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Assessing response surface methodology for modelling air distribution in an experimental pig room to improve air inlet design based on computational fluid dynamics

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The thermal comfort of pigs is strongly correlated with the air motion around the pigs. In a pig production building, it is the ventilation system that influences the indoor air distribution significantly. In the ventilation system design, air inlet is considered to be important on the air motion in room. In this study, the Response Surface Methodology (RSM) was evaluated to develop the prediction model of the air speed in animal occupied zone (AOZ). Three dimensional numerical simulations for an experimental pig room were conducted to estimate the air speeds within the AOZ with the inlet supplying air in different angles and airflow rates on three installation heights of inlets. The results showed the RSM was capable to model the air speed in AOZ. Based on sensitivity analysis, the initial air speed and angle significantly influenced the air speed at the AOZ level, while the installation height was a less significant parameter. The RSM models could be used for design and control of an optimal ventilation system to achieve a better environment for pigs.

1. Introduction

Increasing heat removal is an efficient way to reduce the heat stress and provide thermal comfort for the animals during hot seasons. Air velocity and distribution in the AOZ in livestock buildings has significant impact on the heat removal and consequently animal performance (van Wagenberg and de Leeuw, 2003). There are a number of studies showing that the heat removal, especially convective heat removal from animals, was highly correlated to the air speed in the buildings and higher air velocity will lead to higher convective heat transfer (Gebremedhin, 1987; Li et al., 2016b; Mitchell, 1976; Mitchell, 1985; Monteith and Unsworth, 2013; Wathes and Clark, 1981). In farm animal housing, the air distribution is highly linked with ventilation design. Therefore, it is essential to generate an effective distribution of fresh air within animal occupied space with desired air speed, to enable good thermal comfort for the animals during summer.

The inlet configurations are essential for control of the air motion and distribution in the building, and strongly affect the air speed in AOZ (Bjerg et al., 2002; Zhang et al., 2002). To reduce heat stress of animals, the inlet with jet supplying the air directly to the AOZ has been proved significant effect on the temperature distribution (Bjerg and Zhang, 2013). Additionally, the downward jet has also shown better performance on increasing the convective heat transfer from animal compared with conventional jet inlet with upward or horizontal initial air jet direction at the same flow rate from numerical simulation (Li et al., 2016a). However, further research on the relationship between air speed distribution in AOZ and the inlet parameters is still necessary for the optimal inlet design and control.

It is difficult to measure the real air speed in AOZ directly. Most of the studies in testing the ventilation system use empty rooms to make the measurement of air speeds in AOZ more easily (Bjerg et al., 2002; Randall, 1980; Zong et al., 2015). But the results of those studies can be different from the real condition, since the block effect of pigs are not considered. To measure the air speed in AOZ with pigs involved, van Wagenberg and de Leeuw (2003) use cages to protect the ultrasonic anemometers and place the anemometers in AOZ to measure the air speed. Although the air speed can be measured this way, the blocking from cage may still have effects on the air speed or turbulence intensity. With the development of the computational power of computers, research activity combining with CFD simulation on ventilation and indoor climate of the animal buildings is increasing, due to the lower cost on investigation setups and easier control of study parameters compared to conventional experimental method. Numbers of studies have been conducted on the ventilation study inside the

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livestock building using CFD method (Blanes-Vidal et al., 2008; Bustamante et al., 2015; Kwon et al., 2015; Lee et al., 2013; Mistriotis et al., 1997; Norton et al., 2009, 2010a; Rong et al., 2015; Wu et al., 2012). Animal models in real geometry are also used in some of CFD studies for environment parameters inside animal buildings to make the simulation results more reliable (Bjerg et al., 2008; Gebremedhin and Wu, 2005; Li et al., 2016b; Seo et al., 2012). Therefore, CFD method was adopted in this study to generate the air speed data in different configurations of the inlet.

The relationship between the air speed in AOZ and the selected parameters of inlet configurations is important for both the inlet configuration study and the inlet control model development. To identify the relationship, statistical data-based models, i.e. the meta-model method, can be used (Wang and Shan, 2007). One of the most well-established and easy-to-use meta-modelling technique is the Response Surface Methodology (RSM) (Simpson et al., 2001). With a proper experimental design, RSM can generate high precision prediction model with reduced number of experiments compared with full factory design. RSM has been used in many research aspects in the field of building ventilation study. For instance, the ventilation rate in the natural ventilated building has been modelled based on the parameters of air speed, air direction, and opening size with RSM (Shen et al., 2012, 2013a; Shen et al., 2013b). Based on RSM, the indoor environment was also studied with different ventilation configurations (Ng et al., 2008; Norton et al., 2010b). All the studies showed RSM has strong potential to build the model in the ventilation study. Concerning the inlet design, the feasibility of RSM method is worthwhile to be investigated.

Thus, the objective of this study is to assess the feasibility of RSM method in developing the model for the average air speed inside the animal occupied zone (AOZ) as a function of the parameters of inlet configurations. The established RSM model will be verified based on simulation data in other setup. Finally, sensitivity analyses will be conducted to identify the key parameter in the developed RSM modelling for the inlet design.

2. Materials and methods

2.1. Response surface methodology design

RSM is a combination of mathematical and statistical techniques for formulating the regression model between the selected variables and targeted responses (Anderson and Whitcomb, 2005). Normally, the RSM model can be solved by following four stages, i.e., design of experiment, conduction of the experiments, building the response surface model, and solution optimization.

The RSM model design is highly dependent on the parameters selected as model variables. Before the experiment design, to identify the design factors is necessary. As the inlet in this study was designed with downward jet, the angle of the jet might have direct effects on the flow distribution and air speed in AOZ. Therefore, inlet angle was selected as a design parameter. Ventilation rate was also set as a design parameter. The reason was that the variation of ventilation rate can lead to the changes on the initial air speed in the inlets, and consequently on the air speed in AOZ. Although the opening size can be varied in a limited range in practical condition, in the current study the inlet opening was made into a fixed size in all the cases to simplify the problem. Another parameter can be the inlet installation height, since the significance of effect from height is not clear. From this point, the installation height of the inlet was also involved in the modelling process. There can be more factors, e.g. open size of the inlet, the jet momentum of the flow from inlet, having effects on the air distribution in AOZ. In this research, only the first three mentioned factors were tested at this stage.

RSM can significantly reduce the experiment number based on varied optimal experimental design method compared to the full experiment design. Box-Behnken design, which is suitable for non-sequential experimentation and has been used for both naturally and mechanically ventilated building (Ng et al., 2008; Norton et al., 2010b), was adopted to generate the RSM runs. Based on this design method, three levels including the extreme values were generated for each of the three variables in the current modelling. On fully experimental design, the number of experiments with three variables in three levels can be $3 \times 3 \times 3 = 27$ runs. Whereas through Box-Behnken design, which is based on the combination of the factorial with incomplete block design, the experimental times were reduced by half. Only 13 runs were required to generate the RSM regression model.

The information of design variables and experiments in our study are listed in Table 1, the angle represents the downward jet direction in degree, with 0° as the horizontal condition and 45° as the maximum downward level. The low limit of inlet installation height was 1600 mm, which was around the average body length of pig and pigs cannot reach the inlet even they stand on two feet. The up limitation was 2200 mm, which was almost touching the ceiling of the room. Referred to a Danish common design, the maximum ventilation rate was 100 $m^3\ h^{-1}\ pig^{-1}$. Since 32 pigs were modelled in the simulation in this study, the maximum ventilation rate was 3200 $m^3\ h^{-1}$. The inlet with downward jet was designed for a summer condition, thus the range of ventilation rate in this study was controlled in a relative high level, from 2500 $m^3\ h^{-1}$ to 4800 $m^3\ h^{-1}$, which was around 80% and 150% of the maximum ventilation rate in Danish condition.

After the experimental design and experiments, the response model can be generated based on the experimental data collected in the different runs. The modelling process of RSM can be generally expressed as followed,

$$Y = f(X_1, X_1, X_1, \cdots X_n) + \varepsilon \tag{1}$$

where, Y is the response, f is the response function, X_i are the design variables, and ε is the term of error. Different types of experiments can generate different types of errors, like the measurement errors in physical experiment and the round-off errors or iterative convergence error or discretization error in numerical experiment. While in the RSM, all the errors are assumed to be randomly distributed and concluded into the error term, ε.

The final developed RSM models only contain the predicted response, and can be written as followed (Myers et al., 1989),

$$\hat{y} = \hat{\beta}_0 + \sum_j \hat{\beta}_j x_j + \sum_j \hat{\beta}_{jj} x_j^2 + \sum_j \sum_{k>j} \hat{\beta}_{jk} x_j x_k + \sum_j \sum_{k>j} \sum_{l>k} \hat{\beta}_{jkl} x_j x_k x_l + \cdots + \sum_j \hat{\beta}_{\underbrace{j, \cdots j}_{d}} x_j^d \tag{2}$$

where, $\hat{y}$ is the predicted response, $\hat{\beta}$ is the constant in the prediction model, x_j, x_k, x_l are the designed variables, d is the order of the regression model. The error term, ε, is omitted in the prediction model. In general, the predict model is made up of terms in different orders (i.e., constant term, linear terms, quadratic terms, and other high order terms depending on the requirement of the generated model).

The quality of model in fitting the experimental and prediction results is normally evaluated by the R^2, which has been widely used as a measure of how well the response is likely to be predicted by the model. And in RSM, the R^2 is modified and can be further divided into adjusted R^2 and predicted R^2, with adjusted R^2 evaluating how well the regression models can be by adjusting