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Study on convective heat transfer from pig models by CFD in a virtual wind tunnel

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ABSTRACT

Heat stress strongly affects the pig production in hot climate regions, including the summer of many continental climate regions. Although it is recognized that increasing the local air speed in the animal occupied zone is one of the effective approaches to decrease the heat stress of pigs, few studies have been found to quantify the relationship of air speed and convective heat transfer from the pigs. The main objective of this study is to evaluate the impact of airflow speed, turbulence intensity, and animal orientation on the convective heat transfer so that it can be implemented into ventilation control algorithms to provide a better production environment. The study was mainly performed by CFD simulations in two geometry models, a pig model with actual size and a simplified cylinder model, in virtual wind tunnel. The validation of CFD modelling was conducted by comparing the simulated Nusselt number with the values determined by semi-experimental equation for cylinder geometry model. The effects of air speed, inlet turbulence intensity, air incidence angles and pig skin modelling on convective heat transfer coefficients were studied. It is proved that CFD method could be a very good alternative way for this kind of study. The convection heat transfer of a pig model has similar tendency with the cylindrical model following the increasing of air speed. A correlation of convective heat transfer coefficient was found between the geometry of actual pig model and cylinder model. The orientation and turbulence intensity significantly affect the convective heat transfer coefficient of pig, and the results indicate animal orientation and turbulence intensity need to be considered for model development process of the convective heat transfer of pig.

1. Introduction

Heat stress is generally noticed to affect the production. It is a consensus that the heat stress can be reduced by developing better ventilation technologies. However, due to the extremely harsh environment, it has been always a challenge topic to design appropriate ventilation system economically for pig production buildings in hot climate. According to the heat transfer theory, to increase the air speed and turbulence level in the animal occupied zone is one of the effective approaches to reduce the heat stress of pigs (Massabie and Grainer, 2001; Mount, 1975; Pond, 2003; Stolpe, 1986). However, a systematic study is still needed to reveal the impact of environmental parameters on the heat loss from animal.

The increased heat loss by increasing the air velocity mainly comes from the convective heat transfer. The convective heat transfer from animal is usually calculated based on the surface area of animal, the convective heat transfer coefficient, and the temperature difference between animal surface and the environment. Among the variables, the surface area, surface temperature, and environment temperature generally can be measured directly. However, the convective heat transfer coefficient is a complex function of many factors, such as air velocity, turbulence intensity, the animal geometry, surface roughness, animal orientation, animal sizes, etc. Increasing the local air speed and turbulence intensity at animal occupied zone leads to the increase of heat release from animals to the surrounding air.

A number of studies on the effect of air speed on convective heat transfer coefficient from animals can be found in literatures. Generally analytical and experimental methods were adopted (Monteith and Unsworth, 2013). Theoretical analysis is valuable for providing general insights for simple geometry but less applicable for complex geometries such as animals especially moving animals (Gebremedhin, 1987; Mitchell, 1976). There could be a correlation of convective heat transfer coefficients between simplified geometry (e.g. cylinder due to the similarity of pig shape) and complex pig model, but further investigations and clarifications are necessary. Experimental measurements conducted in wind tunnel

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have been providing support for fundamental knowledge but it was unavoidably hindered by the scale effects (e.g. extending the results to full scale when heat transfer was related), and the experimental designs (e.g. how to position the animals in the wind tunnel) is another difficulty in those measurements (Mount, 1966). The experiments were often conducted in small wind tunnels because it reduced the requirement of airflow capacity and therefor improved the conditions for determine the heat release (Mitchell, 1985; Mount, 1966; Wathes and Clark, 1981). In addition, orientation of animal has been proved to be an important factor on the convective heat loss from a calf model based on the studies by Gebremedhin (1987). However, for pigs, there is still no published report available on this aspect. Due to the complicacy of pig behaviour, the research on the orientation effect on heat convection from pig is necessary. Turbulence intensity is another key factor on heat convection (Yardi and Sukhatme, 1978), the complexity of airflow condition in pig barn makes the turbulence an important parameter to investigate on convective heat loss from pigs. These two parameters, animal orientation to airflow and turbulence intensity, are usually complicated to study in the experimental methodology and are not systematically investigated.

Recently computational fluid dynamics (CFD) has been increasingly applied in studying the design and development of ventilation systems in animal buildings (Bartzanas et al., 2002; Bjerg et al., 2002; Wu et al., 2012). One of the main advantages of CFD modelling is that it allows full control on the influencing factors and it provides detailed information of all parameters distribution in the computational domain. Concerning to the study of convective heat transfer, CFD has also been proved to be a powerful tool not only on the study of bluff body with simple geometry, e.g. sphere and cylinder (Constantinescu and Squires, 2004; Defraeye et al., 2013; Dhole et al., 2006; Dixon et al., 2011; Kondjoyan and Boisson, 1997), but also on the study of complex geometry such as horticultural products and finned cylinder bundle (Defraeye et al., 2012; Tian et al., 2015). Concerning the research of livestock housing, animal models in real geometry are also used in some of CFD studies for environment parameters inside animal buildings (Bjerg et al., 2008; Gebremedhin and Wu, 2005; Seo et al., 2012), most of them mainly focused on the blocking effect of the air movement, and assumed constant skin temperature or heat flux of the animals. None of them considered the skin layer modelling, e.g. thickness and heat conduction of the skin layer, which may have impacts on the surface convective heat transfer process.

In this study, CFD is adopted to investigate the influence of air speed, inlet turbulence intensity, air incidence angle on convective heat transfer of a pig in a virtual wind tunnel. For CFD modelling, it is imperative to perform the validation since the error and uncertainty of the CFD method may exist during the numerical computational process (Roache, 1997). Due to the lack of experimental data achieved from the study of live animals, the validation was performed by using cylinder geometry in the virtual wind tunnel and the simulated results were compared to the calculation of semi-experimental equations found in the literatures. To better simulate the real condition of pig, a test on the skin layer modelling is also conducted.

The objectives of this study are: (1) to validate the CFD modelling by using cylinder geometry in the virtual wind tunnel; (2) to investigate the effect of skin thickness of pigs on convective heat transfer; (3) to provide the correlation of convective heat transfer coefficient between cylinder geometry and actual pig model; (4) to test the effect of air speed, air incidence angle, inlet turbulence intensity on the convective heat transfer of pig.

2. Methods

2.1. Physical model and computational domain

In this study, two configurations, cylinder and pig model, were used in the virtual wind tunnel.

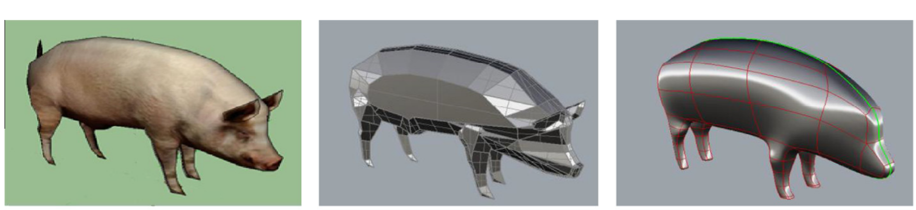
2.1.1. Models

Although actual pig model could be modelled in CFD, two steps of simplification were still processed for ensuring the mesh quality and maintain the affordable mesh number. The pig model (Fig. 1(a)) was generated by modelling software Rhino (Robert McNeel & Associates) and then used for the first-step simplification, and finally it (Fig. 1(b)) was smoothed in order to improve the efficiency of meshing procedure and to control the mesh resolution, Fig. 1(c). The heat conduction from the inner body to the skin surface was not considered in this part of study therefore the pig model and cylinder located in the wind tunnel was only a hollow-closed blocking body. The surface area of the pig model was 1.554 m^2 which corresponds to a pig weight of 80.0 kg accordingly (Brody et al., 1928).

In order to ensure that the convective heat transfer coefficient between cylinder and pig shape model was comparable, the same surface area for cylinder model was used, which leads to the diameter (D) of 0.344 m when the ratio between the length and diameter of the cylinder is 4.0. In this ratio, the cylinder can be treated as infinite so that the calculation results by the semi-experimental equation developed by Churchill and Bernstein (1977) can be used for CFD validation.

2.1.2. Computational domain

Computational domains for both cylinder (Fig. 2(a) and (b)) and pig models (Fig. 2(b)–(d)) were 25D, 15D and 10D in length, width and height, respectively. The models were placed at 5D from inlet, and the cylinder model was placed in two heights, 5D (Fig. 2(a)) and 0.9D (Fig. 2(b)) above the floor, while the pig model stood on the floor. 5D to the bottom corresponds to the condition that cylinder was in the middle in height dimension in which most of experiment on the convective heat transfer from cylinder were carried out. 0.9D to the bottom was calculated based on the leg length of pig in this study. In order to study the orientation effect on convective heat transfer, the pig model was placed in 3 different orientations, with trunk axis perpendicular to wind direction (90°) (Fig. 2(c)), with trunk axis 45° to wind direction (45°) (Fig. 2(d)), and with trunk axis parallel to wind direction with head facing wind (0°) (Fig. 2(e)). The blockage ratio, which describes the frontal



(a) (b) (c)

Fig. 1. The procedure of generating the model pig: (a) The original pig geometry, (b) first-step simplified model, (c) the smoothed model.