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Research Paper

Thermal environment sensor array: Part 2 applying the data to assess grow-finish pig housing

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Current thermal environment (TE) assessment techniques for controlling livestock and poultry facilities often solely use dry-bulb temperature (T_{db}) and occasionally relative humidity (RH) as assessment parameters. The TE sensor array (TESA; Part 1) provides the opportunity to simultaneously quantify T_{db}, RH, airspeed, and black globe temperature, but there are no existing methods incorporating these additional TE parameters to accurately assess the TE based on the thermal demands of the animal. Hence, the goal of Part 2 of this series was to develop a technique for evaluating the TE as a function of mean body temperature difference from thermally comfortable (ΔT_b) using body mass, T_{db}, RH, and airspeed inputs. Multiple regression analysis of the simulated data from the mechanistic thermal balance model for group-housed growing pigs was used to develop the Housed Swine Heat Stress Index (HS2I), which scales impact of the TE from 0 (thermally comfortable) to 10 (severe heat stress). Further, a wetted skin adjustment parameter was included to enable analysing TE with sprinklers. Simulated and predicted ΔT_b agreed well without wetted skin (R^2 = 0.98; RMSE = 0.061 °C) and with wetted skin (R^2 = 0.97; RMSE = 0.054 °C). The HS2I was applied to assess the spatiotemporal TE data collected by TESA in the commercial grow-finish facility presented in Part 1. HS2I can be used to evaluate the potential impact of the TE in existing facilities and as a design tool to explore different ventilation and cooling strategies.

1. Introduction

Livestock and poultry are homoeothermic animals that utilise a cascade of thermoregulatory mechanisms (physiological and behavioural) to maintain a thermal balance with their surroundings. Further, homeotherms must satisfy the following: heat loss (q_{loss}) to the environment must equal the total energy product of metabolism (DeShazer, 2009). An animal can become thermally unbalanced (i.e., body temperature outside the normal narrow range) if q_{loss} exceeds or falls below metabolic heat production (HP) – resulting in heat or cold stress. If the projections on climate change materialise (IPCC, 2014), the intensity and duration of heat stress for housed pigs will continue to increase (Renaudeau, Gourdine, & St-Pierre, 2011). The negative consequences of heat stress are well-documented and include decreased growth performance (Collin, van Milgen, Dubois, & Noblet, 2001; Huynh et al., 2005;

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Nomenclature

BW	body mass (kg)
β_n	Coefficients (dimensionless)
CT	critical temperature (°C)
f	function dependence
FI	feed intake
FFI	fractional feed intake
HP	heat production
HS2I	housed swine heat stress index (0–10 dimensionless)
$\overline{HS2I}$	average HS2I
i	TESA location
n	sample size
NaT	Not-a-Time
R^2	coefficients of determination
RH	relative humidity (% RH)
RMSE	root-mean-square error
S_{on}	binary wetting coefficient (wetted: $S_{on} = 1$; normal; $S_{on} = 0$)
p_n	coefficients (dimensionless)
q_{loss}	heat loss (W)
T_a	ambient temperature (°C)
T_b	mean body temperature (°C)
ΔT_b	simulated mean body temperature difference from 39 °C (°C)
$\Delta T_b{'}$	predicted mean body temperature difference at fixed BW and airspeed (°C)
$\Delta T_b{''}$	predicted mean body temperature difference at fixed BW (°C)
$\Delta T_b{'''}$	predicted mean body temperature difference (°C)
$\Delta T_b{''''}$	predicted mean body temperature difference with wet skin effect (°C)
$\Delta T_{b,w}{'}$	predicted mean body temperature difference between wet and normal skin (°C)
T_{db}	dry-bulb temperature (°C)
TE	thermal environment
TESA	thermal environment sensor array
T_g	globe temperature (°C)
TI	thermal index
T_{mr}	mean radiant temperature (°C)
T_{wb}	wet-bulb temperature (°C)
WDTI	wet-/dry-bulb temperature index
y_n	linear scaling coefficients
γ	uniformity coefficient (dimensionless)
ZLTE	zone of least thermoregulatory effort

Renaudeau et al., 2011) and substantial economic losses (St-Pierre, Cobanov, & Schnitkey, 2003; Stalder, 2015). Hence, techniques to assess the potential impact of the thermal environment (TE) on pig performance are needed to improve heat stress prediction and alleviation through development of management strategies and cooling technologies.

The TE describes the parameters (i.e., dry-bulb, floor, and mean radiant temperature, relative humidity, and airspeed) that influence the partitioning (i.e., convective, conductive, radiative, and evaporative) of q_{loss} between an animal and its surroundings. One TE parameter cannot solely represent or estimate q_{loss}; however, in many animal production systems, only dry-bulb temperature (T_{db}) is associated with the impact of the TE on animal performance and used to control. The recently developed TESA (Part 1) provides a nearly complete TE monitoring solution (neglecting conduction), but due to the limited availability of existing metrics to comprehensively quantify the total TE impact, there is a need for novel approaches to incorporate the TE parameters available from TESA to assess the TE.

Thermal indices (TIs) for livestock and poultry have been well-summarised in literature (da Silva & Maia, 2012; DeShazer, 2009; Fournel, Rousseau, & Laberge, 2017). These TIs substantially simplify complex physical and biological interactions for typically one selected physiological (e.g., body temperature or respiration rate) or performance production response (e.g., feed intake, milk production, mass gain, etc.) given only select combinations of the TE (e.g., T_{db} and RH), while either neglecting or assuming the other TE parameters are constant. Grow-finish pigs currently lack a suitable TI. Previous efforts have resulted in the wet-bulb (T_{wb})/T_{db} temperature index (WDTI) by Ingram (1965) for pigs weighing between 20 and 30 kg. Roller and Goldman (1969) associated the WDTI with three physiological parameters (respiration rate, rectal temperature, skin temperature) for pigs weighing from 30 to 90 kg exposed to T_{db} (34 °C–43 °C) and T_{wb} (23 °C–31 °C) conditions for 200 min. Both these studies fail to capture early onset of heat stress that results in a performance penalty for grow-finish pigs. The enthalpy concept, proposed by Beckett (1965) and later refined by Moura, Naas, Silva, Sevegnani, and Corria (1997), has been useful to evaluate pig environment but fails to incorporate long-wave radiation and airspeed. With many TIs, body mass (BW) is often neglected; however, for growing pigs, inclusion of BW is critical because fasting HP increases as an allometric function of BW ($a \times BW^{0.6}$; NRC, 2012) and the surface area to BW ratio decreases with increasing BW. Both these characteristics have major implications on q_{loss}. However, to accurately design or evaluate the TE for housed pigs, an index that relates q_{loss}, rather than just a fraction of q_{loss} (i.e., mainly convective via T_{db}), as a function of BW to a performance or physiological response is needed.

This study describes the development and application of an approach to evaluate the TE in grow-finish pig housing using TE measurements from TESA and estimated BW as inputs. Hence, the objectives of this paper were: (1) describe a mechanistic thermal balance model to estimate q_{loss} for grow-finish pigs, (2) use the mechanistic model results to derive the Housed Swine Heat Stress Index (HS2I), and (3) apply HS2I to analyse spatiotemporal TESA data from a case study to demonstrate feasibility.

2. Materials and methods

2.1. *Mechanistic model*

The thermal balance model, developed in Matlab (R2017a, The Mathworks, Inc., Natick, Massachusetts, USA), was adapted from Fialho, Bucklin, Zazueta, and Myer (2004) and simulated