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Development and evaluation of an evaporation model for predicting sprinkler interval time

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Abstract

Heat stress in swine causes decreased productivity and economic losses; hence, heat stress mitigation techniques must be developed to be economically and resource efficient. Current cooling strategies for livestock facilities, such as evaporative coolers or sprinklers, are governed by the Water Vapor Pressure (WVP) concentration gradient between the air (a function of dry-bulb temperature; tdb, Relative Humidity; RH, and atmospheric pressure) and the saturated WVP at the wet surface. Traditional sprinkler control systems operate at fixed 'off' intervals (i.e., drying) regardless if the thermal environment (TE) has the capacity or not to evaporate the dispersed water. Therefore, the objectives were to develop and simulate a novel Variable Interval Sprinkler Control System (VISCoS) that dynamically changes the 'off' interval based on tdb, RH, and airspeed feedback. A theoretical simplified pig evaporation model estimated water evaporation rate as a function of the TE, pig surface area and skin temperature, and mass of water applied. To evaluate the model in controlled conditions, a cylinder (assumed geometry of a pig) was placed inside an insulated enclosure where different combinations of tdb, RH, and airspeed could be simulated across the cylinder. The inside surface of the cylinder was heated and controlled to replicate the skin temperature of an animal, while the outer surface was wrapped in a thin chamois. Water was applied to the cylinder via a sprinkler where approximately 40% of the top portion of the cylinder was wetted. Comparison of modeled with measured evaporation time showed reasonable agreement with a root-mean-square error of 7.9 min for evaporation times ranging from 5 to 25 min.

Keywords

Cooling, Heat stress, Precision livestock farming, Swine, Ventilation

Disciplines

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Development and evaluation of an evaporation model for predicting sprinkler interval time

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ABSTRACT. ***Heat stress in swine causes decreased productivity and economic losses; hence, heat stress mitigation techniques must be developed to be economically and resource efficient. Current cooling strategies for livestock facilities, such as evaporative coolers or sprinklers, are governed by the Water Vapor Pressure (WVP) concentration gradient between the air (a function of dry-bulb temperature; t_{db}, Relative Humidity; RH, and atmospheric pressure) and the saturated WVP at the wet surface. Traditional sprinkler control systems operate at fixed 'off' intervals (i.e., drying) regardless if the thermal environment (TE) has the capacity or not to evaporate the dispersed water. Therefore, the objectives were to develop and simulate a novel Variable Interval Sprinkler Control System (VISCoS) that dynamically changes the 'off' interval based on t_{db}, RH, and airspeed feedback. A theoretical simplified pig evaporation model estimated water evaporation rate as a function of the TE, pig surface area and skin temperature, and mass of water applied. To evaluate the model in controlled conditions, a cylinder (assumed geometry of a pig) was placed inside an insulated enclosure where different combinations of t_{db}, RH, and airspeed could be simulated across the cylinder. The inside surface of the cylinder was heated and controlled to replicate the skin temperature of an animal, while the outer surface was wrapped in a thin chamois. Water was applied to the cylinder via a sprinkler where approximately 40% of the top portion of the cylinder was wetted. Comparison of modeled with measured evaporation time showed reasonable agreement with a root-mean-square error of 7.9 min for evaporation times ranging from 5 to 25 min.***

***Keywords.** Cooling, Heat stress, Precision livestock farming, Swine, Ventilation*

Introduction

The effects of heat stress cause annual decreased productivity and economic losses in the US swine industry (Stalder, 2015). Swine are generally regarded to be poor at dissipating heat and must reduce voluntary feed intake to decrease metabolic heat production (Renaudeau, Gourdine, & St-Pierre, 2011). This feed intake reduction consequently causes decreased average daily gain, lower finishing weights, and longer time to market. Hence, heat stress abatement strategies are needed to lessen the impacts of heat stress on productivity and improve economic return for producers.

Currently, there are three common commercial cooling strategies: elevated airspeeds, evaporative pad, and low-pressure sprinkling. Elevated airspeeds increase the convective heat loss and depends on the temperature gradient between the pig's skin and the dry-bulb temperature (t_{db}) of the air. This strategy fails to be effective when skin temperature is greater than t_{db}.

Alternatively, evaporative pads and sprinklers utilize the latent heat of vaporization when water evaporates. Heat can be removed from the air passing through the evaporative pad or the pad itself, or for sprinklers directly from the pig's skin once wetted. Sprinklers use less water than evaporative pads (Muhlbauer, Moody, Burns, Harmon, & Stalder, 2010) and do not cause a large increase in moisture surrounding the pigs (assuming high summertime flowrates commonly associated with heat stress conditions). Therefore, sprinklers are an effective method of reducing heat stress with minimal water.

As air moves over wetted skin, the water evaporates taking heat away from the pig. The amount of heat lost and evaporation time is dependent on t_{db} and moisture, wetted area, airspeed, and skin temperature. However, many traditional sprinkler control systems utilize a constant 'off' interval (i.e., drying time) or an 'off' interval proportional to t_{db} to allow dispersed water to evaporate. The time for complete water evaporation is substantially more complicated than solely t_{db} and needs to include the other thermal environments parameters effecting evaporation.

The goal of this study was to propose the framework for creating a novel Variable Interval Sprinkler Control System (VISCoS) with a dynamic 'off' time based on t_{db}, RH, and airspeed feedback. Therefore, the objectives were to: (1) develop an analytical evaporative transfer model and (2) compare modeled and measured evaporation time in controlled conditions on a simplified pig.

Materials and Methods

An analytical evaporative transfer model was first developed to estimate evaporation time. Then, experiments were performed on a simplified pig in a controllable chamber at different TE conditions to compare the measured evaporation time with predicted.

Analytical Analysis

The pig was assumed to be a cylinder in cross-flow with a 40% wetted area with length and diameter proportional to body weight. The convective heat transfer coefficient (h_c) of a cylinder was estimated from Nusselt number (Holman, 2002) and from a simplified relation using body weight and airspeed (Bruce & Clark, 1979). The ambient water vapor pressure was estimated from t_{db}, RH, and barometric pressure based on altitude (ASHRAE, 2013). The saturated water vapor pressure at the skin was estimated from skin temperature, RH = 98%, and barometric pressure. Lastly, at film conditions, moist air density, thermal conductivity, and humidity ratio were determined. Latent heat of vaporization (h_{fg}) was a function of skin temperature and the specific heat of water ($c_{p,w}$) a function of humidity ratio at film conditions. Thermal and mass diffusivity were calculated at film conditions to determine the Lewis number. The Lewis ratio (LR) was a function of film temperature and density, h_{fg}, $c_{p,w}$, and Lewis number. Although, LR is commonly assumed a constant 16.5 K kPa^{-1} (ASHRAE, 2013). Evaporative heat loss was then calculated from LR, h_c, wetted area and the water vapor pressure gradient. Division of evaporative heat loss by h_{fg} yields the evaporation rate. Finally, evaporation time is calculated from the mass water (on the object) divided by evaporation rate.

Experimental Setup

A chamber (L × W × H) with dimensions of 0.89 × 0.52 × 0.52 m featured a 0.2 m diameter galvanized steel cylinder mounted at the center, spanning the width of the chamber. The cylinder was wrapped in a thin chamois and three flexible heaters were coiled on the inside such that the flexible heaters maintained contact with the interior cylinder walls. A flow straightener separated the chamber from a 0.45 × 0.52 × 0.52 m entry section, which was responsible for transitions to a 0.15 m diameter duct to the square opening of the chamber. An air handling unit provided controlled t_{db} and RH conditions through an insulted flexible duct connected the entry section. A manual damper controlled flow and subsequently airspeed across the cylinder. A tray was placed below the cylinder to collect any water that rolled off.

An custom omnidirectional thermal anemometer (Gao, Ramirez, & Hoff, 2016) was mounted above the cylinder to measure airspeed. A digital infrared thermometer was mounted slightly above the cylinder. The chamois changed color as it dried allowing this color response to be captured by a photocell mounted near the chamois. In addition, inlet and outlet t_{db} and RH were measured.

Data Acquisition and Procedure

A microcontroller with a time-proportioning PI control algorithm controlled surface temperature at a constant 34°C. The microcontroller was also interfaced with two 4-channel, 16-bit ADCs to collect t_{db}, RH, photocell, and airspeed analog responses.

Once the conditions in the chamber were stable, water was sprayed onto the cylinder and allowed to evaporate completely. The mass of water applied was determined as the change in mass of the spray vessel measured before and after spraying, plus the addition of any water that rolled off.

Experimental conditions included the nominal combinations of t_{db} (28°C, 33°C, and 38°C), RH (40% and 65%), and airspeeds (1 and 2 m s^{-1}).

Statistical and Data Analysis

Data were processed in Matlab (R2017a, The Mathworks, Inc., Natick, Massachusetts, USA). Evaporation time was determined based on the photocell analog response. Once the photocell response returned to baseline (i.e., dry) after wetting, the chamois was assumed to be dry. This was verified prior to experiment to ensure accurate results. A linear regression model was fit to the predicted and measure evaporation time to assess the accuracy of the model over the range of conditions.

Results and Discussion

An example of the thermal environment conditions, cylinder surface temperature, and photocell response for one nominal treatment are shown in figure 1. Inlet and outlet conditions are stable and surface temperature decreases once wetted. Further, the PI control increased the heater 'on' time (not shown) to adjust for this disturbance and had minimal overshoot. The decrease in t_{db} and RH observed in the initial minutes were attributed to the opening of the lid to the chamber for the water spraying.

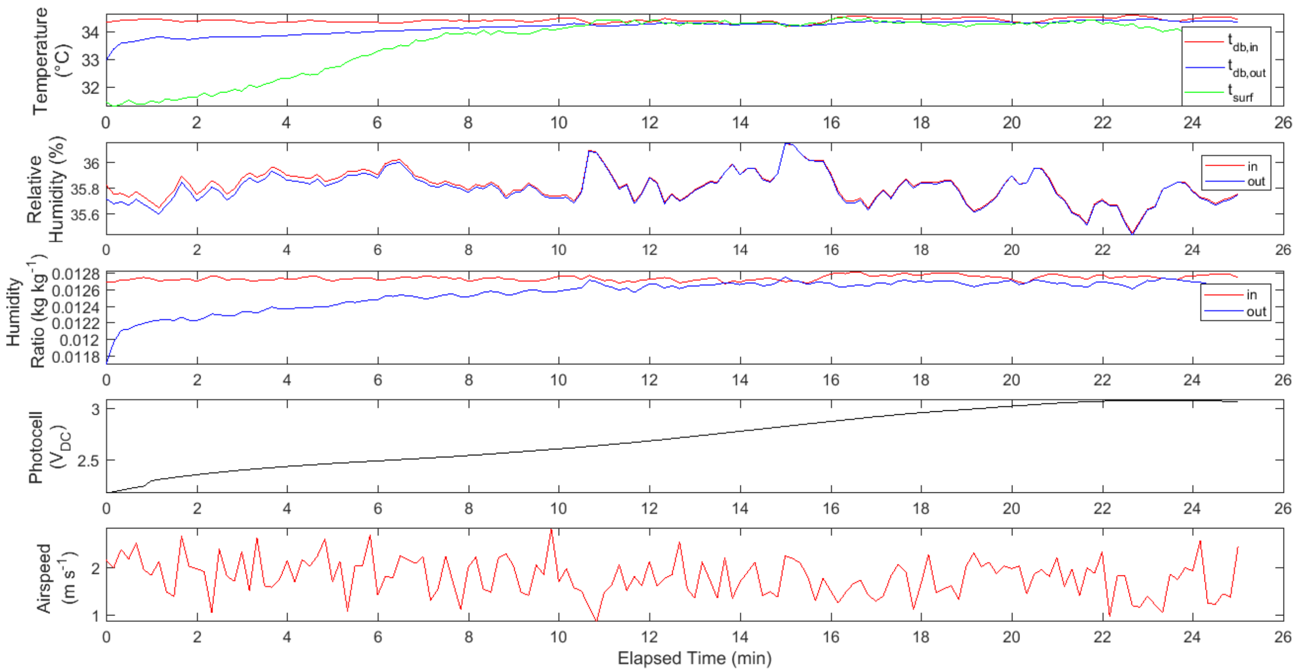

Figure 1. Example of thermal environment conditions, cylinder surface temperature, and photocell response for one nominal treatment.

Results of the modeled and measured evaporation time are summarized in figure 2. There was reasonable agreement with a root-mean-square error of 7.9 min over the range.

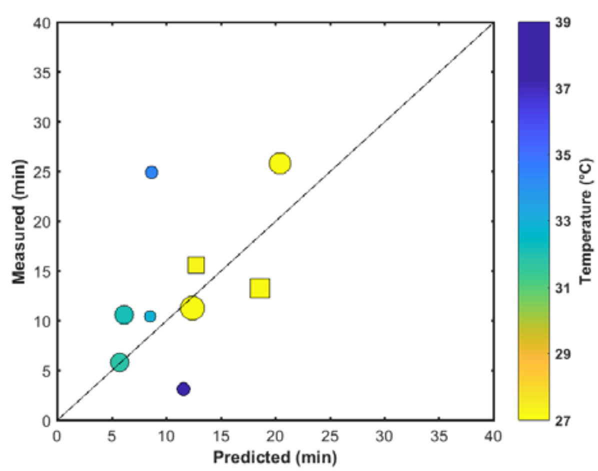

Figure 2. Comparison of modeled with measured evaporation time. Shape size is proportional to airspeed.

Conclusions

A simplified pig evaporation model was developed to estimate water evaporation time for sprinkler “off” time control. The simplified pig evaporation model has reasonable agreement with the measured evaporation time. Since, heat stress is based on the thermal balance between animal and surrounding, the conditions for turning the sprinkler ‘on’ could be improved.

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