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Modeling conductive cooling for thermally stressed dairy cows

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ABSTRACT

Conductive cooling, which is based on direct contact between a cow lying down and a cooled surface (water mattress, or any other heat exchanger embedded under the bedding), allows heat transfer from the cow to the cooled surface, and thus alleviate heat stress of the cow. Conductive cooling is a novel technology that has the potential to reduce the consumption of energy and water in cooling dairy cows compared to some current practices. A three-dimensional conduction model that simulates cooling thermally-stressed dairy cows was developed. The model used a computational fluid dynamics (CFD) method to characterize the air-flow field surrounding the animal model. The flow field was obtained by solving the continuity and the momentum equations. The heat exchange between the animal and the cooled water mattress as well as between the animal and ambient air was determined by solving the energy equation. The relative humidity was characterized using the species transport equation. The conduction 3-D model was validated against experimental temperature data and the agreement was very good (average error is 4.4% and the range is 1.9–8.3%) for a mesh size of 1117202. Sensitivity analyses were conducted between heat losses (sensible and latent) with respect to air temperature, relative humidity, air velocity, and level of wetness of skin surface to determine which of the parameters affect heat flux more than others. Heat flux was more sensitive to air temperature and level of wetness of the skin surface and less sensitive to relative humidity.

1. Introduction

Dairy cows regulate their body temperature to maintain a metabolically favorable temperature. Cows generate heat from metabolism and from physical activity including thermoregulatory mechanisms such as increased respiration, physiological activities such as lactation lead to increased metabolic heat production and thus increased need to dispose of body heat. The variation in core-body temperature (the mean temperature of an animal's deep-body tissues) should be kept within a very narrow margin in order for the animal to stay within the zone of least thermoregulation. Otherwise, when the body temperature of the cow gets too high, heat stress will set in (Mondaca et al., 2013). Even a 0.5 °C change in core-body temperature will negatively affect a cow's performance (Allen et al., 2013). West (2003) reported that failure to maintain homeostasis at temperatures beyond the cow's thermoneutral zone (or zone of least thermoregulation) will result in decreased milk production, reduced fertility, increased water consumption, reduced feed intake, more time spent standing (and fewer resting hours), and increased lameness. Extreme heat stress may lead to abortions or even death (West, 2003). In economic terms, the loss to the U.S. dairy industry due to thermal stress is about one billion dollars per year (St-Pierre et al., 2003). This loss does not take into account what might happen in the face of climate change, higher energy costs, or more water scarcity.

Current practices used to alleviate heat stress of cows include the following: forced convection and evaporative cooling systems that may include fans and misters or sprinklers, feed-line soakers, cross-ventilation, and evaporative cooling units such as Korral Kool. These systems increase heat transfer by evaporation and convection and decrease the temperature of the air surrounding the animal as well as the skin surface temperature. However, these systems will not be as effective under hot and humid conditions because of reduced moisture gradient between the skin surface and ambient air. Some of these systems also require a significant amount of water and electricity. Conductive cooling is an alternative method of cooling dairy cows that will work just as effectively under humid conditions and could also be complementary to existing systems.

Conductive cooling, which is based on direct contact between a cow lying down and a cooled surface (water mattress, or any other heat exchanger embedded under the bedding), allows heat transfer from the cow to the cooled surface, and thus alleviates some of the heat stress of the cow. Conductive cooling has the potential to conserve water (by recycling all the water as a working fluid in a closed-loop system) and may require less energy than evaporative cooling units such as Korral Kool. Conductive cooling may also improve animal hygiene and reduce humidity in the barn compared to evaporative cooling systems.

Animal cooling by conduction is a fairly new concept. There are

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only a few studies in the literature on the subject. To our knowledge, three universities (Cornell University, the University of Arizona and the University of Wisconsin-Madison) have been involved in conductive cooling of dairy cows using some sort of heat exchangers. The references associated with the studies in these universities are discussed below.

The pioneering study in conductive cooling, which consisted of both experimental work and modeling was done by Bastian et al. (2003). The experimental component of the study involved measurement of heat flux that cows lose to waterbeds when they lie down on them. The temperature of the surface (rubber) where the cows lied down was cooler than the skin surface temperature, thus the animals lost heat to the water inside the waterbed. During the experiment, the water in the waterbed was static and was not cooled. The modeling component involved a finite difference model that predicted heat flow from the cow to the waterbed. In the model simulation, the water in the waterbed was cooled to 10 °C, and consequently a cow lying down on the cooled water mattress lost 400 W of heat by conduction. This amount of heat is equivalent to about 25% of an estimated 1586 W of metabolic heat of a cow (Bastian et al., 2003). The study concluded that cows lying down on water mattresses can lose about 20–25% of their metabolic heat by conduction.

Rojano et al. (2011) did a feasibility study of a dual cooling system for dairy cows. They proposed a conductive cooling system in which a heat exchanger placed under the bedding cools the animal while lying down. Subsequently, Mondaca, et al. (2013) developed a computational fluid dynamics-based model that predicts heat loss of cows by conduction and performed sensitivity analysis to determine the effects of a range of parameters on conductive cooling. The focus of their study was on developing a conjugate heat and mass transfer 2-D model that considers physiological responses, hair-coat physical properties, and detailed interface boundary conditions. They solved a set of coupled, elliptic partial differential equations through discretization, and in which each control volume has a volumetric heat generation term. None of these two studies included experimental studies with live animals, and thus the models were not fully validated. Both studies concluded that conductive cooling could alleviate heat stress of cows during hot and humid weather.

Perano et al. (2015a) conducted extensive experimental and empirical studies to determine the effectiveness of conductive cooling in alleviating heat stress of dairy cows. The experimental work involved exposing dairy cows to hot and humid conditions and conductively cooling half of the cows by providing cooled water mattresses for them to lie on. The circulating water in the water mattress was cooled to 4.5 °C or 10 °C. When the cows were cooled at 4.5 °C water temperature, they produced up to 11% more milk than the control group that were exposed to the same environmental conditions but not cooled. The core-body temperature and respiration rate of the cooled cows were up to 1.1 °C and 22 breaths/min, respectively, lower than the control cows. This study conclusively demonstrated that conductive cooling can be an effective cooling mechanism for heat-stressed dairy cows.

Lately, Ortiz et al. (2015) experimentally evaluated the effectiveness of conductive cooling of dairy cows with heat exchangers buried under 25-cm of bedding. They justified the deep bedding to protect the heat exchanger and keep the cows comfortable. The water in the heat exchanger was cooled to 7 °C and sand or dried manure were used as bedding materials. They reported that there was no difference in respiration rate between the cooled and the not cooled cows but the core-body temperature was decreased by 0.13 °C when sand was used as bedding and by 0.14 °C when dried manure was used as bedding. They also reported low value of conductive heat flux (28.63 W/m^2 when sand was used as bedding and 7.35 W/m^2 when manure was used as bedding). These low values of heat flux could be due to the use of deep bedding (25 cm) in the study. They concluded that more work needs to be done to determine the efficacy of conductive cooling.

Based on our literature search, we did not find a fundamentally-based model that predicts conductive heat flow from a cow lying down on a cooled heat exchanger. A fundamentally-based model would provide insight in terms of how much heat of metabolism can be lost by conduction versus by evaporation and radiation, and such a model would enable parametric studies to identify the most sensitive variables to affect heat loss.

1.1. Objectives

The overall objective of this study was to simulate heat exchange between a cow and her surrounding environment (ambient air and water mattress) using computational fluid dynamics (CFD) technique. The specific objectives were to:

1. Develop a CFD model that characterizes airflow, heat transfer, and relative humidity within a space occupied by a cow.
2. Develop a 3-D mathematical model that simulates heat flow by conduction from a cow to a cooled water mattress (heat exchanger) when the cow was lying down.
3. Validate the predictions of the conduction model against measured surface temperature at the interface of a cow lying down and the water mattress.
4. Conduct sensitivity analyses of heat flow with respect to changes in ambient air temperature, relative humidity, air velocity and level of wetness of the skin surface.

2. Model development

2.1. Assumptions

1. Air flow surrounding the cow model was laminar.
2. Air flow and heat transfer were steady state.
3. Cutaneous evaporation occurred only from the skin surface exposed to ambient air.
4. Metabolic heat production was estimated to be 1855 W for a 682-kg cow producing 55 kg/day of milk.
5. Thickness of skin was 5 mm and its thermal resistance was 0.039 m^2-K/W (McArthur, 1981)
6. The length of the cow model was 2.15 m and the contact area was 1 m^2.
7. The space occupied by the model cow was 4 m-length × 4 m-width × 1 m-height.
8. Hair density was 26 hairs/cm^2 and the thickness of the hair coat was 12 mm but the compressed thickness of the hair coat (in contact with the water mattress) was 1 mm.
9. Heat loss by respiration was not included in this study.

2.2. Model formulation

Based on the above assumptions and Fig. 1, the governing equations used to characterize the air-flow field pattern surrounding the animal were the continuity and momentum equations (Eqs. (1) and (2)), the governing equation used to determine the heat transfer between the contact area of the body of the cow and the water mattress as well as the heat transfer between the cow and ambient air was the energy equation (Eq. (3)), and the equation used to characterize the relative humidity was the species transport equation (Eq. (5)). These equations are given below.