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Simulation of flow field of a ventilated and occupied animal space with different inlet and outlet conditions

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Abstract

Simulation of flow field of a ventilated space of a biological object is necessary to determine heat exchange between the object and its environment. In this paper, flow fields of a ventilated space occupied by twenty randomly placed virtual cows are characterized under four different inlet and outlet situations. A three-dimensional turbulence model is used to characterize the flow field. The four inlet and outlet cases are: (1) ceiling-baffle inlet with airflow parallel to the wall with the outlet fan located at the center of the opposite wall, (2) wall-baffle inlet with airflow parallel to the ceiling with the outlet fan located at the center of the opposite wall, (3) the same as in Case 2 but with two inlets and outlets, in which one inlet and one outlet is located in each sidewall, and (4) center-ceiling baffle inlet and an outlet fan located at the center of each sidewall. There is significant variation in the uniformity of the flow field between the four air inlet/outlet locations. Air distribution is more uniform when air enters parallel to the ceiling from two sidewall inlets and exits through two sidewall outlets. The distribution is less uniform when air enters parallel to the ceiling from one sidewall only. Variations in sensible and evaporative heat fluxes are significant between cow locations for the same air inlet/outlet configuration, and for the same cow under the different air inlet/outlet configurations considered.

Keywords: Flow field; Simulation; Ventilated space; Air distribution; Air inlet; Air outlet; Heat exchange

1. Introduction

Characterization of flow field is necessary in order to predict energy budget of animals, energy balance of plants, thermal comfort of human body as well as determining air quality in a mechanically ventilated space. Air inlet and outlet types and locations significantly affect air distribution in a ventilated space. Airflow in a ventilated space is turbulent, and considerable research has been conducted in modeling and experimental testing of ventilated spaces. We did an extensive literature review on the subject and have reported it through this Journal (Gebremendhin and Wu, 2003).

The focus of this study is to characterize the flow field of a ventilated space occupied by twenty randomly placed virtual cows using a computational fluid dynamics (CFD) technique. Four air inlet and outlet cases are studied. To our knowledge, no study is currently available in the literature that has characterized the flow field of a ventilated space for the boundary conditions (inlet and outlet cases), and considering the effect of the actual dimensions and configurations of multiple occupants on the flow field. Furthermore, more realistic characteristic velocities can be calculated from

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simulated flow fields and these velocities can be used to obtain a more accurate prediction of heat exchange between an enclosed biological object and its microenvironment.

This study is the first step for future research on the development of a non-isothermal computational fluid dynamics model, which will account for some important factors such as heat production by a biological object enclosed in a ventilated space, indoor/outdoor temperatures and other modification of building design parameters.

1.1. Objectives

The specific objectives of this study are:

1. To characterize the flow field of a ventilated space using a three-dimensional turbulence model considering the actual dimensions and configurations of twenty randomly placed virtual cows in the space.
2. To determine the effect of four inlet and outlet conditions on the flow field of the ventilated space occupied by the same number of cows.
3. To calculate more realistic characteristic velocities from the simulated flow fields and use these velocities to determine energy exchange between three arbitrarily selected cows and their microenvironments.

2. Model development

2.1. Assumptions

The following assumptions are made in formulating the turbulence model:

(1) Airflow inside the ventilated space is steady state,
(2) Flow is three-dimensional and turbulent,
(3) Air is isothermal (heat generated by the cows is not considered) and incompressible, and
(4) The gravitational force of air for forced convection is assumed to be negligible.

2.2. Model formulation for flow field

Based upon the above assumptions, the governing equations used are (1) the continuity equation, and (2) the conservation of momentum equation (Reynolds-averaged Navier–Stokes equation), and are expressed, respectively, in tensor form as

Continuity equation:

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

and the momentum equation:

$$\underbrace{\frac{\partial u_i}{\partial t}}_{①} + \underbrace{\frac{\partial}{\partial x_j}(\rho u_j u_i)}_{②} = \underbrace{-\frac{\partial p}{\partial x_i}}_{③} + \underbrace{\frac{\partial}{\partial x_j}\left(\mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\overline{u_i' u_j'}\right)}_{④}, \tag{2}$$

where, ① is the transient term, ② the convection term, ③ the pressure gradient term and ④ the diffusion term and u is velocity, μ_t is viscosity, ρ is fluid density, and p is static pressure.

The Reynolds stress term ($-\rho\overline{u_i' u_j'}$), which is initially unknown, cannot be expressed as a function of mean flow variables but is related to known quantities using a turbulence model. The turbulence model considered herein is based on the closure of the Reynolds stress term.

2.3. Boussinesq's eddy-viscosity concept

One approach to turbulence closure is based on Boussinesq's eddy-viscosity concept (Boussinesq, 1877). The Reynolds stress is assumed to be proportional to the local mean velocity gradient, which is analogous to the viscous stress in a laminar flow and is expressed as (Hinze, 1975)

$$-\rho\overline{u_i' u_j'} = -\mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \frac{2}{3}\rho\delta_{ij}k, \tag{3}$$

where, μ_t is turbulent (eddy) viscosity, δ_{ij} is Kronecker delta. $\delta_{ij} = 1$ for $i = j$, and $\delta_{ij} = 0$ for $i \neq j$, and k is turbulent (fluctuating motion) kinetic energy. The left and right terms of Eq. (3) are expressions for Reynolds stress.

The eddy viscosity (μ_t) is not a fluid property as molecular viscosity, but is a flow property that depends strongly on the state of turbulence.

The turbulence model used in this study is the RNG $\kappa - \varepsilon$. Yakhot and Orszag (1986) derived a $\kappa - \varepsilon$ model based on renormalization group methods, thus the term RNG. In this approach, RNG techniques are used to develop a theory for large scales in which the effects of small scales are represented by modified transport coefficients. The RNG $\kappa - \varepsilon$ turbulence model is derived from the turbulent viscosity (μ_t) as

$$\mu_t = \rho c_{p,\mu}\frac{k^2}{\varepsilon}, \tag{4}$$

where $c_{p,\mu}$ is specific heat of the fluid, and ε is the dissipation rate of turbulent kinetic energy.

The transport equations for the turbulent kinetic energy (k) and its dissipation rate (ε) can be expressed, respectively, as

$$\underbrace{\frac{\partial(\rho k)}{\partial t}}_{⑤} + \underbrace{\frac{\partial}{\partial x_j}(\rho u_j k)}_{⑥} = \underbrace{-\frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right)}_{⑦} + \underbrace{(P_k - \rho\varepsilon)}_{⑧}, \tag{5}$$