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Development and Validation of an Animal Thermal Environment Interaction Laboratory

Benjamin C. Smith
Iowa State University

Sara E. Weyer
Iowa State University

Brett C. Ramirez
Iowa State University, bramirez@iastate.edu

Steven J. Hoff
Iowa State University, hoffer@iastate.edu

Richard S. Gates
Iowa State University, rsgates@iastate.edu

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Abstract

A pilot-scale laboratory was designed and built to meet the specific needs of conducting precision livestock farming (PLF) research related to optimizing thermal environment. The two room (8.5 by 3.7 by 2.9 m; W by L by H) laboratory was built inside an existing structure utilizing common construction methods and materials. Each room was fully instrumented to characterize the thermal (dry-bulb temperature and relative humidity) and gaseous (O2, CO2) environment and facilitate both direct and indirect calorimetry measurements. The laboratory's instrumentation set-up allows for expansion into additional thermal (black-globe temperature), lighting analysis (wavelength and intensity) and gas (NH3) as experiments demand. Ventilation was a "modified push-pull" style with one common supply fan and an exhaust fan for each room operating at a slight negative pressure. Each room also featured an airflow measurement device that was individually calibrated. The commissioning of the environmental control demonstrated all sensors were functioning correctly. This laboratory can be used for various poultry and swine experiments for developing and refining PLF technologies before advancing to field trials in commercial facilities. Unique and extensive research laboratories are needed to readily facilitate the research and development of PLF technologies related to characterizing and controlling the animal occupied zone thermal environment that align with industry needs. Traditional production facilities present challenges related to biosecurity, instrumentation capabilities, labor, and travel to remote sites.

Keywords

Commissioning, PLF, poultry, swine, ventilation

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Comments

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2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Development and Validation of an Animal Thermal Environment Interaction Laboratory

Benjamin C. Smith[1], Sara E. Weyer[1], Brett C. Ramirez[1], Steven J. Hoff[1], and Richard S. Gates[1]
[1]Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA

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ABSTRACT. *A pilot-scale laboratory was designed and built to meet the specific needs of conducting precision livestock farming (PLF) research related to optimizing thermal environment. The two room (8.5 by 3.7 by 2.9 m; W by L by H) laboratory was built inside an existing structure utilizing common construction methods and materials. Each room was fully instrumented to characterize the thermal (dry-bulb temperature and relative humidity) and gaseous (O_2, CO_2) environment and facilitate both direct and indirect calorimetry measurements. The laboratory's instrumentation set-up allows for expansion into additional thermal (black-globe temperature), lighting analysis (wavelength and intensity) and gas (NH_3) as experiments demand. Ventilation was a "modified push-pull" style with one common supply fan and an exhaust fan for each room operating at a slight negative pressure. Each room also featured an airflow measurement device that was individually calibrated. The commissioning of the environmental control demonstrated all sensors were functioning correctly. This laboratory can be used for various poultry and swine experiments for developing and refining PLF technologies before advancing to field trials in commercial facilities. Unique and extensive research laboratories are needed to readily facilitate the research and development of PLF technologies related to characterizing and controlling the animal occupied zone thermal environment that align with industry needs. Traditional production facilities present challenges related to biosecurity, instrumentation capabilities, labor, and travel to remote sites.*

Keywords. Commissioning, PLF, poultry, swine, ventilation

Introduction

The variability of microclimates inside intensive livestock production systems can have a substantial impact on animal welfare and productivity. Increased interest in incorporating precision livestock farming (PLF) applications into livestock production is driving rapid creation and adoption of advanced sensing and decision-making systems targeting animal health, welfare, environmental control, management, etc. While there are numerous advanced technologies integrated into modern environmental control, there are limited PLF technologies available addressing key industry needs. Specific situations of interest to production stakeholders related to precision technology and environmental impacts on production include the farrowing room environment in swine production and neonatal housing for both swine and poultry. To address the lack of knowledge of PLF technologies impact on the thermal environment and animal's response, a general-purpose laboratory is needed.

Such a laboratory must be capable of housing multiple species and phases of production in an industry relevant setting to satisfy these research needs. Such combinations of research interest might include laying hens (both cage free and conventional cage), broiler chicks, weaned pigs in a nursery setting, and swine farrowing stalls. Therefore, the objectives of this study were to 1) develop a pilot scale thermal environment interaction laboratory to conduct animal-environment interactions and energetics experiments, 2) commission the environmental control systems.

Materials and Methods

Design

To address the key objectives of the Animal Thermal Environment Interaction Laboratory (ATEIL), a unique structural and thermal environmental modification system (TEMS) design was warranted. ATEIL was located within an existing bay at the Livestock Environment Building Research Complex (LEBRC) at Iowa State University. The ATEIL experimental rooms were designed to be free standing with only ventilation ducts connecting to the existing structure. Due to this location, no live loads, for snow or wind, were necessary, but a dead load for equipment and a live load for an individual walking in the attic were utilized in the structural design. Each room was 8.5 m by 3.7 m with 2.9 m ceilings (28 ft by 12 ft with 9.5 ft ceilings) and shared a 1 m tall common attic space. Ceiling height was selected to accommodate a raised animal housing platform such that a 2.4 m (8 ft) distance from animal floor to ceiling could be maintained for camera use and testing of other technologies. Within each room, a usable area for animal housing was designed as 2.13 m by 7.62 m (7 ft by 25 ft) to provide ample access around the animal occupied zone.

The TEMS was designed to achieve a range of ventilation requirements for various species and phases of production. It was determined that the minimum continuous ventilation rate of possible occupants would be 170 m^3 hr^{-1} (100 cfm), that is, for laying hens in a single layer using California Proposition 12, 2018, spacing requirement and MWPS ventilation rates (Midwest Plan Service, 1983). Maximum ventilation rate was determined as 5,097 m^3 hr^{-1} (3,000 cfm), for lactating sows with 3 week old piglets using current heat production data and a 2°C temperature rise (Albright, 1990; Stinn & Xin, 2014). Design considerations for TEMS included continuous operation from minimum to maximum ventilation capacity so that the laboratory could be reconfigured for a variety of species and experiments. In addition, the minimum ventilation rate could be specified (based on a CO^2 balance) to achieve a minimum difference of 200 ppm CO^2 between ambient and room exhaust for indirect calorimetry experiments. An evaporative cooling pad was needed to reduce potential heat stress conditions due to this ventilation rate range and Iowa climate. In addition, a primary (MERV 8) and secondary (MERV 15) filter pair was added for dust and airborne pathogen control of the incoming air.

To account for the previously mentioned ventilation components with given space constraints at the facility, a unique system curve analysis was conducted to ensure proper ventilation performance, primarily due to the operation of the filter pairs at higher face velocities resulting in significantly higher static pressure drop per filter pair than typically encountered in animal agriculture ventilation (Smith et al., 2019). A theoretical system curve was created from manufacturer's data for the operation of the selected components. The evaporative cooling pad and filter pairs static pressure losses were collected from manufacturer's charts. The pressure difference across the intake and supply duct was estimated using data from ASHRAE assuming smooth duct (ASHRAE, 2013). Fan performance information was collected from the respective manufacturer's literature as discussed in the next section. A combination of one exhaust fan per room) and one intake fan were selected to achieve the desired minimum and maximum ventilation rates necessary for ATEIL given the system curve of the selected equipment. When selecting equipment, only operational performance of the fans at 100% of rated speed were considered.

Construction

The structural shell was built with typical framed wall construction methodology and materials for animal agricultural facilities. Each room featured two viewing windows on their exterior walls. The exterior wall faces and room ceiling was covered with 0.4 mm thick steel sheeting. Walls and duct were insulated with R-value = 2.3 m^2*K W^{-1} fiberglass batt insulation. The ceiling was not insulated since the laboratory was built inside an existing structure and for operation during cold weather, fresh air can be tempered in the attic space. Interior walls and duct interior were covered with a 9.5 mm thick wafer-board sheet and 3.2 mm thick sheet of smooth white finished hardboard.

Within each room, the animal occupied area was built on a metal platform elevated 0.5 m above the floor with a shallow sloped pit underneath it. The animal housing area was 2.1 m by 7.6 m. The shallow sloped pit was built out of five formed plastic panels with a 7.6 cm (3 in.) slide valve in the lowest portion of the pit and had an approximate capacity of 113.6 L (30 gallons) of manure slurry. The platform frame consisted of 76 mm wide, 9.5 mm thick strap steel, and 12.7 mm thick 76 mm wide "T" configured legs. All components were bolted together with 12.7 mm grade 6 bolts. Platform flooring was removable and could be a maximum of 9.5 mm thick. Water was supplied to each room with a 19 mm diameter polyethylene tube (PEX Tubing), with a pressure reduction valve to adjust water pressure supply to the rooms (Model 09624 Watts®, Menards, Eau Claire, WI).

The modified push-pull ventilation system for each room in ATEIL operated at a slight negative operating pressure differential relative to ambient. The air intake featured an evaporative cooling pad (150 mm thick) with a sump pump system (CELdek Cooling Pads, Munters, Hamburg, Germany), a stainless-steel filter grid (New Modern Concepts, Iowa Falls, IA) holding four primary and secondary air filters, an intake air fan (Ø1.4 m; I-Fan Extra, Fancom, Panningen, The Netherlands), and a custom 0.9 m by 0.9 m rectangular duct with smooth siding to transport air to the attic space above the rooms. The supply duct included four 90° turns and an elevation change to deliver fresh air into the attic space above the rooms. The attic space contained a forced air, unvented combustion supplemental heater (22 kW; 75,000 BTU h^{-1}; propane; Dura-Therm, Chore-Time, Milford, IN) located within the air path from the air duct to preheat air for the rooms. The supplemental heater was configured to operate at a reduced thermal output to limit heat to 11 kW (35,000 BTU h^{-1}). Within each room, an 800 W radiant electric resistance heater (Model MR Kalglo®, QC Supply, Schuyler, NE) with built-in thermostat control was installed on the end opposite from the exhaust to allow for individual room supplement heat control. Each room featured its own exhaust fan (Ø 0.94 m; I-Fan Extra, Fancom, Panningen, The Netherlands) and an air distribution system which comprised one row of three actuated bi-flow ceiling inlets (JD1501, Double L Group, LLC, Dyersville, IA) attached to a linear actuator (IM60, Fancom, Panningen, The Netherlands). Exhaust airflow for each room was continuously monitored with an airflow measurement device (AMD; ATM 50, Fancom, Panningen, The Netherlands). Dry-bulb temperature (-40-40°C, ±0.1°C accuracy; F Temp, ControlTech, Bondurant, IA) and relative humidity (0-100% RH, ±3.0% accuracy; WHT-310, Dwyer, Michigan City, IN) sensors were placed outdoors, inside the duct just before entering the attic plenum, and at three locations within each room (exhaust duct, mid room, and back of the room) for controlling the various ventilation, heating, and cooling functions of TEMS. Differential static pressure (SP) transducers (five in total) were installed to measure the static pressure difference from room to ambient (one per room; 0-125 Pa, ±0.25 % accuracy; Model MRG, Setra Systems, Boxborough, MA), across the filter bank, across the intake fan, and from attic to ambient (0-125 Pa, ±1.0% accuracy; MS2-W101-LCD, Dwyer Instruments, Inc, Michigan City, IN). All SP transducers were collocated in a common area near the building automation and control (BAC) system and 6.4 mm clear vinyl tubing was used to sample at each location and filters (490-202-0004, Arnold 4-Cycle In-Line Fuel Filter, Spencer, IA, USA) were installed at the end of all sampling tubes.

Instruemementation

To accomplish the objectives of ATEIL, multiple data acquisition and control (DAqC) systems were integrated to monitor and record numerous data streams. The primary DAqC system was integrated into the BAC, and included the water system (flowrate and pressure, post pressure reduction valve), CO_2 sensors, and power consumption of ventilation and supplemental heaters. The primary DAqC recorded data using a sparse sampling method with a minimum change threshold of 0.2°C, 0.5% RH, 0.5 A, or 0.5% of the specified range of the sensor or at a 5 min interval, if the minimum change threshold had not occurred. The water system had a flowmeter (0.38-83.3 L min^{-1}; VPD, Carlon Meter, Grand Haven, MI) and pressure transducer (0-690 kPa, ±1.0% accuracy; 628-03-GH-P1-E1-S1, Dwyer Instruments, Inc, Michigan City, IN) installed at the inlet to the supply line for the rooms.

Two CO_2 sensors (0-10,000 ppm; ±50 ppm accuracy; Model 19, DOL, Aarhus, Denmark) were installed in each room, one at the center of the room and one in the exhaust air duct. Also, one CO_2 sensor was installed in the supply duct after the intake fan to monitor ambient CO_2 concentrations. Electrical current transducers were installed on the branch circuits for the three fans and supplemental heaters (CCT60-100, Dywer Instruments, Inc, Michigan City, IN). The current draw of these components was utilized as feedback for the operational status of these components in the BAC to confirm operation. The BAC has additional capacity for 15 thermal environment sensor arrays (TESAs; Ramirez et al., 2018a, 2018b). Each TESA has at least a dry-bulb temperature and black globe temperature sensor, and potential inclusion of a relative humidity sensor. These could be installed in numerous arrangements to meet the needs of the individual experiment.

An air quality sampling system was developed to analyze gas concentrations inside each room and ambient. This system comprised of a diaphragm pump (37 W; 107CAB18, Thomas, Sheboygan, WI) to continuously extract air from each sampling location as well as a series of solenoids and a manifold operating under positive pressure to eliminate potential dilution (DeShazer, 2009). Solenoid sequence consisted of alternating between each sampling location every 6 minutes. Sampling flowrate was controlled using a rotameter on the outlet side of the pump and a rotameter after the gas analyzer to achieve a flowrate of 0.5 L min^{-1} supply. Oxygen (O_2) was measured using an electrochemical sensor (Model 6809720 with Polytron 5100 Dräeger, Inc, Houston, TX). The analog output signal was recorded with a datalogger at a fixed interval of 1 Hz since the relatively low change in sensor output and the sparse sampling method of the BAC was not conducive for reliable data recording. The first 5 min of sampling was discarded to allow concentrations to stabilize and only the last 60 s of data were recorded (60 measurements at 1 Hz).

A secondary DAqC system recorded the outputs from the AMDs for each room (Lumina 21, Fancom, Panningen, The Netherlands) and was configured to record data at a 1-minute interval. Data were recorded on a local computer connected to the secondary DAqC via and ethernet to serial converter (Weblink Box, Panningen, The Netherlands).

Enviornmental Control Comissioning

The AMDs were calibrated using the Fans Assessment Numeration System (FANS; S/N 30-0010; 0.76 m by 0.76 m; Gates et al., 2004). The FANS unit was placed on the exhaust side of the fan with a 0.6 m transition from the fan cone and all ATEIL and bay doors were closed for the duration of testing. A multi-point curve was made with increasing (Room 1: n=11; Room 2: n=11) and decreasing (Room 1: n=7; Room 2: n=10) airflow points. At least two flowrate measurements (up and down passes) were performed at each airflow. Data validation required <10% difference between airflow measurements. A unique linear calibration equation was obtained by regressing the FANS measured airflow (dependent) versus the AMD output (as a percentage; independent). The calibrated airflow rate was calculated from the percentage output of the AMD using the inverse of the previous described calibration equation. The SE of the calibration was calculated by dividing the SE of the regression by the slope of the regression (Doebelin, 2004).

A two-point span calibration for the room air temperature and relative humidity sensors was performed using an insulated chamber filled with ice to create a reference "low" temperature point with high humidity, a "high" temperature/low humidity point was achieved using room conditions. A handheld hygrometer (±0.2°C and ±2% RH; Model HMI41, Vailsala, Vantaa, Finland), was calibrated with a salt chamber system (November 2019; Model HK15, Vailsala, Vantaa, Finland) was used as a reference. Sensors were co-located with the sensing element of the handheld unit. Then, for each span point, sensors were allowed to achieve steady-state conditions by waiting at least 15 min or until no changes were noted within 90 s. Slope and offset were evaluated for differences from unity and from zero respectively.

The CO^2 sensors were calibrated in situ by a two-point calibration at an ambient concentration (~400 ppm CO_2) and at a high concentration (3,500 ppm CO_2). Span gas flowing from a compressed gas cylinder (GASCO, Oldsmar, FL) was heated using a warm water bath before being introduced to the sensor using a mask fitted over the filter element of the sensor. Gas was constantly flowing at 0.25 L min^{-1} until the sensor reached steady-state conditions. Successful sensor calibration was considered when a measurement from the sensor at steady state was within the specified tolerance of the gas concentration based on the certificate supplied with the span gas (±10.0% of rated concentration).

The O_2 sensor and sampling system were commissioned using a handheld, four-channel gas meter (calibrated with the manufacturer's bump gas kit: 4/10/2020; ±0.1% O_2, GasAlert Quattro 4-Gas Monitor, BW Honeywell, Calgary, Canada) that included an O_2 electrochemical sensor. The commissioning was performed during the acclimation period for the first experiment with animals present, as discussed in the operational performance section. Each sampling line was commissioned independently by running only that line's pump and placing the handheld gas meter at the sample line inlet, comparison of the meter and sensor reading was performed. Agreeance of the values indicated no leaks in the sample system. This procedure was repeated, but with all three sample pumps operating to check for leaks caused by flow from the additional pumps running.

Results and Discussion

Environmental Control Commissioning

A unique calibration equation was obtained for each AMD (Figure 1) with R^2 values exceeding 0.99 and RMSE less than 2%. A slight hysteresis was noted in each calibration, this may be attributed to the mounting location of the FANS unit and dynamic wind effects during testing. There was no significant difference between the slopes of each AMD linear regression ($P = 0.48$), but a significant difference was noted between the intercepts ($P < 0.05$). The significant difference between intercepts suggests that the individual calibrations were justified. A zero-airflow point was not utilized as the FANS unit registered an airflow due to a slight wind during calibration and the AMD did not register any airflow as exhibited by a lack of rotation during the test. The proprietary software of the secondary DAqC that processed the AMD signal is the direct cause of the output percentage exceeding 100%, that is, the AMD is reading above the proprietary airflow range that is unchangeable in the software inputs.

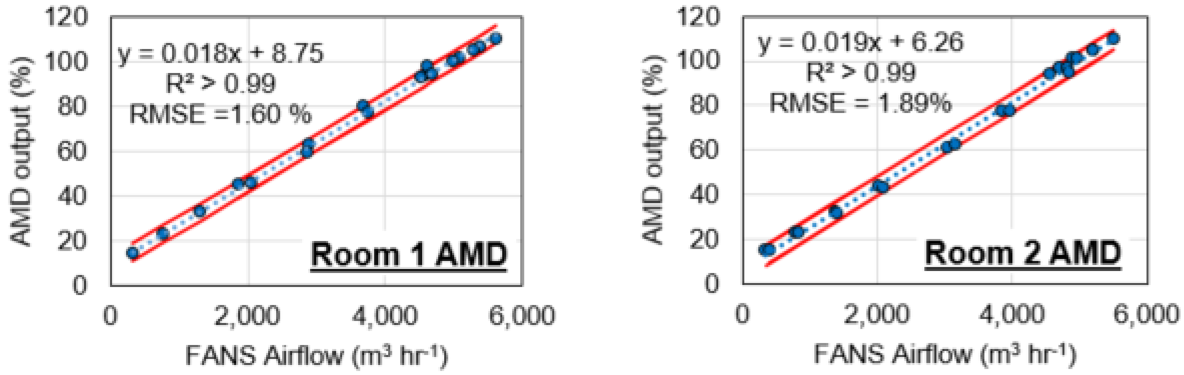

Figure 1. Calibrations for Room 1 and 2 AMD devices against the FANS unit. The red lines represent a 95% prediction interval.

Air temperature and relative humidity sensors calibrated against the hand-held hygrometer showed no significant differences between slopes and unity as well as between offset and zero. Based on this verification, no adjustments were programmed into the BAC. It would be warranted to perform such verifications before the start of future experiments to verify potential long-term drift in the sensors.

The CO_2 sensor verification resulted in all five sensors reading accurately at both concentrations (Figure 2). There was a sensor response time difference noted between the ambient and high concentrations. Exposure to the ambient concentration showed an average response time of 3 min (SD= 0.5 min), while exposure to the high concentration showed an average response time of 15 min (SD=2 min). It was also noted that for a successful calibration of the ambient CO_2 sensor located in the duct and the exhaust sensors all ventilation fans had to be stopped. This may be attributed to the diffusion filter design of the sensor and the manufacturer's time constant of 5 min. It is possible that this could also result in measurement differences between mid-room sensor and exhaust sensor. This issue should not persist with the ambient sensor as the concentration should not change as dramatically as room levels during experiments.

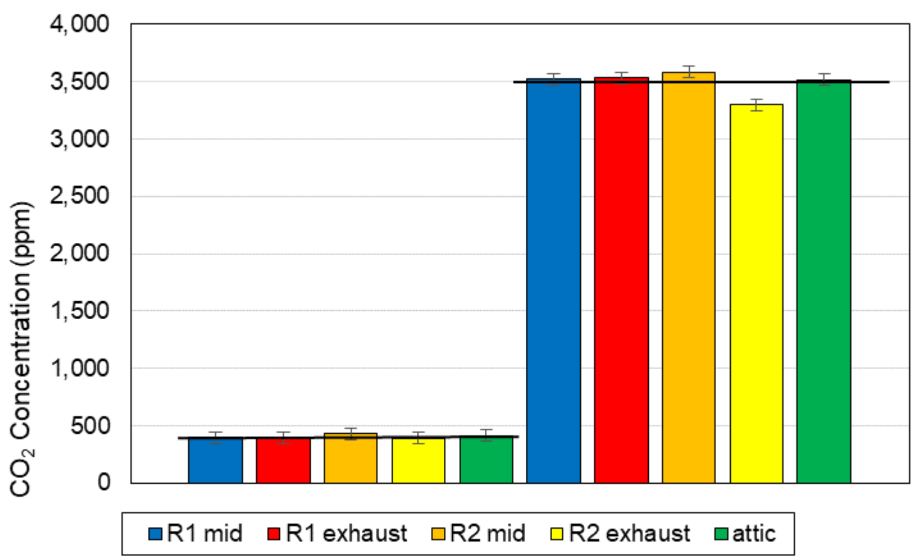

Figure 2. Comparison of the five CO2 sensors to the span gases. All sensors were within the ±10.0% margin of error of the gas concentration, black lines represent the span gas concentration. The error bars represent the 50 ppm accuracy of the sensors.

The O_2 sensor verifications were successful with no notable differences between the sensor and the handheld meter. For both sensors, it is recommended that recalibration and verifications as described here be performed before and after each experiment as well as Respiratory Quotient (RQ) be verified with each experiment.

Conclusions

A custom designed Animal Thermal Environment Interaction Laboratory (ATEIL) was designed and built for conducting animal thermal environment interaction and indirect calorimetry experiments. The laboratory consists of two identical discovery rooms with an animal housing area of 2.13 m by 7.62 m. The commercially available airflow measurement devices were individually calibrated, and the resulting regression equations suggest that was warranted to calibrate them individually. All sensors installed for thermal environmental control and indirect calorimetry measurements passed verification calibrations.

The research applications for this laboratory are tremendous in many poultry and swine production settings. The unique setup and construction of the laboratory offers excellent pilot scale potential for experiments to aid in further development for future field trials, while being in a controlled university laboratory setting.

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