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Full Length Research Paper

Design and Energy Consumption of a Preliminary Water Chilling and Recirculation System for Sow Cooling Pads

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HIGHLIGHTS

- coolant recirculation systems can supply adequate chilled water to swine floor cooling systems
- design capacities within the system are critical to proper functioning
- simplicity and low operating costs will be critical to the success of these systems in commercial applications
- insulation of the coolant distribution system is critical to the overall system efficiency.

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Abstract

Significant work has been performed developing technology for on-floor swine cooling utilizing a simple once-through open coolant supply system. The use of this open system has been expedient during the cooling pad development, but it is unsustainable for commercial application. The design and implementation of an initial closed loop, recirculating coolant supply system is described in this paper. The types of potential chilled water circulation systems that might be used and the metrics to judge their performance are reviewed, and the researchers' objectives associated with this preliminary experience using a recirculating design are relayed. The design's physical installation in this effort was constrained by the characteristics of the available testing facility and its on-going live animal research experiment. The executed design and operational characteristics of the final installed system are detailed, along with an initial performance analysis showing a CoP of 1.11. The general conclusion of this work showed that recirculating coolant systems provide a valid technological approach to execute the heat rejection function needed for a commercial hog cooling pad installation, which should overcome the issues associated with once-through cooling pad installations.

Keywords: Floor cooling pads; indirect calorimeters; recirculating coolant system; swine heat production; average daily gain for piglets.

INTRODUCTION

Genetic selection for larger litters and increased milk production over the past 40 years has increased the metabolic heat production and heat sensitivity of sows, especially during the lactation phase (Bjerg et al., 2019; Stinn and Xin, 2014; Cabezon et. al., 2017a). Commercial producers have expressed concern that this is the biggest single threat to overall production growth in the industry (De Rensis et al., 2017; Ross et al., 2015; Noblet & Quiniou, 1999; Prunier et al., 1997). Multiple researchers have examined a variety of means to reduce the physical discomfort of the animals and improve the economic performance of the herds (Godyn et al., 2020; Bjerg et al., 2019). Active floor cooling seems to hold the most promise as a practical, efficient, and safe system for removing excess sow heat (Shaffer et al., 2017; Silva et al., 2006; Van Wagenberg et al., 2006; Shaffer et al., 2001). Purdue University researchers have developed a simple floor pad cooling system that takes advantage of sow laying behavior and transfers heat into water pumped through cooling coils beneath the animal (Schinckel & Stwalley, 2022; Field et al., 2018; Geis et al., 2015). The device has undergone multiple years of iterative development and testing to reach its current smooth-functioning operational state (Schinckel & Stwalley, 2022; Cabezon et al., 2022; Cabezon et al., 2021; Field et al., 2020; Seidel et al., 2020; Field et al., 2019; Field et al., 2018; Cabezon et al., 2018a; Cabezon et al., 2017b; Geis et al., 2015).

The thermal capacity of the cooling pad and its heat transfer properties have been measured to ensure that the unit is responsive to changes in the animal's condition and local environment (Cabezon et al., 2018a; Cabezon et al., 2017b). The design of the controller, how the placement of the unit's thermal sensors affected the temperature readings, and the number of coils within the device were all investigated to optimize the unit's physical heat exchanger design (Cabezon et al., 2021; Seidel et al., 2020; Field et al., 2019). Variations in the performance of the pad with coolant flow cycle have been extensively examined (Cabezon et al., 2022; Field et al., 2020). The operation of the pad and its effect on live animals' production performance has been well studied (Whitmore et al., 2020; Shirley et al., 2020; Cabezon et al., 2018b; Cabezon et al., 2017c; Cabezon et al., 2017d). The pad's effect on physiological and behavioral metrics in swine has also been quantized (Maskal et al., 2018a; Maskal et al., 2018b; Parois et al., 2018). The initial live animal studies to determine the operational performance of the cooling pad were conducted with open coolant water delivery systems, schematically shown in Figure 1. No previous attempt by the Purdue researchers had been made to recycle the coolant, as all of the former work was concerned with the physical performance of the cooling pads. It has always been recognized that a recirculating coolant system would likely be required in the commercial application of the device. The work presented here is a first attempt to utilize the Purdue pads with a closed coolant system. The balance of this paper will consist of background on recirculating chilled water supply systems, the design and materials used to convert the operation of the Purdue cooling pads into a closed loop system, the operational results from preliminary testing, the initial conclusions about the closed system's design, and the recommendations for further work.

BACKGROUND

The delivery of accurately metered coolant to the Purdue swine cooling pads is not a trivial exercise. The flowrate through the pad is dependent upon the delivery pressure, and that varies with the number of cooling pad units operational at any specific moment in time. In order to maintain known coolant flowrates during operation, it is necessary to 'supercharge' the delivery plenum to a sufficiently high pressure, well above the set operational pressure for the pad. Pressure reduction valves drop the final delivery pressure to a known, lower level for metering and flow through an individual pad. Since the over-pressurized plenum can absorb the pressure drop from multiple cooling pads operating simultaneously, the fluctuation in an individual supply pressure line is eliminated as a variable in its operation. Set flowrates through the cooling pad can then be established and relied upon to be consistent. The overcharged plenum/reduced pressure operational scheme was implemented in a primitive form early in the cooling pad development, shortly after issues with multiple pads operating simultaneously became apparent (Cabezon et al., 2017c; 2017d). Supply to the supercharging pump was via the university farm's potable water system. After picking-up heat in the pad's coils, the water was exhausted into the barn's manure pit. The supply pump system from work performed in 2017 is shown in Figure 2. Today, that equivalent unit, which simply supplies and dumps warm coolant into the manure pit, has been refined, enclosed, and is pictured in Figure 3.

There are typically three types of chilled water systems available for process cooling. The original manure pit-dumping infrastructure system is technically classified as an open, once-through system (Suez Water Technologies, 2022; Incropera & DeWitt, 1981). This is the simplest type of system to install and operate. As long as the incoming water is roughly at the deep ground temperature, 10-15^{o}C, which is relatively cool, rejecting the added heat is simply a matter of dumping the slightly warmed coolant water into the manure pit. This type of system is also simple to maintain, and it does not generally exhibit the potential for equipment scale or corrosion issues. The hog barn environment cannot contaminate the coolant, due to the once-through nature of the coolant pathway. The ammonia, hydrogen sulfide, and dust present in the

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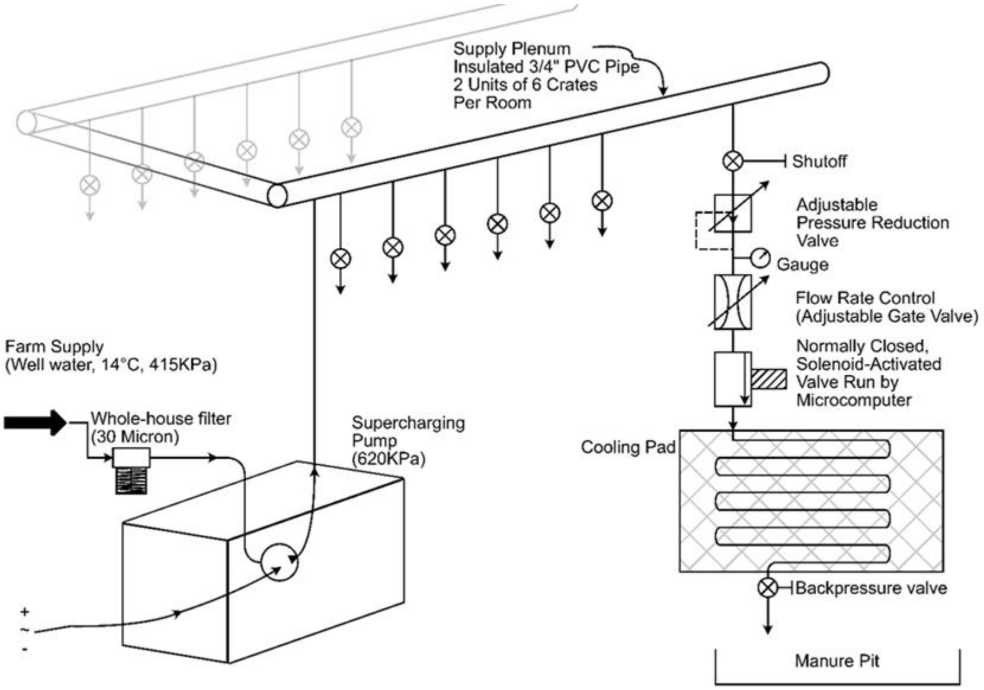

Figure 1: Schematic of the once-through coolant system for the Purdue swine cooling pad installations at the Purdue Animal Science Research and Education Center (ASREC).

atmosphere of a confinement barn, if allowed to diffuse into a circulated coolant water, could cause long-term corrosion problems within a recirculation plumbing system (Schutt & Rhodes, 1996). If the water is never re-circulated, chemical contamination cannot become an issue. The drawbacks of a once-through chilled water system are that it adds volumetric demand to the farm's overall water supply system and the farm's manure handling systems. The current Purdue cooling pad work to this point had been conducted at the Purdue Animal Science Research and Education Center (ASREC), which has sufficient lagoon capacity to absorb the cooling pads' additional water effluent.

For this series of tests, the pads were installed at the nearby USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) facility, inside indirect calorimeters (Johnson et al., 2019) to measure animal heat production under varying environmental conditions (Johnson et al., 2021). An example of one of the calorimeters is shown in Figure 4. These devices allow for the collection of data to complete heat and mass balances for sows and their litters as they grow. These units are sophisticated animal monitoring devices which require exact placement and operation within the FABL facility. Unfortunately, FABL does not have the same substantial manure holding capacity as ASREC. In order to accommodate the cooling pads in the indirect calorimeters within the FABL facility, a coolant recirculation system with sufficient heat rejection had to be designed and installed. Due to the previously mentioned issue with diffused corrosive gasses entering into a solution in the coolant, an open, recirculating system, rejecting heat through the partial evaporation of the circulating water, would have been an unsatisfactory solution for confinement livestock applications. A closed, recirculation system was the only remaining engineering choice for the installation at FABL. Recirculating systems must incorporate some form of chiller to maintain the coolant at the specified conditions, rather than sacrificing a portion of the coolant to evaporation and utilizing the farmstead supply as make-up water. Except for the water required for spillage and leaks, no additional coolant is required for a closed, recirculating system, reducing the potential for contamination from the noxious gases present within the local animal confinement environment.

The sow cooling pad as a heat exchanger application displayed a fairly low heat flux design (Cabezon et al., 2022; Cabezon et al., 2018a), which was somewhat uncommon for chilled water systems. The pads operate around 600 W/m^2 and have a peak energy transfer rate between 450 to 600 W. Most common chilled water designs exhibit higher heat differentials and higher heat transfer fluxes (Suez Water

Figure 2: Initial filtration and pressure supercharging system used in once-through coolant supply installation at the Purdue Animal Science Research and Education Center (ASREC) swine farrowing barns.

Technologies, 2022). The temperature differential between ambient and the depressed, cooled temperature of about 10°C from the pads is tolerable by swine (Silva et al., 2009), and the cooling pad designers have used that top plate temperature decline value as an operating constraint (Cabezon et al., 2022; Cabezon et al., 2021). Typical chilled water systems for building air conditioning can use over 40°C differentials and have thermal fluxes between 15,000 and 45,000 W/m^2. These units can be so sizable that they have energy transfer rates measured in *MW*. (Suez Water Technologies, 2022). The sow cooling pads are fairly small, at 0.75 m^2 of active surface area. These characteristics place chilled water systems operating with the swine cooling pads at the extreme lower end of the current generally-accepted operational range for today's chilled water technologies. It is apparent that the sow cooling pads are a novel chilled water application. Therefore, some of the traditional evaluation metrics for chilled water systems may have unusual values.

Many of the efficiency metrics for judging chilled water systems are based on availability (exergy) analysis. Fang et al. (2017) propose evaluations based upon the degree of matching between the equipment capacity and the demand placed on it. The costs of inefficiency introduced into chilled water systems by mismatched components are significant and have prompted the US Department of Energy (2019) to invest in open-access software to aid in the design development of large-scale projects. Suamir et al. (2020) concluded through a parametric computational study that component matching is the single most critical element in the long-term operation of chilled water system designs. Ferretti et al. (2017) detail how essential it is to have accurate process condition measurements for overall system optimization. Best practice operational strategies for optimizing chilled water plant performance are presented by Ricart et al. (2021). They consist principally of having variable rate pumps available to match the thermal loading needed within the overall system, and for large demand systems, configurable heat exchanger banks to adjust energy flows within the system. Ingersoll Rand (2014) also specifically cautions system designers to 'right-size' components initially, since demand / component mis-matches are the main sources of inefficiency within chilled water systems, and these sub-optimal circumstances exist for the whole lifetime of the equipment's installation.

Figure 3: Next generation modular filtration and pressure supercharging system in once-through coolant supply installation at the Purdue Animal Science Research and Education Center (ASREC) swine farrowing barns.

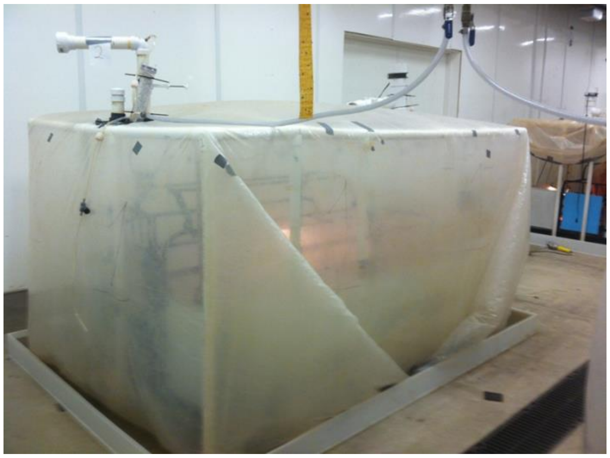

Figure 4: Indirect calorimeter holding farrowing crate for sow and piglets at the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL).

The need for chilled water systems to be ‘right-sized’ and the low temperature gradient and heat flow within hog cooling pads makes the system’s design both novel and fairly complex. The selection of components available for this specific testing was severely constrained, and significant effort was expended at ensuring that the resulting configuration for a recirculating coolant system was a design which would be robust and capable of further development. The specific objectives for this engineering research project were:

1) the specification of the design requirements and

Figure 5: Swine experimentation room at the USDA Farm Animal Behavior and Well-Being Laboratory (FABL).

assembly of a closed recirculating coolant system to support three experimental animals in the indirect calorimeters, plus one spare animal;

2)the collection of processes temperatures and the measurement of energy use by the system components; and

3)the determination of a Coefficient of Performance for the overall system and any performance inefficiencies identified.

These objectives led to the development of the following research questions being investigated during the implementation of this proof-of-concept prototype coolant recirculation system:

1)is it possible to maintain the consistent coolant flowrates in individual pads using the recirculating coolant system, as was exhibited with the once-through system;

2)is it possible to maintain the consistent coolant pad inlet temperatures in individual pads using the recirculating coolant system, as was exhibited with the once-through coolant supply system; and

3)are the energy use and efficiencies of the various components of the recirculating coolant system consistent with those exhibited within existing industrial systems?

The prototype coolant recirculation system was installed and tested at the USDA-ARS FABL facility, in conjunction with scheduled experimentation using indirect calorimeters and lactating sows, as reported by Johnson et al. (2021). Since this was a proof-of-concept installation, the number of units installed was too small for statistical inference with regard to the posed experimental questions. A more extensive testing program, with both once-through and recirculating coolant cooling pads, will be needed for statistical certainty regarding these queries. However, these results had the potential to show general tendencies and provide a necessary initial experience with a recirculating coolant system to aid in the design and construct a more rigorous experiment.

DESIGN, MATERIALS, AND METHODS

The overall experiment was conducted in one of two FABL animal holding rooms, pictured in Figure 5. There were eight, parity 3 sows in the room for each of the two experimental replications. Six of the animals were directly participating in the active experimentation, and two animals were subjected to the same environment to serve as acclimated spares, in the event that an animal needed to be withdrawn from the testing. Three experimental animals and one of the spare animals were on operational cooling pads. The design loading on the coolant recirculation system was only the thermal loading generated by the four lactating sows. The design criteria for the evaluation of a closed recirculating coolant system included the ability to measure and set individual cooling pad flowrates, the ability to measure sufficient process temperatures and electric consumption levels to measure energy transference in the system; a functional, even distribution of coolant; a functional recovery and scavenge of spent coolant; a functional storage and supercharged pumping of coolant; and a functional system rejection of absorbed sow heat through air-cooled electric / refrigeration cycle water chillers. Specifications for property measurement needs were developed from a preliminary analysis of the fluid flow within the envisioned closed recirculation system for the coolant. The functional requirements of the recirculating coolant system were based upon the advantageous features of the previously used once-through coolant system. Aspirationally, the new design was hoped to be a forward step in all of these areas and not represent a reduction in functional utility. The schematic layout of the coolant recirculation system developed for this work is presented in Figure 6.

The measurement and calibration of coolant flowrate was through processes previously established and reported (Cabezon et al., 2022; Cabezon et al., 2021). For this work, it was performed before, during, and after testing. The previous cooling pad work had shown that when operational, the consistency of coolant delivery rate was vital, but that the ability to vary flowrate beyond a simple on / off intermittency was likely not needed, due to the previously measured time constants of the sow / pad system between 5 and 15 *min* (Cabezon et al., 2021; Cabezon et al., 2017b). The coolant delivery components were designed to provide constant coolant inlet conditions for the cooling pad. As long as nothing within a specific leg of a fluid pathway changed, set conditions could be relied upon not to vary. Experience with the once-through design demonstrated that this held true for that system. Since the new return plumbing did not add any backpressure to the delivery system, there was no reason to assume this implementation would be different. For flowrate adjustment, the back-pressure in the system was established with an approximate 10% closure on the exit valve. For measurement, the flowrate control valve was adjusted until 2.0 *l* was flushed through the solenoid valve in a 30 *s* interval, timed by the pad controller. Anytime a repair or adjustment to a cooling pad unit was required, the flowrate calibration was repeated. Given the closed nature of the system, this was made possible by installing a threaded union on the discharge, downstream from the backpressure valve. The only novel consideration in the coolant flowrate measurement experience for the recirculation system was the need to intercept the discharged coolant. A threaded union was installed downstream of the backpressure valve on the discharge side of the plumbing to facilitate this measurement.

The measurement of energy data was conducted at two levels in the overall system: where electrical energy was input to the device and at various key thermo-fluid points throughout the overall process. Electrical consumption was measured for individual components using Intertek P4460 (Sanford, NC) integrating power meters (±0.2%) for each connected load. The various process point temperatures were collected through a variety of means. Digital thermal sensors (±0.5^o*C*), from Digi-Key DS18B20 (Thief River Falls, MN), were used for the pad thermal data collection. Skin contact areas on the cooling pads, as well as inlet and outlet coolant temperature, were logged by the cooling pad controller module. Nothing about these elements within the current work was any different than from previously reported information (Cabezon et al., 2022; Cabezon et al., 2021). The only novel consideration in this section was the collection of sump and coolant reservoir temperatures, which were taken manually using an infrared thermometer with an accuracy of ±1.5^o*C* (FLIR TG-165, Wilsonville, OR). These reservoirs were well mixed and assumed to be at a uniform temperature.

The functional requirement of high-pressure coolant being metered into the cooling pads was accomplished by a new plumbing installation, based upon the prior experience of the team in the ASREC facility (Cabezon et al., 2017c; Cabezon et al., 2017d). The coolant delivery system, which had so far proven successful in this work, was designed to overpressure a larger delivery plenum, and then utilize a pressure reduction value to drop the delivery pressure for individual cooling pads. To achieve repeatable flowrate performance, a pressure consistently above the pressure set on the reduction valve must be delivered to that valve, regardless of how many other cooling pads are running at that moment. At the FABL location, coolant water for the pads was also delivered to the supply plenum by a supercharging pump. The only novel consideration in this physical layout was that the coolant tubing had to enter the calorimeter skin through specially-made gas-tight fittings. Spent coolant exhaust from the calorimeters was routed under the plastic sheeting, through the liquid / gas atmospheric seal.

The entirety of the coolant recovery and scavenge system in this experiment was new and novel, compared to the original process. The back-end of the initial process, dumping coolant into the manure pit, was replaced with a recycling network that transported the exhausted, warmed coolant to a central chilling and pumping location. Gravity flow in the return system was desirable, despite having little potential to utilize in this circumstance. The available floor slope in

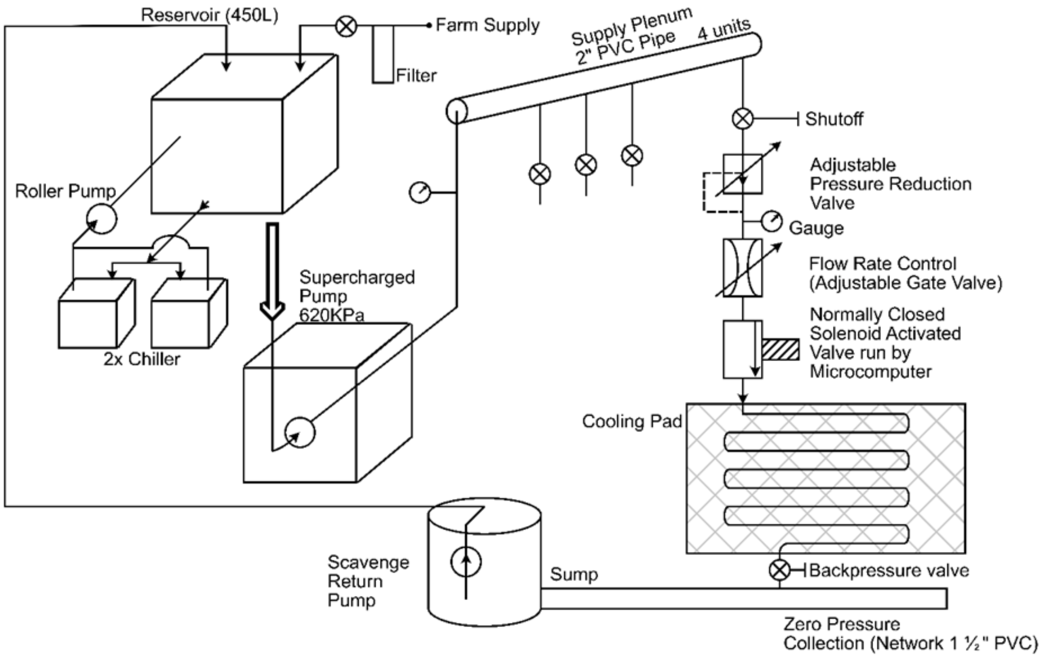

Figure 6: Schematic of the closed recirculating coolant system for the Purdue swine cooling pad installations at the USDA Farm Animal Behavioral Laboratory (FABL).

the FABL barn was less than 0.2 *in* per *ft*. The coolant exhaust plumbing used the standard ½” copper tubing from the cooling pads, which was then transitioned into a larger diameter, no-pressure, return plumbing system. The system was water-tight and given a small additional slope with cut wood blocks. In this experiment, all four operational pads were exhausted into the same return system, eventually draining into a common sump. A lift system consisting of a sump pump and check valve, was designed to refill the main reservoir with the exhausted coolant.

Although the same supercharging pump, a Barracuda ¾ *hp* dual application pump (Minneapolis, MN), was used as in the previous ASREC experimentation, significant modifications were needed for this installation, primarily to meet the necessary inlet conditions for the proper functioning of the supercharging unit. In the ASREC facility, it had been possible to connect the inlet of the supercharging pump to the potable water delivery system for the farm, which supplied water at 350 *kPa*. Under the envisioned connection between the supercharging pump and the coolant reservoir, it was likely that some pump cavitation could develop. Design considerations were made to ensure the pump had good access to coolant, with minimal suction-side line loss when actively charging the delivery plenum. Pump output pressure was adjustable from the internal controls on the device, and pump outlet was directly connected to the coolant delivery network. The functional configuration of the reservoir with the supercharging pump in this work was unique compared to the system used previously, and it required a design revision after preliminary testing to function properly.

The final functional requirement for the new recirculation system was to remove the added sows’ heat and return the coolant to its original chilled condition. This was a new and novel requirement for the overall system. To simplify the installation and diminish component connection and flowrate matching issues, a decision was made to add a separate circulation pump to draw coolant from the reservoir, send it through one of two chillers, and then return it to the reservoir. Unfortunately, this design reduced the 2nd law efficiency of the overall unit by mixing warm exhaust effluent back into the reservoir, instead of directly cooling it before mixing. However, the resulting expediency in plumbing and valving was worth the added operational costs for this initial prototype recirculating coolant system, particularly when including additional manure pit capacity needed for a once-through coolant system. The design of the complete system was such that all component parts were available from local supply stores and national warehouses with instant delivery connections.

The experimental testing was conducted on multiple days across two periods from November 2020 through January 2021. Coolant flow was set and calibrated prior to the beginning of experimentation and checked afterward. Various thermal sensors were checked at ambient room and ice/water temperatures, in a manner similar to past practice (Cabezon et al., 2022). Essentially, an equilibration temperature check between the pad and room was completed, along with establishing a thermal gradient in the pad using ice water in garbage bags on the top plate. All calibration results were nominal, within the expected range values. The controllers for the sow cooling pads were set to record timestamped data every 6 *s* in operation. Manual data collection of key parameters on active experimental days occurred once per hour during the intervals of experimentation. No difficulties or unusual circumstances were encountered during the course of the experiment, although some individual sensors did fail. Redundant data collection was able to overcome this issue.

As a test of the initial prototype system design, this work indicated only functionality, with rudimentary overall reportable specific information. Unlike the simultaneously-running animal science experiment, there simply were not enough treatment combinations of coolant systems present for direct statistical evaluation. The collected data consists of basic operational information, integrated across each of the trials. This represents an acknowledged deficiency of the current effort, common to nearly all preliminary trials of new technology. Further work, including side-by-side comparisons of once-through and recirculating coolant systems, would be required for the determination of any statistical inferences. Error within the microprocessor determination of energy flux was previously demonstrated to be ±4.6 *W* (Cabezon et al., 2022). Accuracy in the power consumption was constrained to ±2.0% *W* (Intertek, 2022). CoP and other derived measures have errors proportional to those uncertainties. More accurate instrumentation and a well-developed set of statistically valid experiments focusing exclusively on the coolant recirculation system, would be needed to overcome these limitations.

RESULTS AND DISCUSSION

The results presented here were taken from engineering systems data recorded during the animal sciences hog calorimetry experiment reported in Johnson et al. (2021). In general, the experimental questions from this work might be summarized as examining the mass balance, energy balance, and operational metrics for this specific design of a recirculating coolant system supporting the sow cooling pads. The pads installed in the four FABL crates were previously used in Shirley et al. (2020), Whitmore et al. (2020), Maskal et al. (2018), Parois et al. (2018). The ambient temperature of the farrowing room was controlled according to a set protocol for the animal science experiment, shown in Figure 7. The mass balance examination looked at the calibration and measurement of the coolant, the functionality of the coolant distribution system, the functionality of the coolant recovery system, the functionality of the coolant scavenge system, issues with the supercharge pump, and the overall mechanical functionality of the coolant recirculation system.

The physical layout of critical systems in the experimental room is represented by the schematic in Figure 8. Much of the actual design was similar to the once-through system used previously in the ASREC experiments (Cabezon et al., 2022, Cabezon et al., 2021). For instance, the central pressurized plenum coolant delivery pipe was made from 2” diameter white PVC pipe shown in Figure 9. The flexible blue tubes in the photograph are ½” PEX individual pad coolant supply lines. The pad’s pressure reduction and flow control valves are visible on the leftmost line shown in the spare sow’s farrowing crate in Figure 10. For the treatment sows, the pressure reduction valve was positioned on the delivery line near the top of the calorimeter. The spent coolant return network is presented in Figure 11. This low pressure, gravity flow network was made from 1 ½” diameter white PVC pipe and was intended to collect all the exhausted coolant from the various pads and deliver it to a single collection sump. The coolant water was then transferred-back to an overhead 130 *l* reservoir using a Barracuda 1/3 *hp* automatic submersible utility sump pump (Minneapolis, MN). The driving head for the return network was the slight increase in elevation above the floor created by the elbowed sections visible in the photograph. The return network entered the collection sump through a bulkhead connector. The scavenge pump system to elevate the spent fluid back to the overall reservoir is shown in Figure 12. The check valve, visible in Figure 12, was necessary to prevent a siphon-type backflow into the collection bucket from the reservoir, when the scavenge pump was not operational.

The selected coolant flowrate measurement strategy of using fixed flowrates at intermittent cycle times was an evolution from the prior process of full instantaneous measurement for finding the optimal heat transfer rates. Several physical factors have promoted this modified technique. Intermittent pulses of coolant minimize the coolant flow and create the

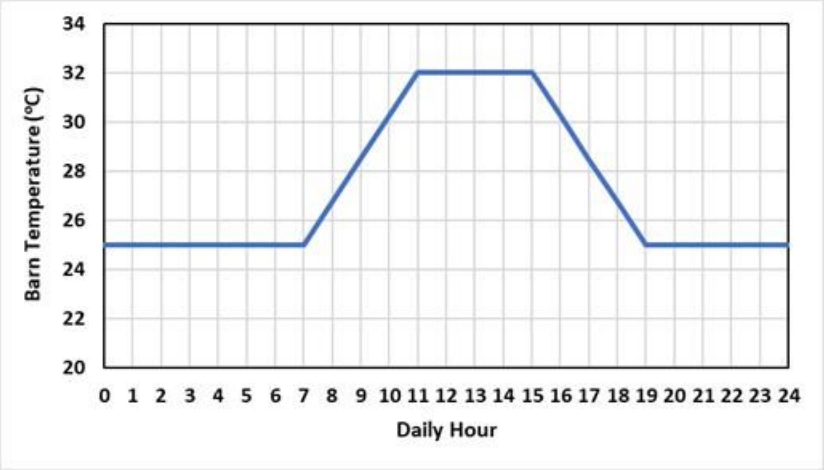

Figure 7: Daily ambient temperature targets for the Johnson, Jansen, Galvin, Field, Graham, Stwalley, & Schinckel (2021) experiment.

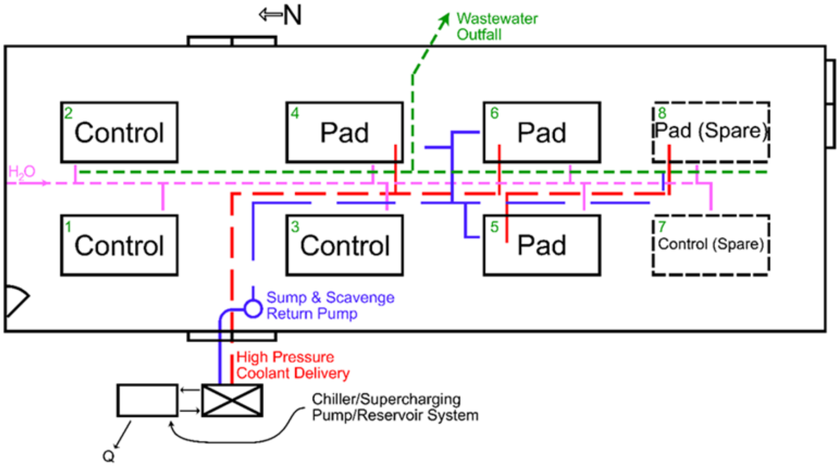

Figure 8: Schematic of experimental test crate identification and critical cooling pad support systems at the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room for the indirect calorimetry experiments.

least waste in a once-through system, and their use constitutes the vast bulk of operational live animal experience with the current cooling pads. An intermittent pulse protocol was used with the coolant recirculation system during the indirect calorimetry experimentation. As shown in the Figure 5 schematic, the physical flowrate for each drop line was adjusted using a gate valve immediately downstream from the pressure reduction valve. The on / off functionality was controlled by a normally-closed solenoid valve activated by the unit's microprocessor. The microprocessor had a calibration function installed, which allowed an accurately timed 30 *s* flush through the cooling pad. The calibration of the unit required intercepting the effluent from the pad's tail piece in a graduated cylinder and adjusting the flow control gate valve, until the proper mass of coolant was collected in 30 *s*. The cooling pad flowrates were always checked and re-calibrated following any plumbing adjustment on an individual pad. Figure 13 shows the

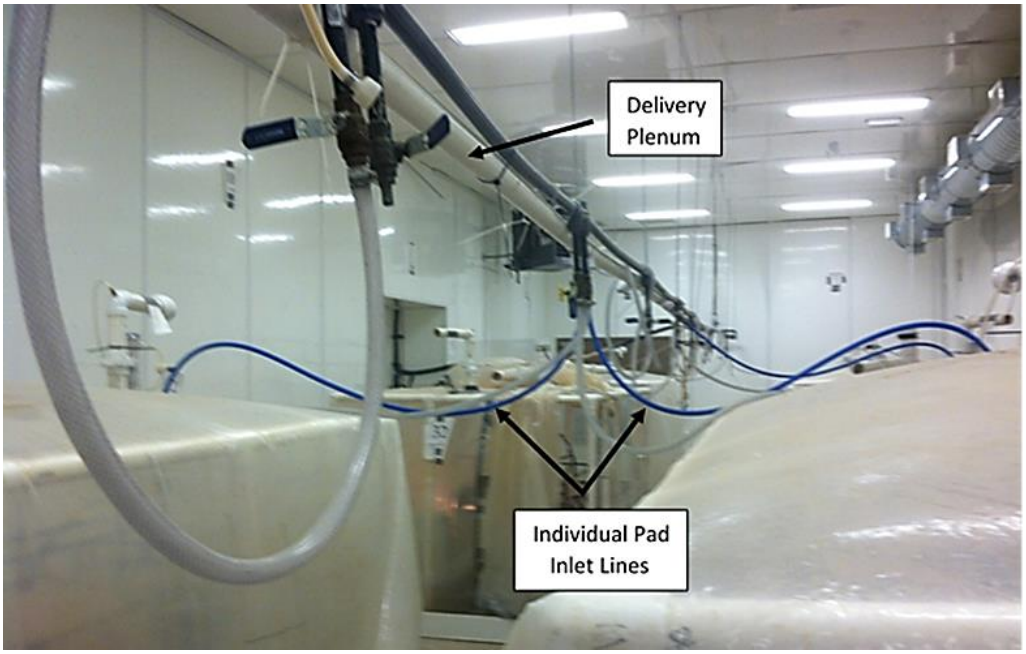

Figure 9: Pressurized coolant delivery plenum (large diameter white PVC pipe) and individual pad inlet lines (small diameter blue PEX flexible tubing) in the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room.

error bands on flowrate through the individual legs of the coolant system and some of the calibration data.

The coolant distribution network used in the calorimetry experimentation mimicked the system previously installed at Purdue ASREC, where all of the previous work had been completed. The large diameter over-pressured plenum served to provide a source for the individual cooling pads that was unaffected by the number of units operational at any specific time. Earlier work demonstrated the futility of expecting constant flowrate calibration on a traditional water inlet pipe system. The flowrate variance is exacerbated, if additional pads become operational at the same time. To solve this issue, coolant was delivered to the individual pads in a large plenum at an elevated pressure created using a supercharging pump to raise the delivery pressure to 95 *psi* (650 *kPa*). This higher-pressure fluid was then reduced to the proper delivery pressure of 15 *psi* (100 *kPa*) on the individual distribution lines ahead of the pads. Testing in the ASREC facility demonstrated calibrated flow with up to three units flushing simultaneously, with a slight drop-off in flowrate, if a fourth pad began running. Although this invariant system result was not reverified in the FABL facility, there were no indications of flowrate variance problems during any re-calibrations of individual cooling pads, while the remainder of the system remained in operation. The coolant delivery system was nominally the same as the system used previously in the ASREC facility, and it worked as expected throughout the calorimetry testing.

The coolant recovery network was new, designed specifically to meet the physical constraints of the FABL facility. The floor of the experimental room was level in the longitudinal direction (< 0.2*”/ft*) and only had a slight slope laterally (0.5*”/ft*) toward the center of the room. A grate covered a gutter running to the FABL sanitary collection pit. The calorimetry boxes used a liquid barrier seal, and the rim of the base was 20 *cm* tall. The coolant pad exhaust line had to drop into the pool of liquid waste, go under the atmospheric barrier, and then clear the rim of the base to reach the return system. The assembled coolant exhaust hardware can be seen from a distance in Figure 10, low, near the bottom of the vapor barrier. The return network was operated only on the gravitational potential created by clearing the rim of the calorimeter base. Because the network was only given a slight 0.5% slope, using 2” nominal wood chunks and ¾” thick plywood strips, the return pipe integrity was critical. When in operation, a significant volume of water was contained within the return network piping. Flow into the sump was slow, laminar, and limited to the times when a pad was flushing. The coolant return system functioned as designed and did not appear to have any detrimental effect on the operation of the cooling pads.

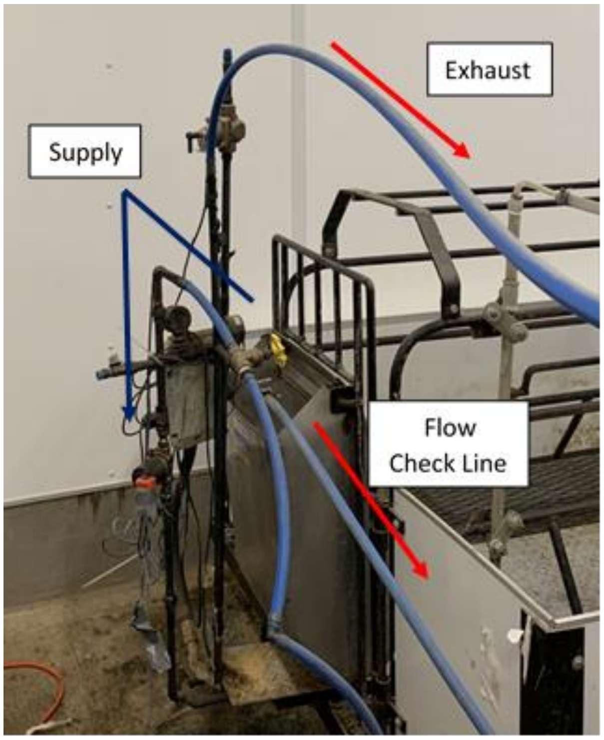

Figure 10: Coolant flow direction and inlet pad control system hardware on the non-calorimeter spare sow farrowing pen at the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room.

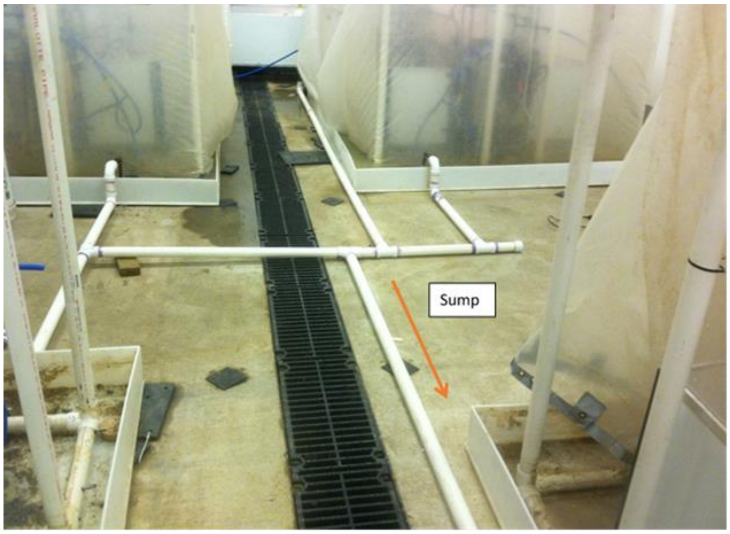

Figure 11: Gravity-flow spent coolant return network on swine calorimetry experiment at the USDA Farm Animal Behavioral Laboratory (FABL) swine experimentation room.

The collection sump, pictured in Figure 12, was constructed from an injection-molded five *gal* plastic bucket. The connection to the coolant return network was through the side of the bucket using a screw-type PVC bulkhead connection, set as low as was feasible. After the return network was filled, it was possible to

Figure 12: Sump, scavenge pump, and check valve used to return spent coolant to the reservoir during the swine calorimetry experiment at the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room.

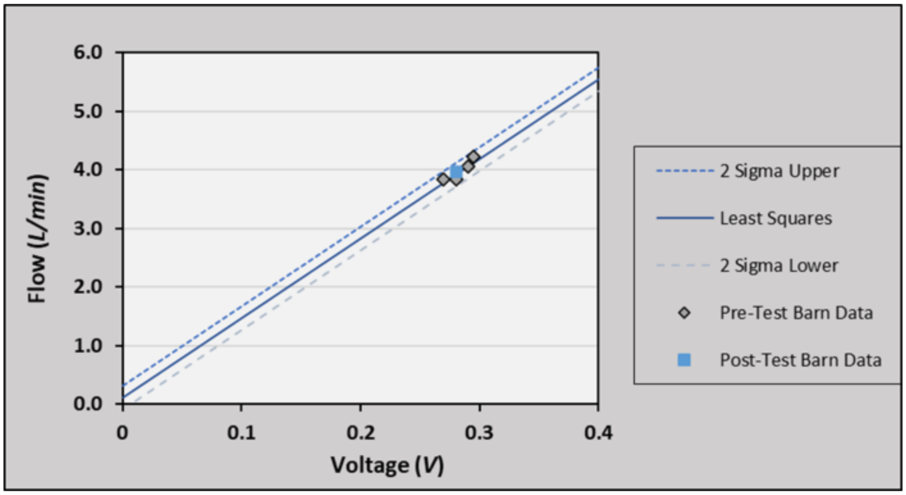

Figure 13: Coolant flowrate calibration data and error bands for recirculating coolant system used in the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room.

see flow into the sump when the pads were in operation. The sump pump selected for use did not have an internal check valve, so it was necessary to add one to the outlet to eliminate backflow from the main reservoir into the sump, preventing an almost continuously running condition for the pump. Once the check valve was installed on the outlet line, the sump and scavenge pump system performed as expected and returned the exhausted coolant to the main reservoir without backflow during non-operational periods.

The supercharging pump pressurizing the coolant

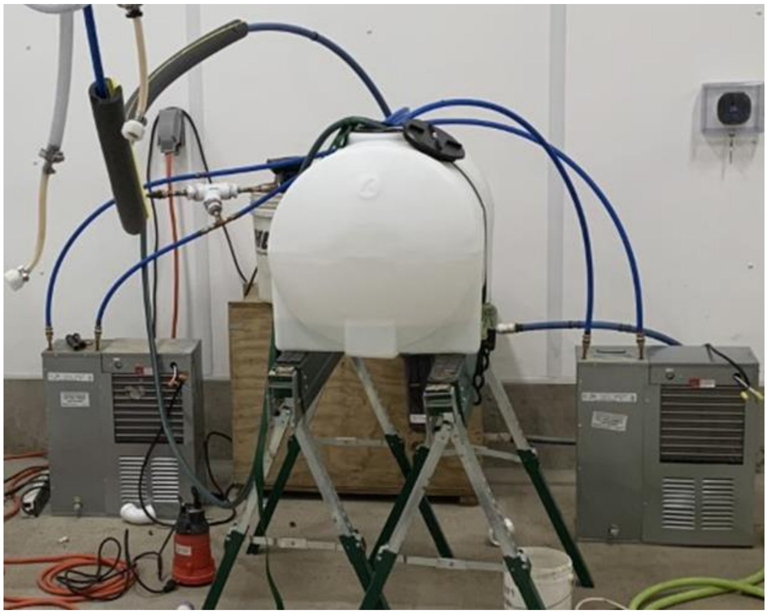

Figure 14: Coolant reservoir on elevated stand beside the water chillers and in front of the supercharging pump in an unsuccessful preliminary design configuration of the coolant recirculation system at USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room.

Figure 15: Supercharging pump inlet plenum inside the reservoir elevation frame in the second and final configuration of the coolant recirculation system for the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) swine calorimetry experiments.

deliver plenum by drawing from a reservoir was novel to this installation compared against earlier layouts. Previously, the supercharging pump had drawn its inlet water from the farm’s potable water supply infras-

Figure 16: Zurn Elkay ER10 1E (Milwaukee, Wisconsin) water chiller used to thermally recondition the system’s coolant and reject the sows’ heat to the environment during the swine calorimetry experiment.

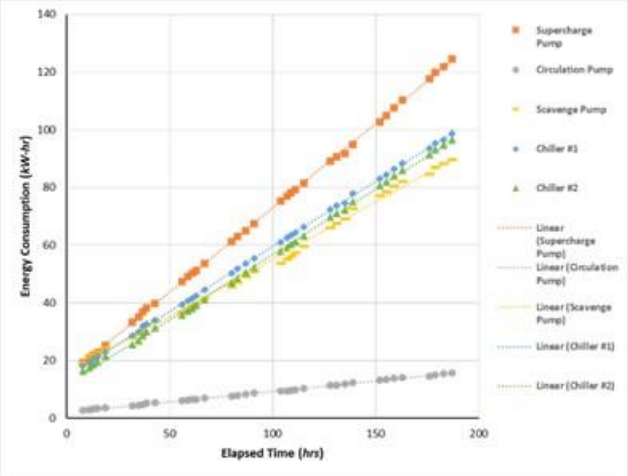

Figure 17: Energy consumption of the recirculating coolant system used to reject the sows’ heat to the environment during the swine calorimetry experiment at the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room.

tructure. This configuration had performed quite satisfactorily in earlier tests. However, the supercharging pump had a minimum inlet pressure that needed to be maintained for proper functioning and the prevention of cavitation. To attempt to alleviate this issue, the reservoir for the coolant system was raised and initially installed on saw horses to feed the supercharging pump, as shown in Figure 14. This was unsuccessful, and it led to significant pump cavitation during operation.

The tank was re-installed on a tall frame, 1.5 *m* above the pump inlet. A bulkhead connector was placed in the bottom of the tank, and 3" PVC pipe was used to provide a direct, low-restriction connection to the inlet side of the supercharging pump. This connection is pictured in Figure 15. This second configuration was marginally acceptable, as the pump continued to cavitate on start-up. The reservoir was not elevated enough to meet the manufacturer's guidelines for the pump inlet pressure, due to the physical constraints of the experimental space, but cavitation during operation was eliminated, except for during the pump start-up transient. While this situation would likely prove undesirable for long term operation, it was deemed acceptable for the duration of the planned calorimetry experimentation. An improved pump / reservoir design would definitely be required for extended service. However, the overall recirculating coolant transport system, as redesigned, marginally met the requirements of the supercharging pump, moved cold water to the cooling pads, and then returned the exhausted fluid to the coolant reservoir successfully through the experiments at the FABL facility. There were no significant coolant leaks during testing, although some plumbing components did develop minor drips.

The energy gained from the sows by the circulating coolant was rejected to the surrounding atmosphere using two Zurn Elkay ER10 E1 720 *W* water chillers (Milwaukee, WI) operating on a separate plumbing circuit, drawing and returning water to the overhead reservoir. One of those chillers is shown in Figure 16. These units were supplied by a Hydro Smart 1/25 *hp* hydronic fluid pump (Elk River, MN) drawing from the reservoir through a smaller bulkhead connector, positioned remotely from the supercharge pump circuit. Cooled water from the chillers was returned to the reservoir through the top access hatch. There were three flow settings available on the hydronic pump, and the lowest one was determined to be the optimal setting for this application, circulating approximately 15 *l/min*. The two coolers had a combined rated heat rejection of 1.4 *kW*. Unfortunately, this did not prove to be quite enough capacity to keep the coolant reservoir at a temperature of $15^{o}C$ during the hottest period of the defined temperature cycle of the calorimetry experiment testing, roughly four hours out of the daily cycle. To combat the insufficient cooling capacity in the chillers and maintain the proper coolant temperature, ice was added to the reservoir in 9 *kg* increments, as needed. This addition had the effect of dropping the overall reservoir coolant temperature by $5\text{-}6^{o}C$. The chiller circuit design was slightly undersized from a per sow energy rejection perspective, and this cooling capacity would need revision upward for further experimental operation.

In terms of overall functionality, the prototype recirculating coolant supply system performed adequately in demonstrating the potential of using a closed coolant circuit for the swine cooling pad technology. The coolant delivery to the pads was unaffected, when compared to the performance of the earlier once-through open system. Metered coolant delivery to the pads remained within specification throughout the trials. It would have been desirable to have more slope on the return network, since it operated using only gravitational potential. However, the functionality of the water return system was not impaired by the retention of some water within the piping. The scavenge pump and sump elements worked as expected. The supercharging pump and reservoir combination needed some further refinement to eliminate the starting cavitation, but otherwise performed in an as-expected nominal manner. The heat rejection coolant loop, while slightly undersized in thermal capacity, also performed acceptably and could have easily been adjusted to have adequate capacity through the addition of a third chiller. In summary, acceptable functionality of the coolant recirculation system was achieved, and it was proven possible to construct a functional coolant recirculation system for the Purdue swine cooling pads.

All of the components of the recirculating coolant system were monitored for energy consumption during the experimental sessions using Intertek P3 (New York, NY) cumulative power meters. The energy consumption results for the calorimetry experimentation are presented in Figure 17. Unsurprisingly, the water chillers consumed the most power at 904 *W*, using an average draw of 452 *W* per unit. It is worth noting that a third unit would have truly been necessary to service the four sows on the cooling pads, but for a larger commercial facility, larger and more efficient cooling units could be used. The supercharging pump required 584 *W*. This is a large energy demand, which might be reduced through the use of a different design, potentially including a high-capacity (~80 *l*) accumulator to decrease the active duty cycle of the component. The scavenge pump also consumed a fair amount of energy, drawing 396 *W*. This was surprising, and the high power consumption of this element may be from the use of a consumer-grade device. It would be feasible to eliminate this component in a barn designed to employ the cooling pads by installing a basement level coolant room, but that was not possible under this circumstance. The hydronic pump used to push the coolant through the chillers consumed 72 *W*, while running at its lowest setting. Each pad controller drew 3 *W*.

The cooling pad performance during operation was recorded internally by the pad controllers and downloaded after the completion of the experimentation. Three pad temperatures, aligned with the sow's shoulders, mid-body, and hip centerline, were archived every 6 *s*, in addition to the coolant inlet, outlet, and ambient temperatures. Consistent with past studies, calibration exercises were performed on the pads before and after the animal science experimentation (Cabezon et al., 2022; Cabezon et al., 2017c; Cabezon et al., 2017d). The thermal instrumentation was provided using Adafruit (New York, NY) DS18B20 digital thermal sensors. Baseline readings were collected at room ambient temperature after a 6 *h* 'soak period' to ensure equilibrium with the environment. An additional calibration data collection run using an ice / water bath was also conducted. Individual digital thermal sensors have unique identification IDs, and their slope and offset values were consistent with previous readings. Multiple temperature values at each condition were collected, and standard deviations were determined for each sensor, both before and after the experimentation. Those values are presented in Table 1. Only a single sensor failed consistency testing during the post-experimentation evaluation. Unfortunately, it was the inlet water temperature instrument on pad #5. This invalided the data from that temperature sensor and prevented the direct measurement of the energy removed from the sow on that pad. The digital sensors had 'true' temperature offsets determined during the pre-trial calibration runs with Mercury thermometers that were applied to all measurements. These temperature offsets are included in Table 1.

Utilizing the known mass flowrate of the water and its specific heat, along with the inlet and exit temperatures, it was possible to calculate the heat energy transferred away from the sows to the cooling pads. Average power ratings were determined by using the heat transfer across the whole coolant flush cycle as divided into 6 *s* intervals. Pad 4, although it passed the calibration tests, also seemed to produce some very erratic thermal readings during the second replicate, with values occasionally shifting multiple orders of magnitude. These data were therefore not included in the detailed daily heat rejection calculations. The wild swings in output readings at rapid rates were typical of failed digital sensors within the confinement facility environment. Table 2 presents directly calculated values heat rejection rates for pads 6 and 8. Since the inlet thermal sensor for pad 5 was unreliable, inlet water temperatures for pad 6, which was physically closest to pad 5, were used to estimate the heat rejection from that sow throughout the analysis. It was well-understood by the researchers that the error introduced by this substitution process could have been significant, but since the inlet temperature in the supercharged plenum was reasonably consistent, this adjustment allowed for a rough estimation of the total aggregate heat being pumped away from the animals by the recirculating coolant system. The sows in the second replicate seemed to require more cooling than those in the first, and the sows in the indirect calorimeters seemed to need more cooling than the spare sow on pad 8. In general, as previously reported by this research team, digital thermal sensors have not been demonstrated to be as reliable as traditional thermocouples for this type of work in livestock confinement facilities (Cabezon et al., 2022; Cabezon et al., 2021; Seidel et al., 2020; Cabezon et al., 2018b; Cabezon et al., 2017a; Cabezon et al., 2017b). Their convenience is undeniable, but they do not seem to provide consistent results and seem to be prone to long-term erratic behavior, due to the failure of their electronic components from exposure to the corrosive atmosphere within the barns, as evidenced by the high pad controller failure rate and repair overhead needed to keep the units functional.

Analysis from Johnson et al. (2021) and Jansen et al. (2021), shown in Figure 18, showed that animals on the floor cooling pads generated approximately 100 *W* more per animal than those on the non-functional control pads throughout the lactation period. This roughly corresponds to the value of energy from the sows rejected by the pads into the recirculation system. The roughly 100 *kcal/h* per animal (~115 *W*) shown by this data also corresponds to the level of increased milk production in the sows. Sows on the active cooling pads and their litters had a 26% average daily gain increase over the control groups. Since sows thermoregulate based upon their comfort levels, sows on cooling pads can consume more feed and create more milk, without suffering from the negative effects of heat stress. This data showed a strong statistical effect with treatment, resulting in the probability of the null hypothesis being under 1%.

Flushing frequency was reviewed as a cooling pad metric, since it relied upon a different digital data channel that was not susceptible to the same uncertainty. Each pad's microcomputer counted the flush periods for each cooling pad. Since several days of operation were recorded, the number of flushes during the ordinal hour of the day could be determined, and multiple days could be averaged for a more consistent value. Figure 19 presents the average flush counts per hour for the first repetition, and Figure 20

Table 1: Thermal sensor calibration data for the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) swine calorimetry experimentation.

Pad	Location	Pre Std. Dev.	Offset (^oC)	Cold Std. Dev.	Post Std. Dev.	Result
4	AMBIENT	0.179	-3.40	0.105	0.244	Pass
4	INLET	0.242	-0.30	0.260	0.245	Pass
4	OUTLET	0.000	-0.50	0.314	0.018	Pass
4	SHOULDERS	0.000	+0.50	0.000	0.000	Pass
4	MID-BODY	0.000	+1.00	0.196	0.094	Pass
4	HIPS	0.000	+0.50	0.000	0.037	Pass
5	AMBIENT	0.000	-1.50	0.247	0.000	Pass
5	INLET	0.000	+1.00	0.000	2.891	Fail
5	OUTLET	0.000	0.00	0.000	0.000	Pass
5	SHOULDERS	0.000	-1.50	0.249	0.139	Pass
5	MID-BODY	0.000	-1.50	0.147	0.000	Pass
5	HIPS	0.025	+1.00	0.00	0.000	Pass
6	AMBIENT	0.109	-1.00	0.250	0.000	Pass
6	INLET	0.000	0.00	0.244	0.000	Pass
6	OUTLET	0.159	+4.00	0.152	0.000	Pass
6	SHOULDERS	0.000	+0.50	0.000	0.000	Pass
6	MID-BODY	0.000	+1.50	0.000	0.000	Pass
6	HIPS	0.025	+1.00	0.059	0.209	Pass
8	AMBIENT	0. 323	+3.30	0.000	0.000	Pass
8	INLET	0.000	-0.50	0.000	0.019	Pass
8	OUTLET	0. 227	+0.20	0.162	0.099	Pass
8	SHOULDERS	0.000	0.00	0.000	0.207	Pass
8	MID-BODY	0.000	-0.50	0.105	0.000	Pass
8	HIPS	0.000	+0.50	0.000	0.000	Pass

presents the averages for the second repetition. In both cases peak flushing seemed to occur between late morning and early afternoon. Overnight periods produced the least number of flushes per hour. These graphs corroborate the anecdotal evidence that the system cooling capacity became marginal during the mid-day period. Variance between sows is also apparent, as the system flushed automatically, based upon the top plate temperature.

Data from the Johnson et al. (2021) experiment were analyzed by (Graham, et al., 2021) to create the predicted internal Rectal Temperatures shown in Figure 21. These data provide a much better match with the pad flushing interval data than the Respiration Rate, which is known to be somewhat of a lagging indicator and appearing only once the animal is beginning to feel heat stressed. The beginning of the day, when the sows wake-up, was evident in the data, and the peak heat production matched the feed consumption periods by a small nominal lag.

Table 3 presents the summarized energy flows from the cooling pads and various system components. Mechanical cooling systems are generally evaluated by a Coefficient of Performance (CoP), the ratio of cooling provided over the energy input. The combined power draw of the prototype recirculating coolant system for the pads was 1.97±0.04 *kW*. The combined thermal energy being pulled from the four sows during

Table 2: Average daily rejection power of cooling pads 6 and 8 over the course of two indirect calorimetry experiments at the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room.

Date	Pad 6 *(kW)*	Pad 8 *(kW)*
24 Nov	0.354	0.059
25 Nov	0.375	0.042
26 Nov	0.156	0.066
27 Nov	0.251	0.180
28 Nov	0.373	0.103
29 Nov	0.210	0.138
30 Nov	0.303	0.319
15 Jan	0.395	0.170
16 Jan	0.330	0.162
17 Jan	0.316	0.249
18 Jan	0.304	0.215
19 Jan	0.256	0.170
20 Jan	0.198	0.171
21 Jan	0.227	0.106
22 Jan	0.163	0.202
23 Jan	0.240	0.338
24 Jan	0.215	0.144
25 Jan	0.183	0.104
26 Jan	0.204	0.202

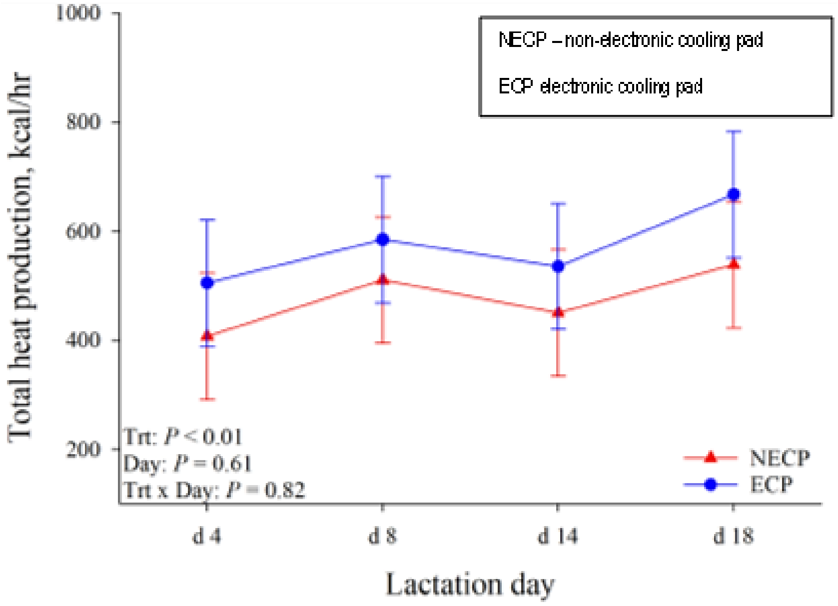

Figure 18: The total heat production of the sows, with and without cooling pads, during lactation based upon data from the Johnson, Jansen, Galvin, Field, Graham, Stwalley, & Schinckel (2021) experiment (Jansen, Galvin, Field, Graham, Stwalley, Schinckel, & Johnson, 2021).

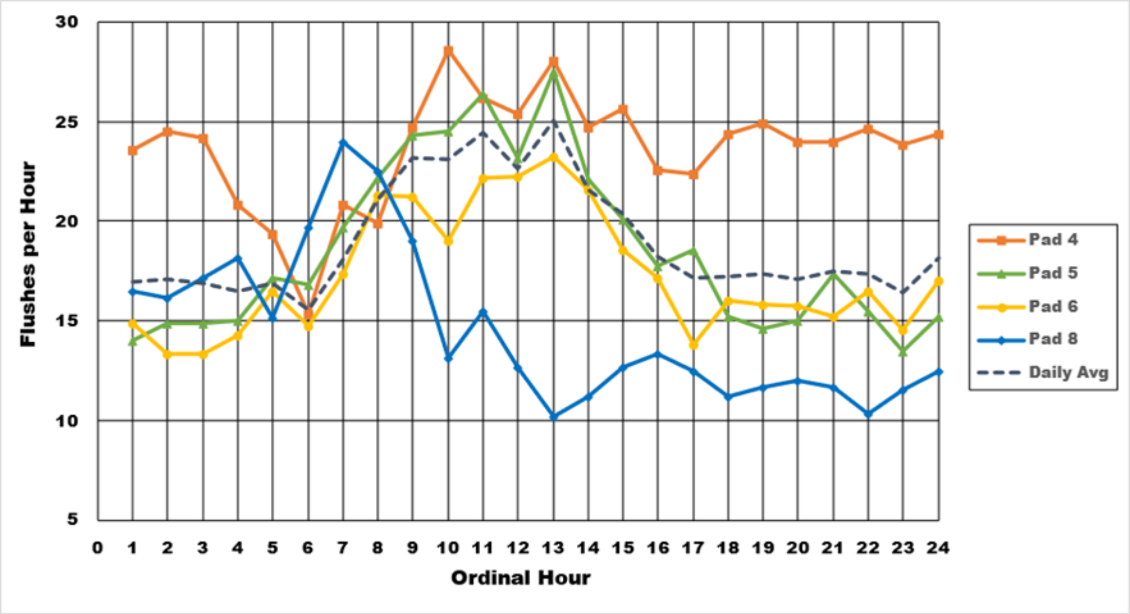

Figure 19: Cooling pad hourly flush rate during the first swine calorimetry experiment at the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room.

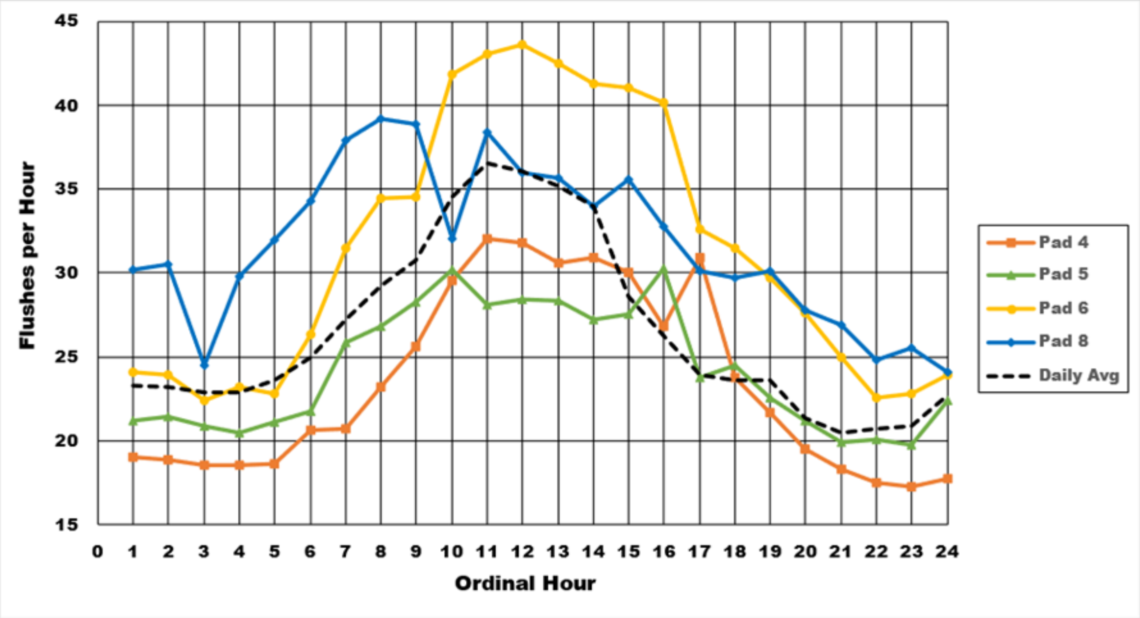

Figure 20: Cooling pad hourly flush rate during the second swine calorimetry experiment at the USDA Farm Animal Behavioral Laboratory (FABL) swine experimentation room.

the experiment was measured by the microprocessors controlling the cooling pads and was 2195±5 *W*. These energy rates result in an overall CoP for the system of 1.11. This prototype design performed well below the minimum standard for commercial air-cooled chilled water systems of 2.1 (Yu et al., 2014). It would initially seem as though the coolant recirculation system for the cooling pads did not produce an acceptable industrially-competitive CoP. However, the result was perhaps not all that unreasonable for a specialized

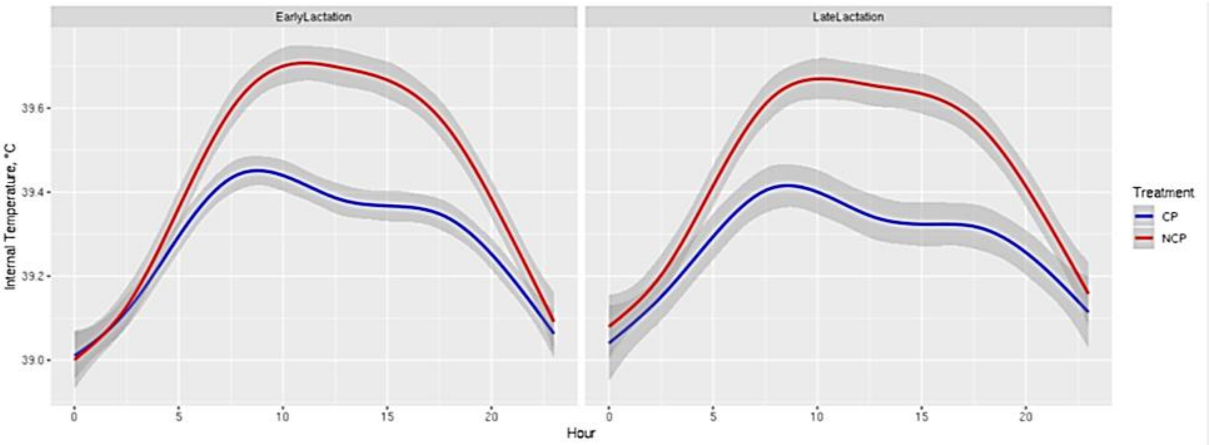

Figure 21: The predicted internal temperature of the sows, with and without cooling pads, during early (left) lactation and late (right) lactation based upon data from the Johnson, Jansen, Galvin, Field, Graham, Stwalley, & Schinckel (2021) experiment (Graham, Galvin, Jansen, Field, Stwalley, Schinckel, & Johnson, 2021).

Table 3: Purdue cooling pad recirculation system energy metrics from the USDA-ARS Farm Animal Behavior and Well-Being Laboratory (FABL) animal holding room during the swine calorimetry experiment for the second prototype coolant recirculating system.

System Component	Power Consumption (*W*)
Air-cooled Water Chiller #1	451
Air-cooled Water Chiller #2	452
Supercharging Pump	584
Scavenge Pump	396
Circulation Pump	72
Pad Microprocessor Controller	4 @ 3
Total System Demand	1970
Pad #4	670
Pad #5	540
Pad #6	350
Pad #8	635
Total System Cooling	2195
Coefficient of Performance$_{\text{act}}$	1.11

system assembled from off-the-shelf components, operating with low thermal gradients and flows. The system was functional, and based upon the present data, eliminating the scavenge pump would improve the CoP to 1.39.

The Purdue cooling pad system required significantly more pumping capacity than a typical chilled water delivery system for a commercial building to maintain accurately metered coolant delivery, adding significantly to the input energy ledger. This installation was also disadvantaged by being on the lower end of size, serving four sows. It was unable to take advantage of the efficiency gains from scale that should result from an application within a commercial facility. Additionally, this system was retrofitted into the FABL facility and was unable to take advantage of several potential improvements that might have come from a better integration of the system into the initial building design. It should be possible within a new facility to eliminate the scavenge pump system. A geothermal loop for the coolant would allow for the deletion of the chillers, but it would require a more powerful hydronic-type pump to drive the cooling loop. Heat gain from the environment had been a measurable problem in earlier studies, but this system took advantage of those previous experiences and was well-insulated for the current round of experimentation. Certainly, the remaining ambient losses could be minimized by further reducing the sensible heat gain from the environment. Energy efficiency results should increase with further design improvements to the system that eliminate unnecessary energy inputs by taking better advantage of gravity. These improvements will have a positive effect on CoP.

The data collected in this preliminary investigation of a prototype chilled water recirculation system for the sow floor cooling pads proved sufficient to complete the research questions for this effort positively. Consistency in the coolant delivery flowrate was maintained throughout the experiment. Inlet coolant temperature at the pads, while ranging higher than desired, never became too warm to be useful, and the collected energy use data indicated that the system performance was poor, compared to expected commercial system metrics. However, the prototype system functioned as needed and showed enough potential to revise and retest in an environment that will allow the collection of better information. Demonstrating that this system was functional within the confinement barn environment has potentially eliminated any questions regarding the sustainability of sow cooling floor pad systems.

CONCLUSIONS AND RECOMMENDATIONS

The use of this preliminary recirculating coolant system design for the swine cooling pads under live animal calorimetry experimental testing demonstrated several areas in the implementation where improvement could be attained. None-the-less, the system functioned as planned. Specific cooling for individual animals was measured, along with the system's overall energy use. CoP for the system was shown to be sub-standard from an industrial perspective, but no alternative model for a comparable system is available at this time. All three engineering objectives for the project were met. It was demonstrated that it was possible to maintain consistent cooling pad flowrate at a reasonable delivered temperature performance with a circulating system. Unfortunately, the energy consumption of the system was large for the amount of cooling effort provided. Numerous elements were identified as targets for improvement in subsequent iterations. The installation of this recirculating coolant system in the FABL research facility represented a typical retrofit situation on a flush-type swine barn floor. Installation within a slotted floor-type barn could potentially prove more satisfactory, due to the ability to use some of the underfloor volume for the recirculation system's plumbing. In spite of the constraints encountered during this initial installation, it is possible to draw the following key conclusions from this effort:

- The supercharging pump inlet conditions are important. Reservoir placement must provide sufficient capacity and pressure to prevent pump cavitation throughout the operational cycle.
- The energy balance within the water chiller system is delicate, making cooling efforts difficult to optimize. Coolant warms quickly with insufficient heat rejection capacity, and extra 'demand' capacity is expensive to purchase and operate.
- Integrity of the spent coolant return network is vital, especially in low head configurations. A significant leak could quickly drain the entire coolant volume, terminating function and harming equipment.
- Gravity flow and low pressure return to reservoir are essential for simplicity and low operating cost. The location of the reservoir and supercharging pump in a below-floor area could eliminate the need for a scavenge pump and would greatly improve the energy use parameters of the system.

There are several additional minor points that should be mentioned as well. Adequate insulation on the coolant delivery network can prevent sweating on the pipes and the unnecessary loss of cooling potential, due to the environmental heat gain. The 'right' sizing of the energy rejection equipment is important in the economic analysis of a commercial system. The addition of a large capacity accumulator to the delivery plenum line should improve the economics of the supercharging pump's operating cycle by reducing the number of "charge" cycles. The lack of adequate cooling capacity can manifest itself within a matter of hours as a significant rise in coolant reservoir temperature. The generalized chilled water system design maxim of 'right-sizing' components is valid for these animal confinement building systems. It is the intention of the Purdue cooling pad researchers to move forward with the lessons learned from this initial coolant recirculating system experience in designing a new unit to be installed at the Purdue ASREC facility. This step will allow a more thorough analysis of a recirculating coolant system. Direct operating comparisons, performed against a once-through comparison system, can be conducted in a barn better suited to the collection of more statistically-determinant results. The long-term commercial product viability of this technology will require the adoption of known chilled water systems for use in confinement agriculture facilities, and closed loop, recirculating systems represent the most likely choice for implementation.

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NOMENCLATURE

ASREC – Purdue University Animal Science Research and Education Center
CoP – Coefficient of Performance
FABL – United States Department of Agriculture Animal Research Service - Farm Animal Behavioral and Well Being Laboratory