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Design-oriented modelling on cooling performance of the earth-air heat exchanger for livestock housing

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ABSTRACT

Access to inexpensive cooling sources is a precondition for developing cost-effective methods to mitigate heat stress among farm animal under hot climate conditions. The earth-air heat exchanger (EAHE) is a promising energy-effective technique that can be used to reduce the cooling load of a livestock building in hot days. Several studies have been carried out to assess the feasibility of EAHE for tempering air in livestock buildings. However, no mathematical model serving for EAHE design for livestock buildings has been developed, in which the EAHE system is often operated continuously to keep animals comfortable and productive. This work firstly deduced a regression model for predicting the air temperature difference between an EAHE tube inlet and outlet ($\Delta T_{i\text{-}o}$) using response surface methodology (RSM) based on the data obtained from validated steady-state numerical simulations. Four key design and operation factors (tube diameter, tube length, air velocity, and the temperature difference between inlet air and the undisturbed soil) were incorporated into the model. Based on the regression model, a mathematical model for predicting the cooling capacity (CC) of an EAHE tube was obtained. Parametric analysis was conducted to reveal the effects of the four factors on both the $\Delta T_{i\text{-}o}$ and the CC. The models on cooling performance allow the designers to optimize the EAHE configuration for cooling livestock buildings.

1. Introduction

Heat stress is a very important issue that troubles the commercial livestock farms in most regions of the world. It adversely affects animal behaviour and health, diminishes the productivity (West, 2003), and incurs significant economic losses (St-Pierre et al., 2003). Cooling is needed to maintain animal comfortable and productive in hot climate conditions; however, current cooling approaches (e.g., evaporative cooling by wet-pads or sprinkling, convective cooling by increasing indoor air movement) consume a large amount of energy and/or water. With the global demand for energy increasing, the cost of energy consumption for cooling livestock buildings in conventional manners would increase. In order to keep farming profitable, it is necessary to investigate alternative energy- and cost-effective cooling approaches for animal housing. In this light, earth-air heat exchanger (EAHE) system could be an option (Ghosal et al., 2004).

EAHE has been intensively studied for several decades, and most studies have been associated with residential buildings (Singh et al., 2018). For animal housing, the first attempt was conducted more than 50 years ago by Scott et al. (1965). Since then, several studies were carried out (Goetsch and Muehling, 1984; Krommweh et al., 2014). According to the literature review, the following conclusions of EAHE application associated with livestock buildings can be drawn: (1) EAHE is normally coupled with another ventilating system (the fresh air can be precooled by EAHE and then distributed by the ventilation system), (2) EAHE can reduce the cooling/heating load and generate better indoor thermal environment with less temperature variation inside livestock buildings, (3) EAHE is an energy-effective and feasible air-conditioning approach in animal housing, and (4) EAHE is often operated continuously in order to keep the animal thermal comfort. However, according to our literature search, no studies serve to optimize the design of EAHE, especially for animal buildings.

A mathematical model that predicts the cooling capacity based on several key design and operation parameters could help the system designers to optimize the EAHE design. From the literature review, several mathematical models have been developed to predict the cooling performance of EAHE system. For example, De Paepe and Janssens (2003) developed a simplified one-dimensional analytical model to evaluate the effects of design parameters (tube length, tube diameter, and number of tube) on the performance of a parallel EAHE

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system and stated that the model could benefit the decision making during the EAHE system design. Recently, Niu et al. (2015) developed a one-dimensional steady-state mathematical model that integrated both latent and sensible heat transfer to predict the cooling capacity of a single EAHE tube. Both aforementioned mathematical models were developed based on an assumption that the temperature of tube surface was constantly equal to the undisturbed soil temperature. In reality, however, due to the heat exchanger between the passing air and the adjacent soil, both the tube and the adjacent soil would be continuously heated with the EAHE continuously operating in cooling mode (Bansal et al., 2013). Mathur et al. (2015) quantitatively reported the temperature of the adjacent soil at 0.1 m in radial direction from tube surface and 5 m in axis direction away from the tube inlet rose from 26.39 °C at the initial phase to 27.27 °C after 5-hour continuous operation, and to 27.96 °C after 8 h. This increase in adjacent soil temperature adversely affects the cooling performance of EAHE system, and therefore, it is crucial to involve the effect of adjacent soil in a mathematical model aiding the design of EAHE systems.

Statistical regression is a commonly used method to develop a mathematical model, and the predictive accuracy is highly dependent on the number of tests (Bezerra et al., 2008). Completing a large number of tests using either laboratory or field experiments are costly, labour-intensive, and time-consuming. As an alternative, the response surface methodology (RSM) was employed to establish the mathematical model because it can reduce the number of tests but without significantly compromising the predictive accuracy (Shen et al., 2012) or the options identify the effects of individual factors or their interactions (Whitcomb and Anderson, 2004). To build the RSM model, computation fluid dynamic (CFD) technology was adopted to simulate all the required tests, because doing so is much cheaper and quicker than either laboratory or field experiment. As a tool solving heat and mass transfer problems, CFD has been used in many studies related to EAHE (Chen et al., 2016; Flaga-Maryanczyk et al., 2014; Jakhar et al., 2015; You et al., 2017).

This study was aimed to develop design-oriented mathematical models to estimate the cooling performance of EAHE for livestock housing. The intermediate objectives include: (1) to build and validate a CFD model of an EAHE tube that can reflect the cooling performance of the EAHE tube in long-term continuous operation; (2) to develop mathematical models for predicting both air temperature difference between inlet and outlet and cooling capacity of an EAHE tube; and (3) to assess the effects of investigated parameters on the cooling performance.

2. Materials and methods

2.1. CFD simulation

2.1.1. Assumptions

To simplify the analysis, the following assumptions have been proposed in the numerical model:

- The soil properties are isotropic and constant, such as heat capacity and thermal conductivity;
- The passing air is incompressible, and its thermal properties are constant;
- Convective and conductive heat transfers are taken into consideration, but radiative and latent heat transfers are omitted;
- The tube and adjacent soil are perfectly contacted, and temperature of the adjacent soil equals the temperature of the external tube surface.

2.1.2. Computational domain and mesh distribution

The computational domain was divided into two sub-domains (domain-air and domain-soil) by a 5 mm-thick PVC tube, as shown in Fig. 1a. The domain-soil was defined as a cylinder with the thickness of 0.5 m from tube surface, because the heat could hardly penetrate beyond ~0.5 m away from the tube surface even in a continuous operation mode (Mathur et al., 2015). Structural grids were generated to achieve high mesh quality by means of O-grid meshing approach using Ansys ICEM. Fig. 1c shows the grid distribution.

2.1.3. Governing equations

Both unsteady and steady states were simulated in this study. The general governing equation in CFD simulation can be expressed in Eq. (1) (Patankar, 1980; Rong et al., 2016).

$$\frac{\partial(\rho\Phi)}{\partial t} + \frac{\partial(\rho\Phi u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma_\Phi \frac{\partial\Phi}{\partial x_j}\right) + S_\Phi \tag{1}$$

where ρ is density, kg m^{-3}; u_j is the velocity component in j direction, m s^{-1}; Φ represents the common variables of interest, i.e., three velocity components, m s^{-1}, temperature, K, species (such as moisture), turbulent kinetic energy, m^2 s^{-2}, and its dissipation rate, m^2 s^{-3}; Γ_Φ is the transport coefficient dependent on Φ; and S_Φ is the source term dependent on Φ.

2.1.4. Boundary conditions

The inlet of the EAHE tube was set as velocity inlet. The turbulent intensity of airflow at the inlet was fixed to 5%, and the hydraulic diameter equalled the EAHE tube diameter. The soil outer surface (Fig. 1b) of the computational domain was treated as a wall with a constant temperature of 12.8 °C, which was the average 2-m deep soil temperature of July (the hottest month in Denmark) (Kristensen, 1959). The reason to use 2-m deep soil temperature is that the undisturbed soil temperature at 2-m under the ground is relatively stable (Baxter, 1992). The EAHE tube was represented using a 5 mm-thick conductive shell. The physical and thermal properties of soil and tube are listed in Table 1.

2.1.5. Solution technique, scheme, and convergence criteria

The realizable k-ε turbulence model was applied in all the simulations because its accuracy in numerical simulation relating to EAHE tube was proved acceptable (Misra et al., 2013). The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was utilized to discrete the governing equations. Second order upwind discretization was selected for momentum, turbulent kinetic energy (k), specific dissipation rate (ε), and energy to improve the accuracy of the final solution. The absolute residuals of continuity, air velocity, energy, k, and ε, as well as the area-averaged air temperature at the outlet and the net mass flow rate of the inlet and outlet, were all monitored during iterating.

In the steady-state simulations, the iteration was considered converged when the entire following three criterion were met: (1) the absolute residuals of continuity, velocity, k, and ε were less than 1×10^{-4}, and the absolute residuals of energy was less than 1×10^{-7}; (2) there was no obvious change (less than 0.1%) of the monitored the area-averaged air temperature at outlet within 100 iterations; (3) the net mass flow rate of the tube inlet and outlet was less than 10^{-4} kg s^{-1}.

In transient simulations, the time step size was set as 120 s, and the maximum iterations in each time step were set as 50 iterations, which was determined after performing some tests to assess the convergence of the solution. The iterations in each time step were considered converged when the absolute residuals of continuity, air velocity, k, and ε were less than 1×10^{-4}, and the absolute residuals of energy were less than 1×10^{-7}. As long as the monitored residuals met the convergence criterion within 50 iterations, the calculation at current time step would end, and start to next time step. However, for cases that the monitored residues have not met the criterion within 50 iterations, the calculation of current time step would also end and move to next time step.