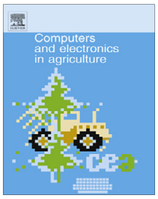
ARTICLE IN PRESS

Computers and Electronics in Agriculture xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag



Numerical study on the convective heat transfer of fattening pig in groups in a mechanical ventilated pig house

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ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form 27 April 2017
Accepted 14 August 2017
Available online xxxx

Keywords:
Pig house
Convective heat transfer coefficients
Air inlet
Air velocity
CFD simulation

ABSTRACT

It is recognized that increasing the local air speed in the animal occupied zone (AOZ) is one of the effective approaches to decrease the heat stress of pigs. To predict the effects of the air speed in an AOZ, knowledge of the relationship between convective heat loss and air speed is essential. In this study, the convective heat losses from pig models were modelled through numerical simulation under semi-practical conditions. The convective heat transfer coefficients of pigs in groups were tested at different inlet speeds. Virtual pig bodies (pig models) corresponding to three different body weights, i.e., 30 kg, 50 kg, and 80 kg, were generated and used in the investigation. Two wall inlet styles, a conventional inlet with an upward guiding plate and a modified inlet that supplied downward airflow directly onto the pigs, were compared to estimate the effect of ventilation system on the convective heat loss of pigs. The results showed that convective heat transfer coefficients of pigs in a group were strongly correlated with the inlet air speeds as well as the reference air speed in the AOZ (the average air speed in AOZ was selected as reference air speed in this study). The weight of the pig models showed no significant effect on the convective heat transfer coefficient. The convective heat transfer coefficient of the pigs in pens with the downward inlet was averagely 60.4% higher than those with the upward inlet.

1. Introduction

Heat stress can strongly affect animal production and animal health, and in extreme conditions may lead to mortality of animals (Johnson et al., 2015). Heat stress can not only occur in tropical/subtropical regions but also in countries located in climate zones with hot summer. Even in Denmark which is normally considered as a cool country, heat stress can happen in a short period during summer if no engineering solution is applied. It is recognized that increasing the local air speed in the animal occupied zone (AOZ) is one of the feasible approaches to decrease the heat stress of pigs (Massabie and Grainer, 2001; Mount, 1975; Pond, 2003; Stolpe, 1986), since the convective heat loss from animal body is strongly correlated to the air speed. Surface area, temperature difference between animal skin surfaces and the environment, and the convective heat transfer coefficient are the three main factors on the convective heat transfer. The first two factors are relatively easy to be measured or estimated. The convective heat transfer coefficient can be more complex, and it can be affected by other factors, like animal geometry, animal size and airflow pattern around the animals (Li et al., 2016a). Therefore, knowledge on convection heat transfer coefficient is essential to provide a better control of the ventilation system.

The convective heat transfer from animals has been modelled against air speed in some research studies (Gebremedhin, 1987; Li et al., 2016a; Mitchell, 1976; Monteith and Unsworth, 2013). However, most of these experiments were conducted under wind tunnel or controlled chamber conditions. To the authors' knowledge, very few experimental studies on the convective heat transfer coefficient of animals in group can be found in production building scale. The reason can be the difficulties in directly measuring the air speed in the AOZ. And to separate conduction and radiation from convective heat transfer is another challenge. Therefore, a systematic study under a controllable condition is necessary to quantify the convective heat transfer of pigs in groups. To achieve this goal, instead of field measurement, numerical simulations basing on computational fluid dynamics (CFD), were applied in this study.

The inlet is important for the ventilation system for animal housing, since the character of the airflow through the inlets can strongly affect air motion and distribution in the room (Bjerg et al., 2002; Zhang et al., 2002). In practical husbandry condition, ceiling jet inlets which suppling the air directly to the AOZ from the ceiling has been commonly used in the summer condition. It

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http://dx.doi.org/10.1016/j.compag.2017.08.013
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Please cite this article in press as: Li, H., et al. Numerical study on the convective heat transfer of fattening pig in groups in a mechanical ventilated pig house. Comput. Electron. Agric. (2017), http://dx.doi.org/10.1016/j.compag.2017.08.013

has been reported by Bjerg and Zhang (2013) that the ceiling jet inlet showed good effect on reducing heat stress under summer conditions. A wall inlet with downward flow might have similar effects as the ceiling jet. If a wall inlet can be configured with additional downward flow function besides the conventional horizontal and upward flow functions, it would be the optimal. However, it is still unknown how the performances will be for a wall inlet with downward flow. Therefore, the wall inlet with downward flow was involved in this study to evaluate its effect on the convective heat transfer coefficient and to compare its performance with that of the normal inlet with upward flow.

The CFD method which is equating the advantages of fully control of boundary conditions, providing the universal data in the computational domain, and lower cost with higher flexibility compared with experimental method, has shown increasing tendency in being applied in studies of ventilation systems for animal buildings (Bartzanas et al., 2007; Bjerg et al., 2013; Lee et al., 2013; Mondaca and Choi, 2016a; Norton et al., 2007; Rong et al., 2016). Furthermore, CFD was also used in modelling of animals thermal conditions in varied environments at building scale. Norton et al. (2010) studied the thermal and airflow condition in a calf building using this tool. And Seo et al. (2012) conducted a detailed modelling process in a commercial pig house based on CFD. As for the CFD usage in studying convective heat transfer from animals, Li et al. (2016a) made a detailed study on a pig model in a virtual tunnel. All these prove that CFD is a competent approach to the research for this field. It is common to simplify the models in CFD simulations. Otherwise the simulation can become too complex for physical modelling in the iterations. For instance, the pig models were considered as a constant surface temperature and the metabolic process was not considered in this study.

Thus, the objectives of this study are using numerical methods to (1) investigate the relationship between the air speed and convective heat transfer from pigs in groups; (2) test the impact from the pig size on the convective heat transfer from pigs under group condition; (3) evaluated the effect of ventilation system on the convective heat transfer from pigs in groups.

2. Materials and methods

2.1. Description of the experiment used for validation

The experimental measurements were conducted in one section of the pig rooms at the climate laboratory in Aarhus University, Denmark. The schematics of the room, measuring locations are shown in Fig. 1. The dimensions of the room were measured as 5.70 m × 4.88 m × 2.67 m (length (x) × width (z) × height (y)) with one working corridor and two full scale pigpens that corresponded to the dimensions of typical Danish pigpens in commercial pig farms. In each pig pen, the floor was made up of one-third of drain floor (1.6 m of length, opening ratio in 8.5%) and two-third of slatted floor (3.2 m of length, opening ratio in 16.5%). Two artificial pigs were placed in each pigpen, with one in the centre of drain floor area and the other one in the centre of slatted floor area. Beneath the floor, there was a 0.69 m deep slurry pit for each pen. The experimental measurements were conducted under non-isothermal conditions with ventilation rate at 2533 $m^3\,h^{-1}$. Sidewall jet inlet supplied the air into the room. Before each measurement, the ventilation system was on for around 3 h to reach steady state inside the room. During the experiments, the ventilation rate was measured by a free propeller and recorded by a climate control system (Vengsys, Denmark) every minute. Using omnidirectional Air Velocity Transducer (TSI, model 8475) and CR1000 data logger (Campbell Scientific Ltd, UK), the air speeds were measured every 0.2 s and averaged every 1.0 s for a measurement period of 60 min at each measurement point. The room temperature and humidity were continuously measured by the sensors equipped in the room and recorded each minute by the climate control system. The surface temperatures of the walls and artificial pigs were measured by thermo couples with a data logger (Eltek Ltd, UK) every 5 min during the experiment.

2.2. CFD modelling

2.2.1. Geometry and calculation domain

To effectively use the computing power and reduce the complexity in the mesh generation, the computational domain was divided into three parts (Fig. 2): above AOZ domain, AOZ domain, and below AOZ domain. The domains were connected to adjacent domains by interfaces. For the below AOZ domain, only one type of geometric model was used. It was exactly following the real building dimensions which have been described in the last section. For the AOZ domain, four types of geometric models were built, namely, one following the geometric model in the validation experiment, and three others containing 32 pig models weighing 30 kg, 50 kg, and 80 kg, respectively. The complexities of animal's geometric shape can affect the convective heat transfer. Therefore, animal models in numerical studies should have accurate shapes close to their real shapes to certain levels (Mondaca and Choi, 2016b). To achieve better simulation results, the pig models in this study were modelled at a computationally affordable level with reasonable simplifications following the procedure presented by Li et al. (2016a) (Fig. 3). The models were scaled up or down based on the weights of the pig models according to a relationship developed by Brody et al. (1928). For the cases with pigs in 30 kg and 50 kg, the distribution of pigs in pens were referred to the layout presented by Bjerg et al. (2011), Fig. 4(a) and (b). For the cases with 80 kg pigs, the models were assumed uniformly distributed in each pen, due to the limited space in the pens (Fig. 4(c)). Two types of inlets were modelled in the above AOZ domain. One was the same as those used in the validation experiment, with the height and length in 0.17 m and 0.62 m, respectively. The inlet was measured having an upward angle of 50 degree. In the contrast to the upward one, a downward inlet with downward angle of 50 degree was modelled. This inlet was intended to guide the air directly to the AOZ. To make those two inlets comparable, the inlets had almost same dimensions. The only differences were the guiding angle and the length of the guiding plate downside. The setups and dimensions of the inlets are illustrated in Fig. 5. The ventilation rates evaluated in this study corresponded to 0.75 times, 1 times, 1.5 times, and twice as high as the standard Danish maximum ventilation rate. The average inlet jet speeds were calculated as 3.1 $m\,s^{-1}$, 4.2 $m\,s^{-1}$, 6.3 $m\,s^{-1}$, and 8.4 $m\,s^{-1}$ accordingly on the inlet side. The detailed combinations of the geometric models for the different cases are listed in Table 1.

2.2.2. Mesh

A mesh generation strategy presented by Li et al. (2017a) was adopted to generate the grids in this study. Different grid schemes were used in different computational domains. In general, structured hexahedral mesh was used in the above AOZ domain and the below AOZ domain where geometries were relatively in regular shapes. Unstructured tetrahedral mesh was used in the AOZ domain wherever the geometry was more complex.

For the mesh used in the validation case (Case 1), the grid numbers of the structured hexahedral meshes in the above AOZ and below AOZ domain were 561,444 and 1,217,494, respectively. And the grid number of the unstructured tetrahedral grids in the AOZ domain was 1,439,820. In both the structured hexahedral and the unstructured tetrahedral mesh, the aspect ratio was kept at 1.2. A detailed grid independence test has been presented by Li et al. (2017a) to compare the mesh in different grids strategies.

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