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ORIGINAL ARTICLE

Estimation of thermal comfort indexes for production animals using multiple linear regression models

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Abstract Enthalpy, physical quantity indicating the amount of thermal energy in the medium, is used by many researchers as an indicator of thermal comfort for humans and production animals. This physical quantity has as input variables the dry bulb temperature, the relative humidity of the air and the local barometric pressure. According to consolidated information of temperature and relative humidity related to the animal homeostasis, it was possible to establish enthalpy ranges for thermal comfort of swine, poultry and cattle, considering the local barometric pressure and its variations, which is not easily accessible in situations of field. Thus, the present study aimed to use multiple linear regression models to estimate enthalpy values by means of easily accessible variables (dry and wet bulb temperatures and relative humidity) which can be obtained by means of psychrometers or even by means of low-cost sensors, currently accessible. Meteorological data from three cities of the Brazilian territory, each representing an animal production system (poultry, swine and cattle) were accessed from the National Institute of Meteorology (INMET) database. According to the analysis of the prediction quality verification indices, the obtained models are efficient in predicting enthalpy values with the use of dry bulb temperature and relative humidity.

Keywords: enthalpy, thermoregulation, well-being

Introduction

There are different types of thermal comfort indices for production animals. The black globe temperature index (BGTI), which requires, in addition to the mentioned measurement, ambient temperature, dew point temperature and also relative humidity of the air (Buffington et al 1981), radiant heat load (RHL) related to the surrounding radiation considering direct and diffuse radiation (Bond and Kelly 1955), black globe temperature index (BGTI), which indicates the joint effects of heating by radiation and convection (Sevegnani 1997) and specific enthalpy of dry air (h), physical quantity that indicates the amount of thermal energy in the environment and has as input variables the dry bulb temperature, the relative humidity of the air and the local barometric pressure (Rodrigues et al 2011).

Such indices are important for decision-making regarding the environment and animal welfare and should be routinely used. According to consolidated information of thermal conditions of animal homeostasis, with indicative of temperature ranges and relative humidity of the air that indicate situations of thermal comfort for cattle, pigs and birds (Conceição 2008; Tolon et al 2010; Abreu and Abreu 2011), it is possible to establish enthalpy ranges for thermal comfort for each locality, using the local mean barometric pressure.

The calculation of enthalpy depends on the barometric pressure, which is responsible for indicating the local atmospheric dynamics, since the enthalpy range of thermal comfort varies due to the altitude of the analyzed region, since the temperature, relative humidity and local barometric pressure together indicate the amount of thermal energy in the environment, a determinant factor for the heat exchange between the environment and production animals (Rodrigues et al 2011; Heidari et al 2016).

The barometric pressure, and its variations, are not accessible in field conditions, and it is not usual instruments that determine such physical quantity. Thus, the present study had as objective to use multiple linear regression models to estimate enthalpy values, obeying the thermal comfort ranges for each locality and animal production system, by means of easily accessible variables such as dry and wet bulb temperatures and relative humidity, easily obtained through psychrometer and sensors with low cost available on the market today.

The goal of the study is to facilitate the calculation of the enthalpy comfort index (h), to name it in a usual way and to disseminate its application to promote reference decision

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making, establishing the ambience needs in rural constructions, in face of climatic conditions and possible productive losses in terms of quality and quantity of production.

Materials and Methods

Data used in this study consisted of dry bulb (T), wet bulb (T_{wb}) temperatures, barometric pressure (P_B) and relative humidity (RH) for three cities in the national territory, close to regions of greater participation in cattle, swine and poultry farms in the country. Data from 2017 and 2018 were used respectively to obtain the models and their validations. The database belongs to the National Institute of Meteorology (INMET), which provides daily meteorological data in digital form, according to the international technical standards of the World Meteorological Organization.

The cities of Indaial (State of Santa Catarina), which represents the region with the largest swine production in the country, Aragarças (State of Mato Grosso), a city in the region of extensive beef cattle production and Catanduva (State of São Paulo), which represents the southeastern of the country, poultry-producing region. These cities were selected because they present data referring to the variables required for the analysis, because they have less amount of missing data and because they are close to the indicated animal production regions.

For each city, the daily dry air specific enthalpy (h) was calculated with data referring to the measurements performed at 12 o'clock using equation (1) (Rodrigues et al 2011):

$$h = 1.006.T + \frac{RH}{p_B}.10^{(7.5\boldsymbol{T}/237.3+T)}.(71.28 + 0.052.T)\ (1)$$

Where T is dry bulb temperature (°C), RH is relative humidity of the air (%) and P_B is the local barometric pressure (mmHg).

The enthalpy range corresponding to the thermal comfort situations, consisting of minimum enthalpy (h_{min}) and maximum (h_{max}), for the adult animals under study, were calculated using the maximum and minimum relative humidity and temperature references, consistent with animal homeostasis situations, which reflect conditions of thermal comfort (Table 1).

Two models were analyzed considering multiple linear regression, the first with dependence on dry bulb temperature (T) and relative humidity of the air (RH) and a second model with dependence on dry bulb temperature (T) and wet bulb temperature (T_{wb}) besides the relative humidity of the air (RH). In order to verify the goodness of fit of each model analyzed for comparison purposes, we used the Coefficient of Determination (R^2), obtained by equation (2):

$$R^2 = 1 - \frac{\sum_{t=1}^{n}(y_t - \hat{y}_t)^2}{\sum_{t=1}^{n}(y_t - \bar{y})^2}\ (2)$$

with y_t representing the calculated values of enthalpy (h), $\hat{y}_t$, the estimated values and $\bar{y}$, the mean of the values calculated by equation (1).

Table 1 Reference values for thermal comfort.

Meteorological variables	Pigs*	Poultry**	Cattle***
T_{max} (°C)	15	32	26
T_{min} (°C)	10	15	18
RH_{max} (%)	70	70	80
RH_{min} (%)	60	60	40

*Tolon et al (2010)
**Abreu and Abreu (2011)
***Conceição (2008)

The enthalpy values, corresponding to daily measurements at 12h, of the year 2017 (January to November) for the three cities studied, were calculated using equation (1) for validation of the chosen models (2, 4 and 6).

For the analysis of accuracy of the models used for validation with the data of 2018, we used the mean error (ME) and root mean square error (RMSE), in addition to the correlation coefficient (r), the slope coefficient between the values observed and predicted (b) by the adjusted model and the coefficient of determination (R^2). Equations (3) and (4) present the formulas used to calculate the mean error (ME) and root mean square error (RSME), considering y_t the value calculated by equation (1), and $\hat{y}_t$ the value estimated by the model and n, number of data.

$$ME = \frac{\sum_{t=1}^{n}(y_t - \hat{y}_t)}{n}\ (3)$$

$$RSME = \sqrt{\frac{\sum_{t=1}^{n}(y_t - \hat{y}_t)^2}{n}}\ (4)$$

The fit of the models, using the *dymlm* function, was carried out in a programming environment R, version 3.5.1, considering 5% of significance (Zeileis, 2016).

Results

Values of specific enthalpy (kJ/kg dry air) throughout the year 2017 are illustrated in figures 1, 2 and 3, for the three cities analyzed, considering the maximum (h_{max}) and minimum (h_{min}) enthalpy ranges of comfort for the production animals of each locality.

For the city of Indaial, the time at which the enthalpy values are outside the comfort range is from December to April, characterizing thermal stress by hyperthermia, in the summer and early fall (Figure 1). The data available for the city of Aragarças, useful for calculating the enthalpy, were from January to September 2017 (Figure 2). It is possible to note that, within the analyzed period, beef cattle are susceptible to thermal stress by heat stress from January to May, illustrated by enthalpy values above the thermal comfort range.

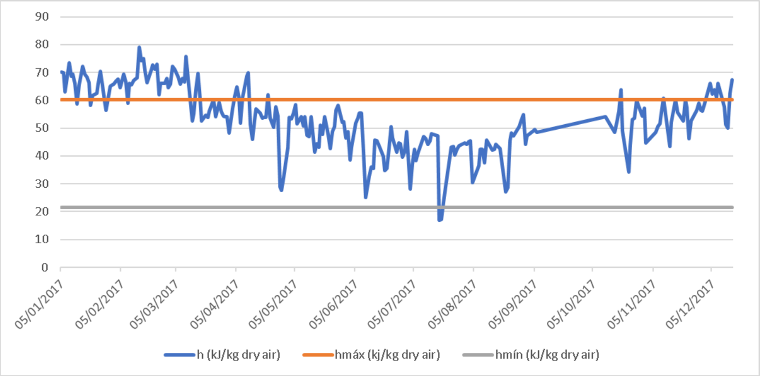

Figure 1 Values of specific enthalpy (kJ/kg dry air) for Indaial, State of Santa Catarina, and thermal comfort range (h_{max} and h_{min}) for pigs.

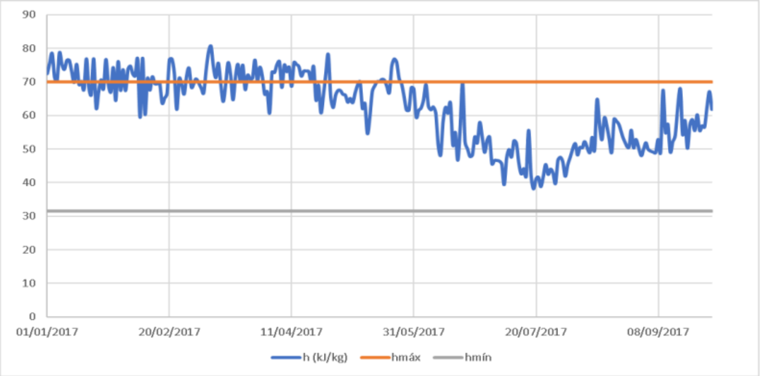

Figure 2 Values of specific enthalpy (kJ/kg dry air) for Aragarças, State of Mato Grosso, and thermal comfort range (h_{max} and h_{min}) for cattle.

In Catanduva, the enthalpy values are within the thermal comfort range, presenting only a peak value below the range, which can be characterized as thermal stress by cold stress, for poultry (Figure 3). The data refers to the period from January to November 2017.

Table 2 lists the six models obtained by means of linear regression, considering the variables of dry bulb (T), wet bulb (Tbu) temperatures present in only three models, and relative humidity of the air (UR). All fit parameters of the models presented *p*-value less than 0.05, therefore significant, and coefficient of determination (R^2) above 98%.

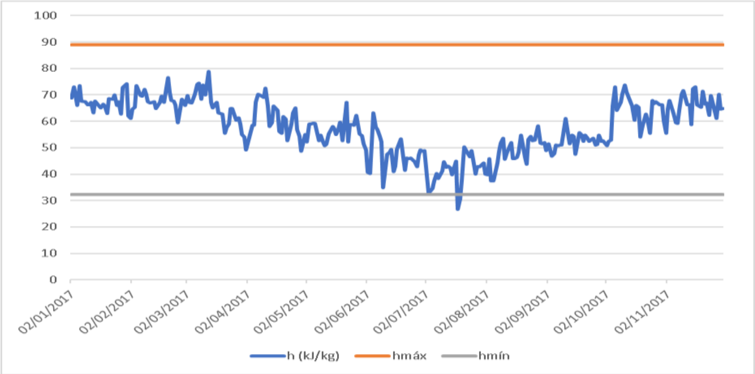

Figure 3 Values of specific enthalpy (kJ/kg dry air) for Catanduva, State of São Paulo, and thermal comfort range (h_{max} and h_{min}) for poultry.

Although the models that considered the wet bulb temperature (T_{wb}) as the input variable had higher values of R^2, we decided to analyze only the models that considered dry bulb temperature (T) and relative humidity (RH), since they have R^2 values close to the other models and have as ease of calculation only two input variables. Therefore, since R² values are considered high when compared to models with three input variables, we decided to analyze the models with the lowest number of inputs.

The models were validated with data referring to the first 11 months of the year 2018 for the cities of Indaial, Aragarças and Catanduva. The indices of quality of fit of the models are listed in table 3.

Table 2 Models of prediction of dry air specific enthalpy (h) and coefficient of determination (R^2).

Animal	Model	R^2
Swine (1)	$h = -1.51 * T + 4.62 * T_{wb} - 0.18 * RH + 13.20$	0.989
Swine (2)	$h = 2.88 * T + 0.32 * RH - 33.15$	0.986
Beef cattle (3)	$h = 1.91 * T + 1.28 * T_{wb} + 0.36 * RH - 38.75$	0.985
Beef cattle (4)	$h = 3.00 * T + 0.54 * RH - 51.92$	0.981
Poultry (5)	$h = -1.09 * T + 4.48 * T_{wb} - 1.21 * RH + 4.23$	0.994
Poultry (6)	$h = 2.97 * T + 0.47 * RH - 44.80$	0.988

Dry bulb temperature (T,°C), Wet bulb temperature (T_{wb},°C) and relative humidity of the air (RU, %)

Table 3 Validation of dry air specific enthalpy prediction models (h) for the year 2018.

Model	*b*	*r*	R^2	*RSME*	*ME*
Swine (2)	1.11	0.96	0.98	1.89	0.37
Beef cattle (4)	1.48	0.96	0.98	1.36	0.37
Poultry (6)	1.39	0.99	0.99	0.86	0.15

b-slope coefficient between the values observed and predicted, *r* - correlation coefficient, R^2 - coefficient of determination, *RMSE* - root mean square error, *ME* - mean error

Discussion

The pertinence of present study is justified by the fact heat stress affects animal production and welfare, reducing the animal production performances as the result from the decreased feed intake (Slimen et al 2015).

Many indexes combining environment factors as temperature, relativity humidity, precipitation and others factors to detect the level of heat stress. Among these factors, temperature and relative humidity are readily available to the producer (Habeeb et al 2018).

Regarding the presented results, it is possible to use only dry bulb temperature (T, ° C) and relative humidity of the air (RH,%) as input variables in the prediction model of enthalpy values. These are easy-to-obtain input variables using low-cost psychrometers or sensors available on the market, and parameter fits are required for each location to be analyzed.

All models (Table 4) presented values close to unity for the linear coefficient of the line (b) of the model, considering also that all have correlation values (r) also close to unity, as well as for the coefficient of determination (R²). The Mean Error (ME) presented values close to zero for all models, which is also indicated as quality adjustment.

There is no reference in the literature to models to estimate enthalpy using temperature and relative humidity. In order to contextualize the importance of enthalpy as an index of thermal comfort, it is possible to observe the prediction potential of other comfort indices. Gomes et al (2011) presented a regression model to estimate the Black Globe Temperature Index (BGTI) using only temperature (T) and relative humidity (RH). The fit of curves of values calculated by means of the characteristic equation and by means of the obtained model presented a coefficient of determination (R²) of 0.41. Lopes (2009) using empirical models of prediction of comfort indices such as radiant heat load (RHL) and black globe temperature (BGTI), by means of temperature and relative air humidity, presented a Mean Error (ME) value of at least 1.80, above the values found for the same parameter in the present study.

Enthalpy presents a direct relationship with temperature and relative humidity of the air. Relative humidity is related to the rainfall rate, but it is also related to wind speed due to air renewal (Rodrigues et al 2011). There is an inverse relationship with barometric pressure, responsible for air retraction in the analyzed region, as well as wind speed, an important factor for atmospheric dynamics (Heidari et al 2016). Thus, the enthalpy quantity can be efficiently predicted by the temperature and relative humidity of the air because these are determinant quantities for the calculation of enthalpy values.

Conclusions

It is possible to use dry bulb temperature and relative air humidity as input variables in a linear regression model for the prediction of dry air enthalpy values, and it is necessary to adjust parameters for a given location.

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