Design of precise air supply system based on convection heat dissipation of pig body

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Abstract

Ventilation is very important among the many factors that affect the environment in the house. Most pig barns still use traditional ventilation with supplementary cooling systems, but this ventilation model cannot guarantee that each pig in the house receives appropriate fresh air. Therefore, this study evaluated an alternative supplementary cooling system, namely the precision air delivery system. This system is composed of a main duct and a distribution duct, which extracts outdoor air through a fan and then blows air to the pigs through the distribution duct. It can effectively eliminate the excess heat in the house and ensure that each animal is in a comfortable thermal environment. In this study, after proposing an improvement plan after field research, the simulation was verified by computational fluid dynamics techniques to investigate the effects of three study parameters (ventilation rate, air supply duct diameter and air supply angle) on the cooling performance of the precise air supply system by taking a standing pig body as an example and finding the best design solution within the study range by response surface analysis (ventilation rate of 400 m^3/h, duct diameter of 0.1m, duct angle of 53°) within the study range was found by response surface analysis, so as to achieve the purpose of improving the production efficiency of pig farming.

Keywords: pig house, ventilation, CFD, precision air supply system, thermal environment

Introduction

Ventilation plays a vital role in pig production and health, and there are various ways of ventilation, such as natural ventilation, mechanical ventilation and mixed ventilation. With the rise of building pig farming mode in China in recent years, the ventilation mode is also reforming and innovating, and the traditional ventilation mode can no longer meet the demand for ventilation in actual production. Since there is no relevant theoretical research and no reference standard for the design of precise air supply system, it is even more impossible to evaluate its actual effect in production. More and more scholars have started to explore the problems around tunnel ventilation and jet ventilation, and involve the microclimate area in the pig housing feeding session (St ender et al., 2003; Hoff， 2013; Zong et al., 2015; Li et al., 2018). However, there are few studies on the comfort of individual pigs, and some recent studies have focused on the problem of precision ventilation for individual pigs, so it has not provided practical solutions or analyzed the effectiveness of precision ventilation systems in the whole house environment (Huang et al., 2022; Wang et al., 2018).

From the existing literature, ventilation systems are mainly studied in the traditional way, as well as tunnel ventilation and jet ventilation, while few scholars have conducted in-depth studies around the thermal comfort of each pig. Therefore, the main purpose of this study is to use CFD technology to simulate and response surface analysis to design a precise air supply system to provide a comfortable thermal environment for each pig in the barn and to ensure that each pig grows and breeds in a suitable ventilation environment, and to evaluate the cooling effect of the system by calculating the convective heat dissipation coefficient of the pig body to provide the best solution within the research scope (the ventilation rate is from

200 m³/h to 400 m³/h , the duct diameter is from 0.1m to 0.2m, and the duct angle is from 35°to 55°). In terms of ventilation compensation for maximizing heat loss and providing a comfortable thermal environment for individual pigs in summer. This will provide a reference basis for the design of the actual precise air supply system, and finally achieve the purpose of improving the production efficiency and economic benefits of the industry.

Materials and methods

Overall approach

In this study, the commercial software STAR-CCM+ (15.02, Siemens PLM software, Plan to, TX, USA) was used for numerical simulation and the software Design Expert10 for response surface analysis method was used for the selection of experimental solutions. The design of the precision air supply system for the pig house was mainly to investigate the ventilation effect of the ventilation rate of the distribution ducts, the duct diameter and the duct angle on the ventilation of a single pig pen position, which was shown by the change of the convective heat dissipation coefficient of the arriving pig body. Therefore, in this study, three design and operational variables of the precision air delivery system were selected as experimental variables. The experimental protocol was as follows.

Table 1: Different design options for precision air supply systems.

Factors / Level	Ventilation capacity (m³/h)	Pipe diameter (m)	Pipe tilt angle (°)
Low level	200	0.1	35
Medium level	300	0.15	45
High level	400	0.2	55

Geometric model of a pig

In order to investigate the variation of the surface flow heat dissipation coefficient of the pig body under different air duct settings, the pig body model was placed in a virtual wind tunnel for simulation study. Creating a valid pig requires accurate measurements of specific parts of the solid pig, such as pig body height, trunk length and total skin surface area. The length of the pig in this study is 1.49 m, the width of the pig is 0.36 m, the height of the pig's trunk is 0.53 m, and the weight of the pig is taken as 200 kg. The height above the ground is set to 0.37 m due to the consideration of the leg length of the standing pig. the volume of the pig is 181818 cm³, and the surface area of the pig is 19593 cm².

Computational domain

In the modeling of the duct, the dimensions of the total duct inlet are 0.9 m×0.6 m (length×width) and the duct length is 6.67 m. The length of the distribution duct is 0.15 m and its duct height above the ground is 1.5 m.

The dimensions of the computational domain are important when performing numerical simulations. Many simulation cases have shown that an inappropriate computational domain has a significant impact on the accuracy of the simulation results (Bjerg et al., 2013, Lee et al., 2007). Therefore, the dimensions of the computational domain were set to 16.5m×10.5m×3.6 m (11L×7L×10I, L means the body length of 200 kg pig is 1.5m, I means the width of 200 kg pig is 0.36 m). The distance from the airflow inlet is 3L (4.5m), the back of the pig is 0.85m from the ground, and the height of the air duct to the back of the pig is 0.5m. As shown in the figure.

In this study, the SSTk-w model is chosen as the turbulence model(Li et al., 2016). To simplify the selection of the cylinder, the temperature of the pig surface was taken as 38°C, without considering the effect of the epidermis.

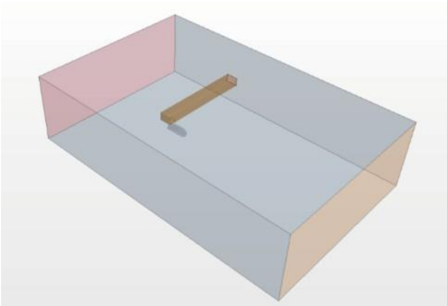

Figure 1: Geometric model schematic

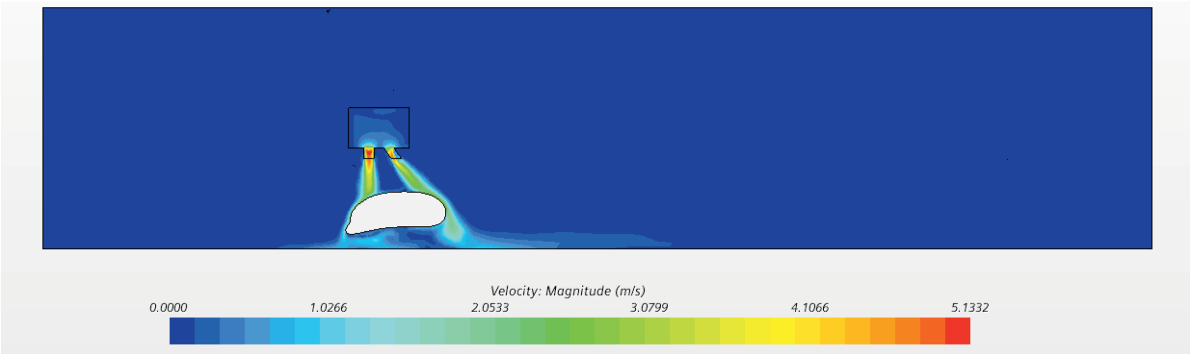

Figure 2: Cross-sectional wind speed diagram

Boundary conditions

The boundary conditions of each part in the model are set as follows.

Table 2: Setting of boundary conditions.

part	region	type	temperature	Velocity (m/s)
Chamber	Ceiling,floor, front,back	wall		
	Chamber-inlet	Velocity Inlet	30°C	0
	Chamber-outlet	Pressure Outlet	30°C	
	pig	wall	38°C	
Tube	Tube-inlet	Velocity Inlet	22°C	0.103;0.154;0.205
	pipe-out	Pressure Outlet	30°C	
	Tube-body	baffle		

Grid independence test

The grid size will directly affect the accuracy of the simulation calculation, so the grid independence test should be conducted before the simulation. As can be seen from Table 3, the mesh size settings in Case 3 meet the requirements of accuracy and computational cost.

Table 3: Grid independence test case

Case	Case 1	Case 2	Case 3	Case 4
Total number of grids	8.09×10^6	42293714.23×10^6	27759762.78×10^6	19425111.94×10^6
Heat transfer (W)	227	222	229	208
Differences	1.000	1.007	0.997	0.886

Convective heat transfer

The main modes of heat transfer in pigs are convection, conduction, radiation and respiratory heat transfer, releasing body heat in the form of sensible and latent heat (Bruce et al., 1979; Mcarthur, 1981). Although there are many ways of heat transfer in pigs as mentioned above, in this paper only convection is studied, and the main factor affecting convective heat transfer is the convective heat transfer coefficient. The relevant equation is:

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

where, h_c is the convective heat transfer coefficient, $Wm^{-2}K^{-1}$, and H_c is the total heat transfer rate, W. In

this study, heat is obtained from surface heat flux. A is the surface area of the animal, m^2; T_s is the surface temperature of the animal, K; and T_∞ is the ambient temperature, K.

Response surface analysis method

Due to the large number of cases to be simulated, design screening is performed using the Box-Behnken design method (BBD). Usually, RSM is used in combination with BBD and is more proficient and robust than other experimental design methods because it requires fewer combinations but can achieve equivalent performance (Karmoker et al., 2019; Shen et al., 2013). In the design of this scheme, the heat dissipation is the dependent variable and the best design solution can be filtered based on the values of the simulation results for each case.

Results

Convection heat dissipation coefficient analysis of different solutions

The design and analysis were carried out according to the response surface analysis method, and 13 out of 27 groups of cases were selected for simulation, and the simulation results were obtained as follows. According to the figure, the model is extremely significant, the larger the F-value and the smaller the p-value, the greater the influence of the factor on the dependent variable. Therefore, it can be learned that among the three studied factors, the factor that has the greatest influence on the convective heat dissipation coefficient is the ventilation rate, followed by the duct diameter, and the duct angle has the least influence. Based on the response surface analysis method, controlling the dependent variable convective heat dissipation coefficient to the maximum value, the best solution is obtained with a ventilation rate of 400 m^3/h, a duct diameter of 0.1 m, and a duct angle of 53°.

Table 4: Simulation results

Serial number	Factor 1 A:Ventilation rate(m^3/h)	Factor 2 B:Duct diameter(m)	Factor 3 C:Duct Angle(°)	Convection heat dissipation coefficient($Wm^{-2}K^{-1}$)
1	200	0.1	45	1.51e+02
2	400	0.1	45	2.72e+02
3	200	0.2	45	1.14e+02
4	400	0.2	45	1.93e+02
5	200	0.15	35	1.32e+02
6	400	0.15	35	2.29e+02
7	200	0.15	55	1.61e+02
8	400	0.15	55	2.61e+02
9	300	0.1	35	1.98e+02
10	300	0.2	35	1.51e+02
11	300	0.1	55	2.36e+02
12	300	0.2	55	1.84e+02
13	300	0.15	45	1.77e+02

Predictive modeling

Based on the above results, a prediction model regarding the mathematical relationships of ventilation rate, air supply diameter, air supply angle and convective heat dissipation coefficient is established as follows. The model can predict not only the design solutions within the test range, but also the solutions outside the study range, so it is a good guide for practical engineering applications.

$$\begin{aligned} Y = {} & 8.60 + 0.02Vr + 4.08d - 0.35\theta - 0.06Vr \times d + 3.42\times 10^{-4} Vr \times \theta \\ & - 0.08d \times \theta - 1.43\times 10^{-5} Vr^2 + 8.99d^2 + 4.50\times 10^{-3}\theta^2 \end{aligned} \quad (2)$$

where, Vr is the ventilation rate, W; d is the duct diameter, m; θis the duct angle, °.

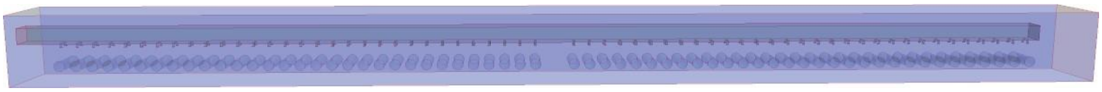

Figure 3: Pig house single column model

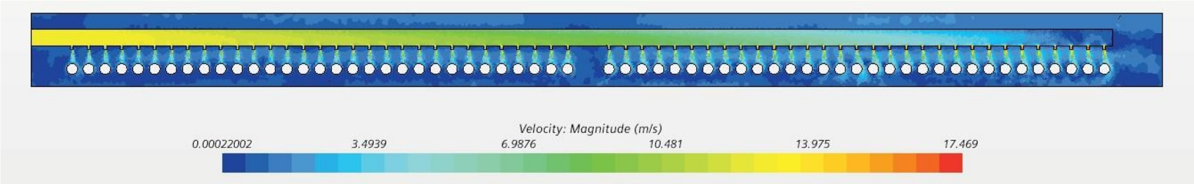

Figure 4: Longitudinal section wind speed

Modeling the pig house in a single column

In order to investigate the practical use of the best design of this precision air supply system in the pig barn, a single column model in the pig barn was established, as shown in figure. The model took one of the columns in the whole barn with dimensions of L×W×H=41.1m×3.1m×2.7m, and there were 62 vertical distribution ducts and inclined distribution ducts on the precision air supply system with an interval of 0.6 m. To reduce the computational cost, the pigs were simplified to cylinders (Li et al., 2017; Mount, 1966), and the study showed that the difference between the calculated values of the cylindrical and actual pig geometric models with similar body surface area in terms of convective heat transfer was small (Li, 2016). Since the surface area of the actual geometric model of a 200 kg pig is 1.96 m^2, the radius of the simplified cylinder geometry is 0.2 m and the length is 1.4 m.

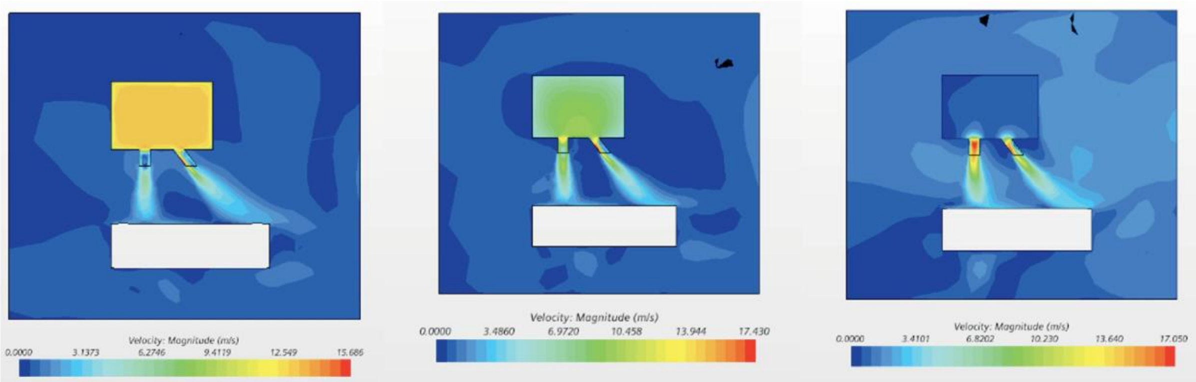

Figure 5: Front cross-sectional wind speed diagram (left column) and medium cross-sectional wind speed diagram (middle column) and post cross-sectional wind speed diagram (right column).

Discussion

Based on the simulation results and response surface analysis, it is known that among the three factors affecting the convective heat dissipation coefficient, changing the ventilation rate has the greatest effect on the convective heat dissipation coefficient of pigs, followed by the duct diameter and finally the duct angle. The best design solution within the research scope of this paper is 400 m^3/h ventilation capacity, duct diameter of 0.1m, duct angle of 53°. In the model study of the single-row whole house, according to the wind speed cloud diagram of the front, middle and rear cross-section, it can be seen that the wind speed at the outlet of the duct is the highest and decays rapidly after leaving the mouth of the duct, because the wind has loss along the way through the duct. The wind speed reaching the surface of the pig body is about 4m/s, which indicates that this precise ventilation system has good ventilation effect

In the study of this ventilation system, the mutual influence between pig bodies is small, and the difference of wind speed between two adjacent pigs is small as the pipeline is arranged independently perpendicular to the individual pig. It is indicated that the jet distribution pipe has good air delivery effect, and the obstacle of airflow between pig bodies is small, which can ensure that each pig can get enough ventilation and has good use effect in practical engineering. In addition, the airflow pattern in the sow barn is always complex due to air obstruction caused by animal activity and facilities. Further investigations for more comprehensive consideration are needed.

Conclusions

In this study, it can be confirmed that the precision air supply system has a good ventilation effect on ventilation compensation, which does not affect the ventilation effect due to the mutual blocking effect between multiple pigs and can ensure that each pig is in a comfortable thermal environment in summer. However, this air supply system has a high resistance along the duct air supply process, which may require the installation of relay fans in the use of the actual project.

Acknowledgments

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