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DEVELOPMENT AND VALIDATION OF CFD MODEL FOR COMPOST BARN WITH ARTIFICIAL VENTILATION

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Computational fluid dynamics
Air velocity

ABSTRACT

Computer simulation can provide reliable information about fluid flow behavior, including ventilation, in animal production systems. The ventilation system is essential for thermal conditioning, as it favors animal comfort and enhance productivity. The objective of this study was to develop and validate a CFD (Computational Fluid Dynamics) model to analyze the ventilation system in a compost barn. A mesh with greater refinement was used near the air inlet and outlet and the floor, that is, in these regions the mesh number of cells was larger, which makes a denser mesh. For the validation, data on air velocity were collected in the barn to compare with the results of the simulation. Dead zones of ventilation were identified in the barn, there was an increase in the average air velocity at the air outlet, and temperatures and air velocity were found below the optimal recommended by the literature. However, the adjusted model showed good fit with the values measured, indicating that is a good tool to predict the behavior of air velocity. In addition, the detection of ventilation dead zones inside the barn demonstrates the need for a supplementary ventilation system.

Palavras-Chave:
Bovino de leite
Fluidodinâmica computacional
Velocidade do ar

DESENVOLVIMENTO E VALIDAÇÃO DE MODELO CFD PARA CELEIRO DE COMPOSTAGEM COM VENTILAÇÃO ARTIFICIAL

RESUMO

A simulação computacional pode fornecer informações confiáveis sobre o comportamento do escoamento de fluidos, incluindo a ventilação nos sistemas de produção animal. O sistema de ventilação é primordial para o acondicionamento térmico, pois favorece o conforto dos animais, beneficiando assim a produtividade. Objetivou-se desenvolver e validar um modelo CFD (*Computational Fluid Dynamics*) para analisar o sistema de ventilação no interior de um galpão *compost barn*. Foi utilizada uma malha com maior refinamento próximo à entrada e saída de ar e no piso, ou seja, nessas regiões o número de células que a malha apresentou foi maior, sendo assim uma malha mais densa. Para a validação, foram coletados dados de velocidade do ar no interior do galpão, para comparação com os resultados obtidos na simulação. Foi identificado a presença de zonas mortas de ventilação no interior do galpão, houve acréscimo da velocidade média do ar na saída de ar e os valores de temperatura e velocidade do ar se apresentam abaixo do ideal preconizado pela literatura. Contudo, o modelo ajustado mostrou boa concordância com os valores medidos, sendo uma boa ferramenta para predizer o comportamento da velocidade do ar. E a identificação de zonas mortas de ventilação no interior da instalação aponta a necessidade de um sistema de ventilação suplementar.

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INTRODUCTION

The confinement of dairy cows is an alternative to improve the animal comfort, as it enables greater control of the environment. Increase in production, milk quality and greater longevity are achieved through this management practice (Pereira et al., 2010). Compost barn is a confinement system for dairy cattle that houses and keeps the animals in a common bedded area. The characteristic of the system is the bed composting process, induced by the periodic turning of the waste for its aeration (Mota et al., 2017). Therefore, an efficient ventilation system is essential for thermal comfort and air quality. Air movement is important for reducing thermal stress, as it favors heat loss by convection and, depending on the relative humidity of the air, it also helps with the evaporation losses. A properly dimensioned ventilation improves the thermal condition of the buildings (Bustamante et al., 2017).

Computational Fluid Dynamics (CFD) is a promising tool for understanding the behavior of airflow inside animal facilities (Saraz et al., 2017). Especially when in situ measurements are time consuming and difficult, besides producing only point data (Mostafa et al., 2012). CFD, in turn, provides a complete representation of the air flow inside the barn. Currently, computational fluid dynamics has been widely used in the study of ambience in animal production units (Vilela, 2020; Drewry et al., 2018; Rojano et al., 2015). In addition, studies show the application of this tool in the assessment of ventilation systems in dairy cattle facilities (Zhou et al., 2019; Yi et al., 2019). Consequently, for a reliable application of this tool, it is essential to carry out the validation procedure (IJEE, 04). Thus, this work aimed to develop and validate a model for the study and improvement of the ventilation system in a compost barn.

MATERIAL AND METHODS

Physical domain

The study was conducted in a milk production unit located in the Zona da Mata Mineira. The climate, according to the Köppen classification, is characterized by a cold and dry winter and a hot and humid summer. A compost barn, 50 m long, 24 m wide and 5 m high, was analyzed. The east and west sides are closed by fixed polyethylene curtains. The north and south sides are open, and the air inlet has an area of 64.8 m^2.

Computational model

The barn geometry was created in DesignModeler, Workbench computational package (Ansys R2 2019). At the creation stage, the following criteria were considered: i) geometry delimited by the floor, walls and ceiling, forming a parallelepiped; ii) absence of animals and fence inside the building; iii) entry and exit area represented by a rectangle with area of 64.8 m^2. The mesh with 49032 nodes was obtained. Further refinement was performed near the floor and air inlets to figure out the effect of air velocity near the barn air inlets.

The CFD technique was used to solve the Navier-Stokes equations and the energy equation, discretizing the velocity, temperature and pressure fields using the finite volume method. The set of governing equations consists of the equations of continuity (Equation 1), conservation of momentum (Equation 2) and energy (Equation 3) (Hajmohammadi et al., 2013).

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_j}{\partial x_j} + \rho g_i \tag{2}$$

$$\frac{\partial}{\partial t}(\rho c T) + \frac{\partial}{\partial x_j}(\rho u_j c T) - \frac{\partial}{\partial x_j}\left(K \frac{\partial T}{\partial x_j}\right) = S_T \tag{3}$$

Where,

p = Pressure (Pa);
g = Acceleration due to gravity (m s^{-2});
τ = Stress tensor (Pa), given by

$$\bar{\tau} = [\nabla \cdot \vec{v} + \nabla \cdot \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} I;$$

ρ = Fluid density (kg m-3);
τ_{ij} = Voltage Tensor (Pa);
c = Specific heat (W kg^{-1} K^{-1});
k = Thermal conductivity (W m^{-1} K^{-1});
S_T = source term.

The considerations assumed the flow as steady, incompressible and turbulent. The domain boundary condition for the entry was of the inlet type, with an average inlet air temperature of 26.5 ºC and air velocity of 2.4 $m.s^{-1}$. For the exit, it was of the outlet type, with an average temperature of the exit air of 27.6 ºC and pressure of 0 Pa. The boundary condition for the wall was the slip wall type, assuming the absence of friction.

Model validation

For validation, air velocity data inside the barn were collected with a hot wire anemometer (manufacturer: Testo, model 425, resolution of 0.01 $m.s^{-1}$, accuracy of ± 0.03 $m.s^{-1}$ and operation range from 0 to 20 $m.s^{-1}$), at two levels, 0 and 1.5 m from the floor, at 10 points along the barn (Figure 1). The external temperature was monitored with a recording sensor (manufacturer: Onset, hobo model UX100-003, with a resolution of 0.024 °C, accuracy of ± 0.21°C and measurement range of -20 to 70 °C) . Data were collected during three consecutive days to obtain average air velocities.

The results of the CFD model were compared with the experimental data based on the normalized mean squared error (NMSE) (Equation 4), using measured (Vm) and simulated (VCFD) values.

$$NMSE=\sum\frac{(V_{CFD}-V_{m})^{2}}{(V_{CFD}\times V_{m})} \qquad (4)$$

Where,

NMSE = Normalized Mean Square Error;
V_m = Measured value;
V_{CFD} = Simulated value.

RESULTS AND DISCUSSION

For validation, air velocity values obtained by CFD were compared with the measured values, in the same physical positions. NMSE was calculated, Table 1 shows the results.

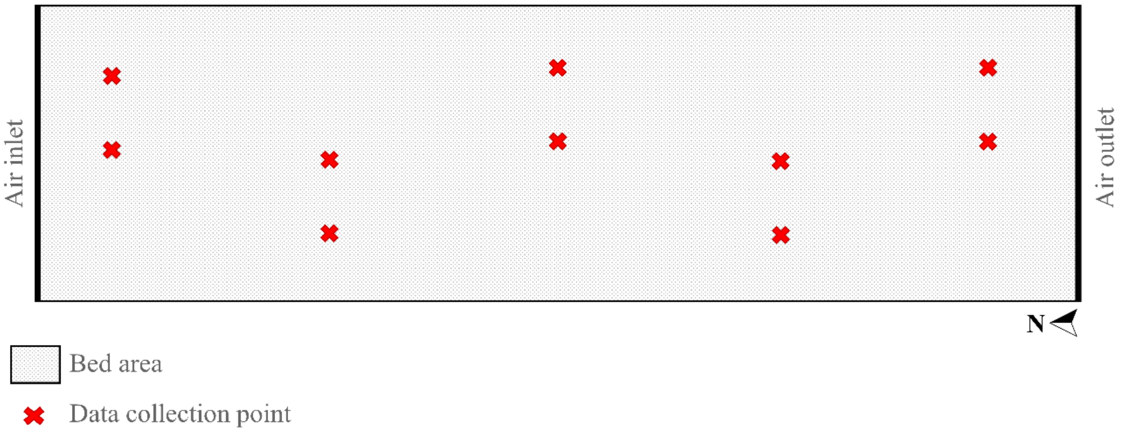

Figure 1. Data collection points inside the barn

Table 1. Normalized Mean Square Error (NMSE) between simulated and experimentally obtained air speed values

Point	Experimental value ($m.s^{-1}$)	Simulated value ($m.s^{-1}$)	NMSE (%)
1	1.65 ± 0.8	1.69	0.056
2	1.90 ± 0.75	1.89	0.002
3	1.39 ± 0.81	1.58	1.667
4	1.61 ± 0.66	1.55	0.136
5	1.40 ± 0.75	1.35	0.129
6	1.50 ± 0.63	1.47	0.029
7	1.51 ± 0.8	1.48	0.048
8	1.86 ± 0.64	1.88	0.003
9	1.75 ± 0.75	1.69	0.057
10	1.81 ± 0.68	1.91	0.138
Mean			0.257

Based on the calculated normalized mean squared errors (NMSE), there is good fit between the measured data and the simulated data at all points studied, except for point 3. This is because, according to Mostafa et al. (2012), NMSE below 0.25 represents good fit between simulated and field data. Sun et al. (2012) studied the airflow inside barns using CFD and found NMSE around 0.2, which is considered satisfactory for predicting air velocity. Mostafa et al. (2012) analyzed different ventilation system configurations in animal buildings and obtained NMSE of 0.152.

The simulation result is shown in Figure 2, on a plane 1.5 m from the floor (average height of the animals). Figure 3 describes the behavior of air velocity along the length of the barn.

Dead ventilation zones are seen near the side closures, floor surface and near the barn ceiling. The ventilation dead zones near the floor hamper the aeration of the bed used in the confinement, as well as diminish the thermal comfort of the animals, requiring an improvement in the ventilation system.

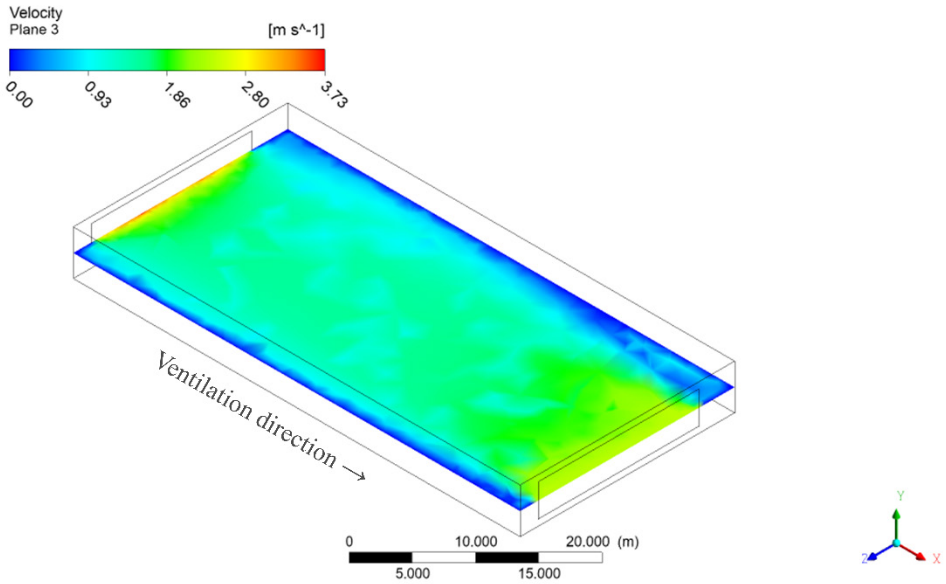

Figure 2. Air velocity plan inside the barn

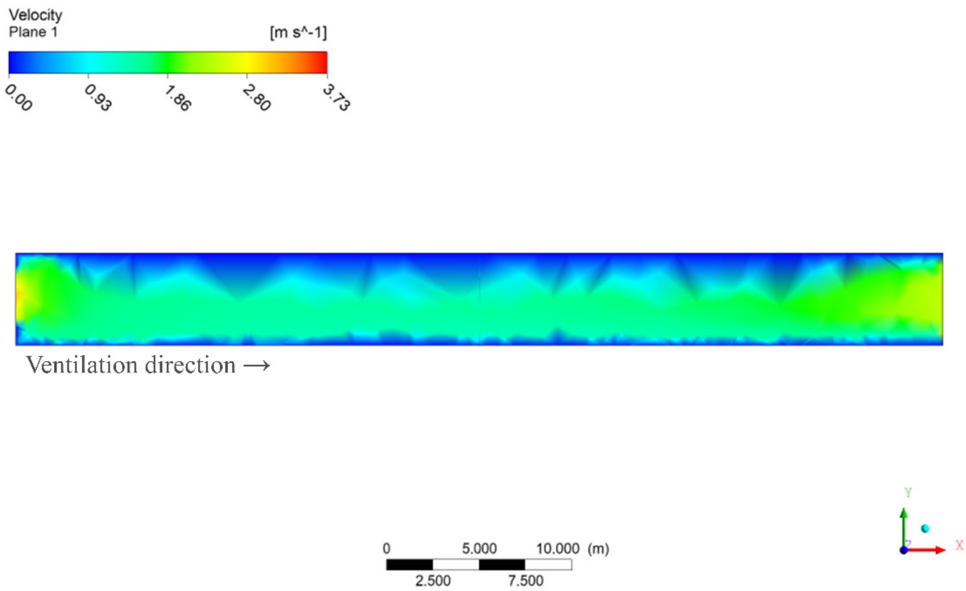

Figure 3. Air velocity plan along the barn length

The ventilation dead zones close to the barn ceiling may be due to the presence of deflectors, which are stratagems to direct the air flow to lower areas of the building. The air velocity at the outlet increases due to the principle of conservation of mass. The average air velocity at the outlet was calculated at 2.9 m.s^{-1}, while at the inlet was 2.4 m.s^{-1}.

Average air velocities for lactating cows are proposed by Harner et al. (2007), indicating 2.6 m.s^{-1} as satisfactory for the animals. Corroborating with these authors, Shiao et al. (2011) proposed 2.3 m.s^{-1} and Ricci et al. (2013), 2.5 m.s^{-1}, with average temperatures of 18°C, 19°C and 17°C, respectively. Contrasting these data, the average temperature obtained in this study was 25°C and the air velocity was 1.6 m.s^{-1}, therefore, they were below the averages recommended in the literature, demonstrating the need to improve the ventilation system in the barn.

CONCLUSIONS

- The adjusted model was proven satisfactory, providing reliable results in the simulation. Thus, it can help predict the behavior of air velocity and improve the ventilation system of the building. The presence of ventilation dead zones inside the barn reinforces the need for an additional ventilation system so that the air flow reaches the cows and the bedding in the confinement system.

AUTHORSHIP CONTRIBUTION STATEMENT

ZANETONI, H. H. R.: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review & editing; **VILELA, M. O.:** Conceptualization, Formal Analysis, Investigation, Methodology, Software; **CARLO, J. C.:** Conceptualization, Supervision, Writing – review & editing; **SOUZA, M. A.:** Formal Analysis, Methodology, Writing – original draft; **PARANHOS, C. O.:** Formal Analysis, Methodology, Writing – original draft; **MARTINS, M. A.:** Conceptualization, Methodology, Software, Supervision, Writing – review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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