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Development and Validation of a Spatial and Temporal Thermal Environment Sensor Array and Data Acquisition System

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Abstract

The Thermal Environment (TE) inside swine facilities has a substantial impact on animal growth performance and facility energy usage; therefore, proper control and measurement are required to maintain the optimal TE that maximizes feed efficiency and consumes minimal resources. An inexpensive and novel sensor network capable of capturing the spatial and temporal distribution of TE is needed to help guide control feedback sensor placement and identify potential issues with the facility's environmental modification system. Hence, the objectives of this research were to: (1) design and construct a Thermal Environment Sensor Array (TESA) and (2) preliminarily evaluate the ability to estimate total heat loss using a TESA compared to a reference Ideal Temperature Source (ITS). A TESA featured a dry-bulb temperature (tdb), black globe temperature, airspeed, and relative humidity sensor. An Arduino was used to control data acquisition and mounted to a custom designed printed circuit board, which was stored in a weather-proof housing that also contained sensor connections, signal conditioning circuitry, and serial communication hardware. Data were transmitted and received on command from a computer with a custom Python data acquisition software. A TESA was suspended in the Animal Thermal Environment Replication and Measurement System (AThERMS) adjacent to the ITS (15.24 cm diameter black copper sphere with a heater immersed in water). Both ITS and TESA were subjected to two nominal airspeeds (~0.5 and 2.0 m s-1), each at three nominal tdb (17°C, 25°C, and 33°C) with mean radiant temperature approximately equal to the nominal tdb. Total heat loss was estimated from heat transfer theory with TESA measurements as inputs and compared to measured root-mean square power required to maintain at a constant water temperature in the ITS. The AThERMS provided a stable TE and the control system programmed onto a microcontroller maintained a near constant ITS water temperature, a critical component for repeatable results. Overall, predicted total heat loss underestimated measured power for all six tests. Future work needs improve the accuracy measuring power at low total heat losses. The TESA will be a novel and effective tool for understanding the TE distribution within swine facilities due its inexpensive components and simplicity.

Keywords

thermal comfort, sensor network, swine, environmental control, and ventilation

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Meat Science

Comments

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Development and Validation of a Spatial and Temporal Thermal Environment Sensor Array and Data Acquisition System

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Abstract. The Thermal Environment (TE) inside swine facilities has a substantial impact on animal growth performance and facility energy usage; therefore, proper control and measurement are required to maintain the optimal TE that maximizes feed efficiency and consumes minimal resources. An inexpensive and novel sensor network capable of capturing the spatial and temporal distribution of TE is needed to help guide control feedback sensor placement and identify potential issues with the facility's environmental modification system. Hence, the objectives of this research were to: (1) design and construct a Thermal Environment Sensor Array (TESA) and (2) preliminarily evaluate the ability to estimate total heat loss using a TESA compared to a reference Ideal Temperature Source (ITS). A TESA featured a dry-bulb temperature (t_{db}), black globe temperature, airspeed, and relative humidity sensor. An Arduino was used to control data acquisition and mounted to a custom designed printed circuit board, which was stored in a weather-proof housing that also contained sensor connections, signal conditioning circuitry, and serial communication hardware. Data were transmitted and received on command from a computer with a custom Python data acquisition software. A TESA was suspended in the Animal Thermal Environment Replication and Measurement System (AThERMS) adjacent to the ITS (15.24 cm diameter black copper sphere with a heater immersed in water). Both ITS and TESA were subjected to two nominal airspeeds (~0.5 and 2.0 m s^{-1}), each at three nominal t_{db} (17°C, 25°C, and 33°C) with mean radiant temperature approximately equal to the nominal t_{db}. Total heat loss was estimated from heat transfer theory with TESA measurements as inputs and compared to measured root-mean square power required to maintain at a constant water temperature in the ITS. The AThERMS provided a stable TE and the control system programmed onto a microcontroller maintained a near constant ITS water temperature, a critical component for repeatable results. Overall, predicted total heat loss underestimated measured power for all six tests. Future work needs improve the accuracy measuring power at low total heat losses. The TESA will be a novel and effective tool for understanding the TE distribution within swine facilities due its inexpensive components and simplicity.

Keywords. *thermal comfort, sensor network, swine, environmental control, and ventilation.*

Introduction

The Thermal Environment (TE) monitoring inside livestock and poultry facilities is vital to improve production efficiency needed to address future food security demands without neglect of environmental impact. The TE influences animal well-being, growth performance, and feed conversion efficiency, as well as places the animal at risk for adverse health effects (Ames, 1980; Close, 1987; Curtis, 1983; Renaudeau, Gourdine, & St-Pierre, 2011; Thuy, 2005). In addition, about 25% of the total energy used in conventional swine production systems (farrow to finish) is attributed to building operation (Lammers et al., 2012). This is often directly related to TE modification and control system operation and performance. Further, operation and performance of TE modification and control systems have led to spatial and temporal distribution of TE to be inconsistent (Carvalho, Moura, & Nääs, 2008; Jerez, Wang, & Zhang, 2014). Sufficient monitoring density and accurate quantification is required, such that the most effective management strategies for optimum thermal comfort for the animals and building designs can be implemented.

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, 2009). Commonly measured parameters of TE include dry-bulb temperature (t_{db}), relative humidity (RH), airspeed, and mean radiant temperature (t_{mr}). While, floor temperature is needed to estimate heat transfer via conduction, it is often difficult to implement in a commercial application. Dry-bulb temperature is frequently the main parameter used to describe and control TE; however, it exclusively impacts only convective and evaporative 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 vapor pressure gradient between surrounding air and the saturated surface or fluid of interest. Airspeed influences convective and evaporative heat transfer rates, and can substantially increase heat loss (beneficial in a hot t_{db}; negative 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 difficulty to instrument, t_{mr} and airspeed are often neglected in livestock facilities; despite, Bond et al. (1952), Mount (1967), Mount (1964), and Beckett (1965) having showed radiative heat losses to be a substantial source of heat loss from swine.

A Thermal Environment Sensor Array (TESA) and Data Acquisition System (DAQS) were developed and experimentally validated for use in capturing the TE spatial distribution and temporal distribution in swine facilities. The utilization of low-cost sensors, open-source software, and microcontroller based control allows this novel network of TESAs and accompanying DAQS to provide sufficient measurement density, such that design and control of TE modification systems can be adjusted to enhance and maintain the optimal TE for improved animal production efficiency and thermal comfort. Hence, the objectives of this research were: (1) design and construct a TESA and (2) preliminarily evaluate the ability to estimate total heat loss using a TESA compared to a reference Ideal Temperature Source (ITS).

Materials and Methods

Thermal Enviroment Sensor Array

An individual Thermal Environment Sensor Array (TESA; figure 1) consisted of four sensors to perform four measurements: dry-bulb temperature (t_{db}), relative humidity (RH), airspeed, and globe temperature ($t_{g;}$ via a black globe thermometer to calculate mean radiant temperature; t_{mr}). Sensor signals from a TESA were connected via a single, ten-conductor wire to screw terminals mounted on the TESA Data Acquisition, Transmission, and Control (TESA DAQTC) custom Printed Circuit Board (PCB).

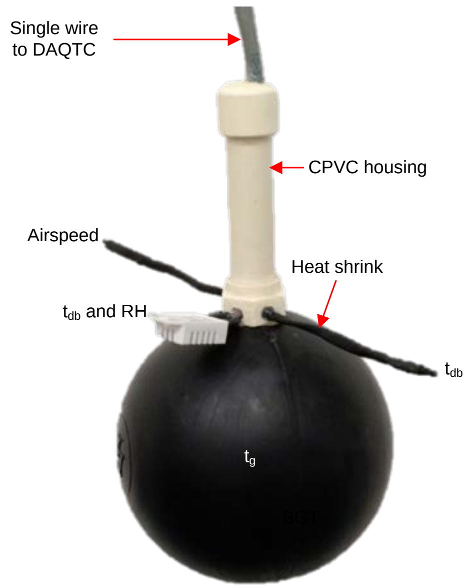

Figure 1. Image of a Thermal Environment Sensor Array (TESA) featuring dry-bulb temperature (t_{db}), relative humidity (RH), airspeed, and Black Globe Thermometer (BGT) sensors. Globe temperature (t_g) is obtained from a t_{db} sensor at the center of the BGT and used to calculate mean radiant temperature (t_{mr}).

Dry-bulb Temperature and Relative Humidity

Ambient t_{db} was measured with a negative temperature coefficient thermistor (figure 1). Additionally, a single wire digital interface t_{db} and RH sensor (RHT03, MaxDetect Technology Co. Ltd., Shenzhen, China; figure 1) was used. Valid sensor operation ranged from -40°C to 80°C (t_{db}) and 0% to 100% (RH; non-condensing).

Airspeed

A custom omnidirectional thermal anemometer (figure 1) was developed to measure airspeeds between 0 and 5.5 m s^{-1}. Detailed information regarding the sensor design, calibration, and t_{db} compensation approach can be found elsewhere (Gao, Ramirez, & Hoff, 2016).

Mean Radiant Temperature

A BGT (figure 1) was constructed from a 0.1016 m (4 in.) diameter, flat black, hollow plastic sphere (3FXE7, W.W. Grainger Inc.) A t_{db} thermistor was mounted at the center of the black globe thermometer.

Data Acquisition, Transmission, and Control System

Printed Circuit Board

The TESA DAQTC was a custom designed (Eagle v7.4, CadSoft Computer GmbH, Pleiskirchen, Germany) and manufactured PCB that featured the signal conditioning circuits for TESA and serial communication circuits. Screw terminals connected the leads from TESA and spring-cage terminal blocks connected power and serial communication signals to the PCB.

Housing

Two TESA DAQTC PCBs (i.e., for two TESAs) were housed in a small weatherproof housing (NBF-32010, Bud Industries Inc., Willoughby, OH, USA) that could be placed inside a swine facility. Three cable grips were installed to provide water tight connections for the two TESA signal wires and one for the supply power and serial communication wires.

Serial Communication Network

The serial data communication network featured bidirectional data transfer between a notebook computer and every deployed TESA DAQTC. A unique identifying number was coded onto each microcontroller to directly send a transmit data request to a single TESA DAQTC and subsequently, distinguish the received data source.

Software

One TESA DAQTC program was developed in the integrated development environment for the microcontroller and returned sequentially measured analog voltages approximately every 2 ms, when prompted by a custom software (Python 2.7, Python Software Foundation, Beaverton, Oregon, USA) on the notebook computer. The custom DRAQC software controlled sampling interval between data transmission requests for each TESA DAQTC and timestamped incoming data sent from each TESA DAQTC. Sampling interval and unique identification numbers for TESA DAQTC microcontrollers were user controlled. Data were saved on removable flash memory.

Funcitonal Performance Evaluation

To ensure the performance of an individual, assembled TESA was not hindered by the placement of a sensor or the orientation with respect to the airflow, a TESA was subjected a constant and controlled TE and compared to a reference.

Theoretical Analysis

An Ideal Temperature Source (ITS) will ultimately balance the power required to maintain a specified temperature with the combined convective and radiative losses of the TE. For any object, the transient sensible thermal balance (equation 1) is:

$$mc\frac{dT}{dt} = q''_{gen} - q''_{conv} - q''_{rad} \tag{1}$$

where

m	= mass (kg)
c	= specific heat of mass (J kg^{-1} °C^{-1})
T	= absolute temperature of an object's mass (K)
t	= time (s)
q''_{gen}	= generated heat flux inside an object (W m^{-2})
q''_{conv}	= convective heat flux (W m^{-2})
q''_{rad}	= radiative heat flux (W m^{-2})

Assuming steady-state and substituting in the appropriate rate equations yields (equation 2):

$$q_{gen} = h_{cv}A(T_s - T_{db}) + \epsilon\sigma A(T_s^4 - T_{mr}^4) \tag{2}$$

where

q_{gen}	= total generated heat (W)
h_{cv}	= convective heat transfer coefficient for an object's geometry (W K^{-1} m^{-2})
A	= object surface area (m^2)
T_s	= surface absolute temperature (K)
ϵ	= emissivity (0.95)
σ	= Stefan-Boltzmann constant (5.6697E-8 W m^{-2} K^{-4})

The sensible TE (i.e., t_{db}, t_{mr}, and airspeed) can be quantified using TESA measurements and then used to estimate the combined convective and radiative losses, with knowledge of the object's geometry. Further, since an ITS is maintained at a constant temperature, the surface temperature can also be assumed. Hence, the right side of equation 2 can be determined and used to predict the heat loss from an object.

The sum of the convective and radiative losses (q_{total}) must equal the rate of thermal energy being generated inside ITS; thus, measurement of electrical power allows ITS to act as the reference value to compare q_{total} (equation 3).

$$P = q_{total} \tag{3}$$

where

P	= measured electrical power to maintain ideal heat source at constant temperature (W)
q_{total}	= predicted combined radiative and convective heat loss by a TESA (W; equation 2)

Experimental Setup

The ITS was a copper sphere painted flat black, and filled with water. The sphere replicated a geometry with well-known empirical heat transfer relations for forced and natural convection. An electrical cartridge resistance heater (HDL00001, TEMPCO Electric Heater Corp., Wood Dale, Illinois, USA) was secured in a hole bored at the top of the sphere. A TRIAC (AC-VXP/N:180V800E, Control Resources, Inc., Littleton, MA, USA) transformed the input to control AC output to the heater. A constant speed DC motor turned a metal wire for stirring. A waterproof temperature sensor was also placed in the water and acted as the feedback sensor for control of the water temperature.

The Animal Thermal Environment Replication and Measurement System (AThERMS) was designed to simulate different radiative, convective, and evaporative TEs a housed animal may experience (Ramirez, Hoff, Gao, & Harmon, 2015). Different t_{db}, RH, and airspeeds can be created at the center of a large chamber where the heated sphere and a TESA were located for the functional performance evaluation (figure 2).

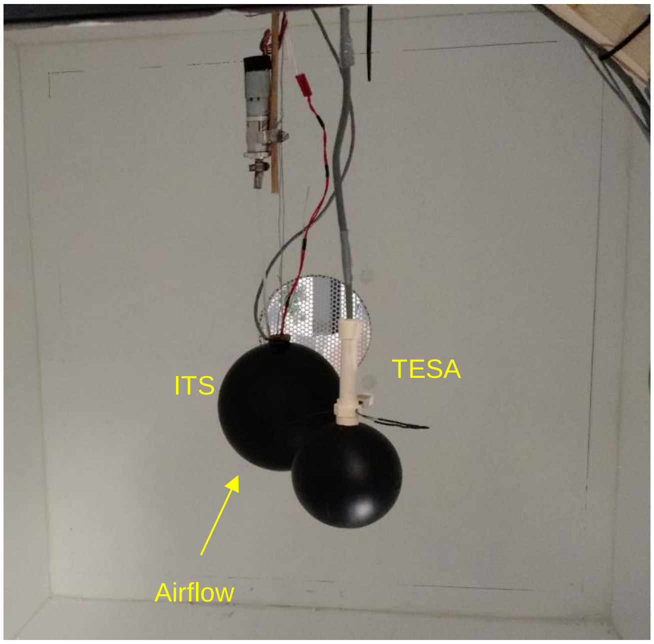

Figure 2. Experimental setup with TESA and Ideal Temperature Source (ITS; black sphere filled with water and a heater).

Data Acqusiton and Prodcedure

Two airspeeds (~0.5 and 2.0 m s^{-1}) were tested for one scenario: three nominal t_{db} (17°C, 25°C, and 33°C) were at t_{mr} equal to the nominal t_{db}.

Data were recorded in a comma delimited text file and processed using Matlab (R2016a, The Mathworks, Inc., Natick, Massachusetts, USA). The t_{db}, t_{mr}, and water temperature of ITS were allowed to reach steady-state prior to estimating q_{total} and for calculating the RMS power required by the IDHS. Once at the steady-state condition, the analysis was conducted over at least a 30 min interval. Raw voltage measurements were transformed to their corresponding physical value, and then the physical quantity was averaged over the steady-state period.

A Simulink model was developed and used to solve for the theoretical q_{total} using TESA measurements and compared to measured power required to maintain the ITS at a constant water temperature.

Results and Discussion

Six experiments were conducted at two airspeeds for three nominal t_{db}. A summary of the steady-state average from measurements obtained at ITS and TESA is provided in table 1. Overall, during the steady-state condition, both the power output of the heater (figure 3) and the TE inside AThERMS (figure 4) were stable; however, airspeed had a range of about 0.1 m s^{-1}, most likely attributed to turbulence. The resultant impact on calculation of q_{total} was negligible. The unique design of AThERMS allows for this fine control and stable supply of different TE.

In order for the ITS to function with ideal behavior, water temperature inside the sphere must be approximately constant. Figure 4 demonstrates that the water temperature is about constant over the steady-state period, with observation of major fluctuations. This narrow control band is most likely attributed to the tuning of the PI controller implemented on the microcontroller.

Table 1. Summary of TE conditions and ITS water temperature during each of the six experiments. The last row, t_{mr_IR}, was obtained to from a cube with an IR sensor mounted on each face to verify the t_{mr} calculation.

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
t_{db_digtal} (°C)	17.20	25.50	33.53	33.15	25.50	18.77
$t_{db\_thermistor}$ (°C)	17.39	25.51	33.56	32.91	25.42	18.82
t_{mr} (°C)	17.39	25.51	33.67	33.20	25.37	18.53
Airspeed (m s^{-1})	2.19	2.22	2.22	0.42	0.43	0.38
t_{water} (°C)	39.02	39.01	39.26	39.13	38.97	39.31
t_{mr_IR} (°C)	17.27	25.24	33.21	33.03	25.13	17.85

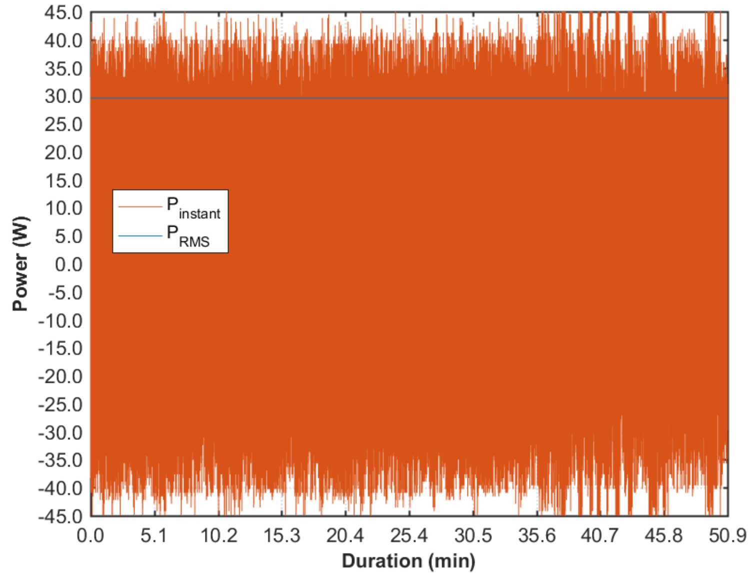

Figure 3. Example of instantaneous power measurement and calculated Root-Mean Square (RMS) power for test 2 during the steady-state period. The RMS power was compared with the theoretical heat loss predicted from TESA measurements and a Simulink model.

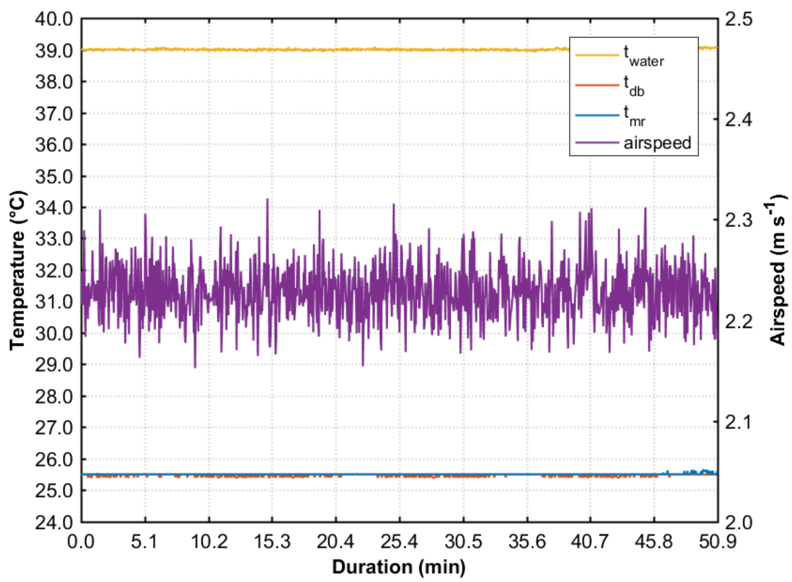

Figure 4. Example of the TE conditions measured by TEAS and water temperature inside the ITS for test 2 over the steady-state period.

The sensible modes of q_{total} were partitioned and for each of the six experiments (figure 5). Convection was the greatest fraction of q_{total} in each experiment. The relative proportion of convection losses to radiative losses increased as airspeed increased except for the 25°C, 0.43 m s^{-1} test, where heat loss due to convection was about three times as much as radiation (figure 5).

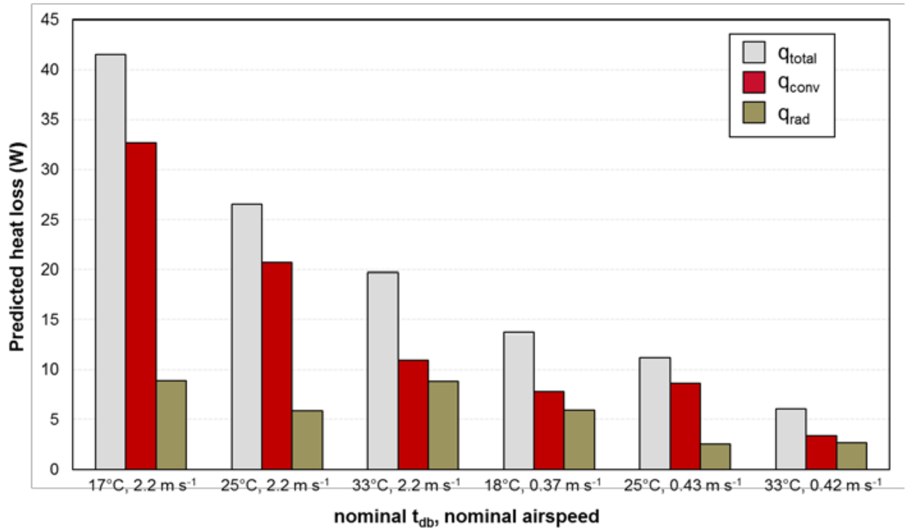

Figure 5. Partitions of convective and radiative heat loss, and total heat loss from the ITS as predicted by TESA measurements of the TE.

When the measured power generated by the ITS to maintain a constant water temperature in the sphere was compared with the predicted total heat loss (q_{total}) by TESA from TE measurements in AThERMS, the predicted q_{total} tended to underestimate measured ITS P_{gen} (figure 6). A potential cause for this consistent underestimation may be due the empirically derived relations used to estimate the convective heat transfer coefficient. Note, at the lowest nominal t_{db} and highest airspeed, predicted q_{total} had the lowest relative difference compared to measured ITS P_{gen}. This is most likely attributed to being able to measure larger values (highest q_{total} among six experiments) with greater accuracy due the full-scale nature of most instruments. Similarly, the lower observed q_{total} had the greatest relative difference between predicted and measured.

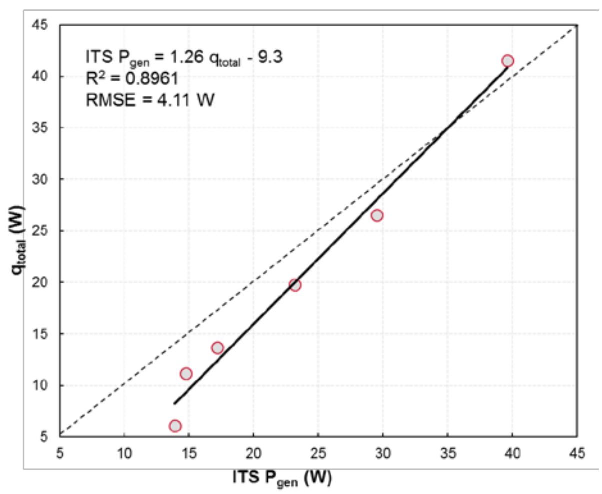

Figure 6. Comparison of the power generated by the ITS to maintain a constant water temperature in the sphere with the predicted total heat loss by TESA from TE measurements in AThERMS.

Conclusions

A novel and robust TESA with an accompanying DAQ was designed, constructed, and empirically evaluated in controlled conditions. At two nominal airspeeds and t_{db} equal to t_{mr}, the feasibility of TESA to estimate the convective and radiative heat losses seems promising; however, improvements in measurement system are needed to better estimate low scale q_{total}. Future work includes the collection and analysis of data for t_{db} not equal t_{mr}. The ultimate goal for TESA is to be implemented in a commercial swine production facility to characterize and compare the TE performance of different ventilation controllers and building designs.

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