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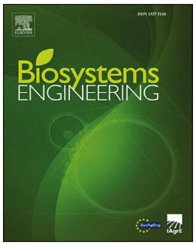

Research Paper

Thermal environment sensor array: Part 1 development and field performance assessment

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Current thermal environment (TE) monitoring and control strategies for livestock and poultry facilities require enhanced measurement capabilities to provide an optimum TE based on the animals' thermal demands. Further, techniques for combining additional parameters are needed to adequately assess the total impact of the TE on the animals. Hence, two papers introduce a spatial network of 44 Thermal Environment Sensor Arrays (TESAs), each with a custom data acquisition system (Part 1) and a technique for evaluating the TE as a function of mean body temperature difference from thermally comfortable pigs using estimated body mass and TESA measurements as inputs (Part 2). The TESAs and new thermal index were deployed in a commercial pig facility to perform a preliminary assessment of robustness and capabilities under production settings. Each TESA measured dry-bulb temperature (T_{db}), black globe temperature, airspeed, and relative humidity (RH), and required a custom circuit board with a microcontroller, signal conditioning, and communication hardware. After closeout (completion of the production cycle), TESAs were validated with a reference system to determine individual time constants and assess if a significant bias correction was needed (except airspeed). Total number of usable measurements for subsequent analysis for all sensors per TESA averaged (95% CI) 202,310 (199,187; 205,437). In summary, 7% T_{db} thermistor, 9% digital T_{db}, and 27% RH sensors required correction after 170 d inside the facility. Utilisation of low-cost sensors, open-source software, and microcontrollers allowed this novel network to provide sufficient measurement density to promote future queries on TE data in animal facilities.

1. Introduction

The growing global population is projected to increase by 2.4 billion people from 2015 to 2050 (UN, 2015) and will require a secure animal-based protein supply raised in energy, water, and feed efficient housing systems that do not adversely impact the environment. A housing system operating within the animal's optimum Thermal Environment (TE) is one approach to enhance animal well-being and growth

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Nomenclature

ADC	Analogue to Digital Converter
BGT	Black Globe Thermometer
CDMS	Custom Data Management Software
CI	Confidence Interval
CTA	Constant Temperature Anemometer
DAQ	Data Acquisition
MTRHR	Mobile Temperature and Relative Humidity Reference
n	number of steady-state measurements
NTC	Negative Temperature Coefficient
OTA	Omnidirectional Thermal Anemometer
PCB	Printed Circuit Board
RH	Relative Humidity (%)
s_{ref}	steady-state standard deviation for reference sensor (°C or % RH)
s_{TESA}	steady-state standard deviation for TESA sensor (°C or % RH)
t	time (s)
t_0	initial time (s)
τ	time constant (s)
T_{db}	dry-bulb temperature (°C)
TE	Thermal Environment
TESA	Thermal Environment Sensor Array
TESA DAQ	Thermal Environment Sensor Array Data Acquisition
T_g	globe temperature (°C)
T_{mr}	mean radiant temperature (°C)
$x(t)$	sensor response as a function of time (°C or % RH)
x_0	initial mean sensor value at time t_0 (°C or % RH)
$\bar{x}_{ref}$	mean reference steady-state value (°C or % RH)
x'^{*}_{TESA}	bias corrected future measure value (°C or % RH)
x'_{TESA}	future measured value (°C or % RH)
z_{calc}	z-statistic
ΔR_{ref}	divider resistor standard uncertainty (reference; Ω)
$\Delta^0 RH$	relative humidity zeroth-order standard uncertainty
$\Delta^0 RH_{ref}$	reference RH zeroth-order standard uncertainty
$\Delta^0 T_{db}$	dry-bulb temperature zeroth-order standard uncertainty (analogue)
$\Delta^0 T_{db,d}$	dry-bulb temperature zeroth-order standard uncertainty (digital)
$\Delta^0 T_g$	globe temperature zeroth-order standard uncertainty
$\Delta^0 T_{ref}$	reference T_{db} zeroth-order standard uncertainty
$\Delta^0 u$	airspeed zeroth-order standard uncertainty
ΔV_{ref}	analogue voltage standard uncertainty (reference; V_{DC})
Δx	difference between x_0 and x at steady-state (°C or % RH)
Δx_{ref}	single sample reference standard uncertainty (°C or % RH)
$\Delta \bar{x}_{ref}$	mean steady-state reference combined standard uncertainty (°C or % RH)
$\Delta^0 x_{ref}$	zeroth-order standard uncertainty for reference sensor (°C or % RH)
$\Delta \bar{x}_{TESA}$	mean steady-state TESA combined standard uncertainty (°C or % RH)
$\Delta^0 x_{TESA}$	zeroth-order standard uncertainty for TESA sensor (°C or % RH)
$\Delta \bar{x}_{TESA}$	mean TESA sensor steady-state value (°C or % RH)

performance (Curtis, 1983; Renaudeau, Gourdine & St-Pierre, 2011), while simultaneously reducing facility resource usage, as well as total feed consumed and days on feed. The TE describes the parameters that influence heat exchange (i.e., convective, conductive, radiative, and evaporative) between an animal and its surroundings (ASHRAE, 2013; Curtis, 1983; DeShazer, Hahn & Xin, 2009); however, all required parameters that describe the TE a housed animal experiences are rarely quantified, resulting in a lack of accurate TE control that is optimal for the animal. Hence, there is a need for advanced techniques to accurately assess and, ultimately, control the TE based on how the animal exchanges heat with its surroundings (Fournel, Rousseau & Laberge, 2017).

The parameters used to describe the TE include dry-bulb temperature (T_{db}), relative humidity (RH), airspeed, and mean radiant temperature (T_{mr}). Dry-bulb temperature is frequently the main parameter used to describe and control TE in commercial animal production systems; however, it exclusively impacts the convective (with airspeed) and evaporative (with airspeed and RH) modes of heat loss. The RH must be known with T_{db} to estimate latent heat loss (i.e., by respiration or wetted skin evaporation) by determining the water vapour pressure gradient between surrounding air and the saturated surface. Airspeed influences convective and evaporative heat transfer rates, and can substantially increase heat loss (beneficial in a hot T_{db}; unfavourable in a cold T_{db}). Lastly, T_{mr} is the uniform temperature of the surroundings in which radiant heat transfer from the animal's surface equals that in the actual surroundings. Due to the instrumentation difficulties, T_{mr} and airspeed are often neglected in livestock facilities, despite Bond, Kelly and Heitman (1952), Mount (1964), Mount (1967), and Beckett (1965) having shown radiative heat losses to be a substantial source of heat loss from pigs.

The incorporation of these four parameters into a single Thermal Environment Sensor Array (TESA) that is robust and practical for application in livestock and poultry facilities would allow the integration and application of advanced techniques. For human occupied buildings, many commercially available TE measurement systems exist to quantify indoor thermal comfort statistical values (e.g., draught rate, predicted mean vote, and predicted percentage dissatisfied; ASHRAE, 2013). These systems are prohibited by cost from use in multi-point Data Acquisition (DAQ) systems, feature proprietary hardware and software that limit flexibility, and are designed for relatively clean, low airspeed environments. In animal production systems, various combinations of T_{db}, RH, airspeed, and/or T_{mr} have been monitored (Brown-Brandl et al., 2014; Hayes et al., 2013; Vilela et al., 2015), but rarely all together. There is a unique opportunity, specific to animal

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