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.

Keywords: *Conductive Cooling, Heat Stress, Dairy Cows, CFD Model, Heat Flux.*

1.0 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

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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 0.5⁰C 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 thermo-neutral 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 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 1,586 W of metabolic heat of a cow (Bastian et al., 2005). 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, Mondeca 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 4.5⁰C or 10⁰C. When the cows were cooled at 4.5⁰C 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 1.1⁰C 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 7⁰C 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 0.13⁰C when sand was used as bedding and by 0.14⁰C when dried manure was used as bedding. They also reported low value of conductive heat flux (28.63 W/m² when sand was used as bedding and 7.35 W/m² 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 laying down.
3. Validate the predictions of the conduction model against measured surface temperature at the interface of a cow laying 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 1855W 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 m²-K/W (McArthur, 1981)
6. The length of the cow model was 2.15m and the contact area was 1m².
7. The space occupied by the model cow was 4m-length × 4m-width × 1m-height.
8. Hair density was 26 hairs/cm² and the thickness of the hair coat was 12mm but the compressed thickness of the hair coat (in contact with the water mattress) was 1mm.
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.

2.3. Continuity equation

The continuity equation used to determine the air flow pattern is expressed as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = S_m \quad (1)$$

where, ρ is air density, t is time, $\vec{u}$ is velocity vector, and S_m is the source term of mass.

2.4. Momentum equation

The momentum equations used to determine the air flow pattern is expressed as (Patankar, 1980)

$$\frac{\partial}{\partial t} (\rho \phi) + \text{div} (\rho \vec{u} \phi) = \text{div} (\Gamma_\phi \nabla \phi) + S_\phi \quad (2)$$

where ϕ represents velocity component, Γ_ϕ is the transport coefficient, and S_ϕ is the source term, which is dependent on ϕ .

2.5. Energy equation

The energy equation used to determine the heat exchange between the cow and its surrounding is expressed as (ANSYS-Fluent Inc., 2013)

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\vec{u} (\rho E + p)) = \nabla \cdot (k_{eff} \nabla T - \sum_j h_j \vec{J}_j + (\vec{\tau}_{eff} \cdot \vec{u})) + S_h \quad (3)$$

where, p is pressure, T is temperature, k_{eff} is effective thermal conductivity, h_j is enthalpy of species j , $\vec{J}_j$ is diffusion flux of species j , $\vec{\tau}_{eff}$ is viscous stress, and S_h is heat source due to metabolic heat production.

In equation (3), E is expressed as

$$E = h - \frac{p}{\rho} + \frac{v^2}{2} \quad (4)$$

where, h is enthalpy and v is velocity.

2.6. Species transport equation

The species transport equation used to characterize relative humidity is expressed as (ANSYS-Fluent Inc., 2013)

$$\frac{\partial}{\partial t}(\rho Y_i) + \Delta \cdot (\rho \vec{u} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i \quad (5)$$

where, Y_i is mass fraction of each species, $\vec{J}_i$ is diffusion flux of species i , R_i is net rate of production of species i by chemical reaction, and S_i is the source term.

2.7. Water evaporation model

The heat transfer by evaporation, convective and radiation were modeled assuming 1-D flow. The interaction among these three pathways is through skin temperature, as shown in the formulation given below.

The latent heat loss, q_{evap} , (W) due to water evaporating from the skin surface was calculated using the model developed by Gebremedhin and Wu (2001), which was based on Fick's law, and is expressed as

$$Q_{\text{evap}} = \lambda j'' \beta A_s \quad (6)$$

where, λ is the latent heat of vaporization of water at the temperature of the skin surface (kJ/kg), β is percent of skin surface that is wet, and j'' is total mass flux of water vapor that evaporates from the skin surface (kg/m²s).

The flux of water that evaporates from the skin surface was calculated as

$$j'' = (C_{\text{skin}} - C_0) / \left(\frac{1}{h_m} + \frac{\delta_1 + \delta_2}{D} \right) \quad (7)$$

where, C_{skin} is the concentration of water vapor (kg/m³) at the skin surface which is a function of skin temperature (T_{skin}), C_0 is the concentration of water vapor (kg/m³) of ambient air, h_m is convective mass transfer coefficient (m/s), δ_1 is thickness of the hair coat (m), δ_2 is thickness of a thin film of air layer above the hair coat (m), and D is mass diffusion coefficient of water vapor (m²/s).

2.8. Convective heat transfer model

208 The convective heat flow, Q_{conv} , (W) from the skin surface to ambient air was calculated as
 209 (Gebremedhin and Wu, 2001)

$$210 \quad Q_{conv} = q_c'' A_s \quad (8)$$

211 where, q_c'' is convective heat flux (W/m^2) calculated as

$$212 \quad q_c'' = \frac{T_{skin} - T_a}{1/h_c + \delta_1/k_{eff} + \delta_2/k_{air}} \quad (9)$$

213 where, T_a is ambient air temperature (K), h_c is convective heat transfer coefficient (W/m^2-K)
 214 calculated according to Gebremedhin and Wu (2001), k_{eff} is effective thermal conductivity of the
 215 hair coat ($W/m-K$), and k_{air} is thermal conductivity of air ($W/m-K$).
 216

217 **2.9. Radiant heat transfer model**

218 The radiant heat exchange, Q_{rad} , (W) between the body of the cow and its surroundings was
 219 calculated as (Gebremedhin and Wu, 2002)

$$220 \quad Q_{rad} = q_r'' A_s \quad (10)$$

221 where, q_r'' is radiant heat flux (W/m^2) calculated as

$$222 \quad q_r'' = \varepsilon f_{fur} f_{eff} h_r (T_{skin} - T_{mrt}) \quad (11)$$

223 where, ε is radiant emissive coefficient of a cow's skin, f_{fur} is ratio of fur surface area to skin
 224 surface area, f_{eff} is coefficient of effective radiant area, h_r is coefficient of radiant heat transfer, and
 225 T_{mrt} is mean radiant temperature assumed to be ambient temperature.
 226

227 **2.10. Computational domain**

228 A cow lying down was represented by a truncated cylinder oriented perpendicular to an incoming
 229 wind (Fig. 2). The simplified geometry of the cow laying down consists of four surfaces (Fig. 2).
 230 S_1 representing the skin surface of the cow in contact with the water mattress assumed to be $1m^2$,
 231 S_2 representing the two ends, and S_3 representing the areas of the skin surface in contact with
 232 ambient air. By solving Equations 12 through 18, the radius of the cylinder (r) and the height of
 233 the arc (h) can be calculated, and thus define the computational domain.
 234

235 **2.11. Determination of arc height of the cow model**

Assuming the length of a cow (2.15m) and the contact area (1m²) between the cow and the water mattress, the arc height, h , shown in Fig. 2, was determined.

The surface area of a cow, A_s , can be estimated from body weight as (Brody, 1945)

$$A_s = 0.15 W^{0.56} \quad (12)$$

where, W is body weight (kg).

The width of the arc can be calculated as

$$2a = S_1 / L \quad (13)$$

where, S_1 is contact area between the cow and the water mattress, L is length of the cow and a is the width of the arc (Fig. 2).

The length of the arc, l_s , of S_2 was calculated as

$$l_s = 2\pi r - \frac{2\pi r}{180} \arctg \frac{a}{\sqrt{r^2 - a^2}} \quad (14)$$

The end surface area, S_2 , was calculated as

$$S_2 = \pi r^2 - \left[r \left(\frac{2\pi r}{180} \arctg \frac{a}{\sqrt{r^2 - a^2}} - 2a \right) + 2a(r - \sqrt{r^2 - a^2}) \right] / 2 \quad (15)$$

The surface area, S_3 , was calculated as

$$S_3 = l_s L \quad (16)$$

The radius of the “cow”, r , can be solved by substituting Eqs. (12-15) into Eq. (17) as

$$A_s = S_1 + 2S_2 + S_3 \quad (17)$$

The arc height, h , was calculated as

$$h = r + \sqrt{r^2 - a^2} \quad (18)$$

2.12. Calculation of Reynolds number

The hydraulic diameter was calculated as

$$D_h = \frac{4S_2}{l_s + 2a} \quad (19)$$

Given D_h , the Reynold number can be calculated as

$$Re = \frac{\rho v_{in} D_h}{\mu} \quad (20)$$

where, v_{in} is inlet velocity and μ is dynamic viscosity of air.

2.13. Physical and thermal properties required for the CFD model

To perform simulation of air flow around the animal model and heat exchange between the animal and its surroundings, the physical and/or thermal properties of the water mattress, air, water, hair coat, and skin need to be defined. The physical properties of air and water and the thermal properties of the water mattress, hair coat and skin obtained from the literature (McArthur, 1981; Gebremedhin et al., 1981; Mondaca, et al., 2013) are given in Table 1. Thermal conductivity of the skin was calculated assuming 5-mm skin thickness and thermal resistance of 0.039 m²-K/W.

2.14. Procedures for measurement of interface temperature

The model temperature prediction was validated against data of temperature of the interface of the rubber mat of the water mattress and the cow's skin when the cow was lying down. The data was collected from live cows cooled with the same waterbeds as were simulated in the CFD model. The experimental cooling system set up is described in Perano et al. (2015b). The data was collected with thermocouples glued to the surface of the rubber mats. The thermocouple temperatures were measured and recorded every 2 minutes with a Campbell Scientific CR1000 data logger beginning 20 min after the cow laid down and continuing until the cow stood up (which ranged from 10 to 90 min of data collection). The thermocouples were installed on the beds of two of the cows. The measured interface temperature data were collected for 5 levels of water temperatures (ranging from 4.6-14.5⁰C) for the circulated cooling water, and each water temperature level was supported by multiple lying events.

The interface temperatures were calculated with linear models, using water temperature level as a fixed effect and bed number and lying event nested within water temperature as random effects. The LSMs for the measured interface temperatures are given in Table 3. The water temperatures in Table 3 were also calculated with linear models and are the average inflow/outflow water temperature in the waterbed during the exact time the interface temperatures were taken. Ambient conditions during the measurements were 29.6°C, 57% RH, and an air velocity of 0.04 m/s.

The convection coefficient (h_c) was estimated from the Nusselt number to be $91 \text{ W/m}^2\text{-K}$ at the location on the waterbed where the rubber-skin interface temperature was measured (see Perano et al., 2015b for the diagram of the waterbed geometry).

2.15. CFD simulation

The input values used for the simulation for the interface temperature were: Air temperature = 29.6°C , relative humidity = 57% air velocity = 0.04 m/s , core temperature = 39°C , temperature range of the water in the water mattress was between 4.6°C and 14.5°C , which is the same as that when the interface temperature was measured. The CFD simulation included grid generation and iteratively solving the governing equations. Meshing the computational domain was done using Gambit (ANSYS-Fluent Inc., 2013), and the governing equations were solved using Fluent (ANSYS-Fluent Inc., 2013). The steps followed in solving the governing equations were: (1) solve the continuity and momentum equations (Eqs. 1 and 2, respectively) to obtain a fully converged flow field, (2) solve the energy equation (Eq. 3) based on the flow field, (3) solve the species transport equation (Eq. 5) to obtain relative humidity based on the flow and temperature fields, and (4) perform post-processing. The calculations for heat exchange between the cow model and ambient air (Eqs. 6 through 11) was performed using our own developed code written in FORTRAN language.

2.16. Mesh-independent test

A numerical solution is sensitive to the number of mesh elements. The smaller the number of elements, the finer the mesh, and the higher the prediction accuracy. A fine mesh requires a longer computing time to obtain one solution. The principal purpose of mesh-independent test is to reach a compromise between computing time and prediction accuracy. In order to obtain an acceptable number of mesh elements, a mesh-independent test is usually performed by checking various mesh sizes and observing how the solution changes with respect to the mesh size. In this study, the mesh-independent test was conducted simultaneously with model validation. Since heat flow from a cow to a water mattress primarily involves the skin surface, meshing the skin surface in contact with the water mattress becomes the point of interest. The mesh-independent test was done by changing the size of the face mesh of the skin surface while keeping the other mesh sizes unchanged. To generate a higher quality mesh, the whole computational domain was divided into a few sub-

domains. Tetrahedral meshes were used for the zone that represents the cow body, while hexahedral meshes were used for the other zones. In addition, size functions were used to control the mesh growth.

3.0. RESULTS AND DISCUSSION

The mesh-independent test was performed to determine the error of the prediction associated with mesh size (Table 2). As shown in the table, the error reduced from 10% to 4% when the number of mesh elements was increased from 128678 to 1117202. When the number of mesh elements were further increased to 1750846, the error was again reduced but at a much lower rate. Using a finer mesh did not seem to significantly improve the accuracy of the prediction but increased the computing time exponentially. For subsequent calculations, a mesh size of 1117202 and a face mesh size of 0.01m were used.

The CFD model prediction of interface temperature was compared to measured temperature at a similar spot of live cows laying down on a water mattress (Table 3). As previously mentioned (Section 2.14), the inputs values for the environmental conditions in the simulation were identical to those under which the interface temperature measurements were made. On the average, the model predicted within 4.4% error (ranging from 1.9 to 8.3%). We consider this result to be very good.

3.1. Prediction of airflow

The continuity and momentum equations (Eqs. 1 and 2, respectively) were solved first to obtain the airflow pattern around the animal model. The blue area in the velocity contour (Fig. 3a) represents low velocity while the red area represents high velocity. The velocity in the red area is greater than or equal to the maximum specified velocity, and the black area represents the model cow. In the entrance region, that is, between the air inlet and the cow model, the flow is relatively uniform because there is no obstruction to the flow path. When air flows through the narrow zone above the cow model, however, the flow accelerates due to reduced cross sectional area of the flow passage. As the flow passes the cow model, it slows down as it moves towards the outlet. The flow pattern is very complex in the leeward side, as shown by several blue and green areas. In addition to the global velocity contour (Fig. 3a), the velocity vector (Fig. 3b) and flow pathlines (Fig. 3c)

are given to better visualize the flow pattern within the space. Each pathline refers to a trace of a single particle in space. As shown in Fig. 3b, the motion of the particles of the fluid appear to be very orderly with all particles moving along a streamline from the inlet to the outlet, which is characteristic of a laminar flow, and consistent with our assumption.

3.2. Prediction of heat flow

After solving for the converged flow field (Section 3.1), the temperature profile from the internal core-body temperature to the water in the water mattress, and also from the core-body temperature to ambient air can be solved from the energy equation (Eq. 3). Figure 4 (a) shows the global view of the temperature profile through the cow model. As expected, the highest temperature is shown at the “internal cow body.” To better visualize the temperature profile, two local profiles, (1) from the internal body (core) to the water in the water mattress, and (2) from the core to ambient, are shown in Figures 4(b) and 4(c), respectively.

Fig. 4(b) shows the temperature changing from red (high) at the core to blue (low) at the water mattress, as it should be. A similar trend is shown in Fig. 4(c). The temperature gradient between the core and the water is more uniform than that between the core and ambient because airflow affects the convective heat transfer at the hair coat-air boundary layer.

3.3. Prediction of relative humidity

Based on the flow and temperature fields, the species transport equation (Eq. 5) can be solved to predict relative humidity. Figure 5 shows the predicted results of relative humidity corresponding to the temperature profile shown in Fig. 4(a). Relative humidity is inversely proportional to temperature; that is, the higher the temperature, the lower the relative humidity. Thus, the relative humidity around the cow body, which is treated as a heat source, is lower than that in the space further away from the cow.

3.4. Sensitivity analysis

Sensitivity analyses were performed to determine the sensitivity of key parameters that affect heat flux/flow. Heat flux from the cow to the water mattress was simulated for five temperatures of the water in the mattress. These temperatures were: 4.6, 6.9, 10.8, 12.7, and 14.5°C. The corresponding

predicted heat fluxes were: 430, 401, 353, 328, and 306W/m², respectively. The conductive heat flux decreased linearly with increasing cooling water temperature because the flux is dependent on the temperature gradient and convective heat transfer between the body of the cow and the cooling water in the water mattress.

Sensitivity of air temperature on skin temperature, convective, radiant and evaporative heat losses are given in Table 4. Because air temperature was lower than skin temperature, heat is lost from the skin surface. The lower the air temperature, the larger the temperature gradient from skin to air. For example, an increase in air temperature from 29.6 to 35°C increased the radiant heat loss much more than the convective and evaporative heat losses. This may be attributed to the fact that convective and evaporative heat losses are highly dependent on flow regimes (laminar or turbulent) whereas radiant heat transfer is a function of temperature gradient (Eq. 11).

Sensitivity of relative humidity on sensible and latent heat losses are given in Table 4. When relative humidity was increased from 57 to 80%, the convective heat loss remained unchanged because air velocity was constant. The radiant heat loss also remained constant because the temperature gradient between the air and skin surface did not change much but the latent heat loss was affected negatively. Increasing relative humidity decreases the vapor concentration gradient between the skin surface and ambient air and thus reduces the evaporative heat loss. A decrease in evaporative cooling resulted in an increase of skin surface temperature, which in turn increased the sensible heat loss. The overall effect of increasing relative humidity was to decrease the total heat loss from the animal.

Sensitivity of air velocity on the heat transfer mechanisms are given in Table 4. Generally, an increase in air velocity results in an increase of convective and evaporative heat losses and consequently reduces skin surface temperature. In this study, however, the influence of air velocity on sensible and latent heat losses was small because the air velocity considered was very low (0.04 m/s). Air velocity affects convective and evaporative heat losses considerably under turbulent flow conditions (Gebremedhin and Wu, 2003). The Reynolds number calculated for the air velocity considered in this study was 1606, which is laminar. When the air velocity in this geometry exceeded 0.5 m/s, the flow becomes turbulent (Reynolds number = 20076). In this situation, an

increase in air velocity increased convective and evaporative heat losses, and consequently reduced the skin surface temperature. A lower temperature gradient between the skin surface and ambient air decreased the radiant heat loss. The total heat loss increased with increasing air velocity because the increase in convective and evaporative heat losses was much greater than the reduction in radiative heat loss.

Sensitivity of level of skin wetness on the three heat transfer mechanisms is given in Table 4. Increasing the level of wetness of the skin surface had no effect on the convective heat loss because the convective heat transfer coefficient was constant because of constant air velocity. Radiation was somewhat sensitive because of the cooling effect of evaporation on the skin. The effect of level of wetness of the skin surface on evaporative heat loss was, however, significant. The greater the level of wetness, the greater the evaporative heat loss and the greater the cooling effect.

The total heat loss (convection + radiation + evaporation + conduction) from the cow model was equal to 895W. This amount of heat loss was for the following environmental conditions: air velocity of 1.0 m/s, ambient air temperature of 29.6 °C, relative humidity of 57% and level of skin wetness of 60%. If we assume a heat of metabolism of 1158 W for a 560-kg cow, the total heat loss (895 W) amounts to 77.3%. The difference could be the heat loss by respiration.

Conclusions

1. The study develop a 3-D CFD model that predicts heat flow by conduction from a cow lying down on a cooled water mattress. The CFD model is capable of predicting the spatial distributions of airflow, temperature, and relative humidity in a space occupied by a cow. The method can be extended to study ventilated spaces with multiple occupants. The heat loss to ambient by convection, radiation and evaporation was modeled as 1-D flow.

2. The cooling performance of the water mattress was dependent on the temperature of the recirculating water inside the water mattress. The predicted heat flux for the 4.6°C cooling water temperature was 430 W/m² and dropped to 306 W/m² for a temperature of 14.5°C.

3. The predicted interface (cow skin - rubber mat interface) temperature from the 3-D conduction model was compared to experimentally measured temperature at a similar spot of a cow laying down on a water mattress for five temperatures of cooling water. On the average, the model predicted within 4.4% error (ranging from 1.9 to 8.3%).
4. Sensitivity analyses showed that heat exchange between a cow and ambient air was sensitive to air temperature and level of skin wetness but less sensitive to relative humidity and laminar airflow.

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505 Fig.1. Diagram showing heat transfer components from cow body to its surrounding. The cow is
506 lying down on a cooled surface.

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(a) 3-D view

(b) 2-D view of cross section

Fig.2. A simplified geometry of cow body.

0 0.03 0.06 0.08 0.12 (m/s)

(a) Contours of velocity profile surrounding the cow model shown in black.

0 0.03 0.06 0.08 0.12 (m/s)

(b) Velocity vectors

(c) Air flow pathlines colored by particles releasing from inlet.

Fig.3. Airflow pattern in the z-x plane at $y = 0$ (based on the Cartesian coordinate system fixed at the center of the water mattress)

(a) Global view of temperature field surrounding the cow model.

(b) Zoomed view of temperature profile for cow in contact with water mattress (Area 1 in a).

(c) Zoomed view of temperature profile for cow in contact with ambient air (Area 2 in a)

Fig.4. Global and zoomed views of temperature profiles surrounding a cow model.

Fig.5. Contours of relative humidity surrounding the model cow shown in black.

Table 1. Thermal and physical properties

	Air	Water	Hair Coat	Skin	Tissue	Water Mattress
Specific heat (J/kg-K)	1006.43	4182	1006.43	3472	3472	4182
Thermal conductivity (W/m-K)	0.0242	0.6	0.26	0.1285	0.52	0.15
Viscosity (kg/m-s)	1.7894x10 ⁻⁵	1.003x10 ⁻³				
Density (kg/m ³)	1.225	998.2	998.2			

Table 2. Grid-independent test based on a cooling water temperature of 4.6 °C.

Mesh cells	Measured temperature (°C)	Predicted temperature (°C)	Error (%)
128678	19.91	17.99	10%
283708	19.91	18.53	7%
1117202	19.91	19.14	4%
1396372	19.91	19.21	4%
1750846	19.91	19.25	3%

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Table 3. Comparison of the predicted and measured temperatures at the top surface of the waterbed (where the cow lays down) for five temperatures of the cooling water .

Temperature of the cooling water (°C)	Measured temperature (°C)	Predicted temperature (°C)	Error (%)
4.6	19.91	19.14	3.8%
6.9	20.09	20.48	1.9%
10.8	20.98	22.73	8.3%
12.7	23.04	23.81	3.3%
14.5	26.02	24.82	4.6%

Table 4. Sensitivity analyses of air temperature, T_a , relative humidity (RH), inlet air velocity, v_{in} , and level of skin wetness, β on skin temperature, T_{skin} , convective, $Q_{conv.}$, radiative, $Q_{rad.}$, evaporative, $Q_{evap.}$, and total, Q_{total} heat losses from the animal model to ambient air.

Simulation parameters	Simulation values	Simulation T_{skin} ($^{\circ}C$)	Results			
			$Q_{conv.}(W)$	$Q_{rad.}(W)$	$Q_{evap.}(W)$	$Q_{total}(W)$
T_a ($^{\circ}C$) ¹	29.6	37.07	14	125	68	207
	32	37.54	10	93	54	157
	35	38.01	6	50	50	106
RH (%) ²	57	37.07	14	125	68	207
	70	37.15	14	126	58	198
	80	37.21	14	127	51	192
v_{in} (m/s) ³	0.04	37.07	14	125	68	207
	0.5	35.91	42	106	184	332
	1.0	35.64	46	101	213	360
β (%) ⁴	20	37.43	14	131	23	168
	40	37.25	14	128	45	187
	60	37.07	14	125	68	207

¹Fixed values: RH=57%, β = 60%, and v_{in} = 0.04 m/s. ² Fixed values: T_a =29.6 $^{\circ}C$, β = 60%, and v_{in} = 0.04 m/s. ³ Fixed values: T_a = 29.6 $^{\circ}C$, β = 60%, and RH = 57%. ⁴ Fixed values: T_a = 29.6 $^{\circ}C$, v_{in} = 0.04 m/s, and RH = 57%.