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An Advanced Conductive Cooling Design to Relieve Heat Stress in Modern Dairies

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Abstract. Dairy cows suffering from heat stress due to extreme climates produce less milk, which leads to lower profits for the dairy's owner. Traditional methods for cooling cows have focused on convective and evaporative cooling systems, but these consume relatively substantial amounts energy and water. In addition, their effectiveness can be limited during periods of high temperature and humidity. In order to develop a better way to cool cows, this study considered an advanced conductive cooling system that involved a specially fabricated water tank positioned underneath the bedding on which the cows usually recline. It was determined that cold water, circulating through the water tank and then a heat exchanger, could help to remove excess heat stored in animal's body. To evaluate and verify this concept, computational fluid dynamics (CFD) was used to simulate the design dimensions, bedding material and depth, coolant temperature and its flow rate. In addition, laboratory experiments validated the simulation outcomes. The results show that this proposed conductive system can effectively prevent heat stress in dairy cows.

Keywords. Dairy, Cooling, Heat exchanger, Computational Fluid Dynamics

Introduction

In the past several decades, the modern dairy has incurred huge economic losses due to reduced milk production. Modern dairy producers strive to achieve consistently high milk production, feeding efficiency, and reproduction efficiency while maintaining the health of their dairy cows (Smith and Harner III, 2012). Among other negative effects on dairy cows, heat stress is considered as a major cause of production losses. In many parts of the world, both milk production and reproduction performance drastically decline during periods of heat stress. In 2006, California's dairy producers lost almost $1 billion in milk because of a heat wave (with temperatures reaching above 38ºC). In 1999, a severe heat wave in Nebraska cost the local dairy owners more than $20 million. During the summer in 1995, a period of extreme heat and humidity caused the deaths of over 3700 cattle in a thirteen-county area of western Iowa (Collier and Zimbelman, 2007).

Heat stress usually occurs when an animal is forced to thermo-regulate its body through physiological reactions or behavioral changes. Normally, cows will give off the excess body heat in the form of latent heat, which is lost as moisture expelled from their lungs evaporates, and sensible heat, which is lost as sweat evaporates from their hide. However, under heat stress, cows tend to accumulate much more heat than usual. As a consequence, their milk output decreases. Moreover, heat stress reduces feed intake, health, and reproduction rate. It is obvious that the challenge of relieving heat stress becomes greater across the United States during the hot summer months, especially in arid Southwest areas such as Arizona. Actually, however, heat stress affects milk production not only during the hot periods but also milk production and reproduction rates during the cooler months (Harner III et al., 2000). As for the modern dairy, nowadays, several common methods have been widely used to relieve the heat stress, and studies showed that milk production losses because of heat stress could be minimized by proper cooling methods. Providing shade in housing areas and in the holding pen of the milking parlor will mitigate the risk of heat stress by reducing the impact of solar radiation. However, shade has no effect on air temperature or relative humidity. Therefore, additional cooling is necessary in a hot, humid climate.

A recently proposed conductive cooling idea involves placing a heat exchanger under the bedding material on which the cows rest, thus focusing on the conduction as the main cooling mechanism. The size of the heat exchanger will follow the ASABE standard. The material, size and shape of the heat exchanger can vary, but the effectiveness of this system depends on how much time cows spend lying down on the bedding. Chaplin and Tierney (2000) and Tucker and Weary (2003) have reported that cows spend an average 12 to 14 hours per day reclining. And several controlled studies found that cows preferred bedding composed of deep straw bedding or a soft rubber mat, rather than loose sand (Manninen et al., 2002). Currently, the proposed conductive cooling system is still in the design stage, and few studies of its performance and efficiency can be found. The conceptual frame work has been evolved over many years (Bastian et al., 2003; Bruer and Steele, 2013; Mondaca et al., 2013). In this study, we sought an advanced design involving a material that could provide a satisfying thermal behavior and also provide the cow an acceptable amount of comfort and safety. The advanced design we settled on uses a new material to achieve these requirements, and our study also considers a special pattern for the system of tubing inside the heat exchanger.

Computational Fluid Dynamics (CFD)

Computational Fluid dynamics (CFD) makes it possible to solve the governing equations of mass, momentum and energy balances in complicated geometries, such as those present in a heat exchanger. The discretized forms of the coupled partial differential equations are applied to a large number of control volumes, which together make up the computational domain. The size and number of control volumes (the mesh density) are user determined and will strongly influence the accuracy of

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the solutions. After boundary conditions have been implemented, the flow and energy balances are solved by an iteration process that decreases the error in the solution until a satisfactory result has been reached. (Nijemeisland and Dixon, 2004)

In this study, a three-dimensional CFD model, based on the design, will be first created in order to estimate thermal behavior so that future experimental efforts will be mitigated. After a series of evaluations, an improved model will be instructed to find the optimal design. The optimal design should not only exhibit good experimental behavior but also show promise of working well at a larger scale, such as that needed by an entire dairy.

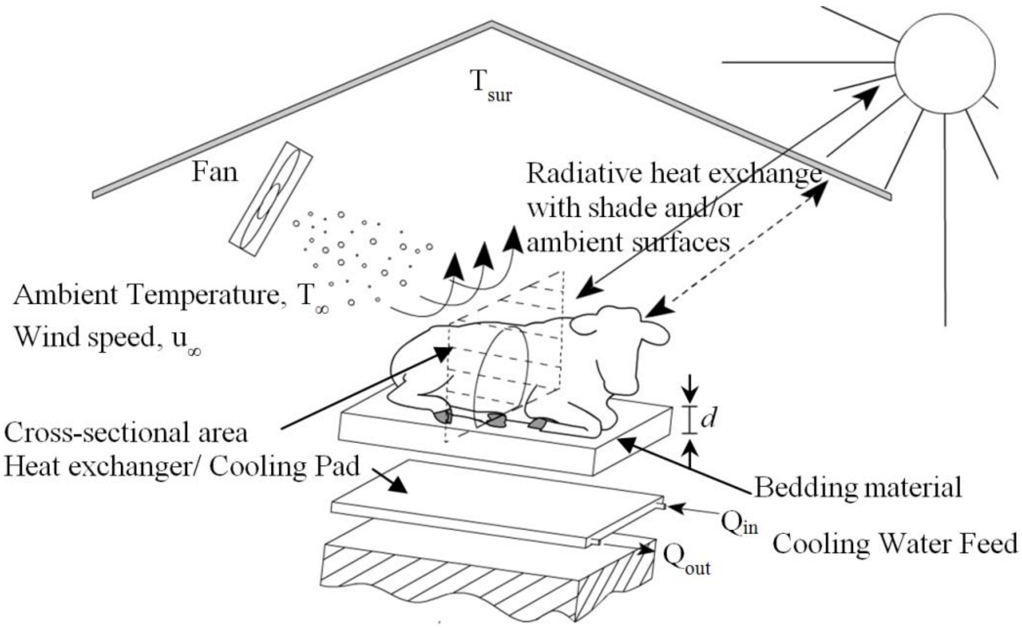


Figure1. A conjugated cooling mechanism in modern dairies (Mondaca et al., 2013).

Materials And Methods

Tube Heat Exchanger

The heat exchanger used in this experiment, was a Fafco heat exchanger, which was provided by Agriaire Company (Chandler, AZ, USA). It was specially designed to serve as a solar collector; i.e., the tubes are held apart and off the mounting surface by an integrated framework attached along the panel's length. Coolant water maintained at 12.8 °C runs through all the pipes, and the flow rate is controlled at 1.89 L min^{-1} (0.5 gal min^{-1}). Due to the size of the solar collector, we insulated part of the area (1.4 m length and 0.8 m) as shown in Fig. 2(a), according to ASABE Standards. The rest of the tubes have been well insulated with fiberglass. We chose sand as the bedding material, and the bedding thickness was 25.4mm (10in), following the common industry practice. Hot water maintained at 35°C was run above the sand to simulate the cow's skin temperature. Pumps were used to circulate the hot water so that the temperature stayed constant at 35°C. Five thermocouples (type K) were placed on top of sand in order to verify the constancy of the temperature (Section A). A set of 5 thin-film, heat-flux sensors (HFS-4 from Omega Engineering Inc., Stamford, Conn., USA) was placed within the sand (Section B), and two thermocouples were placed on top of and below the heat-flux sensor in order to find thermal conductivity of sand. The five heat-flux gauges used had the following characteristics: sensitivity was 1.8 V-W/m^2; thermal resistance was 0.004 °C/m^2; the thermal capacitance was 1000 W-sec/m^2°C; and the time response was 0.7 s. Thermocouples and heat-flux gauges were covered with thermal grease (Omegatherm made by Omega Engineering Inc. Stamford, Conn., USA) in order to maintain stable readings. The thermal grease used has thermal resistance of 0.71 W/m-°C.

The thermo-physical property of a sand bed can vary, and that effects the conductive cooling significantly. Therefore, in order to save on labor and simulate more accurately the environment of a real dairy, we used a bed of dry sand (0.5% moisture level) 254mm (10in) in depth. The heat-flux gauges measure the difference between temperature of heat exchanger and temperature on the upper surface of the bedding (sand). Therefore, the heat-flux values can be considered indicators of the behavior of the whole cooling installation. The average heat-flux values recorded at five selected points on the surface of the sand were studied.

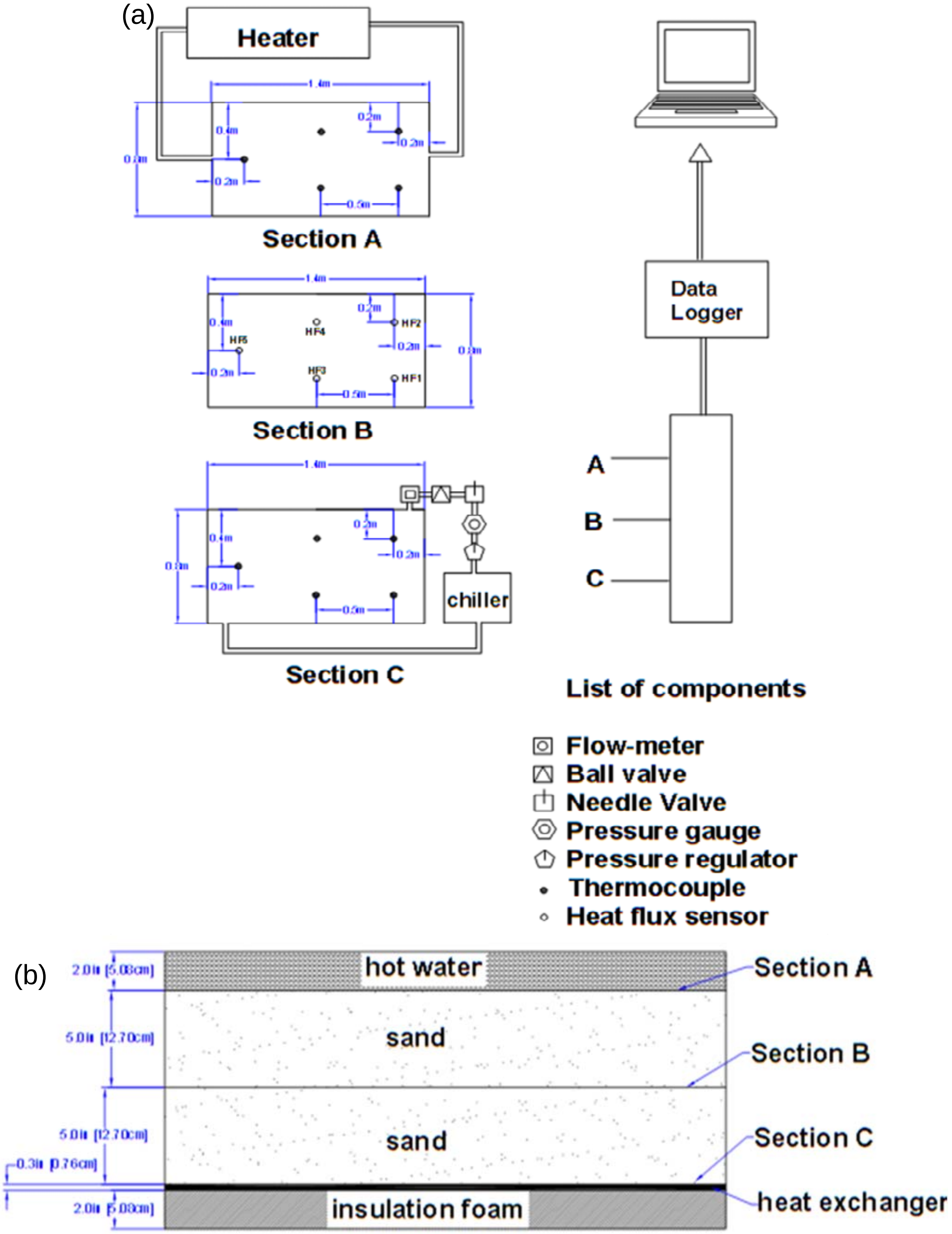


Figure 2. The alternative heat exchanger test setup in terms of top view and general view (a) and front section view (b).

Grooved Heat Exchanger Design

The heat exchanger we also used in this study is a grooved mattress for dairy cows. It consists of a rubber mat on top of a foam mattress. On the surface of the foam mattress we carved water channels through which the coolant water can run. To keep the mattress from deforming under the pressure of the water, a wooden box encloses it on all four sides as well as on the bottom. The wooden box also serves to insulate the mattress and reduce energy loss. We covered the open mattress with the rubber mat. We tested rubber mats of two different thicknesses—2mm (0.0787in) and 8mm (0.3150in) thickness—since these two thicknesses are the most widely used in modern dairies along with traditional beddings such as sand or manure. Screws, washers and a rubber flange were used to seal the rubber mat within the wooden box. In effect, then, the wooden box containing the channeled mattress and the rubber mat topping constituted a waterbed (Fig.3). Because traditional beddings were still going to be used in conjunction with this design, the advanced heat exchanger consisted of two components: the waterbed and the sand layer that served as bedding. However, because the waterbed itself provided comfort, the thickness of the sand layer could be significantly reduced, and this improved the total cooling capacity of the heat exchanger system.

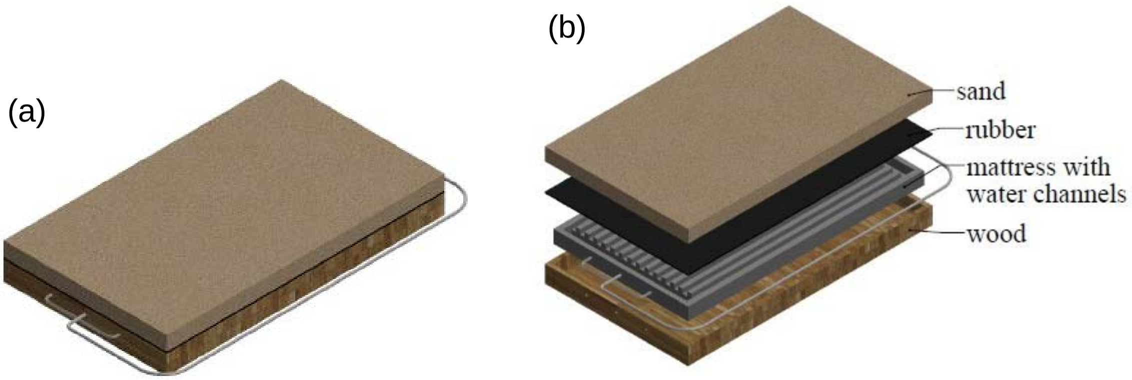


Figure 3. (a) The assembled advanced heat exchanger and (b) an exploded view

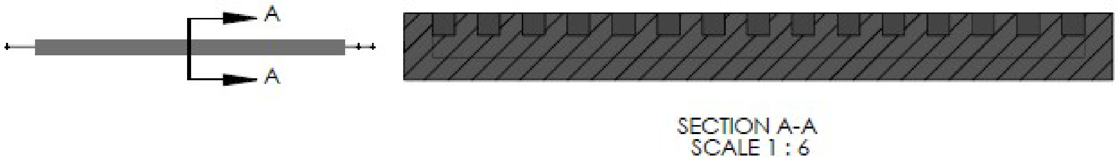


Figure 4. A section view of the mattress with water channels shown

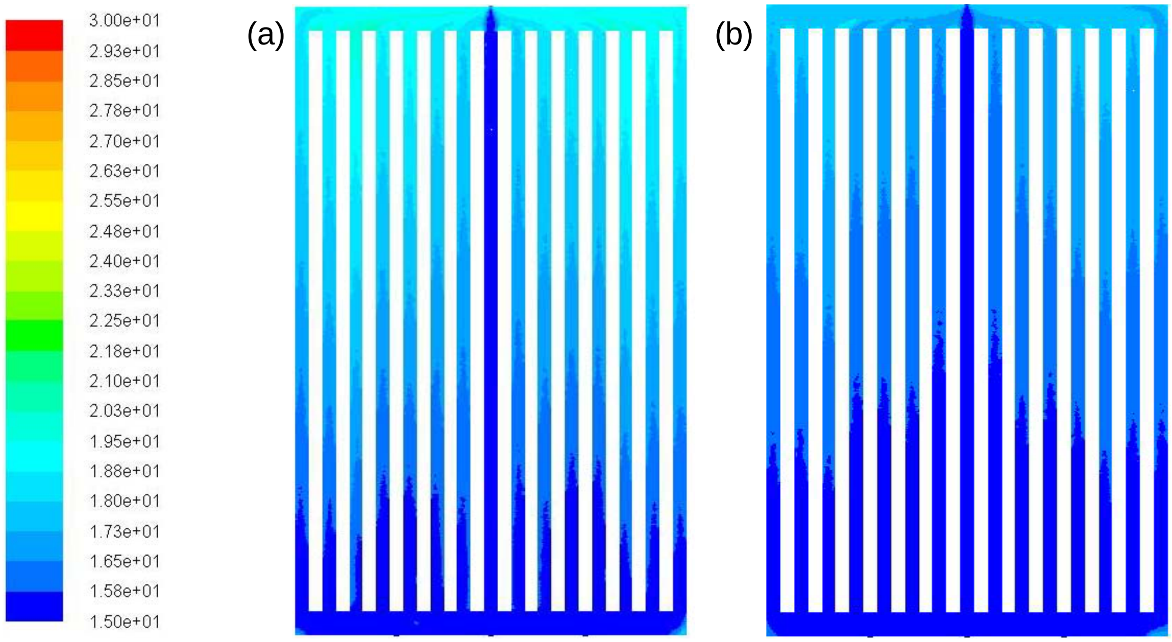
Numerical Analysis Using Computational Fluid Dynamics (CFD)

The computational domain simplified the design of the heat exchanger (depicting only the water channels (eliminating the mattress), but the overall dimensions were the same as those of the real design. The inlets and outlet, rubber mat topping and sand bedding were included. The geometry was generated. Designing and constructing a high quality grid was crucial to the success of the CFD analysis. We used the Mesh component of ANSYS Fluent 13.0 (Canonsburg, PA, USA), and the model was partitioned into three sections: sand, rubber mat and the water channels. For this specific geometry, unstructured grid types were used, which meant that the cells were arranged in an arbitrary fashion, and there were no constraints on cell layout. This geometry would not only provide greater flexibility for discretizing domains but also enable straightforward implementation of adaptive meshing techniques. In order to enhance solution accuracy, the size of the cell was strictly controlled. The minimum and maximum sizes were 0.05mm and 6mm, respectively, and the maximum face size was 8mm, with a growth rate set at 1.2. Thus, for example, the total number of computational cells of 25.4mm (1in) dry, sand bedding with an 8mm (0.3150in) thick, rubber layer model would be 655,000. We also considered skewness and aspect ratio in our evaluation of mesh quality. The skewness was 0.18 and the maximum aspect ratio was 11.73.

As we mentioned above, this computational model was partitioned into three sections. During set-up, the cell zone conditions (sand and rubber sections) were assumed to be solid, and the water section to be fluid. Table 1 provides the material properties, and it should be noted that the sand used in the CFD simulation was assumed to be dry (with 0.5% moisture level based on weight). The fluid properties and boundary conditions were given in SI units. The velocity and temperature were imposed at the inlets, and static temperature at the outlet. The flow rate at the primary inlet was 1 L min^{-1}, which would ensure that the flow was laminar. Water ran through the waterbed under undeveloped laminar conditions (due to the geometry) and a low Reynolds number. The three inlets supplied water to the waterbed evenly, at constant temperature (15 ºC) and flow rate. We used pure water for the coolant, and its properties were obtained from the ANSYS Fluent 13.0 database. The top surface of the rubber mat was maintained at a static temperature of 35 ºC, which simulates a typical cow's skin temperature. The thermal conductivity of the and thinner was 0.10 W/m-K and thicker rubber mat was 0.14 W/m-K. The discretization used second-order upwind for momentum and energy, and the fluid dynamics field was obtained by applying a pressure-velocity coupling algorithm that follows the SIMPLE scheme. At the fluid and solid interfaces, an energy balance was satisfied at each iteration such that the heat flux at the wall on the fluid side was equal in magnitude and opposite to the heat flux in sign on the solid side. To meet this condition, the temperature of the boundary itself was adjusted at each iteration. Fig. 5 shows the static temperature distribution at the middle plane of the water channel. The heat exchanger was placed under a layer of sand bedding at a depth of 25.4mm (1in) and the moisture level of the sand was 0.5% (based on the sand's weight). The water was provided to the heat exchanger at 1 L min^{-1} and at 15ºC. Because of the convection effect, the temperature of water increased as it flowed farther from the inlet, and this explains the heat flux distribution of the sand's top surface, as shown in Fig. 6.

Table1. Material Properties for Analysis

	Density (kg/m^3)	Thermal Conductivity (W/m-k)	Specific Heat (J/kg-k)	Viscosity (kg/m-s)
Sand	1668.5	0.90	2010	-
Rubber	1100.0	0.10/ 0.14	800	-
Water	998.2	0.60	4182	0.001003



Fugure 5. Contours of static temperature (°C) for 2mm (0.0787in) rubber (a) and 8mm (0.3150in) rubber (b)

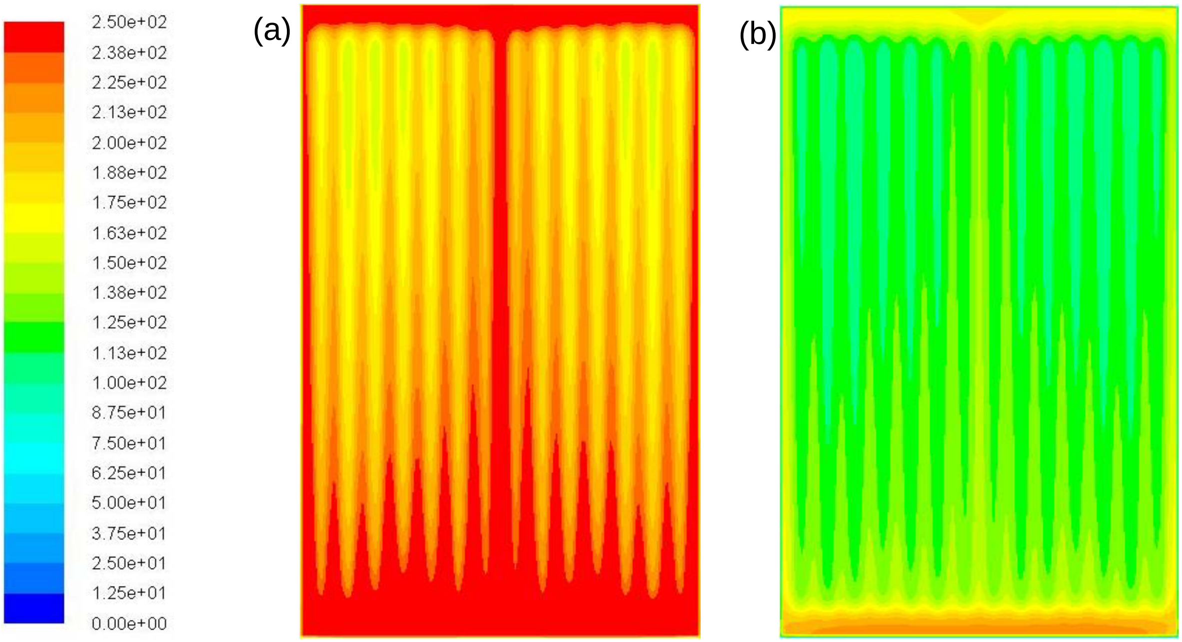


Figure 6. Contours of total surface heat flux (W/m^2) for 2mm (0.0787in) rubber (a) and 8mm (0.3150in) rubber (b)

Results

Tube Heat Exchanger Test

We found that after the system achieved a steady state the ultimate heat-flux value was higher after each of three runs (Run3> Run2> Run1) (Fig. 7). We also solved the problem with the conduction equation at various moisture levels up to 10 %. The heat transfer rate of the mathematical solution is 75 W/m^2 at a 0.5 % moisture level (Fig.8). This mathematical solution overestimates the experimental data probably because of the thermal contact resistance and the placement of the heat-flux sensors. Nevertheless, the third run's value was the closest to the estimated value. This result is reasonable because the sand gradually settles due to the gravity, and so its thermal conductivity increases, the heat-flux values increased after each of the three runs for the same reason. Fig. 9 shows that to cool a cow more efficiently, we would have to reduce the thickness of the sand layer. By using dry sand (0.5% moisture content by weight) to get a 200 W/m^2 heat flux value, which is nearly 10% of the heat a cow generates under average conditions, the sand-layer thickness would have to be reduced to, at most, 101.6mm (4 in) instead of 254mm (10 in). When the bedding depth was reduced to 50.8mm (2 in) (see Fig. 9), the rate ranged from 400 W to 1200W. At a moderate moisture level, we found that approximately 800 W of heat could be removed by the heat exchanger. However, decreasing the bedding thickness increases the incidence of lameness, and the heat exchanger could be damaged whenever such heavy creatures lying down or standing up.

Besides the thickness of the bedding sand, the thermal conductivity of the sand will affect the heat-flux value. This relationship also explains the estimation results shown in Fig. 9. Overall, at the same thickness, increasing moisture content of the sand will improve the thermal behavior of the heat exchanger. However, the higher moisture content creates new problems. In the previous experiment, sand with a 10% moisture content was almost saturated and is therefore not suitable as bedding. Maintaining the sand's moisture content poses another challenge. Also, wet bedding may create a preferred environment for pests and negative bacteria, which can cause the cow to get sick or permanently disabled, at which point the animal must be euthanized. Nonetheless, the heat transfer rate at a 10% moisture level is about 220 W, which is far less than 1,500 W.

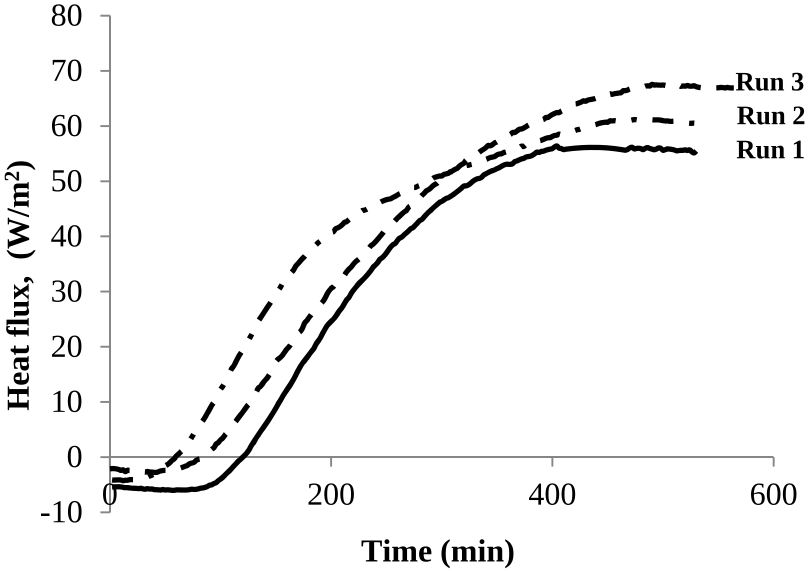


Figure 7. Experimental data for dry sand (0.5% of moisture content, based on weight)

Average heat flux in the transient response

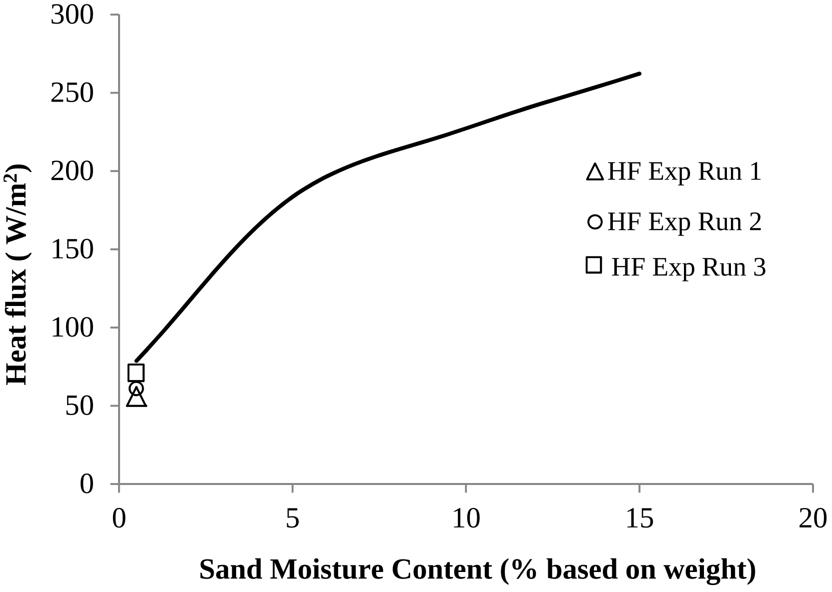


Figure 8. Heat flux comparison between estimated and experiments based on various sand moisture content

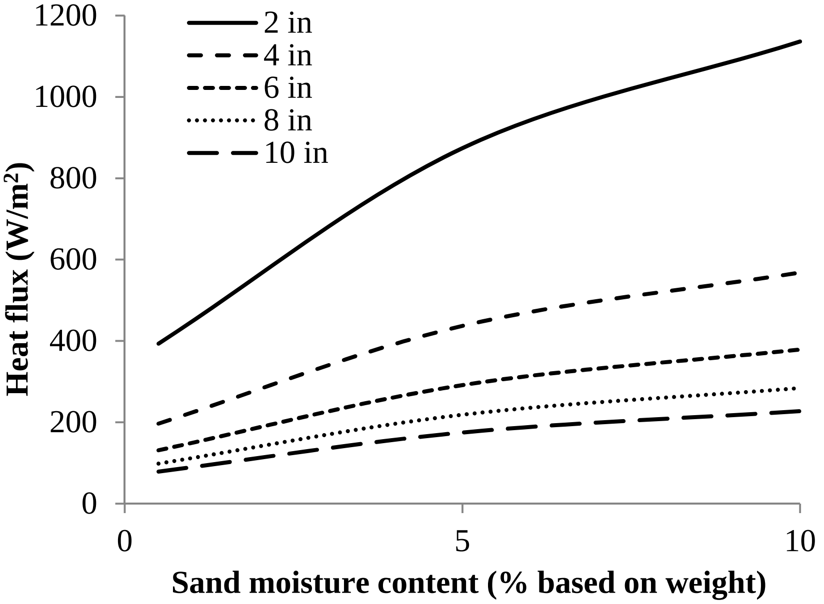


Figure 9. Heat flux as a function of the sand moisture content and bedding depth

Grooved Heat Exchanger Design-Numerical Analysis

Numerical solutions for estimating the cooling capacity of the advanced heat exchanger were achieved by CFD simulation. Different thicknesses of sand were simulated for both 2mm (0.0787in) and 8mm (0.3150in) rubber mat toppings, and the numerical results were compared to the analytical solutions. In this comparison, we considered the maximum value of the analytical solution, which assumes that the entire top surface of the sand has the same heat-flux value. However, in real as well as the numerical analyses, only the area with water channels provides any conduction transfer with the hot top surface of the sand, so the rest of the area was assumed as adiabatic. The active area (with the coolant water running underneath) was 60% of the entire area. Fig. 10 and 11 show that, with the sand bedding thickness increasing, the numerical results range closer to the maximum analytical result, which means that the water channels' effect is decreasing. Therefore, we can conclude that the water channels will only affect the cooling capacity of the heat exchanger under certain conditions. If the thermal resistance of the whole design is high, the cooling efficacy of the heat exchanger will certainly be less. The patterns of the water channels in real design should be considered carefully, and the thickness of the bedding should be the minimum allowed.

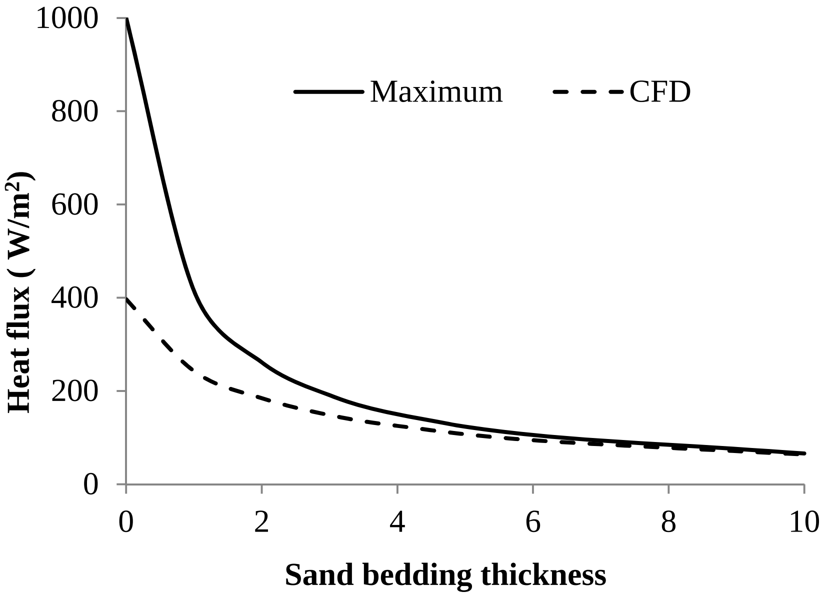


Figure 10. A comparison of the numerical solution (CFD) and the analytical solution (Maximum) for the heat-flux value at the surface of the sand at different bedding thicknesses, 2mm (0.0787in) rubber mat topping

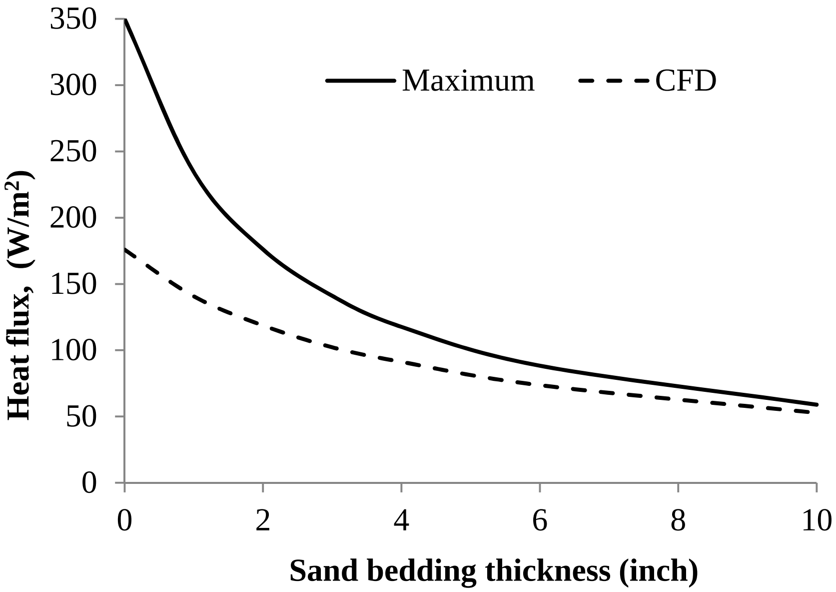


Figure 11. A comparison of the numerical solution (CFD) and the analytical solution (Maximum) for the heat-flux value on the surface of the sand at different bedding thicknesses, 8mm (0.3150in) rubber mat topping

Conclusion

The current study aims to improve the cooling systems used in modern dairies. Conductive cooling is a developing technology, and existing designs have limitations. The proposed advanced heat exchanger follows the basic conductive cooling method but is innovative in the materials used as well the way in which it integrates with the cows' environment. Our evaluation shows that it could augment and significantly improve the total cooling capacity of existing cooling systems. We also believe that this advanced heat exchanger design could likely satisfy larger-scale requirements. Future work should focus on experimentally validating this design as well as developing it for application to a wider network.

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