Conductive Cooling for Heat-stressed Dairy Cattle

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By:

1Kristy Perano, 2Kifle Gebremedhin, and 3Curt Gooch

1PhD Candidate, Department of Biological and Environmental Engineering
2Professor, Department of Biological and Environmental Engineering
3Senior Extension Associate, Department of Animal Science
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**Executive Summary**

Environmental stress due to thermal environment is a challenge facing the dairy industry that leads to significant economic losses. Thermal environmental stress is increased air temperature and/or relative humidity causing stressful conditions to dairy cows. In this paper, environmental stress due to thermal conditions will be referred to as “heat stress.” With increasing per-cow production making individual cows more susceptible and projected climate warming, mitigating heat stress will become more and more important. There are several commonly used methods of cooling dairy cows. Almost all dairy cattle have access to shade and fans during the heat of the day, and the majority of large dairies employ evaporative cooling technology such as sprinklers, misters, or foggers during the hotter months of the year (USDA, 2010). Despite the active mitigation of heat stress by many dairies, the effects of heat stress still affect the dairy industry overall. During the hotter months of the year, milk production, feed intake, and fertility decreases and health problems increase. Thus, there is continued interest in novel methods of cooling cows.

Conductive cooling is one novel cooling technology that has the potential to offer farmers a way to cool cows while conserving water and encouraging cows to have increased lying times over other cow cooling methods. Conductive cooling systems operate by having cows lie on a heat exchanger cooled by circulating cool water through it. One proposed design for conductive cooling systems is embedding pipes in concrete underneath stall bedding and circulating chilled water through the pipes or installing a flat plate heat exchanger in the stall. Such conductive cooling system designs require thick bedding in the stall (usually 8 to 10 inches) to cushion the cow, but this thick bedding will insulate between the cow and the cooling system, making the system less beneficial for the cow. Another method of designing a conductive cooling system is to use a waterbed as a heat exchanger. Waterbeds provide good cushioning and thus only require a dusting of bedding (typically about ½ inch) to be applied daily. Consequently, a conductive cooling system design that uses waterbeds as a heat exchanger greatly reduces the amount of bedding needed compared to other conductive cooling systems.

This white paper presents evidence that a chilled-waterbed based conductive cooling system (rather than a conductive cooling system with thick bedding between the cow and the heat exchanger) is needed to achieve sufficient heat transfer between the cow and the conductive cooling system to have a meaningful impact on the cow’s level of heat stress. Recent research on several aspects of designing and implementing a waterbed-based conductive cooling system are then discussed. Each section of the analysis of conductive cooling is summarized below.

1. A conductive cooling system that uses internally-chilled waterbeds covered with only a thin layer of bedding allows for maximum heat transfer from the cow and can transfer up to 27% of the cow’s body heat. Conductive cooling system designs requiring thick bedding (8 to 10 inches) between the heat exchanger and the cow create too much insulation and can only transfer about 2% of the cows’ body heat once steady-state conditions are reached. Consequently, conductive cooling systems involving thick bedding will not be effective at relieving the heat stress of the cow, so this paper will focus on waterbed-based conductive cooling systems.

2. A 2015 study investigating the production responses of heat-stressed lactating Holstein cows to conductive cooling with chilled waterbeds found that cows that were conductively cooled with 40°F water had rectal temperatures that were 1.8°F lower and respiration rates 18 breaths/min (bpm) lower when compared to the cows that were not cooled, after both
groups were challenged with 8 hours/day of moderate to high heat stress. The cooled cows also maintained 5% higher milk yield and had a 14% higher dry matter intake.

3. The heat flux is directly proportional to the temperature difference between the cow’s skin and the cooling water. For an internally-chilled waterbed conductive cooling system, the total surface area of the cow in contact with the waterbed is assumed to be 10.2 ft² for Holstein cows. Assuming the waterbed is covered in ½ inch of sawdust, the heat flux predicted by computational fluid dynamics is 40.0 Watts per sq. ft. (W/ft²) for 40°F cooling water and 28.4 W/ft² for 58°F cooling water. Consequently, the heat flow ranges from 408 W (40°F cooling water) to 290 W (58°F cooling water).

4. Condensation occurs relatively rapidly in thin bedding (¼ inch) if the cooling water is below the dewpoint temperature of the air. However, one inch of bedding coverage (either sand or sawdust) traps cool air against the surface of the waterbed and reduces condensation by 95% or more. One inch of bedding still allows for effective heat transfer.

5. The heat energy absorbed by a waterbed-based conductive cooling system chilled with 40°F water is on average 793 W per cow during the time the conductive cooling system is in operation and if the waterbed is covered in ½ in of sawdust. If a chilling system for re-cooling the water with a coefficient of performance (COP, i.e., the ratio of energy moved by the cooling system to the energy consumed by the cooling system) of three is used, then 264 W of cooling would be needed for each cow.

6. Cost estimates for building a conductive cooling system are about $450 per cow. An economic analysis found that in cooler climates (2 mo/year of heat stress), neither foggers nor conductive cooling systems are a good investment. In warmer climates (assuming 6 mo/year of heat stress), conductive cooling and foggers would be expected to have a net profit but would still be less economically favorable than a traditional fan and sprinkler system.

**Introduction/Literature Review**

Heat stress is a challenge facing the dairy industry. It was estimated to cause a 4 to 7% revenue loss per year (St-Pierre et al., 2003; USDA, 2006) for the $36 billion US dairy industry (USDA, 2016). Heat stress occurs when cows have trouble disposing of excess body heat. Heat stress may begin to affect lactating cows when the cow environment temperature-humidity index (THI) reaches 68 (Zimbelman et al., 2009). As a lactating cow’s body temperature rises, her metabolism and endocrine function will adjust to the heat stress conditions, and this will result in lower milk production and lower feed consumption.

Heat stress also leads to higher maintenance energy requirements as the cow respires and sweats more and has increased blood flow to peripheral tissues (West, 1999; Gebremedhin et al., 2010). Thus, the cow consumes less feed and spends more energy on maintenance, so both of these effects of heat stress contribute to a negative energy balance (Rhoads et al., 2009). Both heat stress and the negative energy balance caused by it adversely affect reproductive performance and immune function (Esposito et al., 2014; Liu et al., 2014). Although heat stress adversely affects milk production for cows at any production level, it usually has a greater impact on higher producing cows (Ravagnolo et al., 2000; West, 2003; West et al., 2003).
Evaporative cooling can be direct (such as sprinklers, where water is applied directly to the cows) or indirect (such as foggers, where water is used to cool the cows). Most large US dairy farms employ evaporative cooling systems such as evaporative pads, misters, sprinklers, or foggers such as Korral Kool (USDA, 2010), in addition to shade and fans to mitigate heat stress. When cows are exposed to high heat stress, shades and fans alone are insufficient to alleviate heat stress (St-Pierre et al., 2003). Sprinkler systems are the most appropriate evaporative cooling system for higher humidity conditions since these systems use large water droplets to saturate the hair coat of the cow (Collier et al., 2006). Mister systems rely on small water droplets evaporating quickly, and thus are more effective in low humidity than in high humidity conditions (Armstrong, 1994). The fogger systems are high-pressure systems that produce a mist that is generally directed into an airstream generated by a fan. Both misters and foggers cool cows by lowering the ambient air temperature and blowing this cooler air onto the cows.

All evaporative cooling systems introduce more moisture into the environment which may lead to hygiene problems and increased risk of disease. Sprinkler and mister/fogging systems are typically only used in areas where cows are standing to avoid increasing the risk of disease by adding moisture to the bedding (Martin et al., 2012). However, this limits the amount of time the cows benefit from the cooling. Fogger systems are designed to cool the environment (rather than directly wetting the cow) and have been demonstrated to be effective in maintaining dairy cattle milk production even in very hot climates (Ortiz et al., 2015). Fogger systems may provide better cooling than other evaporative cooling systems especially in dry climates; however, fogger systems will likely only be economical under high heat stress conditions. For most US states, fogger systems require a higher investment in cooling systems than is justified for the amount of heat stress (St-Pierre et al., 2003).

Conductive cooling is an alternative, non-commercialized cooling system that provides a way to cool cows while lying down. Heat-stressed cows typically spend less time lying down and may suffer more incidents of lameness due to spending more time standing (Cook et al., 2007). Conductive cooling systems have the potential to encourage cows to lie down more when under heat-stress conditions. The conductive cooling systems also recycle water as a working fluid, thus conserving water and avoiding introducing additional moisture to the environment. Water scarcity can be an issue in arid and semi-arid climates like the Western US, but can also be a concern in the Northeast during drought years or for dairies lacking a sufficient water supply. Increased water mixed with barn manure may also increase required long-term manure storage capacity. Additionally, the effectiveness of conductive cooling systems is independent of the relative humidity (RH) of the air since the amount of heat conducted between the cow and the heat exchanger is not affected by ambient conditions.

An experimental study by Perano et al. (2015) demonstrated that if cows were cooled with 40°F water circulated through a waterbed and then challenged with heat stress, the cooled cows had a 1.8°F lower core body temperature and maintained 4.8 lb/day more milk production than cows that were not cooled. However, a conductive cooling system tested by Ortiz et al. (2015) placed a flat-plate heat exchanger underneath 10 inches of bedding and cooled the heat exchanger with 45°F water. The thick bedding between the cow and heat exchanger was required to protect the heat exchanger, but this design involving thick bedding resulted in 93% less heat flux and consequently little cooling benefit to the cows.

Three studies modeling conductive cooling systems predicted that conductive cooling systems may be effective at relieving heat stress in dairy cattle. Two studies modeling expected heat transfer in
a conductive cooling system using waterbeds like the system tested by Perano et al. (2015) estimated that up to 27% of the cow’s body heat could be removed by the conductive cooling system if the circulating water was cooled to 40 to 50°F (Bastian et al., 2003 and Gebremedhin et al., 2016). Another study by Mondaca et al. (2013) agreed that conductive cooling could effectively reduce heat stress even in hot and humid weather.

An economic analysis by St-Pierre et al. (2003) estimated the cost of heat stress to the dairy industry and modeled the economic benefits of conductive cooling. The study concluded that in most states, fan and sprinkler systems were the most economically beneficial for lactating cows while fan systems were the best option for dry cows and heifers. However, in climates with severe heat stress, a fogger system could be justified. The economic analysis by Ferreira et al. (2016) investigated the economic benefits of cooling dry cows and found that cooling dry cows with fan and sprinkler systems was very profitable in most US climates. Neither of these prior studies considered the economics of conductive cooling systems, but a conference paper by Perano et al. (2017) considered the economics of conductive cooling systems.

The objectives of this paper are to summarize the:

1. Justification for using waterbeds

There are many ways to design a conductive cooling system. Some companies are proposing designs that (1) use water pipes embedded in concrete to cool the concrete surface, which would then require at least several inches of bedding between the cooled concrete surface and the cow or (2) placing a flat-plate heat exchanger beneath thick bedding (generally 8 to 10 inches). Such designs that cool a surface underneath thick bedding are simpler than using a waterbed as a heat exchanger, and these designs also eliminate concerns about condensation accumulating in the bedding. However, conductive cooling systems that require thick bedding do not remove much heat from the cow since the thick bedding provides too much insulation between the cow’s body and the cooling surface. (See Section 3 of this paper for more information about heat flux and Section 4 of this paper for more information about condensation in bedding for conductive cooling systems using chilled waterbeds.)

The two studies that experimentally measured cow response to conductive cooling were Perano et al. (2015) and Ortiz et al. (2015). Perano et al. (2015) measured the response of heat-stressed cows to conductive cooling with internally-chilled waterbeds. The Ortiz et al. (2015) study tested a conductive cooling system that consisted of a flat plate heat exchanger covered by 10 inches of sand or dried separated manure solids. However, the thick bedding in this system design impeded heat flow; in fact, the heat flux measured underneath the 10 inches of bedding was 93% lower than the heat flux estimated by Gebremedhin et al. (2016) for a conductive cooling system using a
waterbed covered with ½ inch of wood shavings as a heat exchanger. This is because the use of a cooled waterbed as a heat-exchanger allows for using only a thin layer of bedding and thus having almost direct contact between the cow and the cooled-waterbed surface to obtain efficient heat transfer. Comparing experimental results from the experiment with cooled waterbeds by Perano et al. (2015) with the results from testing a conductive cooling system with thick bedding (Ortiz et al., 2015) demonstrates the benefits of higher heat transfer.

Perano et al. (2015) conducted extensive experimental and empirical studies to determine the effectiveness of conductive cooling in alleviating heat stress and consequently sustaining milk production of dairy cows. The experimental work involved exposing lactating dairy cows to hot and humid conditions (THI about 80, RH about 58%, temperature about 86°F) and cooling the experimental cows with conductive cooling while leaving the control cows not cooled. The conductive cooling system circulated cooled water through waterbeds with approximately ½ inch of sawdust bedding placed on top of the waterbeds. Compared to cows that were not cooled with conductive cooling, the cows that were cooled with waterbeds internally chilled with 40°F water had 1.8°F lower rectal temperatures and 18 breaths/min (bpm) lower respiration rate. Milk production and dry matter intake were 7% and 14% higher, respectively, for the cows that were conductively cooled versus those that were not cooled.

The other study on conductive cooling was by Ortiz et al. (2015), and they evaluated the effectiveness of conductive cooling of lactating dairy cows with flat-plate heat exchangers cooled with 45°F water and covered with 10-inch thick sand or dried manure bedding. In this study, thick bedding was needed to protect the heat exchangers and to keep the cows comfortable. The Ortiz et al. study was conducted under hot and humid conditions comparable to the climate conditions in the Perano et al. 2015 study. Ortiz et al. (2015) reported no difference in respiration rate between cooled and not cooled cows. Nevertheless, the core-body temperature for the cooled cows versus uncooled cows in the Ortiz et al. 2015 study was 0.23°F lower for sand bedding and 0.25°F lower for dried manure bedding. Ortiz et al. acknowledged that more work is needed to increase the efficiency of conductive cooling since they could not measure much benefit to the cows in their study.

Although the cooled-waterbed conductive cooling approach is much more effective at transferring heat and thus provides more benefit to the cows, if the conductive cooling surface is below the dew point temperature of the air, condensation may occur at the surface and would be absorbed by the bedding material. A recently published paper (Perano et al., 2018) found that at least 1 inch of bedding cover is needed to prevent problems with condensation if the conductive cooling surface is below air dewpoint temperature. (See Section 4 for a more detailed summary of this experiment.) Table 1 summarizes the pros and cons of conductive cooling approaches that use a waterbed as a heat exchanger versus conductive cooling approaches that place a heat exchanger underneath thick bedding. Because of the low heat transfer and little benefit to the cow from conductive cooling designs that use thick bedding, the rest of this paper will focus on an analysis of conductive cooling using a cooled waterbed.
Table 1. Pros and cons of different approaches to conductive cooling of dairy cows

<table>
<thead>
<tr>
<th>Category</th>
<th>Conductive Cooling with Waterbed</th>
<th>Heat Exchanger with 8 to 10 inches of Bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensation in bedding</td>
<td>Condensation will accumulate where the bedding is less than 1 inch thick if the chilling water is below the dewpoint temperature of the air</td>
<td>Not an issue</td>
</tr>
<tr>
<td>Cost of installation</td>
<td>No commercialized product yet</td>
<td>Easier to design and build</td>
</tr>
<tr>
<td>Estimated steady-state heat flow</td>
<td>Up to 27% of total body heat while cow is lying down</td>
<td>About 2% of body heat while cow is lying down</td>
</tr>
</tbody>
</table>

2. Production responses (and expected production responses)

A study published by Perano et al. (2015) reported on the effects of conductive cooling on heat-stressed dairy cows. A heat-stressed dairy cow spends extra energy to maintain body temperature leading to reduced milk production. The effects of heat stress cost the US dairy industry an estimated 4 to 7% revenue loss per year. Cow waterbeds continuously cooled with chilled water can be used to relieve heat stress in dairy cattle. This study used a commercially available modified Dual Chamber Cow Waterbeds as a heat exchanger. Waterbeds were cleaned and covered with ½ inch of sawdust bedding every day.

The experiment lasted seven weeks. Eight 1st lactation Holstein cows producing 76 ± 8 lbs/cow/day at mid-lactation were used in the study. Milk yield, dry matter intake (DMI), and rectal temperature and respiration rate were recorded at least twice a day. During the first week, the cows were not exposed to experimental heat stress or conductive cooling. For the remaining six weeks, the cows were heat stressed for eight hours per day, and four cows were cooled with conductive cooling (experimental cows) and four were not cooled (control cows). At night, the cows were put in individual pens in a well-ventilated room. The conductive cooling system was tested with both 40°F and 50°F cooling water for a total of five weeks. For the last week of the experiment, half of the waterbeds were placed directly on the concrete in the stalls and not cooled. The cows that were conductively cooled with 40°F water had rectal temperatures that were 1.8°F lower and respiration rates that 18 bpm lower than the cows that were not cooled. The cooled cows also maintained 5% higher milk yield and 14% higher dry matter intake. Thus, conductive cooling may be a useful tool to alleviate heat stress in dairy cows. However, placing waterbeds on concrete stalls without additional cooling did not have a measurable effect in alleviating the heat stress of the cows.
Production Responses Study Detailed Summary

Materials and Methods

See Appendix A for description of materials and methods

Results and Discussion

Impact of Conductive Cooling

Rectal temperature decreased by 1.3°F and 1.8°F for cows cooled with 50°F and 40°F circulating water, respectively, compared to control (Figure 1). The rectal temperature of 102.4 ± 0.2°F for the cows conductively cooled with 40°F circulating water was in the normal physiological range of 100.4 to 102.7°F according to the Merck Veterinary Manual (2014). Similarly, other researchers reported rectal temperature of 102.2°F for cows in a thermoneutral environment (Spiers et al., 2004). Thus, conductive cooling reduced the rectal temperature of the cows to levels comparable to rectal temperature under thermoneutral conditions. Because elevated rectal temperature is a reliable indicator of heat stress (Gebremedhin et al., 2008; Suthar et al., 2012), the fact that the conductive cooling reduced the rectal temperature of cows challenged with heat stress demonstrates that the conductive cooling was effective at mitigating some of the heat stress.

Figure 1. Rectal temperatures of conductively cooled versus control cows. Modified from Perano et al., 2015 with permission from Elsevier.

Respiration rate also decreased for the conductively cooled cows compared to the control cows (Figure 2). The respiration rate was 82 ± 2 bpm for control cows (no cooling), 68 ± 2 bpm when cows were cooled with 50°F circulating water, and 64 ± 2 bpm when cows were cooled with 40°F water. Notably, the respiration rate for the 40°F-cooled cows differs little from the respiration rate of 60 bpm reported by Spiers et al. (2004) for cows in a thermoneutral environment. This indicates that the conductively cooled cows effectively experienced minimal heat stress. The high respiration rate observed in the control cows is a clear indicator of heat stress as cows respired more to dissipate excess heat. A high respiration rate can also cause respiratory alkalosis from increased CO₂ loss, which may lead to unhealthy fluctuations in blood pH (Cook et al., 2007).
When cows were challenged with heat stress, milk yield declined for all cows including cows that were conductively cooled (Figure 3). Baseline milk production, which was the cows’ milk production from the first week of the experiment before heat stress was imposed, was 75 ± 9.7 lbs/cow/day at THI = 73. Declines from baseline production were 11.2% for cows in the control treatment, 5.5% when the cows were cooled with 50°F circulating water, and 4.7% when the cows were cooled with 40°F water ($P = 0.04$, compared to control).

Dry matter intake increased over the baseline consumption of 40.7 ± 4.0 lbs/cow/day for all the treatments (Figure 4). Differences in baseline dry matter intake were not significant between the two groups prior to the start of the heat stress. After heat stress was imposed, dry matter intake increased over baseline consumption by 3.3% for the control cows, 11.2% when the cows were cooled with 50°F circulating water ($P = 0.09$, compared to control), and 17.2% when the cows were cooled with 40°F water ($P < 0.001$, compared to control). It is not clear why the cows started eating more even after being challenged with heat stress while yielding less milk apparently because of the effects of the heat stress. However, the cows may have taken more than three days...
to adjust to being housed in the facility, so perhaps the baseline dry matter intake data was artificially low if cows were experiencing stress from being moved to a new facility.

![Figure 4](image)

*Figure 4. Dry matter intake of conductively cooled versus control cows. Modified from Perano et al., 2015 with permission from Elsevier.*

Although the variables considered suggest conductive cooling was effective in mitigating heat stress, milk yield decline was not statistically significant for the 50°F cooling water temperature (Figure 4). This was probably due to the small sample size and individual cow variations. First lactation cows, such as the cows in this study, may also be less sensitive to heat stress than more multiparous cows (Bernabucci et al., 2014). Moreover, the cows were kept in well-ventilated pens at night, and during many of the nights the cows were exposed to cooler conditions than what would typically follow a moderate or severe heat stress day. Igono et al. (1987) reported that regaining normal body temperature overnight is a critical factor in maintaining milk production during heat stress. Thus, the cooler nighttime conditions in our study may have obscured the mitigating effect of the conductive cooling because the control cows were recovering overnight.

**Alternative Conductive Cooling Systems**

When the waterbeds were placed directly on a concrete surface, none of the variables measured showed any difference against the control treatment. The manufacturer recommends installing waterbeds on top of a concrete surface. The concrete surface temperature will be lower than the skin temperature of the cow, so heat will flow from the cow to the concrete surface when the cow is lying down on the waterbed. However, in this study, the cooling effect from the heat flow to the concrete surface was negligible because there was no measurable impact on the heat stress experienced by the cows.

**Conclusions**

Conductive cooling effectively mitigated heat stress in lactating dairy cows. When cows were conductively cooled with 40°F water then challenged with heat stress, conductively cooled cows fared better than control cows. Cooled cows had on average 1.8°F lower rectal temperature, 18 bpm lower respiration rate, 5% higher milk yield, and 14% higher dry matter intake compared to control cows even though all cows were exposed to the same environmental conditions. Rectal temperature was 0.5°F lower when cows were cooled with 40°F circulating water verses 50°F
circulating water, but other variables did not show a significant difference between cooling water temperatures. The cooling system tested in this study requires cooling the circulating water. Heat loss through waterbeds placed directly on a concrete surface showed no measurable effect in reducing the heat stress of the cows.

3. Heat flux and heat flow in a conductive cooling waterbed system

A comparison of advantages and disadvantages of a conductive cooling system design using waterbeds covered with thin bedding is given in Section 1 of this paper. In short, a conductive cooling system design that requires thick bedding (8 to 10 inches) between the heat exchanger and the cow reduces the estimated heat flux by 93%. This means that if (a) thick bedding is present between the heat exchanger and the cow and (b) the conductive cooling system uses 40°F water to chill the heat exchanger, the conductive cooling will remove approximately 2% of the cow’s body heat. This contrasts with up to 27% of the cow’s body heat being removed by a chilled waterbed conductive cooling system using 40°F water (Ortiz et al., 2015, Gebremedhin et al., 2016). Thus, a conductive cooling system design requiring thick bedding between the cow and the heat exchanger will be of little benefit to the cow.

A conference paper published by Perano et al. (2015b) further demonstrated that using thick bedding in a conductive cooling system greatly reduces the heat flux. In this study, a waterbed-based conductive cooling system was tested for heat flux with different thicknesses of bedding by simulating cows lying on the waterbeds with thermostatically-controlled heating pads and sandbags. This study demonstrated there is a rapid decline in heat flux as thicker bedding is used (Figure 5). This study found measurable heat flux to the sand even when the sand was not cooled (control treatment). But the benefit of conductive cooling, defined as the difference between cooled and control treatment, dramatically declined as bedding thickness increased.

![Figure 5. Reduction in heat flux as thicker is bedding is used. Modified from Perano et al. 2015b.](image)

The estimate that a conductive cooling system removed 27% of a lactating cow’s body heat was obtained by Gebremedhin et al. (2016). This study used computational fluid dynamics (CFD) to predict heat flux (amount of heat flow per unit area) for a waterbed-based conductive cooling system. Since heat flux is directly proportional to the temperature difference between the cow’s
skin and the waterbed surface, the estimated heat flux decreases linearly with increasing cooling water temperature (Figure 6).

The surface area of the Holstein cow in contact with the waterbed is assumed to be 10.2 ft$^2$ (Bastian et al. 2003), so the total heat flow from the cow to the conductive cooling system would be 408 Watts (W) for the 40°F cooling water and 290 W for 58°F cooling water. Thus, cooling water temperature is an important consideration. Colder chilling water is less energy efficient to obtain and may cause more problems with condensation, but colder water will also generate more heat transfer.

4. Challenges – bedding depth and condensation issues

Overview

The conductive cooling system using waterbeds was tested for rate of moisture accumulation in sand and sawdust bedding and for levels of RH of air (~60% and ~75%). It was also tested at four bedding thicknesses (¼, 1, 3, and 8 inches). For the 1-inch thick bedding, the moisture measurements were taken both at the top of the bedding and at the surface of the waterbed. The experiment consisted of the following: (1) two waterbeds cooled by circulating water at 40°F, and (2) another two waterbeds (control) where the water in the waterbeds was not cooled. Moisture content of the bedding was measured in duplicate at three locations on the surface of each waterbed for each of 20 treatments (sand and sawdust bedding measured at both ~60% RH and ~75% RH and at five bedding thicknesses/sampling depths). The moisture measurements were taken before and after 2 hours of cooling.

In all treatment combinations, the surface temperature of the cooled waterbeds was at least 13.5°F lower than the dewpoint temperature of the air. For the ¼-inch thick sawdust, condensation rates, calculated as the percent increase in dry basis of moisture content per hour (% d.b./hr), were 3.5% d.b./hr higher for the cooled waterbeds than that for the control waterbeds at ~75% RH and 3.1% d.b./hr higher at ~60% RH. Similarly, the condensation rates for the ¼-inch thick sand were 2.0% d.b./hr higher for the cooled waterbeds than for the control waterbeds at ~75% RH and 1.3% d.b./hr higher at ~60% RH.
higher for cooled waterbeds at ~60% RH. The condensation rate for the 1-inch thick sand bedding measured at the top surface of the waterbed (the bottom ¼ inch of the bedding) was statistically significant but negligible (0.1% d.b./hr). The 1-inch thick bedding did not have any difference in condensation rate at the top of the bedding for cooled vs control waterbeds, nor did the surface of the 3-inch or 8-inch bedding have any difference in condensation rate between the cooled waterbeds and the control waterbeds.

**Condensation Rate Study Summary**

**Materials and Methods**

See Appendix B for a description of materials and methods.

**Results and Discussion**

Differences in condensation rate between the cooled and the control waterbeds for the ¼-inch thick sand and the 1-inch thick sand sampled at the surface of the waterbed are shown in Figure 7. All of the treatments shown in Figure 7 were statistically significantly higher for condensation rate for cooled waterbeds compared to their respective controls (P < 0.005 in all cases). Note that condensation rate was calculated as change in moisture content over time. Therefore, a negative value indicates that the final moisture content was lower than the initial moisture content. For example, in Figure 7, it shows that the condensation rate for the control for the ¼-inch thick bedding at ~60% RH is negative because the bedding dried out over the 2 hours the data was collected, resulting in a slightly negative condensation rate.

![Figure 7](image-url)  

**Figure 7.** Condensation rate of sand bedding for ¼ inch and 1 inch of thickness measured at the waterbed surface. * = statistically significant (p < 0.005 in all cases). Initial moisture content for ¼-inch sand was 0.9 ± 0.3% d.b. and 0.7 ± 0.3% d.b. for higher and lower RH, respectively. For 1-inch sand, initial moisture content was 0.5 ± 0.4% d.b. for higher RH, and 1.3 ± 0.4% d.b. for lower RH. Modified from Perano et al. 2018 with permission from ASABE.
Condensation rate for sawdust bedding showed the same patterns as that for sand bedding but had more variability (Figure 8). Condensation rate for ¼-inch sawdust and ~75% RH was 4.2% d.b./hr for cooled waterbeds and 0.7% d.b./hr for control waterbeds (p < 0.0001). For ¼-inch sawdust at ~60% RH, the condensation rate was 1.0% d.b./hr for cooled waterbeds and −2.1% d.b./hr for control waterbeds (p < 0.0001). For the 1-inch sawdust at the waterbed surface, condensation rates were numerically higher for cooled versus control at both humidity levels, but the differences were not statistically significant.

![Figure 8. Condensation rate of sawdust bedding for ¼-inch thickness and 1-inch thickness at the waterbed surface. P-values for comparison to the respective control were p < .0001 for ¼-inch sawdust at either humidity level. Initial moisture content for ¼-inch sawdust was 18.4 ± 3.3% d.b. for ↑RH and 21.6 ± 3.3% d.b. for ↓RH. For 1-inch sawdust, initial moisture content was 43.2 ± 2.7% d.b. for ↑RH and 11.7 ± 3.3% d.b. for ↓RH. Modified from Perano et al. 2018 with permission from ASABE.](image)

The rate of condensation at the waterbed surface underneath 1 inch of sand or sawdust bedding was much lower than that for ¼-inch thick bedding even though the temperature of the waterbed surface was colder for the thicker bedding. This lower rate of condensation underneath thicker bedding is likely due to a layer of cool air forming near the surface of the waterbed and the bedding preventing significant air exchange with the ambient to bring in more moisture.

To better quantify the condensation rate for the sand bedding, the sand was left undisturbed for longer periods (6 hours for the ¼-inch and 24 hours for the 1-inch thick bedding), and the moisture content was measured at 0 hour, 2 to 3 hours, and again at the end of the experimental period. The results of the longer-term experiment agreed well with the results of the 2-hour duration experiment. Moisture content for the ¼-inch thick sand bedding was 15.8% d.b. after 6 hours, so the condensation rate was 2.4% d.b./hr (Figure 9). For the 1-inch thick sand bedding, the moisture content reached 4.6% d.b. at the waterbed surface and 3.1% d.b. at the top surface of the bedding after 24 hours. Thus, the average condensation rate for the 1-inch thick sand bedding measured at the waterbed surface was 0.11% d.b./hr, hence the condensation rate for ¼-inch sand was 21 times higher than the condensation rate for 1-inch sand at the waterbed surface.
Thicker bedding resulted in lower waterbed surface temperatures and higher bedding top-surface temperatures due to more insulation between the waterbed and the bedding surface. In all cases, the waterbed surface temperature was at least 13.5°F lower than the dew point temperature of the air. The thermal gradient between the cooled, circulating water and the waterbed surface was highest for 1-inch thick sand (2.3°F) and lowest for 8-inch thick sand bedding (0.7°F). This thermal gradient is directly proportional to the 1-D heat flux across the waterbed, so the lower temperature gradient demonstrates that there is less heat flux occurring when thicker bedding is used.

For the 1-inch thick sand bedding, the dew point temperature of the air (57.7 ± 1.3°F) is just below the temperature of the sand at the top surface, which is 59°F. The temperature of the sand at the top surface can be obtained from a linear regression applied to the temperatures measured by the three thermocouples (Figure 10). It is likely that the sand surface temperature being slightly higher than the dew point temperature of the air is the reason for the little condensation occurring at the top surface of the 1-inch sand bedding (Figure 10).
The 8-inch thick sand bedding had a higher calculated bedding-surface temperature (66°F) that was further above the dew point temperature of the air compared to the bedding surface temperature of the 1-inch sand (Figure 11). For sand bedding ≥ 1 inch, the temperature of the sand was below the dew point temperature of the air at most depths (Figures 10 and 11).

![Figure 11. Temperature profile for the 8-inch thick sand bedding. Dimensions are in inches. Ambient conditions were air temperature = 66.4 ± 0.4°F, RH = 79.8 ± 7.2, and dewpoint = 59.9 ± 2.5°F. Modified from Perano et al. 2018 with permission from ASABE.](image-url)

In this experiment, the waterbed surface temperature for all treatments was below the dewpoint temperature of the air. It is likely that in most conditions where a conductive cooling system would be used, the temperature of the cooling water will be below the dew point temperature of the air in the barn. However, for bedding thicknesses ≥ 1 inch, there was little condensation even at the surface of the waterbed. This may be because the thickness of the bedding sufficiently reduced the flow of air to the cold waterbed surface such that little or no moisture accumulated. Furthermore, the cooler air closer to the waterbed surface is denser than the air above, and thus there is no driving force for convection.

Therefore, when there is sufficient bedding thickness, the surface that is below the dew point temperature of the air may accumulate moisture in the adjoining bedding at a slow enough rate that the moisture would not be a concern. In fact, the small amount of condensation would be a fraction of the moisture that may be introduced by other means such as cows soiling their bedding. Potential bacterial growth due to the high moisture content of bedding in systems using recycled sand or recycled manure are typically managed for suppression of harmful bacteria by mixing in hydrated lime, sodium bisulfate, or other commercially available products (Hogan et al., 1999; Kristula et al., 2008; Calvo et al., 2010). Such products could be used in conductive cooling systems where moisture accumulation due to condensation becomes a concern. Also, if the conductive cooling system remains in operation continuously, the bedding will remain cool at all times, and this would help prevent rapid bacterial growth.

Another possibility is to use warmer water in conductive cooling systems, as this may alleviate some of the problems associated with condensation. Drier climates may not pose an issue for condensation. Conductive cooling will likely have the most appeal for use in hot and humid climates because cooling systems using evaporative cooling are less effective in humid environments because of reduced moisture gradient. Thus, in humid environments, conductive
cooling may be an ideal alternative alone or with other evaporative cooling systems, so management options for condensation in conductive cooling systems should still be considered.

When thicker bedding is used, it eliminates the problems with condensation but reduces heat flow from the cow to the water in the waterbed, especially for organic material. In this case, the idea of cooling the cow is defeated (as detailed in Section 3 on heat flux). The study on moisture accumulation demonstrates that 1 inch of bedding is sufficient to eliminate most condensation. However, in a production setting, the bedding will be moved around and a uniform depth cannot be maintained. Thus, to obtain an effective 1-inch thick bedding over the stall, the nominal depth would need to be greater than 1 inch.

The waterbed in our design deflects when a cow is lying down and conforms to the configuration of the cow’s body in contact. Waterbeds are designed to support most of a cow’s weight while the cow is lying down and to provide cushion against the concrete surface below the waterbed. The waterbeds used in this study were designed to be isovolumetric (i.e., filled with 14 gallons of water and sealed), but the waterbeds were modified to be isobarometric and were pressurized with 1.5-ft head. This was enough pressure to suspend most of the cow’s weight when a cow was lying down, allowing the circulating water in the waterbed to cool most of the area of the cow in contact with the waterbed. Consequently, the hindrance to heat flux from thick bedding is much more detrimental to heat flow than the decrease in actively cooled surface area for areas of the cow not suspended by the waterbed.

**Conclusions**

The following conclusions can be drawn from this study:

1. Condensation was not measurable for bedding thicknesses greater than 1 inch.
2. Adjusted condensation rate for the ¼-inch thick sand bedding was 20 times higher than that for the 1-inch thick sand bedding. Adjusted condensation rate is defined as the difference between condensation rate of the cooled waterbeds and that of the control waterbeds.
3. For the ¼-inch thick sand bedding at ~75% RH, condensation rate was 2.0% dry basis per hour (d.b./hr) and was statistically significantly higher (p = 0.002) than the condensation rate at ~60% RH, which was 1.2% d.b./hr. For the non-cooled waterbeds (control), the corresponding condensation rates were zero at ~75% RH and −0.1% at ~60% RH. Negative values for condensation rate mean that the bedding dried out over the course of the two hours.
4. Similarly, adjusted condensation rates for the ¼-inch thick sawdust bedding were 15 to 19 times higher than that for the 1-inch thick sawdust bedding. At RH of ~75% and ~60%, the rates for the ¼-inch thick bedding were 3.5% d.b./hr and 3.1% d.b./hr, respectively. Adjusted condensation rates for the 1-inch thick sawdust measured at the waterbed surface were 0.2 d.b./hr at both ~75% and ~60% RH.
5. It can be concluded that, as long as there is ≥1 inch of bedding thickness and the top surface of the bedding is kept at or above the dew point temperature of the air, there will be little condensation in the bedding. This will be the case even if the surface temperature of the waterbed is below the dew point temperature of the air because of less air flow from within the bedding to the surface of the waterbed.
6. Potential water condensation in the bedding should be a design consideration when conductive cooling systems are installed in dairy barns. Although 1-inch thick bedding can effectively minimize condensation, from a management standpoint, it would be impractical to maintain the bedding thickness uniformly in the stall because of cow movement.

5. System parameters and energy requirements

The recommended prospective system design is using a modified waterbed as a heat exchanger. However, there is not yet a commercialized conductive cooling waterbed, so Perano et al. (2015) engineered a system using DCC waterbeds they had modified and flowed 40°F water through the waterbeds. The bedding used was ½ inch of sawdust. The total heat absorption by this system was 919 W when the cow was lying down, which includes heat absorbed from the cow and heat absorbed by the ambient air around the edges of the lying cow. The total heat absorbed when the cow was standing up was 588 W due to heat absorbed from the ambient air across the whole cooled waterbed surface. Since the cows were lying down 62% of the time, the weighted average of the energy needed was 793 W (per cow being cooled, unpublished data).

To engineer a conductive cooling system, a centralized chiller would be needed. Cooled water would be distributed from a reservoir, pumped through each waterbed, and re-chilled in a closed loop system. Centralized coolers could be ground source coolers or liquid-to-liquid chillers. Ground source cooling would be expected to have a COP of about 3. (Coefficient of performance is defined as the energy moved divided by energy consumed.) A liquid to liquid chiller could have a COP of up to 6, and such a system could be used to help heat wash water. However, this process becomes efficient as the temperature difference between the water streams increases, and this would produce much more partially heated water than the dairy operation could likely use. If the system is assumed to be a ground source cooling system with a COP of 3, then it would require 264 W/cow to run the chiller for the conductive cooling.

Capital cost estimates for a central chiller were about $200 per cow, assuming the dairy has at least 500 cows to benefit from economy of scale (Kuntz, 2014). For further analysis of the potential economics of the system, it was assumed that the conductive cooling system was designed with waterbeds and ground source cooling. The cost was estimated to be $400 per cow ($200 for the waterbed and $200 for the cow’s contribution to the cooling system). It was further assumed that the heat absorption of the conductive cooling system was comparable to the data collected by Perano et al. 2015. The economic analysis presented below gives more details.

6. Economic comparison of cooling systems

Heat stress in lactating dairy cattle reduces milk production as well as cow comfort and health. Commercial systems for reducing heat stress in dairy cattle include fan only, fan and sprinkler systems, and fogger systems. Conductive cooling is a potential alternative system. Fan only or fan and sprinkler systems are more economical to install and operate than fogger or conductive cooling systems, but fan systems are not as effective at relieving heat stress in dairy cattle. Fan and sprinkler systems may lead to more moisture in the environment and increase the chances of mastitis or other diseases. Fogger systems such as Korral Kool incorporate the water in small droplets into the air and conductive cooling systems do not add additional moisture to the environment so may be more hygienic than fan and sprinkler systems. However, both conductive
cooling and fogger systems have higher installation and operating costs than fan and sprinkler or fan and mister systems. For this analysis, heat stress was assumed to be present for either 2 mo/year (cooler climate) or 6 mo/year (warmer climate) and absent at other times. Heat stress was assumed to be 10 hr/day of THI 80 – 85, with nighttime cooling to below THI 72 so that cows were able to re-gain normal body temperatures overnight (Igono et al., 1987).

A total annual cost-benefit economic analysis of milk production vs cooling costs of the four cooling systems (fan only, fan and sprinkler, Korral Kool/foggers, and conductive cooling) was conducted. Marginal milk profit (i.e., milk price minus feed costs) was assumed to be $0.15/lb (Ferreira et al., 2016). Other costs of heat stress besides loss of milk production, including decreased fertility or decreased immunity, were not included in the analysis but also have an impact on heat-stressed dairy cows (West, 2003). The analysis estimated that in climates with 2 mo/year of heat stress, fan only and fan and sprinkler systems would have a positive economic benefit of $10.37/cow/year for fan only and $18.25/cow/year for fan and sprinklers. The fogger and conductive cooling systems were projected to cost more in capital, maintenance, and operating expenses than they generated in increased milk production (losses of $29.78 and $35.68/cow/year, respectively). However, in warmer climates with 6 months per year of heat stress, all four systems give a positive economic benefit compared to no cooling at all, but fans and sprinklers are still the most economically favorable. The estimated net economic benefit in $/cow/year for the four systems in warmer climates is $45.41 for fans, $76.32 for fans and sprinklers, $7.34 for a Korral Kool fogger/fan system, and $32.92 for conductive cooling.

**Detailed Summary of Economic Analysis**

**Materials and Methods**

See Appendix C for a description of materials and methods.

**Table 2. Inputs to economic model**

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal milk profit</td>
<td>$0.15/lb (Ferreira et al., 2017)</td>
</tr>
<tr>
<td>Relationship between milk loss and increase in core body temperature (CBT) due to heat stress</td>
<td>3.7 lb/day/°F of CBT (Spiers et al, 2004; Perano et al, 2015)</td>
</tr>
<tr>
<td>Water cost</td>
<td>$200/acre-foot</td>
</tr>
<tr>
<td>Energy cost</td>
<td>$0.15/kWh</td>
</tr>
</tbody>
</table>

**Results and Discussion**

**Cost of each system**

The initial capital cost for the fan only and fan and sprinkler systems were $50/cow and $75/cow, respectively, and energy was 93 W/cow (Table 2). This gave a daily cost for energy of $0.11/day (assuming an energy cost of $0.15/kWh) for both systems and an additional water cost of $0.01/day for fan and sprinkler systems. Capital depreciation (deprec.) for 6 mo/year use for 10 years was $0.04 and $0.06 for fan only and fan and sprinkler systems, respectively, but increased to $0.11 and $0.17 for 2 mo/year use since the annual costs were distributed over fewer days per year. It
was assumed that the capital and maintenance costs would be equivalent to the cooling system lasting for 10 years then being replaced by a new cooling system. Consequently, maintenance was not considered independently of capital cost. For 2 mo/year of heat stress, even the cheaper fan and fan and sprinkler systems had capital and maintenance costs equal to or exceeding operational costs for energy and water. Foggers and conductive cooling systems required much higher initial capital costs ($353/cow for foggers and $450/cow for conductive cooling) and also had higher daily operational costs since both foggers and conductive cooling systems used more energy than the fan only and fan and sprinkler systems (Table 3).

Table 3. Capital and operation costs for each cooling system

<table>
<thead>
<tr>
<th>System</th>
<th>Initial capital cost ($)</th>
<th>Energy (W)</th>
<th>Energy ($/day/cow)¹</th>
<th>Water (L/min)</th>
<th>Water ($/day/cow)</th>
<th>Deprec. for 6 mo/year use ($/day)</th>
<th>Deprec. for 2 mo/year use ($/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fans only</td>
<td>50</td>
<td>93</td>
<td>0.11</td>
<td>none</td>
<td>none</td>
<td>0.04</td>
<td>0.11</td>
</tr>
<tr>
<td>Fans and Sprinklers</td>
<td>75</td>
<td>93</td>
<td>0.11</td>
<td>0.05</td>
<td>0.01</td>
<td>0.06</td>
<td>0.17</td>
</tr>
<tr>
<td>Korral Kool + fans</td>
<td>353</td>
<td>275</td>
<td>0.34</td>
<td>0.28</td>
<td>0.05</td>
<td>0.26</td>
<td>0.80</td>
</tr>
<tr>
<td>Conductive cooling + fans</td>
<td>450</td>
<td>357</td>
<td>0.43</td>
<td>none</td>
<td>none</td>
<td>0.38</td>
<td>1.15</td>
</tr>
</tbody>
</table>

¹ Assuming energy costs of $0.15/kWh

A graphic of the daily operating costs for all four systems when the cooling system is used for 6 mo/year is shown in Figure 12. Foggers such as Korral Kool and conductive cooling have higher operating costs as well as higher capital costs compared to fan only and fans and sprinklers, but in all cases the capital depreciation costs are less than 50% of the total costs. Although water consumption was a minor part of the cost even for the fan and sprinkler and fogger systems that consumed water, the study assumed that water was available at typical agricultural rates.

Figure 12. Cost components of cooling systems in $/cow/day for 6 mo/year of use. Fan = fans only, FS = fans + sprinklers, KK = Korral Kool (including fans), and CC = conductive cooling.
Figure 13 shows the cost breakdown if the cooling systems are only in use for 2 mo/year, and thus the capital costs are distributed over 60 days instead of 180 days. Note that the assumption was made that the system would last for 10 years whether it was utilized for two months or for six months per year. For cooler climates, the capital costs are approximately equal to operational costs for fan only and fan and sprinkler systems but approximately three times higher than operational costs for foggers and conductive cooling systems.

![Figure 13. Cost components of cooling systems in $/cow/day for 2 mo/year of use. Fan = fans only, FS = fans + sprinklers, KK = Korral Kool (including fans), and CC = conductive cooling.](image)

Expected net economic benefit

For warmer climates with 180 days of heat stress per year, all four cooling systems gave a positive return on investment (Table 4). The most economically advantageous system was the fan and sprinkler system since it gave good results for cow cooling (60% as much cow cooling as conductive cooling) but without the high capital and operating costs of the fogger or conductive cooling systems. The higher cost fogger and conductive cooling systems did give better results for cow cooling than fans and sprinklers but cost three to four times as much per cow per day. Thus, under more severe heat stress than what was considered here, the more expensive systems could be a more favorable investment than the fans and sprinkler system if more cow cooling were needed.
Table 4. Cost and benefit per cow per day for different cooling systems for 6 mo/year of heat stress.

<table>
<thead>
<tr>
<th>System</th>
<th>Decrease CBT (°F)</th>
<th>Increase Milk (lb/cow/day)</th>
<th>Marginal Milk Profit ($/cow/day)</th>
<th>Cost ($/cow/day)</th>
<th>Economic benefit ($/cow/day)</th>
<th>Economic benefit ($/cow/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fans only</td>
<td>0.7</td>
<td>2.6</td>
<td>0.40</td>
<td>0.15</td>
<td>0.25</td>
<td>45.41</td>
</tr>
<tr>
<td>Fans and Sprinklers</td>
<td>1.1</td>
<td>4.0</td>
<td>0.59</td>
<td>0.18</td>
<td>0.42</td>
<td>76.32</td>
</tr>
<tr>
<td>Korral Kool + fans</td>
<td>1.3</td>
<td>4.6</td>
<td>0.69</td>
<td>0.65</td>
<td>0.04</td>
<td>7.34</td>
</tr>
<tr>
<td>Conductive cooling + fans</td>
<td>1.8</td>
<td>6.6</td>
<td>0.99</td>
<td>0.81</td>
<td>0.18</td>
<td>32.92</td>
</tr>
</tbody>
</table>

Figure 14 graphically shows the net annual return per cow for each of the four systems.

![Figure 14. Yearly net returns per cow for cooling systems with 6 mo/year use. Fan = fans only, FS = fans + sprinklers, KK = Korral Kool (including fans), and CC = conductive cooling.](image)

Climates with 60 days per year of heat stress have lower daily and yearly returns for cooling systems since the annual costs for capital are distributed over fewer days per year. Consequently, higher capital cost systems (foggers and conductive cooling) are not economical in climates with less heat stress (Table 5). All cooling systems provide less pay back per year when less heat stress is present, but fan only and fan and sprinkler systems still generated a positive net income, and fan and sprinkler systems were still the most economically favorable. However, fan systems were closer to fan and sprinkler systems in their return on investment because of the higher capital costs for fan and sprinkler systems distributed over fewer days.
Table 5. Cost and benefit per cow for different cooling systems for 2 mo/year of heat stress.

<table>
<thead>
<tr>
<th>System</th>
<th>Decrease CBT (°F)</th>
<th>Increase Milk (lb/cow/day)</th>
<th>Marginal Milk Profit ($/cow/day)</th>
<th>Cost ($/cow/day)</th>
<th>Economic benefit ($/cow/day)</th>
<th>Economic benefit ($/cow/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fans only</td>
<td>0.7</td>
<td>2.6</td>
<td>0.40</td>
<td>0.22</td>
<td>0.17</td>
<td>10.37</td>
</tr>
<tr>
<td>Fans and Sprinklers</td>
<td>1.1</td>
<td>4.0</td>
<td>0.59</td>
<td>0.29</td>
<td>0.30</td>
<td>18.25</td>
</tr>
<tr>
<td>Korral Kool + fans</td>
<td>1.3</td>
<td>4.6</td>
<td>0.69</td>
<td>1.19</td>
<td>−0.50</td>
<td>−29.78</td>
</tr>
<tr>
<td>Conductive cooling + fans</td>
<td>1.8</td>
<td>6.6</td>
<td>0.99</td>
<td>1.58</td>
<td>−0.59</td>
<td>−35.68</td>
</tr>
</tbody>
</table>

Water consumption was a minor component of the expenses and was less than 10% of the daily operating costs even for the fogger system that consumes significant amounts of water. For this study, it was assumed that as much water as was needed was available at typical agricultural rates for drier climates ($200 per acre-ft). If water is abundant and readily available, this water cost could be less than what was modeled here. However, if water is scarcer, for example under drought conditions or in a dry climate, water for cooling cows could be more expensive or unavailable. Furthermore, if water were a limiting resource, using more water on cow cooling would reduce the overall carrying capacity of the dairy and make a water-conserving system such as conductive cooling more favorable.

Unless there are high levels of heat stress, higher capital cost cooling systems are not economical when compared to lower capital cost cooling systems that are available. This result agrees with St-Pierre et al. (2003), which reported that “high” heat stress abatement (a fan and sprinkler system) was the most economically favorable in the majority of US states, but a handful of the hottest states would benefit from “intense” cooling (a Korral Kool fogger system in their study). Thus, the St-Pierre study results concurred that more expensive systems such as foggers (and also the conductive cooling system considered in this study) are only justified in climates with several months per year of heat stress, such as Florida or Texas. Ferreira et al. (2016) considered the economic effects of cooling dry cows with a fan and sprinkler system and concluded that cooling dry cows was very profitable in most cases.

Although fogger systems require more investment to build and operate than fan and sprinkler systems, there may be other motivations for using a fogger system. For example, fogger systems disperse fine water droplets into the air so cool the air instead of wetting the cow (Ortiz et al., 2015). Thus, fogger systems may be more hygienic than fan and sprinkler systems. Conductive cooling systems had the highest cost but also the most benefit to cow cooling. Thus, conductive cooling would become more favorable under more severe heat stress. Conductive cooling would be used in conjunction with other systems and has the added benefit of cooling cows while they are lying down which can help encourage cows to lie down more. Unpublished data from the experiment described in Perano et al. (2015a) indicated that conductively cooled cows spent approximately one extra hour per day lying down. This study assumed conductive cooling systems would be used in conjunction with a fan system, but a fan and sprinkler system could also be used in conjunction with a conductive cooling system in hotter climates with high-producing cows, where more heat stress relief is needed.
Other costs of heat stress besides loss of milk production include decreased fertility and compromised health, but these costs were not quantified in this analysis. Thus, this economic analysis likely underestimates the economic benefits of cooling. A sensitivity analysis should also be performed to estimate the relative effects of different assumptions that were made in the analysis including different milk prices and energy prices.

Conclusions

The following conclusions can be drawn from this analysis of cost and benefit of cooling systems for sustaining milk production during heat stress:

- Foggers (such as Korral Kool) or conductive cooling with fans have a much higher cost to own and operate than fans only or fans and sprinklers.
- In cooler climates with 2 mo/year of heat stress (THI 80 - 85 for 10 hr/day with nighttime cooling to below THI 72), neither foggers nor conductive cooling systems are a good investment.
- In warmer climates with 6 mo/year of heat stress (defined the same way as for 2 mo/year climates, but with three times more days per year of heat stress), any cooling system (fans, fans + sprinklers, foggers, or conductive cooling) is more economical than no cooling but fans + sprinklers were still the most economically beneficial.
- Conductive cooling was the most effective cooling system considered, according to literature values for reduction of CBT. Thus, the more heat stress is present, the more benefit from conductive cooling. Conductive cooling can also be used in conjunction with other cooling systems, in cases of severe heat stress. The present study only considered conductive cooling in conjunction with fans and not when used with evaporative cooling.

Summary/Conclusions

Conductive cooling is a novel cow cooling approach that may offer farmers a way to cool cows while conserving water and encouraging cows to lie down more. A farmer-ready conductive cooling system has not been fully designed nor is one commercially available at this time. More work is needed to verify system cost and benefit estimates presented herein and to evaluate conductive cooling system designs and cow responses.

This white paper presents recent research on a chilled waterbed-based conductive cooling system and discusses how a chilled waterbed conductive cooling system compares to other designs, expected production responses, estimated heat flux and heat flow, when condensation may occur, the energy requirements to run a conductive cooling system, and the potential economic benefit of conductive cooling. Each of these aspects is summarized below.

1. Designing a conductive cooling system to use waterbeds covered with only a thin layer of bedding allows the maximum heat transfer from the cow and can transfer up to 27% of the cow’s body heat. Conductive cooling system designs requiring thick bedding (8 to 10 inches) between the heat exchanger and the cow cause too much insulation and can only transfer about 2% of the cow’s body heat once steady state conditions are reached. Consequently, this paper focused on waterbed-based conductive cooling systems.
2. A 2015 study investigating the production responses of heat-stressed lactating dairy cows to conductive cooling with chilled waterbeds found that cows that were conductively cooled with 40°F water had rectal temperatures that were 1.8°F lower and respiration rates 18 bpm lower, compared to the cows that were not cooled. The cooled cows also maintained 5% higher milk yield and had 14% higher dry matter intake.

3. The heat flux is directly proportional to the temperature difference between the cow’s skin and the cooling water. For an internally-chilled waterbed conductive cooling system, the total surface area of the Holstein cow in contact with the waterbed is assumed to be 10.2 ft². The heat flux predicted by computational fluid dynamics is 40.0 W/ft² for 40°F cooling water and 28.4 W/ft² for 58°F cooling water. Consequently, the heat flow ranges from 408 W (40°F cooling water) to 290 W (58°F cooling water).

4. Condensation occurs relatively rapidly in thin bedding (¼ inch) if the cooling water is below the dewpoint temperature of the air. However, one inch of bedding coverage (either sand or sawdust) traps cool air against the surface of the waterbed and reduces condensation by 95% or more without hindering effective heat flow.

5. The average heat energy absorbed by a waterbed-based conductive cooling system chilled with 40°F water is 793 W per cow. If a refrigeration system with a COP = 3 is used, then 264 W of cooling would be needed for each cow. Cost estimates for a centralized system would be about $200 per cow.

6. An economic analysis on the marginal cost and benefit of sustained milk production found that in cooler climates (2 mo/year of heat stress), neither foggers nor conductive cooling systems are a good investment. In warmer climates (assuming 6 mo/year of heat stress), conductive cooling and foggers would be expected to have a positive return on investment but would be less economically favorable than a traditional fan and sprinkler system.
Appendix A – Summary of Materials and Methods for Section 2: Production responses to conductive cooling

The experiment was conducted in the Large Animal Research and Teaching Unit (LARTU) at Cornell University using eight bred, mid 1st lactation Holstein cows that produced 76 ± 8 lbs/day of milk (mean ± SD). Four cows each were housed in two identical climate-controlled rooms with tie stalls. In each room, two experimental (conductively cooled) cows were housed on one side of the room and two control (not cooled) cows were housed on the other side of the room. The conductive cooling system used DCC waterbeds (Dual Chamber Cow Waterbeds, Advanced Comfort Technologies, Reedsburg, WI), with some modifications as described in the Cooling System Design section.

The cows were milked twice daily at 6 AM and 6 PM, and the milk weights were recorded at each milking. Prior to the morning milking, the cows were moved into the climate-controlled rooms at 5:30 AM. Experimental heat stress was imposed from 9 AM to 5 PM, and all the cows remained in the stalls with waterbeds during the daytime. At 7 PM after evening milking, the cows were placed individually in night pens so that they could exercise. All the night pens were in a large and well-ventilated room.

All the cows were fed a wet (moisture content ~58% wet basis) total mixed ration (TMR) formulated for primiparous, mid-lactation Holsteins. Fresh feed was mixed daily and made available to the cows at 12 PM. The cows had ad libitum access to water and to the TMR at all times as well as to timothy grass hay through the night. Daily feed refusals from both daytime and nighttime feed bins were weighed at 9 AM for each individual cow. Milk yield and feed intake were measured using certified scales.

Cooling System Design

The conductive cooling system circulated chilled water through the modified DCC waterbeds. All eight stalls were installed with waterbeds, which were 6 ft. long and 3.8 ft. wide. The non-cooled waterbeds were filled with 14 gallons of water as per the manufacturer’s recommendations. The four cooled waterbeds were modified for water circulation by installing bulkhead fittings underneath the waterbed on diagonally opposite corners and inserting spacers in the restricted flow channels. The waterbed outlets were pressurized with 1.75 ft. of head to maintain a pressure and volume comparable to that of a non-cooled waterbed with a cow lying on it. Approximately ½ inch of sawdust bedding was sprinkled on top of each waterbed and replaced several times a day whenever the bedding became soiled. All waterbeds (i.e., cooled and non-cooled) were placed on a sheet of ¾-inch thick plywood on top of insulation (R = 1.76 K·m²/W) and individually secured in the concrete stalls. During the last week of the study, the insulation beneath the four non-cooled waterbeds was removed to determine if there was measurable cooling from heat loss through the concrete floor when cows were lying down on the waterbeds.

Water was pumped through each cooled waterbed at the rate of 2.7 gal/min and measured with a turbine flow rate sensor. Thermocouples inserted into the pump inlet filter and water outlet flow stream were used to record data on the water temperature. The two cooled waterbeds in each room shared a 42-gal capacity reservoir, where the water was chilled to maintain the desired water temperature (Figure A1). The temperature and humidity of each of the two climate-controlled rooms and the night pen were recorded with HOBO® Pro v2 data loggers.
Experimental Design

During the 1st week, baseline physiological and production data was collected with the cows in the facility but with no conductive cooling and no experimental heat stress applied to any of the cows. Next, the conductive cooling system was tested at two different daytime thermal environments, a lower average temperature-humidity index (THI) of 79.0 ± 1.0 (Thermal Environment 1) and a higher average THI of 80.7 ± 0.9 (Thermal Environment 2). Although the thermal environments were statistically significantly different, the cows’ responses were not significantly different so the data from both of the thermal environments was combined for statistical analysis. The conductive cooling system was also tested with cooling water at 40°F and 50°F. For the 2nd through 5th weeks of the experiment, the four combinations of thermal environment and cooling temperature were tested for one week each. The control and experimental cows were then switched and the treatment with Thermal Environment 1 (THI of 79.0 ± 1.0) and 40°F cooling water was repeated.

The THI was calculated from the equation used by Dikmen and Hansen (2009), and is expressed as

\[
\text{THI} = T_{DB} - [(0.55 - 0.0055 \times \%RH) \times (T_{DB} - 58.8)]
\]

where, \(T_{DB}\) is dry bulb temperature in °F and \(%RH\) is relative humidity in percent

For the final treatment during the 7th week, the waterbeds for two of the experimental and two of the control cows were placed directly in the concrete stall with no additional cooling. Each treatment lasted seven days, but the first three days of data was discarded to give the cows a chance to adjust to the new conditions.

Rectal temperature and respiration rate were recorded at 7:30 AM before heat stress was imposed on the cows and again at 5 PM, which was after about 8 hours of heat-stress exposure. In addition, respiration rates were measured at 10:00 AM, 12:30 PM, and 2:45 PM which gives a total of five measurements per day. Rectal temperatures were taken with a digital livestock thermometer with precision and accuracy = 0.1°F. Respiration rates in breaths per minute (bpm) were determined by visual inspection of flank movement for 30 sec. Data was processed with mixed linear models in the software package JMP.
Appendix B – Summary of Materials and Methods for Section 4; Bedding depth and condensation issues

The experiment described herein was conducted at Cornell University’s Large Animal Research and Teaching Unit (LARTU). Four waterbeds (Dual Chamber Cow waterbeds from Advanced Comfort Technologies) were set up in a climate-controlled room. The two control waterbeds were not cooled but the two experimental waterbeds were cooled by internally circulating 40°F water. The set-up of the conductive cooling system was similar to a previous experiment (Perano et al., 2015). Moisture content of the sand and sawdust bedding was measured before and after a 2-hour cooling period. Measurements were taken for each bedding thickness. For the ¼-inch thick bedding, the sample was taken of the entire depth. For the 1-inch thick bedding, both the top and bottom ¼ inch of the bedding was sampled. For the 3-inch and 8-inch thickness, only the top ¼ inch was sampled. The ten combinations of bedding type and bedding thickness/sampling depth were repeated for two levels of RH of the air (which will be referred to as RH). These two levels were ~60% RH and ~75% RH.

The waterbeds and cooling system used are described in more detail in Section 1. Based on the manufacturer’s recommendation, the two control waterbeds were filled with 14 gal of water, and the same volume was maintained for the duration of the experiment. The two experimental waterbeds were modified to allow water circulation. Thermocouples were glued at three locations on the surface of each waterbed. For 1, 3, and 8 inches of bedding, thermocouples were also embedded in the bedding at the midpoint and ¼ inch below the surface to measure the temperature profile. The RH of the air was increased by using misting fans (Lasko Misko Outdoor Misting Fan 7050) that generated mist and air movement. Fans were installed on a 2-m high scaffolding and pointed to the back of the room. Two misting fans were used for the lower RH (~60%) conditions and four were used for higher RH (~75%). The scaffolding was positioned in front of the waterbeds so that mist from the fans was directed away from the waterbeds.

The conductive cooling system was tested for condensation rate for 20 treatments. These treatments were combinations of two bedding types (sand and sawdust), two relative humidities (~60% and ~75%), and five bedding thicknesses/sampling depths (¼-inch thick bedding, 1-inch bedding sampled at the waterbed surface, and 1, 3, and 8-inch thick bedding sampled at the top of the bedding). Moisture content of the bedding was measured after equilibrium was reached and again 2 hours later. Equilibrium was defined as when the system had been operating undisturbed for at least 1 hour but up to 8 hours, and the surface temperature of waterbeds was stable. The surface of the bedding was exposed to ambient air. Condensation rate was calculated in percent increase in dry basis of moisture content per hour (% d.b./hr). Moisture content for sand bedding at ~75% RH was also measured over a longer period of time (6 hours for ¼-inch thickness and 24 hours for 1-inch thickness).

Duplicate moisture samples were taken from three locations on each of the four waterbeds (two experimental and two control waterbeds). Samples were weighed, dehydrated, and then re-weighed to determine dry basis moisture content. Moisture content for each sample was calculated as follows:

\[ \text{Moisture content} = \frac{\text{Moist sample weight} - \text{Dry sample weight}}{\text{Dry sample weight}} \]
Condensation rate for each sample was calculated as follows:

\[
Condensation\ rate\ (\%\ d.b.h^{-1}) = 100 \times \frac{Moisture\ content\ final - Moisture\ content\ initial}{2\ h}
\]

For the ¼-inch thick bedding, samples were taken by sweeping a 2-inch × 2-inch area and collecting the pile into a weighing dish. Samples for the thicker bedding were collected by scraping off the top ¼ inch from a 2-inch × 2-inch area. Additionally, samples were collected from the surface of the waterbed for the 1-inch thick treatments by removing the top 1.75 inch and scraping the bottom 0.25 inch from a 2-inch × 2-inch area.
Appendix C – Summary of Materials and Methods for Section 6: Economic comparison of cooling systems

Amount of heat stress
The economic effects of relieving heat stress were modeled for two different climates. For a mild climate, THI of 80 – 85 was assumed to be present for 10 hr/day for two months of the year. For a hotter climate, six months of the year were assumed to have heat stress conditions for 10 hr/day. For both simulated climates, it was assumed that nighttime temperatures dropped below THI 72 to give cows relief at night (Igono et al., 1987). For the purposes of the analysis, it was assumed that the heat stress was either present or absent.

Initial capital and depreciation
The equipment was assumed to last for 10 years regardless of whether it was used for 2 months or 6 months per year. It was also assumed that the money was borrowed at an interest rate of 6% to find the annualized cost of the investment. The annual cost of the investment was then divided by the number of heat-stress days per year to find the average daily capital cost of the cooling system. It was also assumed there was no salvage value and no disposal cost at the end of the 10 years. For the conductive cooling system, it was assumed that the farm had at least 500 to 1000 cows so that a centralized cooling system could benefit from economy of scale.

Estimated capital costs for fan only, fan and sprinkler, and fogger systems came from St-Pierre et al. (2003) and were $50 per cow for a fan system, $75 per cow for a fan and sprinkler system, and $353 per cow for a fogger system. Cost estimate for conductive cooling systems per cow was $200 for the waterbed (Advanced Comfort Technologies, 2013), $200 for each cow’s share in a centralized refrigeration system for the conductive cooling water (Kuntz, 2014), and $50 for fans. (It was assumed that if a conductive cooling system were installed, fans would still be used in addition to conductive cooling.)

Energy and water use and cost
It was assumed that the cooling systems were operated at maximum capacity for 10 hr/day and turned off for the other 14 hr/day. Energy and water consumption for fan only and fan and sprinkler systems were derived from St-Pierre et al. (2003). For fogger systems, specifications on Korral Kool’s website were used (Korral Kool, 2016). Water was priced at agriculture rates $200 per acre-ft. The conductive cooling system was modeled as a closed-loop system using water as a working fluid and thus not consuming water, so water costs were not included for conductive cooling systems. Data for energy required by the conductive cooling system described in Perano et al. (2015) was used to estimate how much energy would be needed by a conductive cooling system. The COP of the cooling water refrigeration system used in the study was assumed to be three. The average heat absorption was measured for when the cows were standing up as well as when they were lying down. The expected average heat absorption of the conductive cooling system during the 8 hrs per day it was in operation was calculated by using the ratio of the time spent lying vs. standing and the average heat absorption of the system with and without a cow lying on it. For this calculation, it was assumed that the barn was stocked at 100% stocking density and had no sensor to shut off the cooling system when the cow was not lying in the stall. Energy cost was assumed to be $0.15/kWh.
Decrease in Core Body Temperature (CBT)

All of the studies that were used to determine expected reduction in CBT had THI conditions considered to be in the moderate range by (Reneau, 2017). Average THI for the study evaluating fan and sprinkler systems was 84.7, and cows had on average a 1.1°F reduction in CBT due to cooling (Chancai et al., 2010). Based on models in St-Pierre et al. (2003), fans are 65% as effective as fan and sprinklers, so the estimate for a fan only system was a 0.7°F reduction in CBT. For foggers the average THI was 83.4 and average reduction in CBT was 1.3°F (Tarazon-Herrera et al., 1999). For conductive cooling the average THI was 79.6 and average reduction in CBT was 1.8°F (Perano et al., 2015). Although the THI was lower for the conductive cooling study than the other studies, the air was quite still since the cows were housed indoors in a well-ventilated room but did not have any fans. Thus, the level of heat stress shown by the cows was higher than expected by the actual THI. Although the Perano study did not use fans to supplement conductive cooling, for this economic analysis it was assumed that farmers would use fans in addition to conductive cooling. Therefore, the cost to install and run the fans was included in the conductive cooling system cost estimates.

Increase in milk production and milk profit

Reductions in CBT and increases in milk yield due to cooling were assumed to have a linear relationship of 3.7 lb/°F increase in milk yield per decrease in CBT. This relationship was the average of the 4.6 lb/°F reported by Spiers et al. (2004) and the 2.7 lb/°F reported by Perano et al. (2015).

Daily Net Profit

Daily net return was calculated for both sample climates as daily milk profit minus daily costs. Annual net return was calculated as daily return for each climate multiplied by the number of assumed heat stress days (60 days/year for a cooler climate and 180 days/year for a warmer climate).
References


