression and its parameters, as well as the coefficient of determination (R^2).

Validation of the model

To validate the proposed model of black globe temperature prediction, the estimated data were compared through correlation analysis with black globe temperature data measured with the help of a standard black globe thermometer.

RESULTS AND DISCUSSION

The resulting equation, which allows to estimate the black globe temperature from the monitored environmental variables and their respective interactions, corresponds to:

$$Tgn = 4{,}068 + 0.993 \times Tar - 0.754 \times UR - 0.0737 \times Var \tag{3}$$

The model presented in Eq. 3 is satisfactory for estimating the black globe temperature in the study environment, based on the variables monitored, presenting a coefficient of determination $R^2 = 0.9166$, showing that 91.66% of the dependent variable (Tgn) can be explained by the generated model.

Turco et al. (2008) defined a model to estimate the black globe temperature for outdoor workplaces based on meteorological data and to be able to measure heat stress indices. However, they found serious problems in calculating the index based on meteorological data, due to the lack of measurements of the black globe temperature by weather stations in most countries.

Abreu et al. (2011), proposed an equation to estimate the black globe temperature in protected environments taking into account only the air velocity, and obtained results similar to results of the present study.

Hajizadeh et al. (2017) carried out a study giving similar results. The authors found a significant relationship between the black globe temperature and air temperature, solar radiation and relative humidity. The model obtained was proposed to estimate the black globe temperature in a hot and dry environment and considered useful in assessing occupational heat stress in outdoor workplaces.

In present study, during the validation of the model, we observed a strong correlation between the data collected with the black globe thermometer and the data estimated by equation 3, as shown in Fig. 1.

The correlation coefficient between measured values and values estimated by the generated model is 0.9730.

The model presented an average error of 0.02%, which shows reliability in the given data. This result corroborates with Coelho et al., 2013, who studied the prediction with the use of alternative materials and found high reliability.

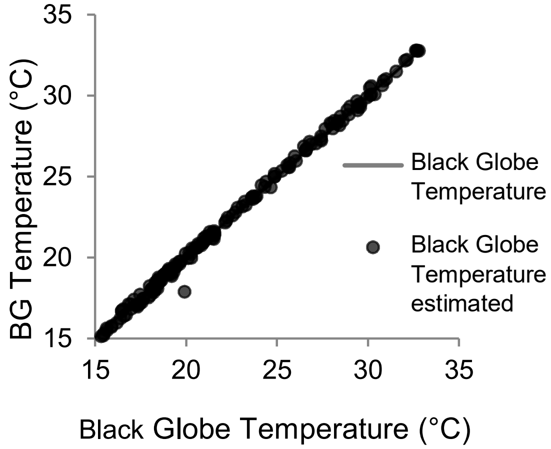

Figure 1. Correlation between the data collected and estimated by the proposed model.

CONCLUSIONS

Thermal comfort conditions of animals inside a barn are essential to improve well-being and to obtain good productive performance. Black Globe-Humidity Index (BGHI) acts as a producer management tool for farmers to monitor the microclimatic situation inside the barn, assisting them in the management of the thermal environment and in decision making how to protect animals from heat stress.

In the present study, a high relation between the data estimated by the model with the data obtained by the standard black globe thermometer was demonstrated.

The mathematical model, based on air temperature, relative humidity and air velocity as environmental variables, is satisfactory for estimating the temperature value of the black globe thermometer, and it becomes an aid tool in the decision-making of the producers to identify and ensure animal thermal comfort.

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