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

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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 by varying the air speed in AOZ, knowledge of convection heat loss and air speed is essential. In this study, the convective heat loss from pig is studied based on numerical simulation on a semi-practical condition. The convective heat transfer coefficients from grouped pigs were tested under different inlet speeds. The pigs in three different body weights, i.e., 30kg, 50kg, and 80kg were used in investigations. Two inlet styles, conventional inlet with upwards airflow direction and modified inlet which supplied the air directly on the pigs in pen, were compared to estimate the effect of ventilation systems on the convective heat loss of pigs. The results showed that convective heat transfer coefficient of pigs in group was strongly correlated with the inlet air speed. The weight of pig models showed no significant effect on the convective heat transfer coefficient ($P<0.05$). Comparison between the group pigs with downwards inlet and upwards inlet indicated that the convective heat transfer coefficient was averagely 60.4% higher in the case with downwards inlet than the upwards inlet.

Keywords: Air speed, CFD modelling, weight of pigs, inlet design.

1. Introduction

Heat stress strongly affects the pig production in hot climate regions, including the summer of many continental climate regions. 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 with the air speed. There are three main factors contribute on the convective heat transfer, i.e. surface area, temperature difference between animal skin surface and the environment, and convective heat transfer coefficient. The first two factors are relatively easy to measure or estimate, while the convective heat transfer can be furtherly affected by some other factors, like animal geometry, animal size and airflow pattern around animals. Therefore, knowledge on convection heat transfer coefficient is essential to provide a better control of the ventilation system.

There are a number of literatures can be found on the topic of the convective heat transfer coefficient from animals (Gebremedhin, 1987; Li et al., 2016; Mitchell, 1976; Monteith and Unsworth, 2013). However, most of the experiments were conducted in the wind tunnel or chamber condition. To our knowledge, very few experimental studies on the convective heat transfer coefficient of animal can be found in a building scale. The reason can be the difficulties in directly measuring the air speed in AOZ level and separating the effects of other types of heat transfer from convective heat transfer. Therefore, a systematic study on semi-practical in research lab and numerical simulation is necessary to reveal the regulation of convective heat transfer of pigs in group. To achieve this goal, numerical simulation, e.g. computational fluid dynamics (CFD), is applied in this study.

The inlet is important for the ventilation system inside the animal houses, since the character of the airflow through the inlets can strongly affect the air motion and distribution in the room (Bjerg et al., 2002b; Zhang et al., 2002). In practical husbandry condition, ceiling jet inlet which suppling the air directly to the AOZ from the ceiling has been commonly used in the summer condition. It has been reported by Bjerg and Zhang (2013) that the ceiling jet inlet showed good effect on reducing heat stress during the summer time. The inlet with downwards flow can have similar effects with the ceiling jet, but it can avoid the double investment for both wall and ceiling inlet. Therefore, the wall inlet with downwards flow was involved in this study to test its effect on the convective heat transfer coefficient and compared with the normal inlet with upwards flow.

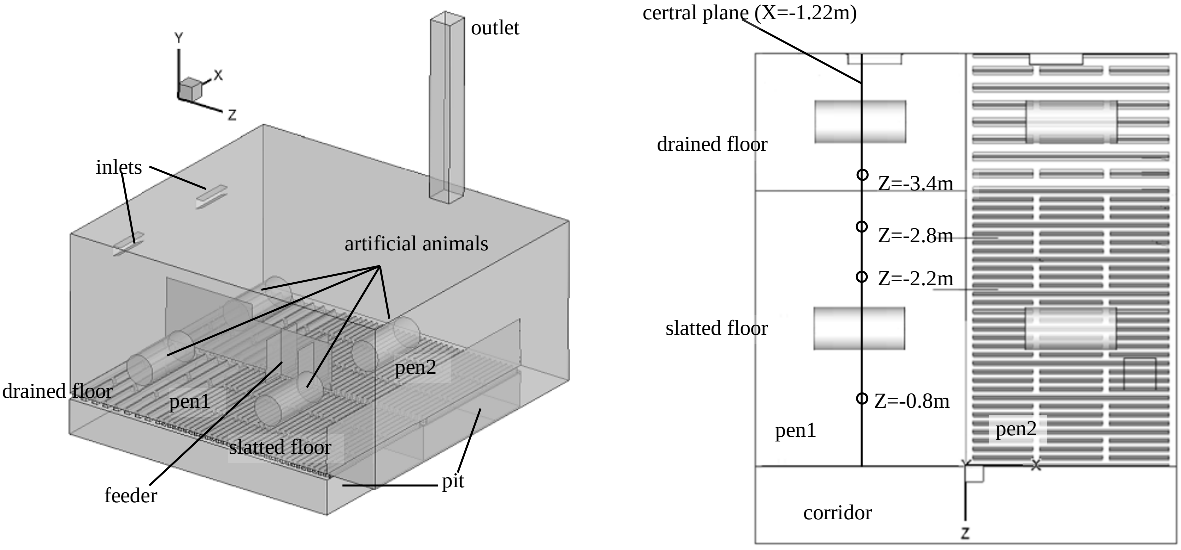
CFD method which is equating the advantages of fully control of boundary condition, providing the universal data in the computational domain, and lower cost with higher flexibility compared with experimental method, has shown increasing tendency in being applied in studying the design and development of ventilation systems in animal buildings (Bartzanas et al., 2002; Bjerg et al., 2002a; Rong et al., 2016; Wu et al., 2012) . Furthermore, CFD was also used in modelling of animals thermal conditions in varied environments at building scale. Norton et al. (2010) used the tool to study the thermal and airflow condition in a calf building. And Seo et al. (2012) conducted a detailed modelling process in a commercial pig house based on CFD. As for the usage in studying convective heat transfer from animal, Li et al. (2016) made a detailed study on a pig model in a virtual tunnel condition. All these prove that CFD has strong power in research for this field. It is commonly to simplify and approximate the model when CFD method was applied, otherwise the simulation can become too complex for physical models in the simulation. Taking this study as an example, the pig models are considered as constant surface temperature and the metabolic process are not considered.

Generally, the objectives of this study are using numerical method to 1) investigate the relationship between the air speed and convective heat transfer from pigs in group; 2) test the impact from the size on the convective heat transfer from pigs in group in a practical condition; 3) test the effect of ventilation system on the convective heat transfer from pigs in group.

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 dimension of the room is measured as 5.78 m ×4.88 m× 2.67 m (length (x) ×width (z) ×height (y)). Inside the room, there are two full scale pig pens and a working corridor. In each pig pen, the floor was made up of one-third of drained floor (1.6 m of length, opening ratio of 8.5%) and two-third of slatted floor (3.2 m of length, opening ratio of 16.5%). Two artificial pigs were arranged in each pig pen, one in the centre of drained floor area, one in the centre of slatted floor area. The experimental measurements were conducted under non-isothermal conditions with ventilation rate of 2533 m^3 h^{-1} and side wall jet supply inlet. Before each measurement, the ventilation system was on for around 3 h to reach steady state condition in the room. During the experiments, the ventilation rate was measured by a free propeller and recorded by a climate control system (Vengsys, Denmark) each minute. Using omnidirectional Air Velocity Transducer (TSI, model 8475) and CR 1000 data logger (Campbell Scientific Ltd, UK), the air speed was measured every 0.2 s and averaged every 1.0 s for a measurement period of 60 min at each measuring points. The room temperature and humidity were continuously measured by the sensors equipped in the room and recorded each minute by the climate control system (Vengsys, Denmark). The surface temperature of wall and artificial pigs were measured by thermo couples with a data logger (Eltek Ltd, UK) every 5min during the whole experimental process.



(a) (b)

Figure 1 The sketch of the geometry (a) and the measurement points for the air speed (b)

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 different parts (Figure 1), up AOZ domain, AOZ domain, and down AOZ domain, with different grid strategies. And the domains are connecting to adjacent domain by interface. For the down AOZ domain, only one type of geometry was made which is exactly following the real condition which is described in the last section. For the AOZ domain, four types of geometry models were built, namely, the AOZ domain which is following the validation experiment, three other AOZ domains which containing 32 pig models weighing 30kg, 50kg, and 80kg, respectively. The pig models are simplified from geometry in real pig shape following the procedure by Li at el. (2016) (Figure 2) and were scaled up and down based on the weight according to the relationship by Brody et al. (1928). For pigs of 30kg and 50kg, the distribution of pigs in pens are referred to the layout by Bjerg et al. (2011), Figure 4(a)(b). For pigs of 80kg uniformly distributed pigs in each pen is assumed, due to the limit space in the pen (Figure 4(c)). Two types of inlets were modelled, one was the same as that used in the experiment, and another one that guides the supply air directly to the AOZ. The setups and dimensions of the inlets are illustrated in Figure 5. The detailed combination of geometry models for different cases is listed in Table 1.

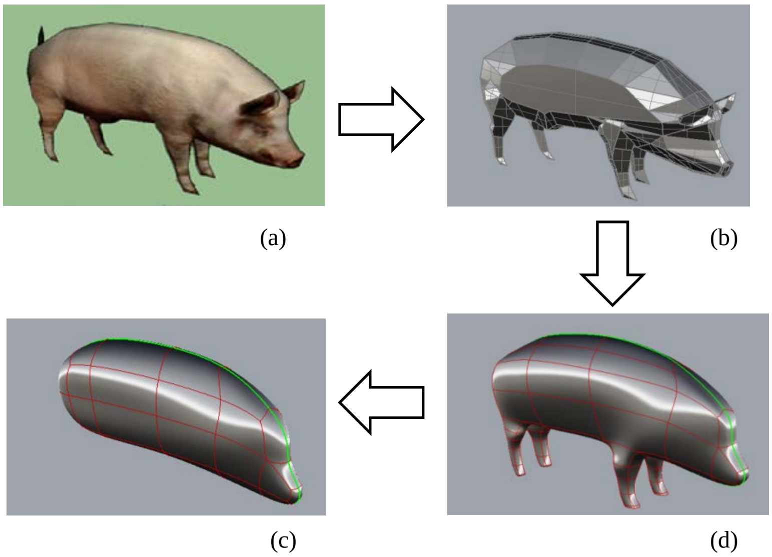

(a) (b)
(c) (d)

Figure 2 The procedure of generating the model pig: (a) The original pig geometry, (b) first-step simplified model, (c) the smoothed model, (d) the final simplified pig model.

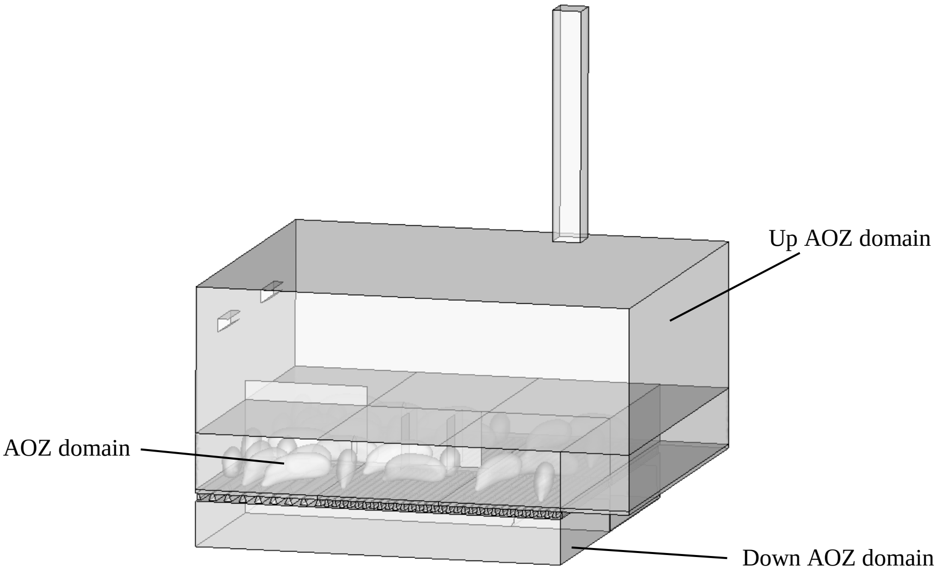
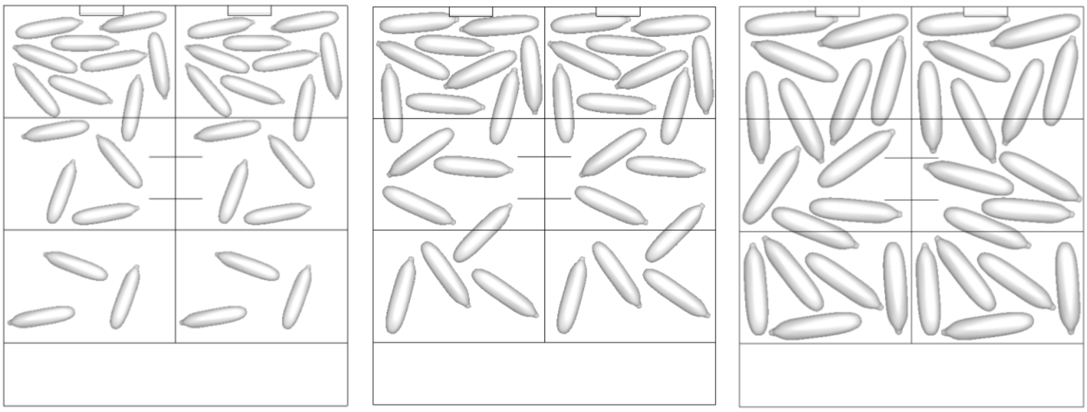


Figure 3 Geometry and the division of the computational domain

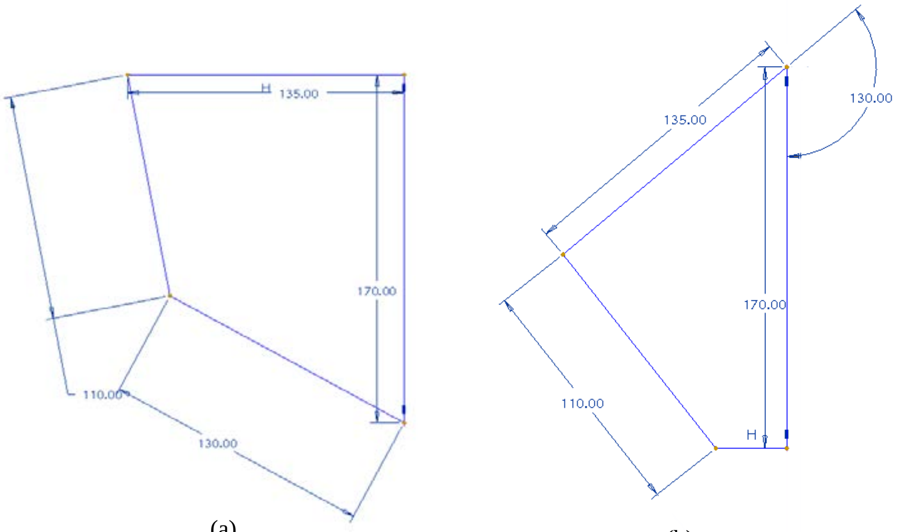


(a) (b) (c)

Figure 4 Distribution of pigs in weight of (a) 30kg, (b) 50kg, and (c) 80kg

Table 1 Combination of the three parts of computational domain in different cases

		Up AOZ domain	AOZ domain	Down AOZ domain
Case 1	Validation test	Upwards inlet as experiment	Artificial pig(cylinder)	Geometry following experiment
Case 2	Simulation containing pig models in pig shape	Upwards inlet as experiment	Pig model in 30kg	
Case 3		Upwards inlet as experiment	Pig model in 50kg	
Case 4		Upwards inlet as experiment	Pig model in 80kg	
Case 5		Down wards Inlet directly supplying air to AOZ	Pig model in 50kg	



(a) (b)

Figure 5 The dimension of the inlets, (a) the inlet with upwards flow; (b) the inlet with downwards flow

2.2.2. Numerical method

Commercial CFD code ANSYS Fluent 15 (Ansys Inc.) was adopted in the simulations. Steady Reynolds-averaged Navier–Stokes (RANS) method was applied in the research. Standard k epsilon model was used for turbulent modelling.

Velocity and turbulence terms for convection were all discretised using second order upwind scheme. SIMPLE method was employed for the pressure-velocity correction.

2.2.3. Boundary conditions

In mechanically ventilated pig house, both the thermal plumes from the pig model (buoyant force) and the jets from the inlet (inertial force) affect each other. In general, the buoyant effect is related to Grashof number (Gr), and the jet momentum is related to Reynolds number (Re). Richardson number (Ri) is commonly used to evaluate the relative importance of the two forces. In this study, Ri in all the cases were below 1, it is concluded that the forced convection is dominating the airflow.

Therefore, the measured air temperature was defined at inlet as well as artificial pig surface. The walls of the building were considered to be adiabatic and non-slip wall. The boundary conditions in this research were summarized in Table 2.

Table 2 Boundary conditions

Validation test	Inlet	Pressure inlet (0 Pa), temperature of 19.8 ^{o}C.
	Outlet	Mass flow inlet with revised flow in 0.862kg s^{-1} (equal to 2533m^3h^{-1}).
	Walls and floor	Setup1: Non-slip wall, adiabatic. Setup2: Non-slip wall, with the wall boundary on an average temperature of 20.8℃ and floor in 19.7 ℃.
	Artificial pig (cylinder)	The two pigs closing to inlet, surface temperature of 36.2 ^{o}C; The two pigs closing to the working corridor, surface temperature of 33.3 ^{o}C.
Case study	Inlet	Pressure inlet (0 Pa), temperature of 30.0 ^{o}C.
	Outlet	Mass flow inlet with revised flow in 0.817kg s^{-1}, 1.089kg s^{-1}, 1.633kg s^{-1}, and 2.178kg s^{-1} (equal to 2400m^3h^{-1}, 3200m^3h^{-1}, 4800m^3h^{-1}, and 6400 m^3h^{-1})
	Walls and floor	Non-slip wall, adiabatic.
	Pig model	Surface temperature of 39 ^{o}C

2.2.4. Post process of CFD simulation

The AOZ area was defined as a cuboid zone with a dimension of 4880mm×780mm×4800mm which is spreading in both pen1 and pen2. In each pen, the AOZ was divided into three parts in z direction in an equal length of 1600mm (Figure 4). In total, there were six sub-zones in the analysis after simulation and the average value in each sub-zone were used in analysis.

The average convective heat transfer coefficient of the animal body surfaces, h_c, is calculated based on the equation (1), given total convective heat loss, surface area, and temperature difference between environment and surface of pig bodies:

$$h_c = \frac{H_c}{A \times (T_s - T_\infty)} \tag{1}$$

where, h_c is the averaged convective heat transfer coefficient (W m^{-2} K^{-1}), H_c is the convective heat rate (W), derived from the surface heat flux by the numerical simulation, A is the surface area of pig in the computational subzone (m^2), T_s is the skin surface temperature of pig (K), and T_∞ is the averaged ambient temperature in the subzone (K).

In a wind tunnel condition the bulk flow velocity is often applied as the reference air speed to study the convective heat transfer (Defraeye et al., 2011; Stephen, 2000), due to the dominating airflow direction limited by the tunnel. However, due to the complex of building geometry and the pigs' distribution, the airflow pattern within AOZ can be very complicated and sophisticated. Therefore, the average air speed is considered to be the correct way in describing a general air speed level within AOZ and therefore it was selected as the reference air speed. In analysis, the speeds were averaged on two planes and one volume, i.e., the planes across the centre of pig model and 10cm above the pig model, and the volume of each subdomain. All the calculations were carried out on the plane or volume exclusive the area or regions occupied by pigs.

3. Results and Discussion

3.1. Model validation

The air speed profile around the animal is the most highly correlated factor for the convective heat transfer coefficient from animal. In addition, it is relatively easy to measure in the experiment. Therefore, in this study, the validation of the CFD model was based on the air speed profile by comparing the simulation result with experimental result in the full scaled pig room with artificial animals. The speed profiles on the vertical measurement line from both the numerical and experimental methods were showed in Fig. 6. Generally, the numerical results agreed with the measurement results very well. In addition, the results indicated that the two assumptions on the thermal boundary condition of wall had little effect on the predicted airflow profiles.

In the mild climate, it is generally accepted that the maximum ventilation rate can be 100m^3 h^{-1}pig^{-1}. In this study, the evaluated ventilation rates were 0.75, 1, 1.5, and 2 times of the maximum ventilation rate, respectively. The ventilation rates are relatively high in the simulation, and therefore the mechanical driving force was dominating the airflow pattern inside the testing domain. It is a normal method to assume the thermal boundary as adiabatic condition, especially when the boundary is hard to define and has less effect on the final result (Defraeye et al., 2010). Proper assumption is necessary for the CFD study, since the simulations are not always in accordance with experimental studies with exactly same setup. Taking this study as example, it is different to have exact thermal boundary condition for the wall for the cases containing the real pig model in group. Since the ventilation rates were relatively high in this study with the mechanical ventilation dominating the airflow pattern, the impact from the temperature difference become a less important factor, the adiabatic boundary condition was adopt for the wall in the simulation with pig models in this study.

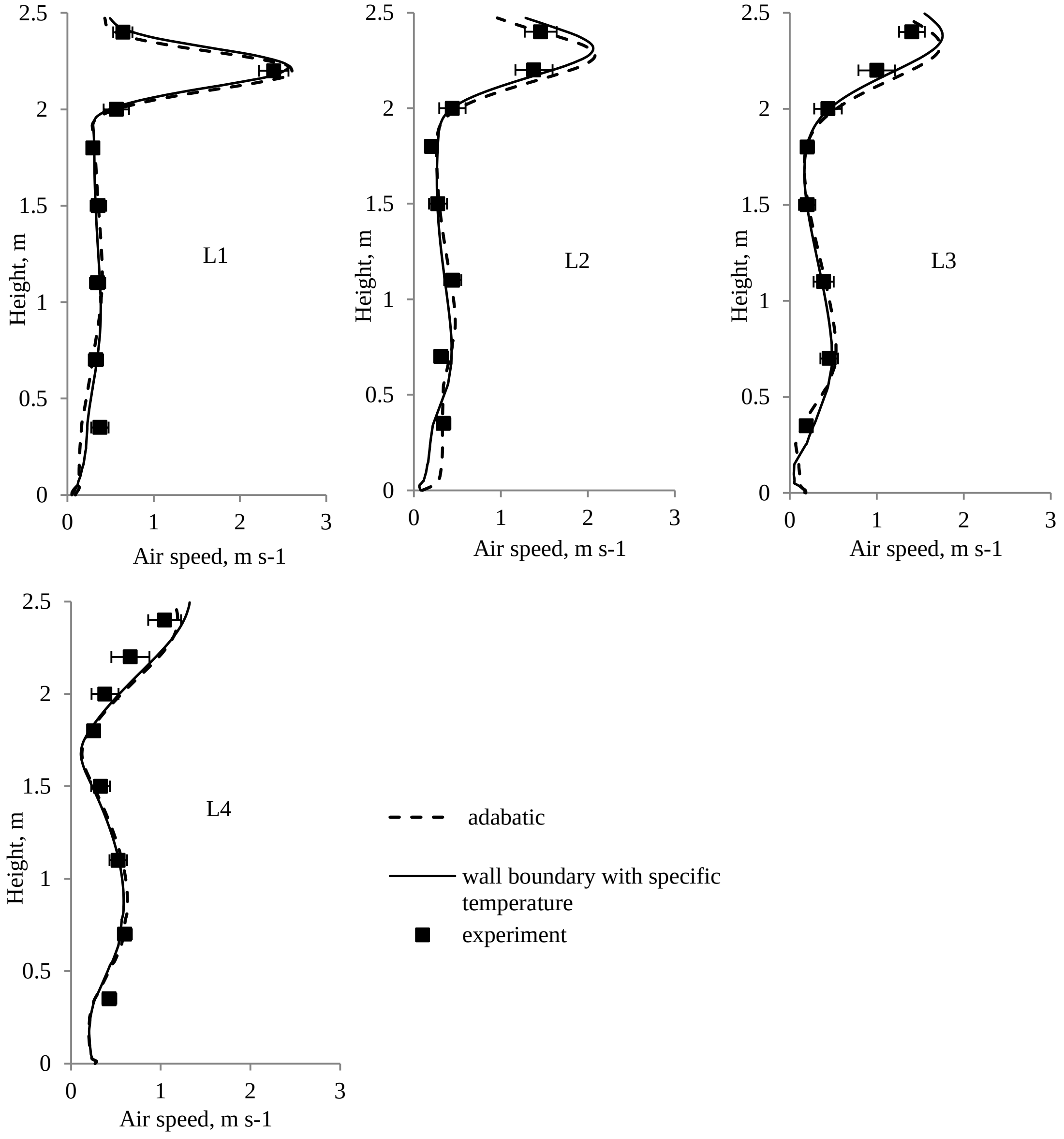


Figure 6 Validation of air speed on the measured vertical lines

3.2. Effect of ventilation rate on convective heat transfer coefficient of pigs in group

Based on the results for pigs of 50kg, the overall convective heat transfer coefficient increased with the ventilation rates, the average convective heat transfer coefficients were 4.81 W m^{-2}K^{-1}, 5.70 W m^{-2}K^{-1}, 7.65 W m^{-2}K^{-1}, and 9.21W m^{-2}K^{-1}, respectively on the four investigated ventilation rates ranging from 2400 m^{3}h^{-1} to 6400m^{3}h^{-1}. Evaluating the convective heat transfer coefficient by each subdomain, the convective heat transfer coefficient showed a clear tendency of increasing with air speed (Figure. 7). It is also noticed that based on different reference air speeds, the correlation between convective heat transfer coefficient and air speeds can be quite different.

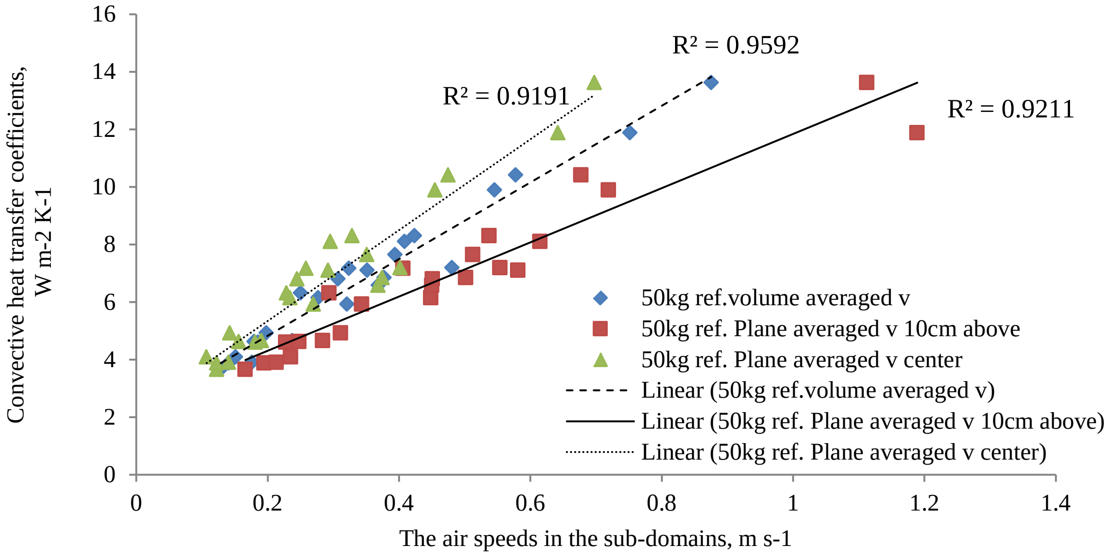


Figure 7 Convective heat transfer coefficients of pigs in group verses varied reference air speeds

Since the inlet size was remained unchanged in the investigations, with the increase of the ventilation rates, the inlet air speed increases accordingly and leads to a higher air speed in the AOZ. It has been reported by Li et al. (2016) that the convective heat transfer coefficient increase with the air speed for a single pig in a virtual wind tunnel condition. In this study of pigs in group in pen, the results showed a similar tendency on the convective heat transfer coefficient. However, the block effect of the pigs in group increased the complexity of air flow pattern in the study, and make it more complicated compared to horizontal uniform flow condition. Using average air speed in AOZ, the convective heat transfer coefficients of pigs in group were modelled with a relative high correlation. It indicated that the convective heat transfer coefficient could be described as a function of the average air speed in AOZ, which would provide reference in the control system inside the pig building. Within the three average air speeds tested in this study, the volume average speed is considered to be the best representative based on regression analysis. , it can not only describe the air speed level in the entire evaluated zone, but also shows the highest R^2. However, in practical condition, the volume averaged air speed is the hard to measure inside the pig barn. Similarly, it is un-practical to measure the averaged air speeds in any of the two plans defined in the AOZ in a field condition. Since all the averaged air speed required enough measurement points to generate concrete data. Therefore, further study on modelling of the air speed in AOZ is preferred, i.e., to determine and validate the correlation on the air speeds in AOZ and supplying air jet momentums, including ventilation rate, inlet openings and inlet air velocity. And this is also essential to make the convection heat transfer model applicable in an online control algorithm in real condition.

3.3. Effect of the weight of pigs in group on the convective heat transfer

The convective heat transfer coefficients achieved using numerical investigations at different animal weights are shown in Fig. 8, versus to air speed levels. The differences on group convective heat transfer coefficient between groups were beneath 10% level (Table 3). And the ANOVA analyses showed that the differences were not significant ($P<0.05$). The convective heat transfer coefficient of pigs in the weight of 50kg was found slightly higher than the other two groups in weight of 30kg and 80kg.

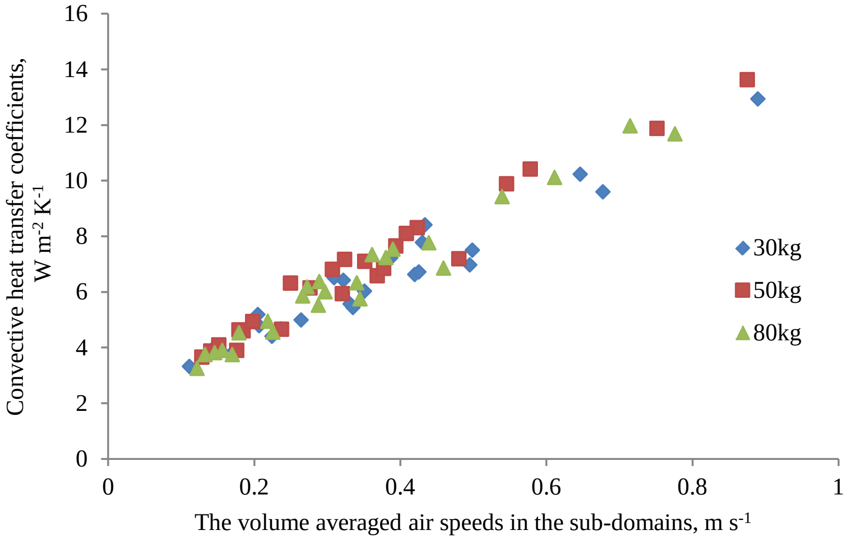


Figure 8 Convective heat transfer coefficients of pigs in group with different weights verses volume averaged air speeds

Table 3 The average convective heat transfer coefficient of pigs in group under different weights verse varied ventilation and the relative difference between groups in different weights

	Ventilation rates (m^3 h^{-1})			
	2400	3200	4800	6400
Pig models in 30kg (W m^{-2} K^{-1})	4.48	5.37	6.92	8.73
Pig models in 50kg (W m^{-2} K^{-1})	4.81	5.70	7.65	9.21
Pig models in 80kg (W m^{-2} K^{-1})	4.52	5.47	7.11	8.64
Relative difference (30kg vs. 50kg)	7.2%	6.3%	10.5%	5.5%
Relative difference (50kg vs. 80kg)	-6.1%	-4.1%	-7.1%	-6.2%
Relative difference (30kg vs. 80kg)	-0.7%	-1.9%	-2.6%	1.0%

There is strong correlation between pig model and cylinder in the same characteristic length (Li et al., 2016), based on this correlation, the convective heat transfer coefficient of the single pig in the weight of 30kg, 50kg, and 80kg on 0.5 m s^{-1} should be 6.16 W m^{-2} K^{-1}, 5.68 W m^{-2} K^{-1}, and 5.26 W m^{-2} K^{-1}, respectively. The convective heat transfer coefficient decrease with pig weight and the relative differences of 30kg vs. 50kg, 50kg vs. 80kg, and 30kg vs. 80kg are 7.0%, 6.4%, and 14.6%, respectively. In general, the difference between different weights is not high. In this study with grouped pig models, the difference between the groups in different weights was very small. However, it is the case with pig models in 50kg showing the highest values, but not the case with the pig models in 30kg. One reason can be the difference of pig distribution inside the pens. The distribution of pig models in 80kg was not same with the other two cases. Even the cases of pig models in 30kg and 50kg were in similar distribution, due to the differences in height and size, the resulting air flow pattern can be different, which can lead to different results with the single pig in the horizontal flow condition. Another reason can be the usage of the average air speed as the reference speed. Since the blocking and allocation of pig models can be varied in different cases, the air flow pattern around pig models can be very complex, which may result in large variations between the average air speed in AOZ and the true air speed near animal body boundary layers. The usage of average air speed involved some air space between the pig models and the space sizes varied at different body weights and the integrated effects of blocking and space of the pigs may contribute to the in-significant difference of the convective heat transfer coefficients of the pigs in group with different weights. In addition, it should be acknowledged that this study was based on the simplified cases in both geometry and boundary condition, and the numerical method used in this simulation may generate additional errors. In real condition, the movement of pigs can make the flow pattern more complicated. Further studies on both modelling and validation in the field condition are still needed.

3.4. Effect of the ventilation design on the convective heat transfer of pigs in group

The ventilation design showed significantly impact on the convective heat transfer of group pigs (Table 4). Under the same ventilation rates, the convective heat transfer coefficient of pigs in group with the inlet which suppling the air directly to the AOZ is significantly higher than the convective heat transfer coefficient of pigs in group with the conventional inlet, with a relative difference in 64.4% higher.

Table. 4 The average convective heat transfer coefficients on different ventilation rates

	Ventilation rates(m^3 h^{-1})			
	2400	3200	4800	6400

Convective heat transfer coefficient of pigs under upwards jet (W m^{-2} K^{-1})	4.81	5.70	7.65	9.21
Convective heat transfer coefficient of pigs under downwards jet (W m^{-2} K^{-1})	7.69	9.55	12.26	15.67
Relative difference	60.0%	67.4%	60.2%	70.0%

The inlet is important for the ventilation system of animal houses, since the character of the airflow through the inlets can strongly affect the air motion and distribution in the room (Bjerg et al., 2002b; Zhang et al., 2002). Based on jet decay theory the jet momentum decreases with the travel distance(Strom et al., 2002). In this simulation study, with the downwards jet the air was directly supplied to the animal body. Energy loss which may happen in the air cycling process in the case with upwards jet can be avoided. On another aspect, the opening sizes of the two inlets were almost the same, in the same ventilation rate, the initial air speed on the inlet were same. However, the convective heat transfer coefficients were significantly different in the same ventilation rate. It indicated that the downwards jet inlet can be an efficient way to increase the convection compared to the upwards inlet. In this study, only a simple comparison of two inlet types was conducted. However, there can be more factors that will impact on the convective heat transfer and the air distribution in the AOZ, for instance, only focusing on the inlet, the jet angle, the inlet height, and the initial air speed on the inlet will all contribute. A systematical study on the inlet design can be conducted in the further research.

4. Conclusions

In this study, the CFD model for studying convective heat transfer coefficient of pigs in group was firstly validated by experiment in an experimental pig house using artificial pigs.

The convective heat transfer coefficient increases with ventilation rate as well as air speed. The different types of reference air speeds have been found to have strong effect on the relationship between the convective heat transfer coefficient and air speed. Further study on modelling the air distribution inside the pig building is needed.

Within the tested weights, 30kg, 50kg, and 80kg, no significant difference was found between the studied cases ($P>0.05$). The convective heat transfer coefficients of cases with 50kg pigs were slightly higher than other cases with 30kg and 80kg pigs, and the relative difference was within 10% level.

The angle of airflow through inlet showed strong impact on the convective heat transfer of pigs in groups. With the downwards inlet, the convective heat transfer of pigs was significantly higher than that in the case which the inlet provided upwards airflow.

Acknowledgements

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