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REVIEW PAPER

The specific enthalpy of air as an indicator of heat stress in livestock animals

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Abstract

Along with recognition of environmental effects on the performance and welfare of livestock animals, studies have been proposing new methodologies and parameters to diagnose the heat stress of animals through the physical properties of air. This article aims to present the state-of-the-art on the use of the specific enthalpy of air as an indicator of heat stress in livestock animals. As a starting point, conceptual considerations were made about the connection between homoeothermic animals and the environment. Variables for heat stress evaluation based on psychrometric air properties are then described, including dry bulb temperature and relative humidity, which are often used microclimate variables, and the specific enthalpy of dry air, which acts as a thermal comfort index. Final considerations highlight the recent history of the use of specific enthalpy of air equations as indicators of heat stress in livestock animals, with the intention of better understanding the relationship between animals and the environment. As a conclusion, the specific enthalpy of air is recommended as an indicator in the assessment of livestock housing conditions as, unlike other indices, it is based on thermodynamic air properties and not on linear regressions.

Keywords Thermoregulation · Specific enthalpy of air · Livestock housing · Livestock bioclimatology · Thermal comfort index

Introduction

In livestock production, one of the major problems that affect both small and big farmers is the effect of the thermal environment on the welfare and zootechnical performance of animals (Bloemhof et al. 2013). This concern, shared by the vast majority of livestock species' breeders, is exponential in countries under tropical and subtropical climates—such as Brazil—where high temperatures during a long period of the year are common. In addition, the effects of climate change on livestock production over the next years have become a major point of concern (Rojas-Downing et al. 2017; Rashamol et al. 2018).

Even indoors, where farm animals are protected from weather conditions, thermal problems are common due to the high density of livestock, misuse of natural resources (such as the sun and wind), and other factors that directly influence animal metabolism and the heat exchanged between animals and their environment (Mathur and Horst 1994).

Thus, the management of livestock animals in hot climates is a challenge. In the short term, the physiological and behavioral changes induced in these animals compromise their welfare, breeding, health, and zootechnical performance, resulting in final products (eggs, milk, and meat) with unsatisfactory characteristics (Bloemhof et al. 2013; Sanker et al. 2013). In the long term, studies indicate that climate changes predicted for the near future will cause new health problems (mainly in the spread of disease-causing pathogens in food and water supplies) and the mortality of livestock animals (Collier and Gebremedhin 2014).

Poultry farming, for example, is greatly influenced by meteorological variations, since animals, even those living about 42 days in profitable systems, need different environmental conditions throughout their production cycle. Lara and Rostagno (2013) and Mascarenhas et al. (2018) report that chickens subjected to chronic heat stress present a decrease in feed conversion ratio and low growth performance. Heat stress also has effects on animal performance and welfare during transport (Santos et al. 2020) and affects the quality

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of the final product, by increasing the occurrence of PSE meat (pale, soft, and exudative) (Wang et al. 2017) and decreasing the percentage of breast meat, which is the part of main economic interest (Lara and Rostagno 2013).

The effects of critical climatic variables have also been demonstrated in laying hens. Researchers point out that, in cases of heat stress, a decrease in feed intake and greater apathy are observed; the birds are less physically active and losses in quantity (less eggs produced) and quality (lower egg weight, lower percentage of eggshell, lower Haugh unit, and lower yolk index) of the final product are found (Silva et al. 2012; Oliveira et al. 2014).

Concerning pig farming, some effects of heat stress are decrease in food intake, incidents of metabolic disorders, impaired reproduction (both for boars and sows), and lower carcass quality (more fat and less lean muscle mass) (Ross et al. 2015). In gestating sows, the stress caused by high temperatures negatively affects abortion rates, embryonic mortality, time of gestation, and the weight of piglets at birth (Lucy and Safranski 2017).

Several studies report the influence of climate on the welfare and productivity of dairy cattle. Bertocchi et al. (2014), Herbut et al. (2018), and Madhusoodan et al. (2019) state that the main effect of heat stress is a reduction in milk production and quality, with negative impacts also on breeding and the fertility of cows—as an effect of problems in the estrus cycle. In bulls, stress leads to low sperm production, while in calves and heifers, hot climates are correlated with lower immunity, lower growth rate, and smaller body size (West 2003; Padilla et al. 2006).

Heat stress effects are also observed in beef cattle. One direct consequence is the decrease in feed intake and therefore lower weight gain (Gonzalez-Rivas et al. 2020). In reproduction, heat stress is related to a lower intensity of estrus, shorter estrus duration, lower pregnancy rates, and higher embryonic loss (Kajaysri and Wattananorasate 2018). Consequences of heat stress are also apparent in the final product (meat), with a decrease in tenderness and a higher incidence of dark, firm, and dry (DFD) meat (Gonzalez-Rivas et al. 2020).

Saint-Pierre et al. (2003) conducted a study in the USA to estimate the economic impact of heat stress in livestock. Minor losses were observed in poultry production, reaching 51.8 million dollars. In egg production, the authors indicated that heat stress generated an economic loss of approximately 98.1 million dollars. For beef cattle, heat stress was responsible for an economic loss of approximately 282 million dollars due to decreased performance and death, while in pig farming, the loss ranged from 299 to 316 million dollars annually. The greatest loss, however, was observed in milk production that ranged from 897 to 1.5 billion dollars.

With respect to the problems caused by heat stress, several methods of assessing the environment where livestock animals are housed have been developed, and updated over the last decades. The purpose of this study was, as a bibliographic review, to present the state-of-the-art on the use of the specific enthalpy of air as an evaluation method of heat stress in broiler chickens, laying hens, pigs, dairy cattle, and beef cattle. First, basic concepts regarding the relationship between animals and the environment are presented. Then, psychrometric properties are introduced as an alternative to evaluate animal housing. The paper draws attention to three of the psychrometric variables: dry bulb temperature and relative humidity, easily collected and historically widely used in the assessment of heat stress, and the specific enthalpy of air, which is a thermal comfort index with great potential for its practical application.

Although the use of these psychrometric variables is quite recurrent in the literature, this article brings an original approach. The major contributions of the study are the critical investigation of using dry bulb temperature and relative humidity (independent variables) as indicators of heat stress for livestock animals and the comparative analysis of using specific air enthalpy (in a combination of psychrometric variables) as a comfort index.

Heat stress and thermoregulation

Heat stress can be defined, according to Dikmen and Hansen (2009) and Ferrari et al. (2013), as the sum of external forces—from the environment—acting on an animal, causing an increase in its body temperature and eliciting a physiological and/or behavioral response. Physiologically, heat stress occurs because farm animals are homeothermic: they have the ability to maintain the internal temperature of their organisms relatively constant, despite the thermal fluctuations of the environment. Henry et al. (2012) point out that homoeothermic animals adjust body temperature within a range of ± 0.5 °C, in order not to damage their bodily functions.

The process of the biological control of internal body temperature is characterized as thermoregulation, in which the thermal energy balance, characteristic of each animal, is represented by the equation of metabolic heat production, heat gain from the environment by radiation, convection, and conduction, in addition to heat lost to the environment through sweating and breathing (Renaudeau et al. 2011). According to Dantas et al. (2012), such terms—expressed in W/m^2—represent sensible heat loss (not evaporative, such as conduction, radiation, and convection), most frequent in cold environments, and latent heat (evaporative), more frequent in hot environments.

Farm animals bred within the thermoneutrality zone, or thermal neutral zone (TNZ), are in thermal comfort. In these conditions, according to Baêta and Souza (1997) and Polsky and Von Keyserlingk (2017), the housing environment for livestock animals supports their physiological system, there being no requirement for activating an organism in thermal equilibrium. In addition, each species has a specific TNZ, which varies according to its growth and physiological adaptability (Rashamol et al. 2018).

In the heat stress zones, between the upper limit of the TNZ and the upper critical temperature (UCT), and between the lower critical temperature (LCT) and the lower limit of the TNZ, an animal's organism requires energy resources to maintain homeostasis. According to Baêta and Souza (1997), cases of hyperthermia and hypothermia (above the UCT and below the LCT, respectively) expose animals to critical survival situations, which can lead to death.

Livestock animals respond to variations in their environment using physiological and behavioral mechanisms, which are not the main interest of this study. However, the comprehension of the physiological and behavioral responses of poultry, swine, and cattle under heat stress has been already examined by several researchers (Mello et al. 2017; Romanello et al. 2018; Hooper et al. 2019; Nascimento et al. 2019; Rashamol et al. 2019; Madhusoodan et al. 2019; Vieira et al. 2019; Bueno et al. 2020; Li et al. 2020; Vasconcelos et al. 2020).

Psychrometry as an assessment method

After understanding the theoretical basis and the effects of heat stress on livestock, it is necessary to evaluate the different kinds of environment in which animals are housed. For productive and scientific purposes, the microclimatic variables of air have been used to assess the heat stress situation of production animals, with an emphasis on those that constitute psychrometric properties.

Psychrometry is defined as the science that investigates changes in the properties of moist air, using the physical criteria, conventions, and hypotheses proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers - ASHRAE (2009) and following the principles of thermodynamics.

Singh et al. (2002) and Britto (2010) emphasize that the properties of a water, steam, and dry air mixture can be diagrammed in Psychometric Charts, which are elaborated according to an atmospheric pressure reference—the standard Psychometric Chart considers the atmospheric pressure at sea level (760 mmHg) (Ren 2004). From a point P of the Psychrometric Chart, it is possible to determine the psychrometric variables of air, which depend on P and are interdependent. Those variables are dry bulb temperature, dew point temperature, wet bulb temperature, relative humidity, mixing ratio (or specific humidity), specific volume, and specific enthalpy (Ren 2004; Britto 2010).

From the psychometric variation of a given system (from a point P to a point P′), it is possible to outline strategies for environmental control, referred to as thermogravimetric air treatments by Britto (2010). Among the processes for modifying the physical properties of a given studied atmosphere, the following are the most common: simple cooling, adiabatic cooling, cooling associated with dehumidification, simple humidification, simple heating, dehumidification associated with heating, and non-adiabatic humidification and cooling (Britto 2010). It is noted that such procedures are related to the integrated actions of drying, humidifying, cooling, and heating a given surrounding.

The thermodynamic principles of psychrometry are very relevant in the development of technologies for heating and cooling environments in the conservation of food (mainly grains) and in meteorology (Ren 2004; Kumar et al. 2016; Kerr 2019; Teitelbaum et al. 2020). Over time, the principles of psychrometry have been included in livestock housing studies, in order to understand how such complex air properties interact with the physiological principles of animal thermoregulation. Below, we highlight the use of outdoor temperature, relative humidity, and the specific enthalpy of air to indicate heat stress in farm animals.

An interpretation of individual variables

Among the microclimate variables that are part of the psychrometric properties of air, the two most important are dry bulb temperature (T) and relative humidity (RH) (North and Bell 1990; Soldatos et al. 2005; Oliveira et al. 2006). According to Cossins (2012), dry bulb temperature is directly related to an animal's thermoregulation and heat exchange, involving the chemical, physical, and biological mechanisms of the animal's organism, which are activated in order to deal with thermal fluctuations in the environment. On the other hand, the relationship between relative humidity and heat stress is not as clear as to temperature. The ability of animals to withstand heat is inversely proportional to the relative humidity content present in air (Oliveira et al. 2006): when relative humidity is high, livestock animals find it more difficult to remove internal heat through breathing (one of the main means of heat exchange). It is important to highlight that species use different thermoregulation mechanisms: heat loss by respiration is the main mechanism in poultry and pigs, but not in cattle (cutaneous evaporation).

Furthermore, in air conditioning systems, the cooling and heating (associated with dry bulb temperature) and drying and humidification (associated with relative humidity) mechanisms can occur simultaneously and jointly (for example, in evaporative adiabatic cooling systems (Al-Hassan 2018; Lontoc et al. 2018; Sultan et al. 2018)).

Over the past few years, several authors have proposed a specific range for TNZ, LCT, and UCT for dry bulb temperature and relative humidity for farm animals. Considering that, a systematic review was used (Pereira and Galvão 2014) following these steps: compilation of scientific papers published in the main international journals databases that used thermoneutrality zones in their evaluations; identification of the reference texts (such as books and papers) of the thermoneutral values used in the papers; search for reference texts in gray literature (texts that are more difficult to find in traditional search channels); and cataloging TNZ, LCT, and UCT ranges, according to the reference text and the year of publication.

In this study, the thermoregulation zones of broiler chickens, pigs, dairy cattle, laying hens, and beef cattle were investigated. These species were selected due to their commercial importance in countries with hot climates. The same species were also considered in the study conducted by Saint-Pierre et al. (2003). Moreover, livestock animals were divided into growing stages, since they have different thermal needs during development (Ribeiro et al. 2018).

Table 1 summarizes the classification of thermoregulation zones (TNZ, LCT, and UCT) for broiler chickens, subdivided into 6 weeks of profitable production. Thirty-five (27.6%) from the total of 127 registers collected were for broilers. As indicated, some papers offer the ideal ranges for all ages (Curtis 1983; Leal and Nääs 1992; Abreu and Abreu 2011; Cassuce 2011) with a relatively constant number of studies for each growing stage.

In general, it is observed that thermal demand decreases as the birds grow: For example, according to Abreu and Abreu (2011), the TNZ for chicks is from 32 to 35 °C, while birds in the last week of life have a TNZ of 20 °C, a decrease of about 13 °C during the productive cycle. The intervals between LCT, TNZ, and UCT for broilers are relatively short. This is because these animals are very sensitive to thermal fluctuation, and small variations can lead to death (Brossi et al. 2018).

When compared with T, RH has fewer cataloged records. However, the authors' consensus is greater, with TNZ for RH ranging from 50 to 70%. Unlike T, TNZ for RH remains constant throughout the production cycle. Lastly, none of the reference texts presents LCT for RH, and only Leal and Nääs (1992) indicate UCT, of 80%.

Table 2 shows the compilation of thermoregulation zones for pigs, representing 39 (30.7%) of the total records. A greater amount of work was registered for sows (12 records) and piglets (8 records), which are productive stages that require greater attention, since sows and piglets must live together in the same environment, but demand different housing conditions.

Piglets demand warmer environments for their survival; however, there are discrepancies concerning the range of TNZ: for example, Hannas (1999) suggests a range of 27 to 28 °C while Sobestiansky et al. (1987) suggests a range from 32 to 34 °C. Lower temperatures are required during animal growth: adult pigs, for example, have a TNZ between 12 and 18 °C, according to Leal and Nääs (1992). In addition, TNZ,

Table 1 The thermoregulation zones of broiler chickens, considering dry bulb temperature (*T*) and relative humidity (RH): thermal neutral zone (TNZ), lower critical value (LCT), upper critical value (UCT)

Broiler chickens	*T* (°C)			RH (%)		
Authors	LCT	TNZ	UCT	LCT	TNZ	UCT
1st week						
Curtis (1983)	34	35	39	-	-	-
Leal and Nääs (1992)	30	33–35	39	-	60	80
Macari and Furlan (2001)	-	33–35	-	-	60–70	-
Menegali et al. (2009)	-	32–34	-	-	50–70	-
Abreu and Abreu (2011)	-	32–35	-	-	60–70	-
Cassuce (2011)	-	32–34	-	-	-	-
Cândido et al. (2016)	-	33	-	-	-	-
2nd week						
Curtis (1983)	34	35	39	-	-	-
Leal and Nääs (1992)	34	30–33	37	-	60	80
Menegali et al. (2009)	-	28–32	-	-	50–70	-
Abreu and Abreu (2011)	-	29–32	-	-	60–70	-
Cassuce (2011)	-	28–32	-	-	-	-
Cândido et al. (2016)	-	30	-	-	-	-
3rd week						
Curtis (1983)	15	18–28	32	-	-	-
Leal and Nääs (1992)	23	27–30	34	-	60	80
Menegali et al. (2009)	-	26–28	-	-	50–70	-
Abreu and Abreu (2011)	-	26–29	-	-	60–70	-
Cassuce (2011)	-	26–28	-	-	-	-
Cândido et al. (2016)	-	27	-	-	-	-
4th week						
Curtis (1983)	15	18–28	32	-	-	-
Leal and Nääs (1992)	20	24–27	31	-	60	80
Baêta and Souza (1997)	-	18–28	-	-	50–70	-
Abreu and Abreu (2011)	-	23–26	-	-	60–70	-
Cassuce (2011)	-	24–26	-	-	-	-
5th week						
Curtis (1983)	15	18–28	32	-	-	-
Leal and Nääs (1992)	17	21–24	28	-	60	80
Baêta and Souza (1997)	-	18–28	-	-	50–70	-
Abreu and Abreu (2011)	-	20–23	-	-	60–70	-
Cassuce (2011)	-	18–24	-	-	-	-
6th week						
Curtis (1983)	15	18–28	32	-	-	-
Leal and Nääs (1992)	14	18–21	25	-	60	80
Baêta and Souza (1997)	-	18–28	-	-	50–70	-
Macari and Furlan (2001)	-	21–23	-	-	60–70	-
Cassuce (2011)	-	18–24	-	-	-	-
Abreu and Abreu (2011)	-	20	-	-	60–70	-

Table 2 The thermoregulation zones of pigs, considering dry bulb temperature (*T*) and relative humidity (RH): thermal neutral zone (TNZ), lower critical value (LCT), upper critical value (UCT)

Pigs	*T* (°C)			RH (%)		
Authors	LCT	TNZ	UCT	LCT	TNZ	UCT
Sows						
Veit and Troutt (1982)		-	-	-	50–70	-
Perdomo (1995)	7	12–18	23	-	-	-
Nienaber et al. (1987)	-	-	-	-	60–70	-
Noblet et al. (1989)	-	8–23	-	-	-	-
Leal and Nääs (1992)	0	12–18	30	40	70	80
Black et al. (1993)	-	12–22	-	-	-	-
Baêta and Souza (1997)	-	16–22	-	-	-	-
Lucas and Cruz (1997)	-	8–23	-	-	-	-
Silva (1999)	-	18–21	-	-	50–70	-
Moura (1999)	-	18–21	-	-	-	-
Hannas (1999)	0	12–18	30	-	50–70	-
Mostaço (2014)	5	12–17	25	-	-	-
Boars						
Nienaber et al. (1987)	-	-	-	-	60–70	-
Leal and Nääs (1992)	0	12–18	30	40	70	80
Mostaço (2014)	7	14–21	27	-	-	-
Piglets						
Veit and Troutt (1982)	-	-	-	-	50–70	-
Nienaber et al. (1987)	-	-	-	-	60–70	-
Sobestiansky et al. (1987)	-	32–34	-	-	-	-
Leal and Nääs (1992)	15	30–32	35	40	70	80
Black et al. (1993)	-	30–37	-	-	-	-
Hannas (1999)	15	27–28	35	-	-	-
Silva (1999)	-	22–25	-	-	50–70	-
Mostaço (2014)	20	30–32	36	-	-	-
Nursery						
Nienaber et al. (1987)	-	-	-	-	60–70	-
Le Dividich (1991)	-	22–25	-	-	-	-
Leal and Nääs 1992	10	21–22	31	40	70	80
Silva (1999)	8	20–24	31	-	50–70	-
Hannas (1999)	10	21–24	31	-	-	-
Mostaço (2014)	10	18–24	31	-	-	-
Growing						
Nienaber et al. (1987)	-	-	-	-	60–70	-
Leal and Nääs (1992)	5	16–18	27	40	70	80
Hannas (1999)	5	16–18	27	-	50–70	-
Silva (1999)	-	18–21	-	-	50–70	-
Mostaço (2014)	7	16–21	28	-	-	-
Finishing						
Nienaber et al. (1987)	-	-	-	-	60–70	-
Leal and Nääs (1992)	5	12–18	27	40	70	80
Hannas (1999)	5	16–18	27	-	50–70	-
Silva (1999)	-	18–21	-	-	50–70	-
Mostaço (2014)	5	12–21	27	-	-	-

LCT, and UCT for finishing pigs are similar to gestating sows and boars, being all adult animals. Only two texts used as reference have T ranges for boars, suggesting little research on these animals. There are fewer records for RH when compared with T (for example, Veit and Troutt (1982) and Nienaber et al. (1987)). In addition, RH requirements are constant throughout the production cycle (between 50 and 70).

Table 3 The thermoregulation zones of dairy cattle, considering dry bulb temperature (*T*) and relative humidity (RH): thermal neutral zone (TNZ), lower critical value (LCT), upper critical value (UCT)

Dairy cattle	*T* (°C)			RH (%)		
Authors	LCT	TNZ	UCT	LCT	TNZ	UCT
Calves						
Curtis (1983)	10	18–21	26	-	-	-
Leal and Nääs (1992)	8	16–21	23	30	70–80	-
Dalcin (2013)	-	-	-	-	50–70	-
AHDB (2018)	-	15–20	-	-	-	-
Heifers						
Leal and Nääs (1992)	− 5	12–19	25	30	70–80	-
Nääs (1998)	-	10–26	32	-	-	-
Dalcin (2013)	-	-	-	-	50–70	-
Lactating cows						
Yousef (1985)	-	6–21	-	-	-	-
Nääs (1989)	5	13–18	24	-	-	-
Huber (1990)	5	-	26	-	-	-
Leal and Nääs (1992)	− 5	12–18	25	30	70–80	-
Baêta and Souza (1997)	-	0–16	27	-	-	-
Nääs (1998)	-	5–24	30	-	-	-
Roenfeldt (1998)	-	5–25	-	-	-	-
West (2003)	-	0–20	-	-	-	-
Pereira (2005)	-	0–16	-	-	-	-
Azevêdo and Alves (2009)	− 10	0–17	27	-	-	-
Gonçalves et al. (2009)	5	10–20	25	-	-	-
Dalcin (2013)	-	-	-	-	50–70	-
Garcia (2017)	5	12–18	25	30	50–70	80
Dry cows						
Yousef (1985)	-	6–21	-	-	-	-
Nääs (1989)	5	13–18	24	-	-	-
Huber (1990)	5	-	26	-	-	-
Leal and Nääs (1992)	− 5	12–18	25	30	70–80	-
Baêta and Souza (1997)	-	0–16	-	-	-	-
Pereira (2005)	-	0–16	-	-	-	-
Azevêdo and Alves (2009)	− 10	0–17	27	-	-	-
Dalcin (2013)	-	-	-	-	50–70	-
Bulls						
Huber (1990)	5	-	26	-	-	-
Pereira (2005)	-	0–16	-	-	-	-
Azevêdo and Alves (2009)	− 10	0–17	27	-	-	-
Dalcin (2013)	-	-	-	-	50–70	-

Table 3 offers the compilation of thermoneutral zones for dairy cattle, where 32 references (25.2% of the total) were registered. Greater emphasis is given to lactating cows (13 registers), as they are directly responsible for milk production.

When evaluating the reference temperatures for dairy cattle, it can be observed that such animals are more comfortable in cold environments. LCT, for example, can reach temperatures below zero (Leal and Nääs (1992); Azevêdo and Alves (2009)). Therefore, as shown by Polsky and Von Keyserlingk (2017), the thermal challenge for housing dairy cows is huge, especially in regions of long summers (such as Brazil and southwestern United States), but even in colder regions (such as Canada and central Europe). As the major issue for dairy cows is their exposure to high dry bulb temperatures, some works (not cataloged) present only UCT (Igono et al. 1992; Dikmen and Hansen 2009).

Table 4 shows the thermoneutral zones for laying hens. Compared with other livestock production, there are fewer scientific reports: 13 records were found, 10.2% of the total. In addition, the literature is focused on birds in the laying phase, direct egg producers, compared with other growing stages.

All cataloged content presents TNZ for T. On the other hand, there is a lack of records for LCT and UCT, with only a few authors indicating these values (Holik 2009; Leal and Nääs 1992). It is also noticed that with laying hens, as in other species, younger animals have higher TNZ intervals. For RH, the authors suggest that this variable varies from 40 to 80%, with LCT and UCT values not being cataloged for RH.

Finally, the thermoneutral zones for beef cattle are presented (Table 5). Only 8 records (6.3% of total) were identified for this species, and the literature focuses on two growing stages (calves and adult cattle). The investigated data for T show great divergent thermoregulation zones for calves, with authors agreeing about UCT. For adult beef cattle, Baêta and Souza (1997), Pereira (2005), and Azevêdo and Alves (2009) agreed that the TNZ for these animals is in the range 10–27 °C. Furthermore, Pereira (2005), Azevêdo and Alves (2009), and Yousef (1985) indicated that the UCT for beef cattle is 35 °C. Only one record was observed for RH, where Baêta and Souza (1997) indicated a range of 60–70% as the TNZ for adult beef cattle.

Regarding the lack of scientific research on the parameters of thermoneutral zones for beef cattle, two possible justifications emerge. The first one is about a common sense that Zebu cattle are well adapted to heat stress, since most animals are raised in pastures in tropical countries with few or no environmental control (Hansen 2004). The second suggests the difficulty of establishing ranges for beef cattle due to the high variation between breeds. Studies conducted by Valente et al. (2015), Katiyatiya and Muchenje (2017), and Menegassi et al. (2016) show that Nelore, Angus, Nguni, and Boran, among others breeds, respond differently to thermal fluctuations in the environment. In addition, the difficulty of establishing comfort zones for beef cattle is intensified for crossbred animals.

By grouping the texts considered under this study, it is possible to highlight the following: many of them present only the ideal thermal comfort zone (TNZ), without characterizing

Table 4 The thermoregulation zones of laying hens, considering dry bulb temperature (*T*) and relative humidity (RH): thermal neutral zone (TNZ), lower critical value (LCT), upper critical value (UCT)

Laying hens	*T* (°C)			RH (%)		
Authors	LCT	TNZ	UCT	LCT	TNZ	UCT
Chicks						
Andrade (2017)	-	33	-	-	-	-
Teeter and Belay (1996)	-	35	-	-	-	-
Growing (stage 1)						
Andrade (2017)	-	23–28	-	-	-	-
Growing (stage 2)						
Teeter and Belay (1996)	-	24	-	-	-	-
Tinôco (2001)	-	15–25	-	-	50–70	-
Holik (2009)	-	18–24	30	-	-	-
Andrade (2017)	-	19	-	-	-	-
Laying						
Leal and Nääs (1992)	5	11–22	30	-	-	-
Teeter and Belay (1996)	-	24	-	-	-	-
Baêta and Souza (1997)	-	20–30	-	-	50–70	-
Silva and Sevegnani (2001)	-	21–28	-	-	-	-
Tinôco (2001)	-	15–25	-	-	50–70	-
Holik (2009)	-	18–24	30	-	-	-

Table 5 The thermoregulation zones of beef cattle, considering dry bulb temperature (*T*) and relative humidity (RH): thermal neutral zone (TNZ), lower critical value (LCT), upper critical value (UCT)

Beef cattle	*T* (°C)			RH (%)		
Authors	LCT	TNZ	UCT	LCT	TNZ	UCT
Calves						
Yousef (1985)	7	-	27	-	-	-
Hahn (1997)	−30	0–15	27	-	-	-
Azevêdo and Alves (2009)	10	18–21	26	-	-	-
Adult cattle						
Yousef (1985)	7	-	35	-	-	-
Baêta and Souza (1997)	-	10–27	-	-	60–70	-
Hahn (1997)	−18	5 a 15	27	-	-	-
Pereira (2005)	5	10–27	35	-	-	-
Azevêdo and Alves (2009)	0	10–27	35	-	-	-

the critical zones; most of the studies establish clear parameters for T, but few present the specific limits for RH, placing this variable as a secondary characteristic in determining heat stress; many of the works date from the 1980s and 1990s, with few updates for modern breeds and lineages. In this scenario, Cassuce et al. (2013) updated the thermoneutral zones for broilers from 0 to 21 days old and Andrade et al. (2019) presented similar work for laying birds in the growing stage.

Finally, several authors agree that the specie, breed, sex, age, physiological state, acclimatization process, and other factors must be considered to understand the thermoregulation of farm animals (Martello et al. 2004; Nascimento et al. 2019). However, this paper collaborates with the literature by grouping reference values extracted from several studies, data which are not usually considered together. Dry bulb temperature and relative humidity values presented in this study will allow future works to establish comparisons between data, and focus on determining thermoneutral zones of growing stages that are still little explored. Furthermore, this work encourages similar studies on other livestock species, such as sheep, goats, and rabbits.

An interpretation of combined variables

Although dry bulb temperature and relative humidity, themselves, are reference parameters for assessing heat stress in livestock animals, Ricci et al. (2013) highlighted the combination of both variables for a better understanding of the different farm environment conditions. Furthermore, air is characterized as a complex and dynamic system, consisting of interdependent physical properties.

In order to understand the impacts of the physical properties on livestock environment, thermal comfort indexes have been developed and used as guides for decision-making, allowing the effects of heat stress to be minimized or avoided (Azizpour et al. 2013). Several indexes have been used to indicate the heat stress in livestock animals, such as the Temperature and Humidity Index, THI (Thom 1959); the Black Globe Temperature and Humidity Index, BGTHI (Buffington et al. 1981); and the Radiant Heat Load, RHL (Esmay 1979), among others.

Researchers have developed parameters to classify the thermal comfort of farm animals (Hahn 1985; Baêta 1985; Lima et al. 2007), and are of great practical use. On the other hand, Martello et al. (2004) present some observations regarding the use of thermal comfort indexes which, if seen as generic tools, cannot express all physiological needs of animals. In addition, some indexes were established through linear regressions associated with experiments from specific countries and using specific breeds (Sarnighausen 2019).

In order to avoid such limitations, psychrometric considerations have also been used to develop thermal comfort indexes, such as the specific enthalpy of air. Physically, the specific enthalpy of air (*h*) is defined as the total amount of energy existent in a unit of dry air mass (kJ/Kg of dry air). The characteristic energy in psychrometric processes is heat: thermal energy that flows between bodies, through the temperature difference surrounding them (Britto 2010).

Specific enthalpy, being the only psychrometric variable that encompasses the concept of thermal energy in the environment, comprises the sum of latent and sensitive heat. Sensitive heat promotes a temperature variation in a body without a change in the state of aggregation. Latent heat does not promote changes in temperature, but it can change its physical state (Dal Piva et al. 2008). Having such properties, the justification for the use of the specific enthalpy of air as a thermal comfort index is the application of these physical concepts of heat exchange to animals and their environment.

The specific enthalpy of dry air (*h*) is determined by calculating other variables of psychrometric interest. Albright (1990) proposed the determination of enthalpy (*h*, kJ/Kg of dry air) by combining the dry bulb temperature (*T*, °C) and the mixing ratio (*w*, g of water vapor/Kg of dry air), or humidity ratio, of air (Eq. 1).

$$h = 1.006\mathrm{T} + \mathrm{w}(2501 + 1.805\mathrm{T}) \quad (1)$$

Equation 1 has been used over the years to evaluate facilities for broilers (Nazareno et al. 2009; Ferraz et al. 2018; Lourençoni et al. 2019), dairy cows (Almeida et al. 2011; Silva et al. 2015), and pigs (Nazareno et al. 2012; Silva-Miranda et al. 2012; Cecchin et al. 2017; Borges et al. 2018; Nepomuceno et al. 2018), thus consolidating the specific enthalpy of air as a scientifically relevant thermal comfort index.

Furlan (2001), based on unpublished data from Villa Nova, presented a new equation for the calculation of specific enthalpy (Eq. 2), using it to evaluate different management and cooling systems for protected locations for crops. Specific enthalpy (*h*, Kcal/Kg of dry air) was based on air temperature (*T*, °C) and relative humidity (RH, %), which are physical and easily measurable variables, in addition to being better known to farmers when compared with the mixing ratio.

$$h = \left(6.7 + 0.243\mathrm{T} + 2.216 * \left(\left(\frac{\mathrm{RH}}{100}\right) * 10^{\left[\frac{7.5T}{237.3+T}\right]} - 1\right)\right) * 4.18 \quad (2)$$

Equation 2 was later adapted by Barbosa Filho et al. (2007), Eq. 3, maintaining the specific enthalpy unit used by Albright (1990). As examples, Damasceno et al. (2010), Camelo et al. (2015), Dalólio et al. (2016), and Silva et al. (2020) used, in their farm housing studies, the aforementioned equations adapted by Furlan (2001) and Barbosa Filho et al. (2007).

$$h = \left(6.7 + 0.243\mathrm{T} + \left(\left(\frac{\mathrm{RH}}{100}\right) * 10^{\left[\frac{7.5T}{237.3+T}\right]}\right)\right) * 4.18 \quad (3)$$

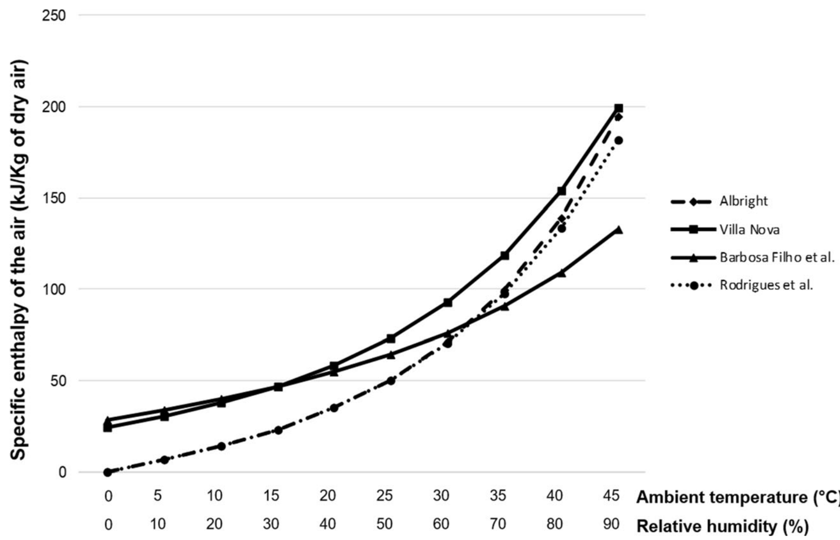

Fig. 1 Enthalpy values calculated by the equations of Albright (1990), Villa Nova as published by Furlan (2001), Barbosa Filho et al. (2007), and Rodrigues et al. (2011) (adapted from Garcia 2017)

However, the formulations of previous equations did not consider other properties related to the physical principles of psychrometric properties. Britto (2010) and Beltrán-Prieto et al. (2015) emphasize that psychrometric variables vary according to the local atmospheric pressure, based on their direct relationship with the volume and temperature of air masses. With that consideration, Rodrigues et al. (2011), starting with Eq. 1 and following the physical considerations presented in the technical notes of ASHRAE (2009), included local atmospheric pressure (Pa, mmHg) in the calculation of the specific enthalpy of air, Eq. 4.

$$h = 1.006\mathrm{T} + \left(\frac{\mathrm{RH}}{\mathrm{Pa}}\right) * 10^{\left[\frac{7.5T}{237.3+T}\right]} * (71.28 + 0.052\mathrm{T}) \qquad (4)$$

The enthalpy equation proposed by Rodrigues et al. (2011) has been used in the evaluation of several livestock production systems, being applied, for example, in the studies of Queiroz et al. (2017) and Camargo et al. (2015) for broilers, Nazareno et al. (2013) for fertile eggs, Almeida Neto et al. (2014) and Barnabé et al. (2015) for dairy cows and calves, Sevegnani et al. (2016) for buffaloes, and Nunes et al. (2014) and Zotti et al. (2019) for pigs. Sarnighausen (2019), in turn, used linear regression models from Eq. 4 to estimate the specific enthalpy of air, considering the comfort conditions of poultry, swine, and cattle located in different Brazilian cities.

Garcia (2017), in his study with dairy cows, compared the enthalpy equations proposed by Albright (1990), Furlan (2001), Barbosa Filho et al. (2007), and Rodrigues et al. (2011) (Fig. 1). For the calculation of the mixing ratio (w) and the enthalpy of Rodrigues et al. (2011), an atmospheric pressure of 760 mmHg was considered.

Although all of the curves follow an increasingly exponential pattern, the equations of Villa Nova as published by Furlan (2001) and Barbosa Filho et al. (2007) show the greatest divergences when compared with the equation presented by Albright (1990). As pointed out by Garcia (2017), the specific enthalpy values calculated by the method of Villa Nova as published by Furlan (2001) are overestimated, using

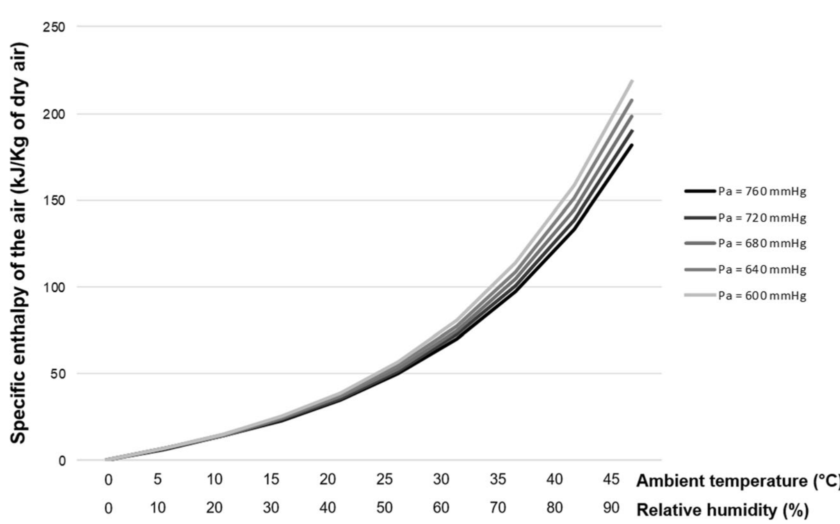

Fig. 2 Enthalpy calculated by Rodrigues et al. (2011), varying the values of local atmospheric pressure

Albright (1990) as a reference. The equation used by Barbosa Filho et al. (2007) presents overestimated values in situations of low temperature and low humidity and underestimated values in cases of high temperature and humidity.

The corrected equation by Rodrigues et al. (2011) presents the closest specific enthalpy values to the equation proposed by Albright (1990). The results are consistent because in both cases it is necessary to consider the local atmospheric pressure when calculating specific enthalpy. Thus, recognizing the importance of this microclimate variable, Fig. 2 shows the behavior of specific enthalpy curves considering variations of local atmospheric pressure.

It is noticed that local atmospheric pressure influences the results of specific enthalpy, especially when dry bulb temperature and relative humidity are high. In places of low altitude (at sea level, with Pa close to 760 mmHg), the specific enthalpy reading is lower when compared with places of high altitude and lower pressure. Considering a dry bulb temperature of 45 °C and a relative humidity of 90%, the specific enthalpy calculated is 182.03 kJ/kg of dry air for locations at sea level (Pa = 760 mmHg). Under the same conditions, the enthalpy value is 211.57 kJ/kg of dry air for Campos do Jordão-SP, the Brazilian city with the highest altitude (Pa = 625 mmHg). Therefore, at the same temperature and relative humidity, the amplitude of enthalpy between these extreme regions was 29.54 kJ/kg of dry air.

In a practical way, the calculation of enthalpy based on dry bulb temperature and relative humidity, as proposed by Rodrigues et al. (2011), is faster and easier to measure when compared with the use of the mixing ratio by the equation of Albright (1990).

In addition to applying specific air enthalpy in the assessment of livestock production environments, authors have developed standards to classify enthalpy according to the comfort ranges of farm animals. Barbosa Filho et al. (2007), for example, used Furlan's eq. (2001) to develop practical tables for classifying heat stress from specific enthalpy. The classification tables included the situations of comfort (associated with the color green), alert (color yellow), critical (color orange), and lethal (color red).

Queiroz et al. (2012), in turn, adapted the classification methodology of Barbosa Filho et al. (2007), using the mathematical considerations proposed by Rodrigues et al. (2011). The new practical tables were developed for broiler chickens throughout the production cycle, considering atmospheric pressure (760 mmHg) as a static value.

Results indicate that specific air enthalpy has been used in several livestock science studies in the last decades. However, the evaluation of the different equations proposed in this study suggests that they present diverging specific air enthalpy values. In summary, although specific air enthalpy is consolidated as a thermal comfort index and its updates have made it physically more reliable and with greater practical applicability, it is still necessary to refine and improve the thermal comfort classification process using techniques such psychrometric property, considering the local atmospheric pressure and updating the reference parameters, as Queiroz et al. (2012) have done, for other species and growing stages.

Conclusion

When physical environment variables are used to evaluate heat stress in livestock animals, the psychrometric properties of air offer a potential approach. Dry bulb temperature and relative humidity, as variables of psychrometric interest, are easily collected and interpreted. However, when cataloging the scientific data that indicate TNZ, LCT, and UCT for livestock animals, divergences are observed which may influence the decision-making of those who use them as reference data. When using these variables together, the specific enthalpy of air is characterized both as a psychrometric property and a thermal comfort index. Although it has been updated over time to better suit thermodynamic considerations, future studies are necessary to update the critical and comfort ranges of specific enthalpy for different species and growing stages.

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Conflict of interest The authors declare that they have no conflict of interest.

Code availability Not applicable.

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