Effect of conductive cooling pads on heat and moisture production of gilts in hot and thermoneutral environments

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Abstract: Swine productivity, reproductivity, and well-being are reduced during periods of high temperature and the most commonly used cooling method, evaporative cooling, is not very effective under high humidity conditions. Conductive cooling pads made from pipes with cool water passing through them have the potential to cool swine under both high temperature and high humidity conditions. A study was conducted to determine some responses of gilts to conductive cooling pads under heat stress conditions. Conductive cooling pads 15 cm wide by 127 cm long were made from 13 mm diameter copper pipe and were fastened to the slatted flooring of a standard sow stall. The size and placement of the pads was such that the gilts could lie on them completely, lie on them partially, or avoid contact with them. Cool water (18°C) was pumped through one of the pads at a flow rate of 4 L min^{-1} for the treatment gilts and the control gilts had no water flowing though the cool pads. Each gilt was acclimated to thermoneutral conditions (16°C), and then placed in the stall in a convective indirect calorimeter under heat stress conditions (35°C). The animal's total heat production, respiration rate, and moisture production were determined. Results show that during the heat stress periods, the conductive cooling pads reduced the gilt's heat production by around 10%, moisture production by 34%, and respiration rate by 22%. In most cases, the cool pads significantly reduced the onset of panting.

Keywords: swine, conductive cooling, heat production, moisture production, respiration rate

Citation: Shaffer, C. S., G. L. Riskowski, and P. C. Harrison. 2017. Effect of conductive cooling pads on heat and moisture production of gilts in hot and thermoneutral environments. Agricultural Engineering International: CIGR Journal, 19(4): 13–19.

1 Introduction

The detrimental effects of heat stress on swine include reduced feed intake, decreased activity, increased respiration rates, increased rectal temperatures, slower growth, and poor reproduction compared to that in thermoneutral conditions (Fraser, 1970; McGlone et al., 1988; Santana, 1993). Many current cooling systems rely on increased convective heat loss (higher air velocity, snout coolers) or increased evaporative heat loss (water sprinkling, dripping, evaporative pads), which are only moderately effective under high temperature/high humidity conditions (Barbari et al., 2007; Barbari and Conti, 2009; Huynh et al., 2006).

Received date: 2017-08-09 **Accepted date:** 2017-09-16

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Conduction is an effective method of heat transfer and, if swine would use conductive cooling pads, it could be a relatively effective method of alleviating heat stress. Conductive cooling pads (CCP) have cool surfaces and are fastened onto the floor. When an animal lies on the cool pad, it will lose heat to the pad. Studies have shown that sows and pigs will use CCPs or cooled floor sections when subjected to heat stress (Santana, 1993; Bull et al., 1997; Shi et al., 2006; van Wagenberg et al., 2006), which reduced their respiration rates and rectal temperatures. In fact, sows significantly preferred the CCPs to snout coolers and drip coolers (Bull et al., 1997). The CCP construction was a simple and low cost configuration of 13 mm diameter pipe with cool water flowing through it. The cost to cool the relatively low amount of flowing water should be lower than the cost to cool and dehumidify air in the swine facility. Silva et al.

(2009) subjected sows with pigs to cooled and uncooled concrete floors and the pigs of the sows on the cooled floors had a number of improved parameters. Huynh et al. (2004) tested growing finishing pigs on water cooled concrete floors and found that the pigs ate more and grew faster on cooled floors.

However, the previous research did not determine if there was a reduction in the metabolic rate from using CCPs, and how much the metabolic rate was reduced relative to swine under thermoneutral conditions. This data must be acquired to determine the benefit of CCPs in reducing heat stress in terms of energy balance gains. Heat stress is known to increase swine energy use due to the need to invoke cooling mechanisms (MWPS, 1983). If swine can balance heat loss with heat production by using the CCPs, then they would use less energy to maintain an energy balance.

The overall objective of this research was to determine the effects of CCPs on total heat production, moisture production, and respiration rate of open gilts (non-pregnant female swine before first litter) when exposed to hot and thermoneutral environments.

2 Materials and methods

2.1 Indirect convective calorimeter

This study was conducted in an indirect convective calorimeter at the University of Illinois. This calorimeter was designed to maintain air temperature, relative humidity, air velocity and fresh air exchange rate. It was a 230 cm wide by 305 cm long by 160 cm high insulated, sealed, galvanized steel chamber which could house various configurations of animal pens, waterers, feeders, and manure collection/handling systems. This chamber was developed to house small groups of animals under typical production systems. The air movement was recirculated within the chamber to allow air conditioning and to create the desired air velocity for the animals. Air flowed horizontally through the animal area, then up through a set of filters into a partitioned plenum area over the animals where it was conditioned. The air then moved around and through a bank of eleven in-line fans that moved the air through a set of screens back into the animal area, as shown in Figure 1. The two screens (one with 10% open area and the other 50% open area) acted as a settling means to provide a more even distribution of air velocities approaching the animal area. In this study, the target air velocity approaching the animal area was 0.25 m s^{-1}. Air velocities were measured using a TSI Velocicheck (Model 8330) hot wire anemometer. Recirculated air was passed through a chiller, which reduced temperature and condensed out moisture. This chiller was operated to remove more heat and moisture than desired, then water was added back with a humidifier and heat was added back with electric heaters to achieve the final desired air relative humidity and temperature. Air temperature approaching the animal area was measured with calibrated thermocouples.

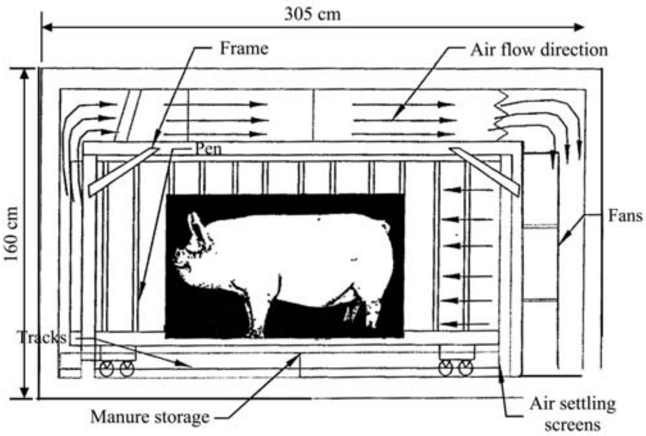

Figure 1 Cross-section of calorimeter showing gilt and stall location as well as airflow directions

Data obtained was oxygen consumption, carbon dioxide production, total heat production via indirect calorimetry, water production, and respiration rate. For fresh air exchange, air was pumped out of the calorimeter at a port just downstream from the animal area at a rate of 120 L min^{-1}, which drew the same amount of fresh air into the chamber through an inlet in the air conditioning portion of the chamber. The air removal rate was measured with a Gilmont Instruments flow meter (Tube size 6; calibrated and certified traceable to NIST). The chamber was operated at a slight negative pressure (≈15 Pa) so fresh air was drawn in through the inlet. The air drawn out of and flowing into the chamber were analyzed for concentrations of O_2, CO_2, and moisture. Since the airflow through the chamber was precisely known, the mass consumption and generation rates of these gases could be calculated. Oxygen was measured with a Beckman Model OM-11 infrared analyzer and carbon dioxide was measured with a Rosemount Analytical (Model 880A) infrared analyzer. Both analyzers were calibrated with certified two standard gasses at least once per day (Standard gas #1: 1.6% CO_2, 19% O_2; Standard gas #2: 0.55% CO_2, 17% O_2). Total animal heat production was calculated using the oxygen consumption and carbon dioxide production via indirect calorimetry methods (Northeast Regional Research Project NE-61, 1983; Nienaber and Maddy, 1985). These were calculated by the difference between incoming and outgoing concentrations and multiplied by the total pressure and temperature corrected volume of air. Relative humidity was measured with electronic humidity transducers (General Eastern; Model RH-5-V) that were calibrated against a psychrometer prior to each test. Water removed by condensing on the chiller cooling coils was collected and its mass was determined with a scale. Moisture production rates were calculated from this data. A video camera was placed in the calorimeter just above the animal so respiration rate and animal behavior could be observed. Respiration rates were taken at least every 30 minutes and more often during heat-stress periods of the test.

Prior to the tests, the accuracy of the calorimeter was verified by burning a known amount of 100% ethanol inside to determine the mean recovery ratios of oxygen and carbon dioxide (Northeast Regional Research Project NE-61, 1983). The procedure served as an integrated check on all components of the calorimeter. An ethanol lamp was filled with absolute ethanol (EtOH), placed on a precision balance, lit, and the empty calorimeter sealed shut. After the lamp established a steady burn, ethanol weight disappearance was compared to measured recovery rates of oxygen and carbon dioxide to determine if there was a balance. The ethanol lamp calibrations allowed us to determine if the measured respiratory quotient (R.Q.) was similar to the theoretical value for ethanol combustion (0.67), and if the average oxygen recovery and the average carbon dioxide recovery were near the ideal (1.0).

2.2 Stalls with conductive cooling pads

For this study, the calorimeter was fitted with a standard commercial 61 cm wide by 214 cm long sow stall. The slats were woven wire mesh with rod diameters of 1 cm. Manure and water spilled from the waterers were collected in a pan beneath the slatted flooring. Because the manure collection pan was within the calorimeter, water evaporating from the surface of the waste contributed to the moisture production rate that was measured by this system, as it would for normal swine production.

The CCPs were made from 13 mm diameter copper pipe that was looped back and forth approximately 5 cm apart to cover an area approximately 15 cm wide by 127 cm long, as shown in Figure 2. Two CCPs were placed in the stall so there was one on each side. One of the CCPs was connected to a water cooling system and the other was open to the air and was not cooled. The non-cooled CCP was used so the gilt's laying behavior would not be affected by having pipes on the floor of only one side of the stall. When the water cooled CCP was operating, cool water (18°C) was pumped through the pipe at 4 L min^{-1} (the same flow used by Bull et al. (1997) for their CCPs), which kept the outer surface cool. The CCP was placed on the floor so the gilts could lie on it to keep cool. However, the gilts were not forced to lie on the CCP; they could choose whether they wanted to lie on the CCP, on the identical CCP that was not cooled, or on other floor areas.

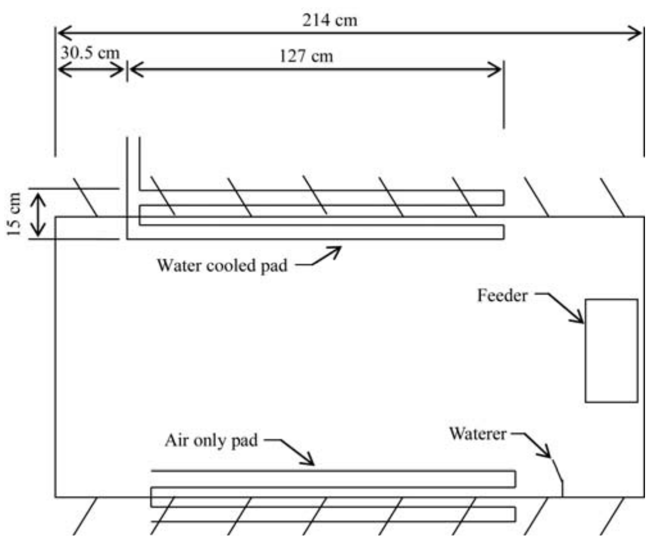

Figure 2 Top view of sow stall layout showing locations of water cooled pad, air only pad, waterer and feeder

2.3 Animal tests

There were three groups of two mature open (not pregnant) gilts tested in each treatment for a total of 6 animals for the experiment. However, one of the gilts was taken off the study because it was unintentionally subjected to heat stress while in the calorimeter. The animals were mature Pig Improvement Company (PIC-14) gilts. The gilt weights averaged 105.8±3.03 kg (mean ± standard error of mean (SEM)). The light schedule was 24 h light. Water and feed were available *ad libitum* via a standard commercial sow feeder and nipple waterer, respectively, installed in the front of the stall. They were fed once per day with a maintenance diet (4,000 g day^{-1} standard finisher feed-balanced ration with 13.45% crude protein, 3,395 ME Kcal kg^{-1}). The amount of feed was sufficient to allow the gilts to eat *ad libitum* during the tests. Water disappearance was measured over the 24 h test period. All animal test protocols were approved by the Animal Care Committee of the University of Illinois prior to tests being conducted.

All tests were conducted during November and December of 1999. For each experimental run, two gilts were selected from the research farm herd. Each set of two gilts was tested in the calorimeter over a two week period as shown in Table 1. They were moved to and tested in the calorimeter on alternate days and tested with the CCP on (cool water flowing) and off (no water flowing). Each animal was subjected to four test runs (two with CCP on and two with CCP off) for a total of 20 test runs, so each treatment was replicated twice for each gilt. During each thermal test period (thermoneutral, heat up, heat stress, and recovery) there were 2 to 7 observations taken.

Table 1 Schedule of calorimeter tests for each set of two gilts

	Monday	Tuesday	Wednesday	Thursday	Friday
1st Week	Move gilts	Gilt #1 CCP On	Gilt#2 CCP Off	Gilt #1 CCP Off	Gilt#2 CCP On
2nd Week	Gilt #1 CCP On	Gilt#2 CCP Off	Gilt #1 CCP Off	Gilt#2 CCP On	Move gilts

Note: Three sets of gilts (2 gilts/set) were tested in this study.

At around 1:00 pm of the first test day (Monday), the gilts were brought to the Environmental Research Laboratory from the University of Illinois Swine Research Center. They were placed in a separate environmental chamber at thermoneutral conditions (average for study was 16°C±2°C, 50%±10% relative humidity) in stalls of the same design as in the calorimeter. This period allowed them to adjust to the stalls and the move. At around 7:00 pm, one of the gilts was placed in the calorimeter for a 24 h test. The calorimeter was maintained at thermoneutral conditions over night. Calorimeter data collection was started at 7:00 am of the test day and continued until 7:00 pm of that same day. The heat stress replications were done in a manner that simulated temperatures heating up for a period of time in mid-day then decreasing towards evening, as shown in Figure 3. First, there was a thermoneutral period from 7:00 am to 9:00 am. Next, the heaters were set to gradually increase temperatures (10°C h^{-1}, called heat-up period) until heat-stress conditions were reached at 11:00 am. The heat-stress period lasted for 2 h until 1:00 pm, then the air temperature was gradually reduced (2.5°C h^{-1}, called recovery period) until the test gilt was removed from the calorimeter at around 7:00 pm. During the tests where the CCP was "on", the water flowed through the CCP from 7:00 am to 7:00 pm.

3 Results

3.1 Calorimeter performance

The ethanol lamp calibrations gave a R.Q. value of 0.65±0.0022 (theoretical value for ethanol combustion = 0.67). The average oxygen recovery was 1.02±0.0089 and the average carbon dioxide recovery was 0.94±0.0253 (ideal = 1.0). On average over the entire experiment, the calorimeter maintained the inside temperature at 15.5°C± 0.8°C under thermoneutral conditions and 35.5±0.7°C under heat stress. The average relative humidity was 54%±4.5% for the course of the experiment. Approach air velocity was 0.26±0.14 m s^{-1} on average throughout the study.

3.2 Total heat production

Total heat production was determined for the four thermal periods during each test run – 1) thermoneutral period, 2) heat-up period, 3) heat-stress period, and 4) recovery period, Table 2. Figure 4 shows the average total heat production for each treatment over the entire experimental period. All the heat production data is presented as a function of animal body weight to the ¾ power to allow more accurate comparison of animals of different weights. Past research has indicated that animal metabolic rate is more closely related to body surface area than to body mass – often called the Body Surface Law (Esmay, 1969.) For mammals, the body surface area can be approximated by using the body weight to the 0.75 power. The heat production was always higher when the CCP was off, than when it was on. There was no statistically significant difference ($p \geq 0.05$) between the heat production means when CCP was on or off during the thermoneutral, heat-up, and recovery periods. However, these means were significantly different during the heat-stress period ($p<0.05$). Consequently, the CCP did significantly reduce total heat production of the gilts during heat stress conditions. During the heat-stress period, the mean total heat production was almost 10% less with the CCP on than when the CCP was off.

Table 3 presents thermoneutral heat production data of this study, along with other studies where heat production was determined for larger swine under thermoneutral conditions. Although there was variation in important factors between these studies, Table 3 offers a good comparison of heat production from swine for more recent studies and the 1959 study by Bond et al. (1959). Clearly the change in genetics since 1959 has increased heat production from swine on a W $kg^{-0.75}$ basis, and modern ventilation systems should be designed accordingly. The thermoneutral heat production from this study was somewhat higher than the other recent studies, but this difference may be a result of the higher air velocity, different genetics, variation in feed intake, and relatively low air temperature.

Table 2 Mean total heat production (W $kg^{-0.75}$) during different thermal conditions with and without operation of the cooling pad

Thermal condition	Cooling pad operating Mean± SEM, W $kg^{-0.75}$	Cooling pad not operating Mean±SEM, W $kg^{-0.75}$	n	Difference between operating and non-operating cooling pad, %
Thermoneutral period	9.63 ± 0.177	9.90 ± 0.177	35	+2.8[a]
Heat-up period	9.76 ± 0.156	9.76 ± 0.229	45	0[a]
Heat-stress period	9.14 ± 0.143	10.11 ± 0.320	40	+10.6[b]
Recovery period	9.00 ± 0.108	9.34 ± 0.162	60	+3.8[a]

Note: [a] The difference of the means between operating and non-operating cooling pads was not statistically significant (p 0.05); [b] The difference of the means between operating and non-operating cooling pads was statistically significant ($p<0.05$).

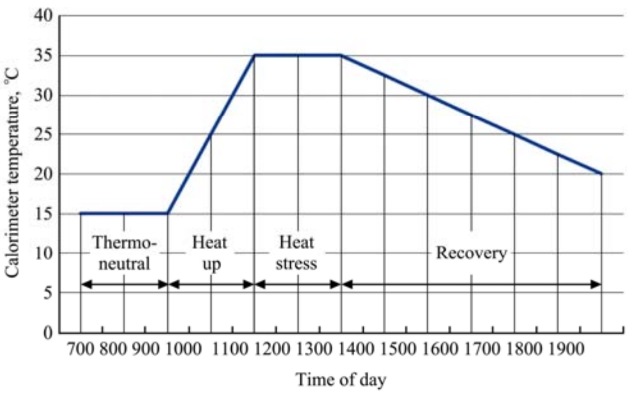

Figure 3 Target air temperature levels over the experimental period

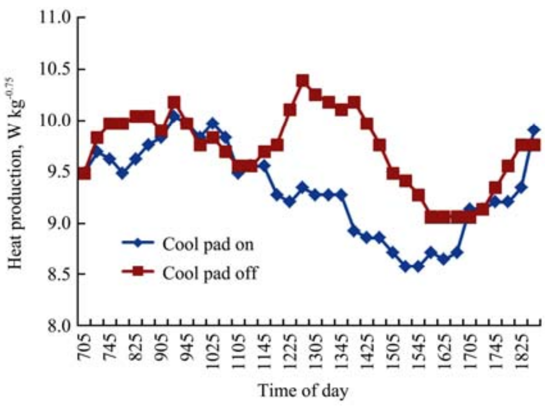

Figure 4 Average total heat production levels with the cool pad on and with the cool pad off over the experimental period

Table 3 Comparison of the thermoneutral heat production of studies of swine over 80 kg

	Air temp, °C	Swine breed	Swine weight, kg	Air velocity, m s^{-1}	Feed access	Total heat production, W $kg^{-0.75}$
Current study	15	Pig Improvement Company (PIC)	100	0.26	*ad libitum*	9.00-9.90
Noblet et al. (1994)	24	White × Pietrain	100	NR	restricted	7.04
Brown-Brandl et al. (1998)	18	White × Landrace	84	< 0.15	*ad libitum*	8.02
Brown-Brandl et al. (2014)	16	Landrace × Yorkshire × Duroc	84	NR	*ad libitum*	7.88
Nienaber et al. (1987)	15	Chester × Landrace × White × York	87	NR	*ad libitum*	7.74
Becker et al. (1993)	18-21	Landrace × Yorkshire × Duroc	114	NR	*ad libitum*	8.65
Bond et al. (1959)	15	NR	100	0.075-0.15	*ad libitum*	6.35

Note: NR = Not reported.

3.3 Respiration rate

As expected, respiration rates increased significantly during the heat-up period, reached their maximum during the heat-stress period, and decreased during the recovery period, as shown in Table 4 and Figure 5. There was no significant difference in mean respiration rates of the gilts with and without the CCP on during the thermoneutral, heat-up, and recovery periods. However, the CCP significantly reduced respiration rates during the heat-stress period (from 107 breaths min^{-1} with CCP off, down to 84 breaths min^{-1} with the CCP on). This was around a 22% reduction in respiration rate during the heat-stress period due to the CCP. Although the gilts with the operating CCP still had higher respiration rates during heat-stress than during thermoneutral conditions, the CCP generally was able to prevent the onset of panting. In this study, respiration rates over 100 breaths per minute were considered to be panting (Bull et al., 1997).

Table 4 Mean respiration rate (breaths min^{-1}) during different thermal conditions with and without operation of the cooling pad

Thermal condition	Cooling pad operating Mean ± SEM, breaths min^{-1}	Cooling pad not operating Mean ± SEM, breaths min^{-1}	n	Difference between operating and non-operating cooling pad, %
Thermoneutral period	22.5 ± 0.522	21.6 ± 0.523	20	- 4.4^{a}
Heat-up period	35.7 ± 3.99	43.8 ± 5.62	36	+ 18^{a}
Heat-stress period	83.5 ± 3.84	107.3 ± 4.85	44	+ 22^{b}
Recovery period	38.6 ± 2.67	43.8 ± 4.49	72	+ 12^{a}

Note: ^{a} The difference of the means between operating and non-operating cooling pads was not statistically significant (p>0.05); ^{b} The difference of the means between operating and non-operating cooling pads was statistically significant (p<0.05).

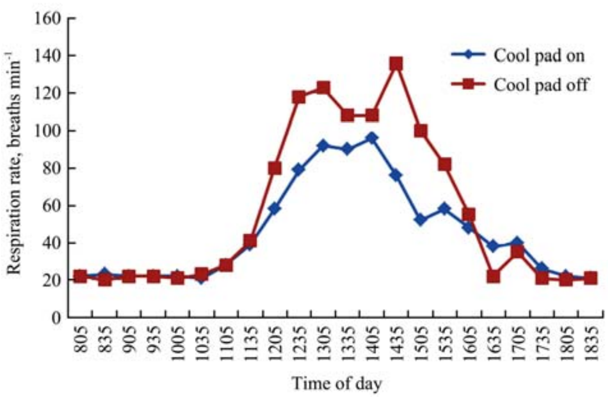

Figure 5 Average respiration rates with the cool pad on and with the cool pad off over the experimental period

3.4 Moisture production

Since moisture production had to be determined over an entire 24 h test period, it could not be determined over each thermal period. The CCP significantly reduced the overall moisture production from 65.9±8.26, 10 (mean ± SEM, n) g H_2O kg^{-1} day^{-1} with the CCP off, down to 43.6±3.97, 10 g H_2O kg^{-1} day^{-1} with the CCP on. The difference in these means was statistically significant (p<0.05). This was around a 34% reduction in moisture production during the test due to the CCP. This reduction could be partially explained by the reduction in respiration rate and the corresponding reduction in moisture release from the respiratory tract. However, the gilts also tended to lean on the nipple waterer more when the CCP was not operative and released more water into the chamber. Brown-Brandl et al. (2014) conducted calorimetry studies on individually penned gilts and reported moisture production rates of 17.4 g H_2O kg^{-1} day^{-1} at 16°C for finishing gilts (54-113 kg) and 55.8 g H_2O kg^{-1} day^{-1} at 32°C which are somewhat similar to the current study. However, one can’t make a direct comparison between these two studies because the gilts were acclimated to the constant temperatures reported in the Brown-Brandl et al. (2014) study while the temperatures varied over the 24 h period for the current study.

3.5 Potential problems with CCPs in production units

To be most economical, the CCP system would most likely need to be installed as a water recirculation system where cool water would be pumped to the individual CCPs and the warmer water returned to a water chilling system. Tap water would generally be cool enough to have a sufficient cooling effect but large quantities of water would need to be supplied and properly discharged. The plumbing system would require a manifold (parallel flow) system so each CCP would receive water at approximately the same temperature. If water flowed in a series flow system from one CCP to the next, there could be large temperature differences from the beginning to the end of the line. The pipes that supply water to the CCPs would most likely need to be insulated to reduce energy losses and condensation.

Moisture condensation on the cool surfaces of pipe could also lead to cleanup and health problems in the facility. This would especially be a concern for farrowing facilities. The CCPs in this study were installed onto wire mesh flooring so any condensation would drip into the pit area directly below. If they were installed on a solid floor, proper water drainage would need to be provided. Some form of rugged insulation material placed between the CCP and the flooring would reduce any unwanted cooling of the flooring. Obviously, the CCPs need to be well fastened to the floor since swine can exert large forces in an effort the root the CCPs around.

4 Conclusions

The CCP significantly reduced some symptoms of heat stress in gilts (105.8 kg) during periods of heat stress (35°C):

- CCPs reduced heat production by around 10% (from 10.11 to 9.14 W $kg^{-0.75}$).
- CCPs reduced respiration rates by around 22% (from 107 to 84 breaths min^{-1}).
- CCPs reduced moisture production by around 35% (from 65.9 to 43.6 g H_2O kg^{-1} day^{-1}).

CCPs must be installed to handle moisture condensation runoff and to resist high forces from the swine rooting on them.

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