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Research on inspection route of hanging environmental robot based on computational fluid dynamics

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Abstract

The environment of a closed piggery is commonly characterized by spatial unevenness, and there are currently no specific standards for installation points of various environmental monitoring sensors. Therefore, the project team used the hanging track inspection robot (HTIR) as an environmental monitoring platform to seek the environmental monitoring points and ensure the scientific layout of monitoring points. Ansys-CFD software was used to study the change rules of environmental parameters at 1.6 m (α plane), 0.7 m (β plane), and 0.4 m (γ plane) above the ground. The 300 monitoring points ((x_1~x_{30}) ×(y_1~y_{10})) in each plane were analyzed to determine the most suitable monitoring points and inspection routes for HTIR. The results showed that: (1) All monitoring points could be arranged directly below the y_3 track. (2) Monitoring points (x_1, y_3), (x_{10}, y_3) and (x_{30}, y_3) were environmental feature points. At (x_1, y_3), the maximum relative humidity and NH_3 concentration on the α plane could be detected, and the maximum wind speed, maximum temperature, and maximum NH_3 concentration on other planes could also be detected; At (x_{10}, y_3), the minimum temperature and maximum relative humidity of the β and γ planes could be detected; At (x_{30}, y_3), the maximum NH_3 concentration in the α plane and the minimum relative humidity in all planes could be detected. This study scientifically arranged the inspection track and monitoring points for HTIR, improved the accuracy of environmental monitoring, and put forward suggestions for reducing NH_3 concentration in closed piggeries, laying the foundation for the next step.

Introduction

In order to reduce the mortality rate of pigs and improve the environmental quality of piggeries, more and more attention is paid to the research and development of environmental monitoring equipment for piggeries (Zou et al., 2017; Zeng et al., 2021; Madona et al., 2022; Fu et al.,2022). Temperature, humidity, NH_3, and wind speed are the most important monitoring parameters in the piggery. Currently, the existing environmental monitoring standards for piggeries (GB/T 17824.1; National standard of the People's Republic of China, 2008) only specify the height at which temperature and humidity should be monitored. There is a lack of specific guidelines for monitoring points such as temperature, humidity, wind speed, and NH_3. In practical applications, environmental monitoring sensors are typically installed at specific points (installed on fixed objects such as walls or beams). However, due to the uneven spatial environment of livestock and poultry houses, it becomes crucial to conduct scientific research and planning to determine the appropriate monitoring points.

Computational fluid dynamics (CFD) has proven to be effective in analyzing the building structure of livestock houses and studying the distribution and changes of various environmental parameters (wind speed, temperature, humidity, CO_2, and NH_3, etc.) within these houses (Jackson et al., 2020; Babadi et al., 2022; Gao et al., 2022; Hou et al., 2022; Küçüktopcu et al., 2022). The piggery environment simulation utilizes the standard k-ε model and Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) for solution calculations, which can ensure low simulation errors. In the process of simulating and analyzing the temperature, wind speed, CO_2, and NH_3 in the piggery, Tabase et al. (2020) simplified the concrete slatted floor and pigs into porous media models and semi-cylinders, respectively, selected the pressure solver and SIMPLE algorithm for calculation, and used the second-order upwind scheme to calculate equations such as momentum and turbulent kinetic energy. Yeo et al. (2020) compared standard k-ε, RNG k-ε, standard k-ω, and LES models and found that the standard k-ε model was the most suitable turbulence model for simulating odor diffusion in piggeries. Tomasello et al. (2019) conducted unstructured meshing on the simulation model, employing the standard k-ε model (Saha et al., 2020; Bovo et al., 2022), the SIMPLE algorithm, and the second-order upwind scheme for calculations. During the simulation of natural ventilation in semi-open dairy farms, it was observed that the relative error of 85% of the monitoring points was less than 30%. Jung et al. (2023) used the standard k-ε model and the steady-state Reynolds-Averaged method to solve the Navier–Stokes equations (RANS), while the RANS equations were solved using the SIMPLE algorithm and second-order upwind scheme (Wang et al., 2018; Mondaca., 2019). The average error in the ventilation system of the simulated livestock house was controlled at about 3.7%. Pakari et al. (2021) used the standard k-ε model to solve the RANS in simulating the mechanical ventilation system of a dairy farm. The average difference between the measured values and the simulation results was about 15.3%. For environmental field analysis of greenhouses, CFD technology is also applicable (Limtrakarn., 2012; Guzmán., 2018; Li et al.,2020; Xu., 2021; Nurmalisa., 2022). In the process of simulating the influence of natural ventilation on the temperature and humidity of a solar greenhouse, Zhang et al. (Zhang., 2019) used a tetrahedral mesh to divide the model, set the upper and lower vents as pressure outlets and velocity inlets, respectively, and used the Realized k-ε model to solve the transient model. The actual decrease in water vapor concentration was only 0.97% lower than the theoretical value when the exhaust port opening was 20%. It is evident that the error between CFD simulation results and actual measurement results can be controlled within a lower error range, among which the relative error of temperature can be controlled between 0.28% and 5.99%; the relative error of humidity can be controlled at 0.06% to 13.14%; environmental parameters such as NH_3 and CO_2 also have good simulation accuracy (Li et al., 2023; Gonçalves et al., 2023; Kibwika et al., 2023).

The environmental changes in closed livestock buildings are non-linear, and fixed environment monitoring can easily lead to optimal local conditions. Fixed sensors cannot monitor locations far away from the installation point, and a large number of sensors will easily increase management difficulty and sensor maintenance costs and increase the probability of sensor failure. Wheeled monitoring equipment can only walk in the aisles, and it is difficult to monitor the environmental conditions above the pig activity area. The hanging track inspection robot (HTIR) has been widely used in the production management of piggeries due to its many advantages, such as convenient operation, high flexibility, comprehensive functions, and simple structure (Li et al., 2023).

In summary, due to the high flexibility and practicality, HTIR is widely used in the environmental monitoring of livestock buildings. However, there are no specific standards for the selection of environmental monitoring points and the layout of inspection routes. It is necessary to find a way to scientifically arrange HTIR inspection routes and monitoring points to improve the accuracy of environmental monitoring data. CFD technology is extensively employed in the environmental analysis of livestock buildings and other locations. It enables a more accurate simulation of environmental changes within livestock buildings. Based on this, the research team used HTIR as a research platform to conduct a study on the distribution of environmental parameters in the main planes of closed piggeries, mainly to solve the problem of inaccurate monitoring data caused by incorrect installation of environmental sensors and proposed a CFD technology-based route planning method. This method only needs to collect a small number of necessary environmental parameters and structural parameters of the building on site and use fixed calculation methods to Perform the environment field calculation inside the piggery. Finally, all the environmental parameters at the preset points are analyzed to seek the environmental feature points. This research method can be applied to identify environmental feature points in various agricultural scenes, including piggeries, cattle houses, and chicken houses. It significantly enhances the accuracy of environmental data monitoring and serves as a foundation for future research on environmental control technology. This study provides a basis for the layout of environmental monitoring equipment in livestock buildings, greatly improves construction efficiency, and reduces the production costs of breeding enterprises. This study method has universality in the layout of environmental monitoring points in enclosed spaces.

Materials and Methods

Experimental piggery

The closed nursery piggery of Henan Zhucheng Agriculture and Animal Husbandry Technology Co., Ltd. (114.28′ E, 35.75′ N) was used as the research object. The closed nursery piggery structure and on-site photos are shown in Figure 1. The closed nursery piggery is designed with a central aisle and pig pens (pig activity area constructed from solid panels) on both sides. It features a wet curtain at the front section and a negative pressure fan at the back section. The ground is divided into two sections: a concrete slatted floor area and a solid ground area. The dimensions of the closed nursery piggery are 41.6 ×10 ×2.5 (length × width × height) m. The pig pens in the closed nursery piggery are symmetrically distributed, with ten pig pens on each side. The middle aisle has a width of 1 m, while the dimensions of each pig pen are 4.4 ×4 ×1 (length × width × height) m. The area of the concrete slatted floor in the pig pen is 12 m^2, and there is a temporary septic tank under the concrete slatted floor. The wet curtain on the front wall of the piggery is 1.7 m wide and 4 m long; the back wall is equipped with six negative pressure fans (3 models in total), with opening sizes of 1.5 ×1.5 m, 1.1 ×1.1 m, and 0.8 ×0.8 m. There are a total of 360 nursery pigs in this piggery, with an average of 18 pigs in each pig pen and an average weight of 25 kg.

Methods

CFD simulation is an mature technology in the environmental analysis of livestock houses, which can not only ensure accurate analysis results but also greatly reduce scientific research costs (Sousa et al., 2018; Yeo et al., 2020; Jackson., 2020; Zhao et al., 2023). The specific research steps and test methods of this project are as follows.

(1) Selection of monitoring height and setting of environmental analysis points.

The piggery was divided into α plane (human breathing height, 1.6 m above the ground), β plane (temperature and relative humidity monitoring height specified by national standards, 0.7 m above the ground), and γ plane (breathing height of nursery pigs, 0.4 m above the ground) (National standard of the People’s Republic of China, 2008; Fang et al., 2022). According to the current situation of the piggery, the monitoring points shown in Figure 2 are developed. The axis y_3 is the center line of the long side of the pig pens No. 1 to 10. The other four axes (y_1, y_2, y_4, and y_5) are parallel to y_3, and the distance between adjacent axes is 0.8 m; $x_{(2+3n)}$ is the center line of the wide edge of the pig pens, $x_{(1+3n)}$ and $x_{(3+3n)}$ is parallel to it, and the distance between adjacent axes is 0.8 m. The intersection of the x-axis and the y-axis is the environmental monitoring point, and the monitoring points on the left and right sides of the piggery are symmetrically arranged. The piggery has a total of 20 pig pens, with a total of 300 monitoring points on each plane and a total of 900 monitoring points in the entire piggery.

(2) Measuring the structure of the piggery and collecting relevant environmental parameters were necessary conditions for CFD simulation. Environmental data collection equipment is shown in Table 1.

(3) The CFD calculation model, which was widely recognized in the field of animal husbandry, was used to simulate the piggery environment.

(4) According to the piggery environmental management standards, the simulation results were analyzed to determine the environmental monitoring points that needed to be focused on, and the HTIR inspection route was determined accordingly. The environmental management standards for nursery piggeries are shown in Table 2.

CFD calculation

Model establishment and meshing

In order to reduce the difficulty of pig modeling and improve the quality of grid division and calculation efficiency, four cubes of the same volume were used to simulate the distribution of pigs as realistically as possible (Fang et al., 2022). The average body length of nursery pigs was 0.7 m, the body width was 0.25 m, and the height was 0.5 m. Combined with the number of pigs in each pig pen, the volume of each cube was determined to be 0.39 m^3. Factors such as ventilation ducts, feeding ducts, and lighting equipment that had a small impact on the simulation results were ignored; feed troughs between adjacent pig pens were ignored. Ansys-ICEM CFD (Version 14.5) was used to conduct a 1:1 three-dimensional modeling of the piggery and perform non-structural meshing. In the process of meshing, mesh densification was performed on the entrance, exit, pig body, and other parts. After grid independence verification, the number of grids was determined to be 2,731,242.

Calculation

This project used Ansys-Fluent (Version 14.5) to set boundary conditions and solve calculations, simplifying the concrete slatted floor into a porous media model (Rong et al., 2015; Drewry et al., 2018; Wang et al., 2022). The concrete slatted floor of the experimental piggery was a universal type, and the parameters required to simplify it into a porous medium were as follows: the z-direction inertial resistance coefficient was 173.44 m^{-1}, the viscous resistance coefficient was 118408.41 m^{-2}; the y-direction inertial resistance coefficient was 20.99 m^{-1}, the viscous resistance coefficient was 16251.26 m^{-2}; The x-direction was blocked by the slats, so its resistance coefficient was set much larger than the other two directions (Xin et al., 2021).

The temperatures of walls, roofs, and outdoors were set to a constant temperature state, the operating state of the fan was set to a constant air volume, and the simulation state was set to a steady state. The heat production of pigs was ultimately used to maintain body temperature, so the pigs were set to a homeothermic body while the respiratory heat of the pigs was ignored (Zeng et al., 2020). The wet curtain was set to the pressure inlet, and the fan was set to the speed inlet (negative value). The NH_3 concentration in the septic tank under the concrete slatted floor was stable at 30.1 $mg \cdot m^{-3}$ and was set as the source of NH_3, ignoring other NH_3 production pathways. The coupling effects between factors such as temperature, humidity, and NH_3 were ignored. The specific values of boundary conditions are shown in Table 3. In order to simplify the model and improve calculation efficiency, the following assumptions were made for the simulation model: (1) All the gases in the piggery were Newtonian fluids; (2) All the gases in the piggery were incompressible during the flow process; (3) Water vapor would not condense on the wall; (4) The piggery had good air tightness. The standard k-ε model was selected for simulation, SIMPLE was selected for the solution, and the second-order upwind scheme was selected for momentum, turbulent kinetic energy, and specific dissipation rate. The iterative calculation was considered to have converged when the residuals of the energy equation reached 1×10^{-6}, the residuals of the other equations reached 1×10^{-3}, and the values of the monitoring points reached a stable state.

Results

Result analysis

Wind speed

Ventilation volume is the main factor in regulating the environmental quality of piggeries. Combining the analysis of Table 4 and Figure 4, it is evident that the wind speed status on the left and right sides of the piggery is symmetrically distributed, and there is no significant difference between the left and right sides in each plane ($p > 0.05$). The average wind speeds in the α, β, and γ planes are 0.87 $m \cdot s^{-1}$, 0.16 $m \cdot s^{-1,}$ and 0.09 $m \cdot s^{-1}$, respectively, and there are extremely significant differences in wind speeds between each plane ($p < 0.01$). In the α plane, the wind speed shows a step-by-step decreasing trend from the wet curtain to the negative pressure fan. From this, it can be judged that the concentration of harmful gases at the back section of the piggery is higher than that at the front section. From the analysis of Figure 4-B, it is evident that the wind speed is higher in the pig pens located at the front and back sections, while the wind speed between the pig pens in the middle section of the piggery is relatively gentle. According to the analysis of Figure 5, it is observed that in the pig pens No. 1 and 10, the air flow from the concrete slatted floor moves upwards and merges with the upper air flow, resulting in an increased rate of entry for harmful gases into the pig pens. In the middle section of the piggery, there are cyclones parallel to the ground, leading to the accumulation of pollutant gases. Notably, the wind speed in pig pens No. 1, 10, 11, and 20 is significantly higher than in the other pig pens, approximately 36% higher than the average wind speed in this plane. Therefore, it can be concluded that in the α plane, the wind speed is faster, and the retention of harmful gases is less likely. Conversely, in the β and γ planes, the air flow in the front and back pig pens is heavily influenced by the concrete slatted floor, making it easier for harmful gases to enter the pig pens.

The α plane pertains to the breathing height of individuals. In short-term work, the impact of wind speed on people is not significant; thus, wind speed monitoring points are not required in this plane. However, there is a notable difference in wind speed in the β and γ planes, necessitating separate monitoring according to the established requirements. Regarding pig pens, attention should be focused on the pig pens at the front and back sections of the piggery, which are considered extreme areas in terms of wind speed. There is no significant difference in wind speed between the left and right sides of each plane of the piggery, so only one side needs to be monitored. Figure 5 illustrates that in this construction pattern, the air flow can easily carry harmful gases from under the concrete slatted floor into the pig activity area, resulting in excessively high concentrations of harmful gases. Therefore, it is necessary to minimize the concentration of harmful gases under the concrete slatted floor or consider switching to a floor ventilation system (top-down ventilation mode) to prevent any adverse effects on the pig activity area.

Temperature

Temperature is a crucial factor in determining the health status of pigs. By analyzing Table 4 and Figure 6, it is evident that the temperature in the piggery ranges from 293.28 K to 299.34 K. The average temperatures of the α, β, and γ planes are 294.81 K, 296.26 K, and 296.25 K, respectively. There are extremely significant differences between the α plane and the β and γ planes respectively ($p < 0.01$), while there is no significant difference between the β and γ planes ($p > 0.05$). Combining Figure 4 and Figure 6, it is evident that wind speed and temperature exhibit a significant negative correlation ($p < 0.01$, $r = -0.836$). The temperature is lower in areas with higher wind speeds, resulting in a higher average temperature at the back section of the piggery compared to the front section. In the α and β planes, there is a significant temperature difference between the left and right sides ($p < 0.01$). This difference is primarily influenced by the wall temperature on both sides. Figure 6-B analysis reveals that in the β and γ planes, the temperature inside the pig pens at the front and back sections is higher. The front pig pens (No. 1 and No. 10) experience relatively high temperatures, mainly due to the temperature in the septic tank. The temperature gradually increases towards the back section of the piggery as the air flow drives excess heat backward. The solid panels in the pig pen contribute to a relatively uniform temperature distribution, maintaining an average temperature of 296.15 K, which is 274.49 K higher than the α plane temperature. In the β and γ planes, pig pens No.1 and 11 at the front of the piggery, as well as pig pens No. 10 and 20 at the back, exhibit relatively high temperatures.

The wind speed on the α plane is relatively high, resulting in lower temperatures compared to other planes. In the non-pig activity area on the α plane, there is no need to specifically arrange monitoring points. There is no significant difference in temperature between the β and γ planes ($p > 0.05$), allowing any plane to be monitored based on monitoring needs. The rising air flow in the front pig pens of the piggery is influenced by the temperature in the manure tank and the body temperature of the pigs. On the other hand, the back pig pens act as a heat collection area where the air flow ends. Figure 6-B indicates that pig pens No. 4 and 14 have the lowest average temperature among all the pig pens. In the α and γ planes, there is a significant temperature difference between the left and right sides of the piggery ($p < 0.01$), requiring separate monitoring during the monitoring process.

Relative humidity

The relative humidity in the piggery ranges from 55.49%RH to 70.61%RH, which meets the environmental management standards for nursery piggeries. By combining Figures 6 and 7, it is evident that there is a strong negative correlation ($p < 0.01$, $r = -0.987$) between relative humidity and temperature. In areas with higher temperatures, the relative humidity tends to be lower. The relative humidity at the front section of the piggery is significantly higher than at the back section, which is influenced by temperature and wind speed. Figure 7 and Table 4 indicate that the overall range of relative humidity in the α plane is 63.06%RH to 77.06%RH, with an average relative humidity of 71.17%RH. The average relative humidity in the β and γ planes is approximately the same, around 66%RH, which is about 5% RH lower than the α plane. There is a highly significant difference between the α plane and the β and γ planes ($p < 0.01$), while there is no significant difference between the β and γ planes ($p > 0.05$). Additionally, there are extremely significant differences between the left and right sides within each plane ($p < 0.01$). Based on Figure 7-B, it is evident that pig pens No. 4 and 14 exhibit the highest relative humidity, while pig pens No. 10 and 20 have the lowest relative humidity. Pig pens No. 1 and 11, which are situated closer to the wet curtain, demonstrate relatively low relative humidity levels. This can be attributed to the solid panels that prevent water vapor from entering the front pig pens. Overall, there is a gradual decrease in relative humidity with increasing distance. Additionally, relative humidity and temperature display a strong negative correlation, making it feasible to monitor them at the same point as temperature.

In the α plane, it is important to prioritize areas with higher relative humidity to prevent excessive relative humidity that can lead to corrosion of metal equipment. The relative humidity levels in the β and γ planes do not show any significant difference ($p > 0.05$); hence, monitoring can be done in either plane. However, it is crucial to monitor the left and right sides of each plane separately due to the substantial difference in relative humidity between them.

NH_3

Ventilation is the primary method for regulating the concentration of harmful gases in piggeries. The distribution of harmful gases is strongly influenced by changes in the wind speed field ($p < 0.01$, $r = -0.737$, r is the Pearson correlation coefficient). From the analysis of Table 4 and Figure 8, it is evident that the concentration of NH_3 decreases as the height increases. This is primarily due to the higher wind speed at greater heights, which prevents the accumulation of NH_3. The γ plane exhibits the highest NH_3 concentration, with an average of 16.989 $mg \cdot m^{-3}$. There are significant differences in NH_3 concentrations among the α, β, and γ planes ($p < 0.01$), but no significant difference between the left and right sides within each plane ($p < 0.05$). In the α plane, the NH_3 concentration is higher at the back section of the piggery due to the influence of wind speed.

In order, the average NH_3 concentration values of the α, β and γ planes increase successively. Therefore, it is only necessary to focus on the γ plane with the highest concentration. There is no significant difference in NH_3 concentration between the left and right sides of each plane, so monitoring only one side is sufficient. The distribution of NH_3 is greatly influenced by the ventilation pattern, necessitating a change in the ventilation pattern to better regulate NH_3 concentration within the piggery. The presence of solid panels can easily lead to an increase in NH_3 concentration in the front section of pig pens. Besides, replacing the concrete slatted floors between the wet curtain and pig pens (No. 1 and 11) with solid ground can effectively modify the air flow pattern. According to the simulation results, the NH_3 concentration in the γ plane exceeds the standard concentration. This phenomenon is primarily attributed to the excessively high NH_3 concentration in the septic tank. The most effective measure to reduce NH_3 concentration in piggeries is to decrease the NH_3 concentration in the manure tank to prevent it from becoming a source of harmful gases.

Monitoring area analysis

α plane

The α plane is 1.6 m away from the ground, representing the height of human breathing. It is crucial to consider relative humidity and harmful gas concentration in this plane. In the animal husbandry industry, NH_3 is the primary harmful gas of concern. To mitigate its adverse effects on workers, attention should be focused on areas with the highest NH_3 concentration, such as the back section of the piggery. The relative humidity level in this plane is higher compared to the other two planes. It is important to monitor the relative humidity peak value to prevent excessive local humidity and its corrosive effects on metal equipment. There is a significant difference in relative humidity between the left and right sides of the α plane. Therefore, the monitoring point should be set up in the area with the highest relative humidity value on the left side, specifically above pig pen No. 1. In terms of NH_3 concentration, there is no significant difference between the left and right sides of the α plane.

Hence, the monitoring point can be set above either the No. 10 or No. 20 pig pen at the back section of the piggery, where the NH_3 concentration is highest.

β and γ planes

The β and γ planes are inside the pig pen, where the γ plane is the breathing height of the pigs. There is a significant difference in wind speed value between β and γ planes. To better monitor the wind speed value in the piggery, the γ plane is set as the monitoring plane. In the γ plane, there is no significant difference in wind speed value inside the left and right of pig pens, so the left side was selected for monitoring. Among the pig pens on the left, the wind speed in pig pen No. 1 is the fastest, while the wind speed changes in other pig pens are relatively gentle. Any pig pen can be selected to measure wind speed to reflect the average wind speed in that plane. There is no significant difference in temperature between the β and γ planes, so during the monitoring process, only the β plane can be monitored to avoid damage to the sensor by pigs. The temperature in pig pens No. 1 and 10 is the highest, followed by pig pens No. 10 and 20, and the temperature in pig pens No. 4 and 14 is the lowest. There is no significant difference between the relative humidity in the β and γ planes, but there is a significant negative correlation with the temperature. The relative humidity can be monitored at the same monitoring point as the temperature. There is a significant difference in NH_3 in the β and γ planes, so the γ plane needs to be monitored. There is no significant difference in NH_3 on the left and right sides of the γ plane, so the monitoring point is set on the left side. In the left area, the area with the highest NH_3 concentration is pig pen No. 1, followed by pig pen No. 10.

Draft HTIR route

From an industrial application perspective, y_1~y_{10} is represented as ten routes, and a comparative analysis is conducted on them. A comparison of the average environmental parameter values between each trajectory is shown in Figure 9. Through the analysis of Figure 9-A and Figure 9-B, it is evident that the four tracks y_4~y_7 are situated above the solid ground and are unable to effectively monitor the harmful gases emanating from under the concrete slatted floor. The average NH_3 concentration measured below these tracks is 34.51% lower than the overall average. Moreover, y_4~y_7, being close to the aisle, are susceptible to the high-speed air flow in the aisle, resulting in an average wind speed that is 18.92% higher than the overall average wind speed. On the other hand, y_2 and y_9 are located in a low wind speed area, with an average wind speed that is 24.32% lower than the overall average. However, the NH_3 concentration in this area is 25.78% higher than the average, while the impact on temperature and relative humidity is not very significant. The positions of y_1 and y_{10} are close to the walls of the piggery, with y_1 being close to the left wall and y_{10} being close to the right wall. These positions are in an area with the highest concentration of NH_3, which can lead to a high average NH_3 concentration in the entire track area. In the β and γ planes, the temperatures of y_1 and y_{10} are noticeably high, primarily due to the influence of wall temperature. Comprehensive analysis shows that the average environmental variables measured by the y_3 and y_8 orbits are closest to the overall average. The maximum deviation of the average wind speed is 0.03 $m \cdot s^{-1}$, the average temperature deviation is 273.24 K, the average relative humidity deviation is 0.49%RH, and the average NH_3 concentration deviation is 1.61 $mg \cdot m^{-3}$.

The environmental changes on the left and right sides of the piggery are approximately symmetrical. Therefore, for monitoring purposes, all monitoring points can be set on the left side. The average values of temperature, relative humidity, NH_3 concentration, and wind speed in the y_3 orbit on the γ plane are 296.08 K, 67.86%RH, 19.523 $mg \cdot m^{-3}$, and 0.08 $m \cdot s^{-1}$, respectively. When compared to the γ plane, the parameters of the y_3 orbit on the β plane do not show significant differences in temperature, relative humidity, and wind speed ($p > 0.05$). However, the NH_3 concentration is reduced by 14.34%, which is a highly significant difference ($p < 0.01$). This indicates that when setting up monitoring points in the β plane to monitor the environmental conditions of the pig activity area, it is necessary to consider the deviation in NH_3 concentration.

Set monitoring points

Combining data analysis and practical application requirements, the monitoring points were finally determined to be (x_1, y_3), (x_{10}, y_3), and (x_{30}, y_3). The schematic diagram of the HTIR route is shown in Figure 10. To establish multiple monitoring points in the β plane for monitoring the environmental conditions of the pig activity area, simply move the monitoring points in the γ plane upward. However, it is important to note that the NH_3 concentration needs to be increased by 14.34%.

α plane

There are two environmental feature points on this plane, namely (x_1, y_3) and (x_{30}, y_3). At (x_1,

y_3), the maximum relative humidity value can be detected; at (x_{30}, y_3), the maximum NH_3 concentration value can be detected.

β and γ planes

In the β and γ planes, a total of three environmental feature points need to be set, namely (x_1, y_3), (x_{10}, y_3), and (x_{30}, y_3). There is no significant difference in temperature and relative humidity between the β and γ planes, so all monitoring points are set on the γ plane. At (x_1, y_3), the maximum value of wind speed, temperature and NH_3 concentration can be monitored. The monitoring point (x_{10}, y_3) is located in pig pen No. 4. At this monitoring point, the average wind speed value, the lowest temperature value, and the maximum relative humidity value can be detected. At (x_{30}, y_3), the maximum value of relative humidity as well as the temperature and NH_3 concentration values in the back section of the piggery can be monitored.

Discussion

Research results

Compared to traditional environmental monitoring technology, HTIR monitoring technology offers improved flexibility and is better suited for monitoring the environment of closed livestock houses. This research project aimed to summarize the environmental change trends in universal closed nursery piggeries and identify the differences between each plane. It determined the track layout plan and monitoring points on each plane and derives the optimal inspection route for HTIR. The calculation method used in this study is applicable to a variety of livestock scenarios, including piggeries, dairy houses, and chicken houses.

Simulation error analysis

According to the data analysis, it is evident that compared with the actual measured values, the simulation results have a relative error of temperature between 0.28% and 5.99%, and a relative humidity error between 0.06% and 13.14%. It also has good simulation accuracy for environmental parameters such as NH_3 and CO_2. At the same time, the simplified model and simulation calculation model in this project have been proven by many scholars, so they can ensure good simulation accuracy (relative error < 30%). Using computational models that have been widely recognized can avoid unnecessary comparative verification and greatly reduce the consumption of scientific research resources.

This simulation model ignores factors such as feeding pipes and beams in the piggery, which may cause the actual measured results of α plane wind speed to be lower than the simulated value. However, the β and γ planes will not have much impact. The targeted ventilation in the piggery is close to the edge of the wall and is only opened in summer, so it will not have a major impact on the wind field in the piggery in spring, autumn, and winter.

Innovation and advantages

Currently, fixed environmental monitoring is the most commonly used method in the field of animal husbandry. However, there is limited research data available on monitoring points. HTIR environmental monitoring is a novel approach to environmental monitoring, and thus, no scholars have yet utilized CFD technology to plan and analyze its route. This study aimed to conduct more rigorous research and analysis on the HTIR inspection route, offering a theoretical foundation for the planning of such inspection routes.

Research findings

After CFD simulation analysis, the inspection route of the HTIR can be better determined, and the robot's operating goals can be adjusted in a targeted manner to save operating time. The NH_3 concentration at 0.4 m is significantly higher than the other two planes. There are two main reasons for this phenomenon.

1) The NH_3 concentration in the manure tank is too high and enters the pig activity area through volatilization.

2) The ventilation mode has an impact on the movement of NH_3 under the concrete slatted floor, causing it to enter the pig activity area along with the air flow. Due to the presence of solid panels, the air flow in pig pens No. 1, 2, 10, and 20 mostly moves upwards, resulting in worse environmental conditions compared to other pig pens. In the remaining pig pens, cyclones are formed, leading to the accumulation of NH_3. Ground ventilation, where the air flows from top to bottom, is the most effective ventilation method for solid panels as it significantly reduces the concentration of NH_3 in pig activity areas.

Application prospects

This livestock house environmental analysis method can be applied to most agricultural breeding scenarios. Faced with differences in seasons and livestock building construction patterns, only the boundary conditions or model structure need to be changed without changing its core parameters and calculation models.

As for livestock houses, the most common ones in Henan are rectangular livestock houses. In spring, autumn, and winter, the ventilation pattern inside the piggery will basically not change significantly; in summer, targeted ventilation will be installed, which will affect the air flow structure in the pig pen, but you only need to add a few more entrances to the structural model, and there is no need to make too many changes to the model.

Potential challenges

In all environmental monitoring situations, especially in confined spaces, as long as the boundary conditions are reasonably determined, this method can effectively simulate the environmental distribution state, thereby formulating a reasonable track inspection route. However, the larger the space, the more environmental variables there are and the greater the burden on the computer.

HTIR operation analysis

The average moving speed of HTIR is 0.24 $m \cdot s^{-1}$, while the lifting speed of the lifting mechanism is 3.8 $cm \cdot s^{-1}$. Additionally, the average sampling time is 3 minutes. Based on these values, it can be observed that the movement of HTIR within one inspection cycle takes 156.7 seconds, the lifting process takes 189.5 seconds, and the five monitoring points require a total of 9 minutes. Consequently, the total average time for the inspection is 14.8 minutes. It is worth noting that the average time spent at each sampling point during the inspection process is relatively high. Therefore, it is crucial to consider shortening the sampling time in future studies.

The γ plane is the best monitoring position for monitoring the living environment of pigs. However, in this plane, pigs can easily cause damage to the monitoring equipment, so protection measures need to be added to the monitoring area. In special cases, monitoring points can be set up in the β plane to reflect the environmental status of the pig activity area, but the deviation of environmental parameters needs to be considered. There is an average wind speed difference of 0.07 $m \cdot s^{-1}$ and an average NH_3 concentration difference of 3.08 mg·m^{-3} between the β and γ planes; however, there is no significant difference in temperature and relative humidity.

Conclusions

This study used CFD simulation technology to perform calculation and analysis and used the environmental data of pig breathing height as the basis for judgment to rationally plan the HTIR inspection routes and monitoring points in the piggery. The main research results are as follows:

(1) The distribution patterns of environmental parameters in each plane are not completely consistent. In the α plane, there are fewer obstacles, allowing harmful gases to accumulate in the back section area of the piggery due to the rapid air flow. The β and γ planes refer to the planes inside the enclosure. The relative humidity level inside the front pig pen is too low and the temperature is high. Additionally, some air flow directly enters the front pig pen through the slatted floor, resulting in NH_3 concentration exceeding 20 mg·m^{-3}. The environmental changes in the middle part of the piggery are relatively gentle and comply with environmental management standards. As the air flow moves, harmful gases accumulate at the back section of the piggery, and the average NH_3 concentration inside the terminal pig pens reaches more than 20 mg·m^{-3}. Therefore, appropriately increasing the air flow rate can prevent excessive NH_3 from accumulating in the piggery.

(2) (x_1, y_3), (x_{10}, y_3), and (x_{30}, y_3) points are environmental feature points and can be used to arrange related environmental monitoring sensors. Details are as follows: At (x_1, y_3), the maximum relative humidity value of the α plane and the maximum wind speed value, the maximum NH_3 concentration and the maximum temperature of the γ plane can be monitored; At (x_{10}, y_3), the minimum temperature and maximum relative humidity of the γ plane can be monitored; At (x_{30}, y_3), the minimum relative humidity as well as the temperature and NH_3 concentration in the terminal pig pens of the piggery can be monitored.

(3) The NH_3 concentration deviation in different planes is large and needs to be compensated based on the γ plane. During the implementation of breeding in China, environmental data monitoring is generally carried out on the β plane. Through this simulation analysis, it was confirmed that the NH_3 concentration in the β plane has an average deviation of −4.4ppm compared with the γ plane. NH_3 concentration has a greater impact on pig health, so it is very necessary to compensate for the beta plane detection data. During the actual operation, the two planes can be simulated and calibrated

in field tests to obtain the compensation data of the two planes under different environmental fields for correction.

(4) The top-down ventilation mode can effectively reduce the NH_3 concentration in the pig activity area. This ventilation mode can effectively solve the problem of harmful gases under the slatted floor entering the pig activity area.

This study utilized CFD technology to analyze the distribution patterns of temperature, relative humidity, wind speed, and NH_3 concentration in the α, β, and γ planes within a closed nursery piggery. Based on the environmental condition distribution patterns, the placement of monitoring points in the piggery was carefully planned and arranged, thereby enhancing the scientificity and effectiveness of the monitoring points arrangement. It has been observed that NH_3 can easily enter the pig activity area through air flow under the concrete slatted floor. Therefore, future research should focus on studying the ventilation structure in the piggery to minimize the entry of harmful gases into the pig activity area.

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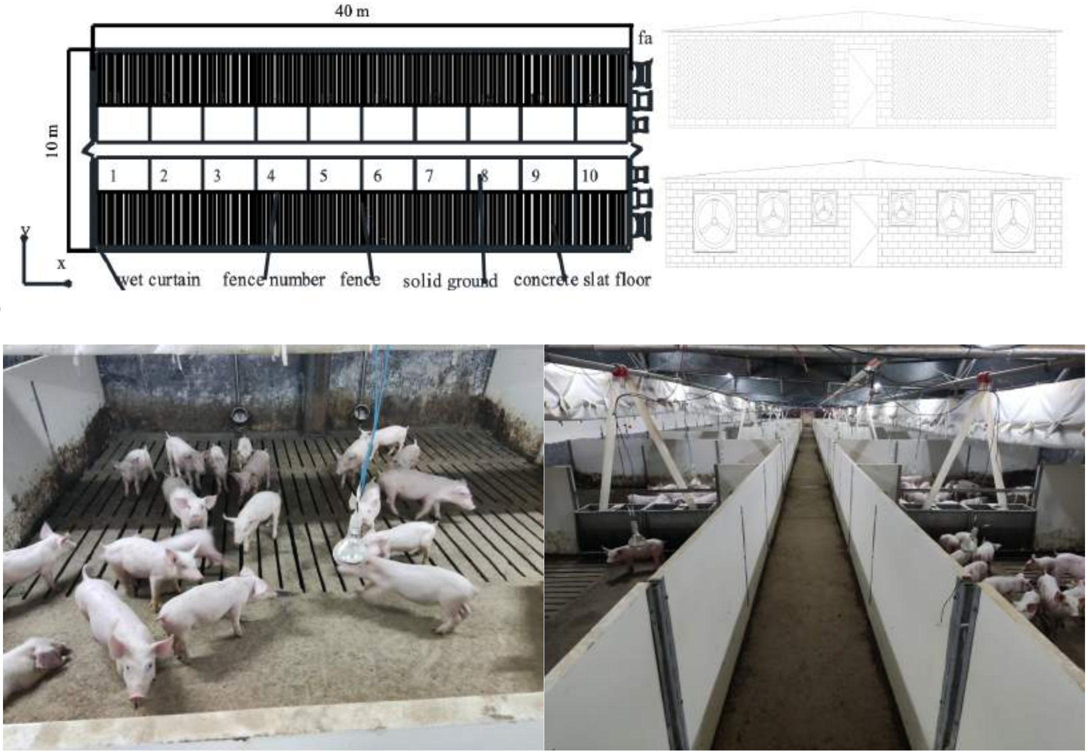


A) B)

B) C)

Figure 1. Piggery structure and photos. A) Piggery floor plan; B) Front and back wall structural drawings; C) Piggery interior scene; D) Inside scene of the pig pen. The positive y-axis points to the right side of the piggery; the positive x-axis points to the back section of the piggery; the positive z-axis points to the roof of the piggery, and the negative direction points to the manure tank.

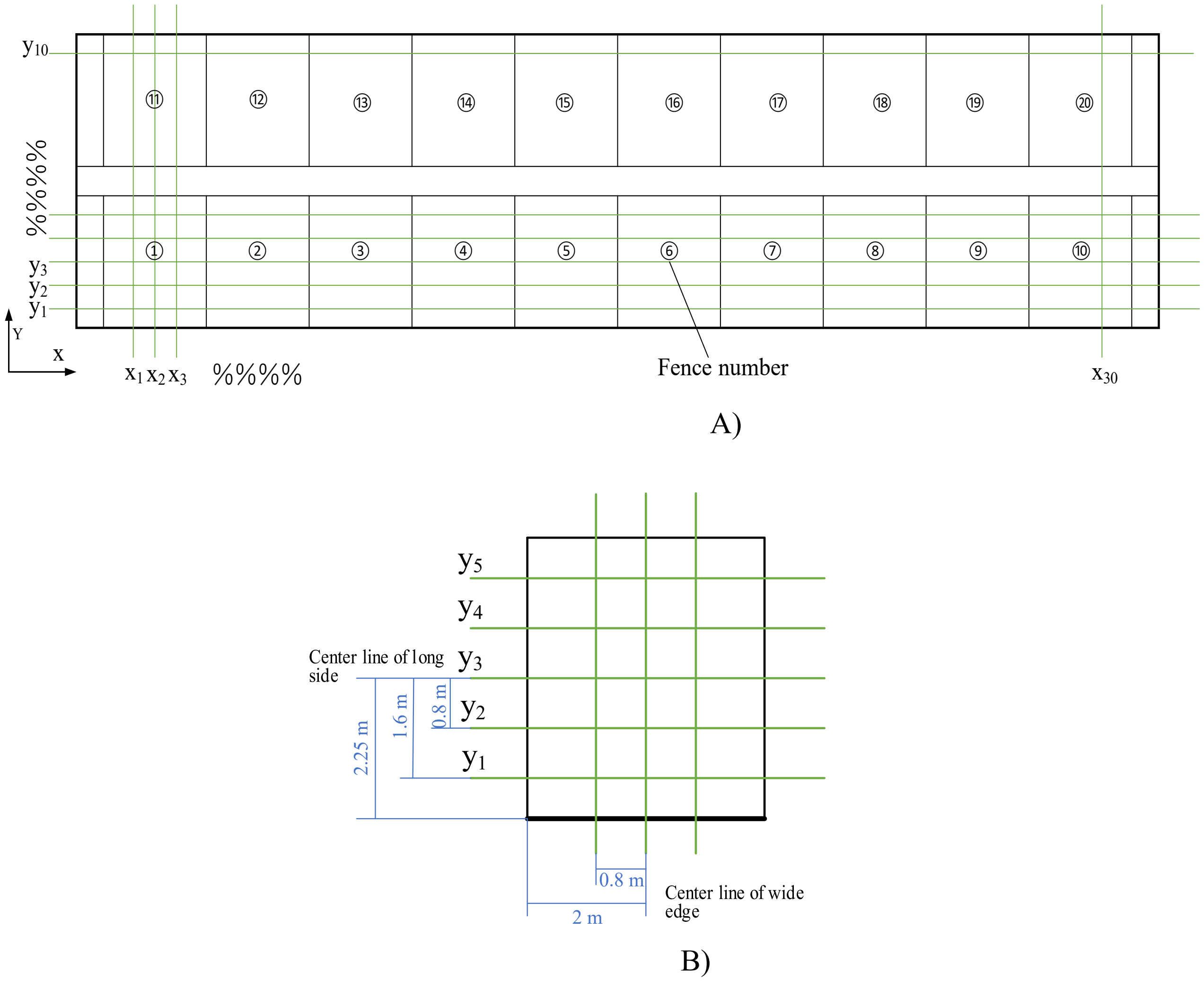


Figure 2. Monitoring point layout. A) Monitoring point distribution; B) Distribution of monitoring points in the pig pen.

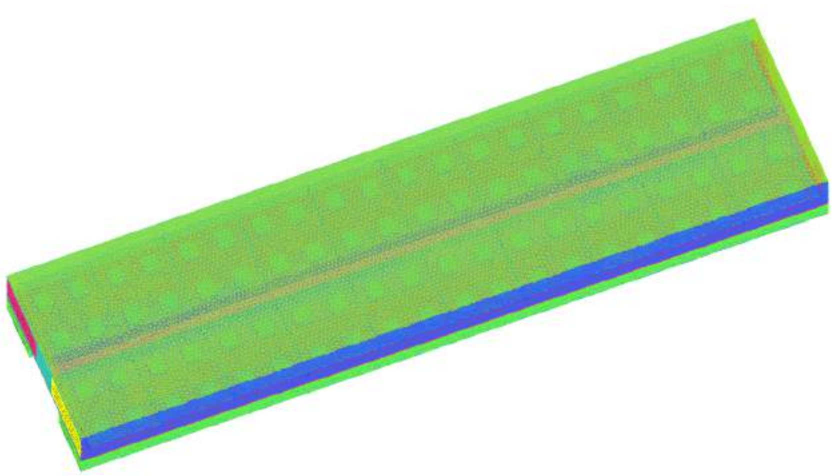
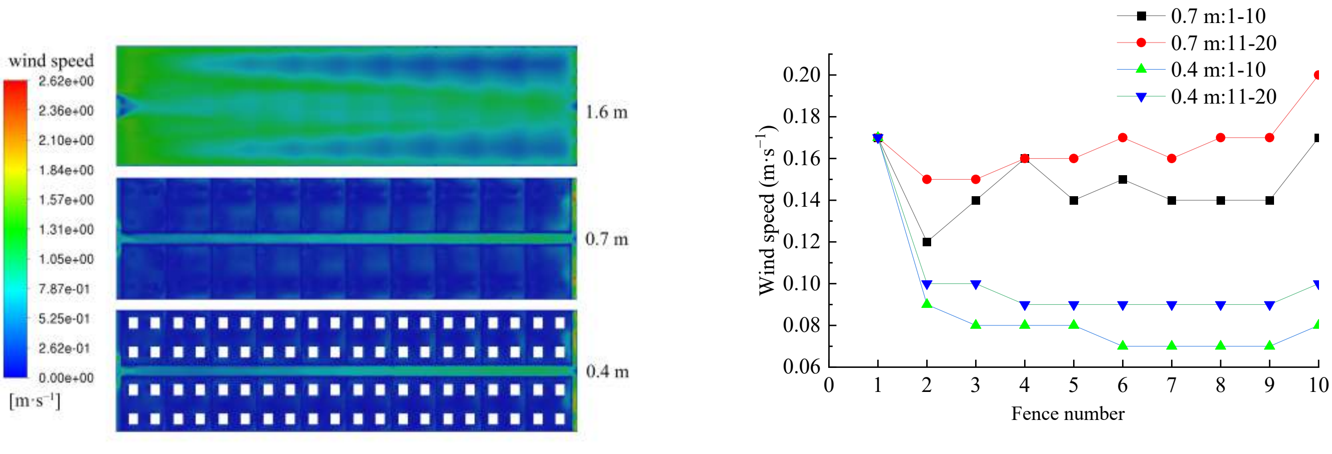
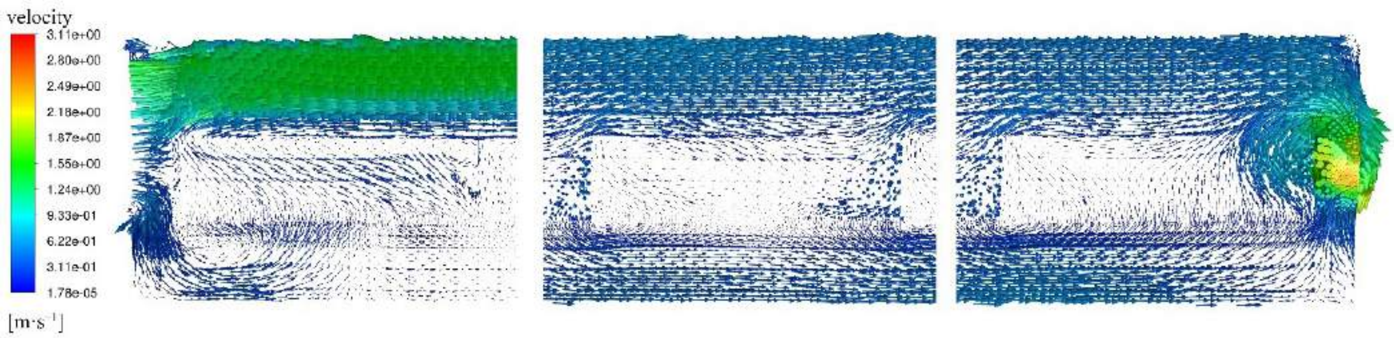


Figure 3. Model and grid display.



A) B)

Figure 4. Changes in wind speed in piggeries. A) Wind speed change chart; B) Comparison of average wind speed values in the pig pen.



A) B) C)

Figure 5. XZ plane wind speed vector diagram: A) Wind speed vector diagram at pig pen No. 1; B) Wind speed vector diagram at pig pen No. 6; C) Wind speed vector diagram at pig pen No. 10.

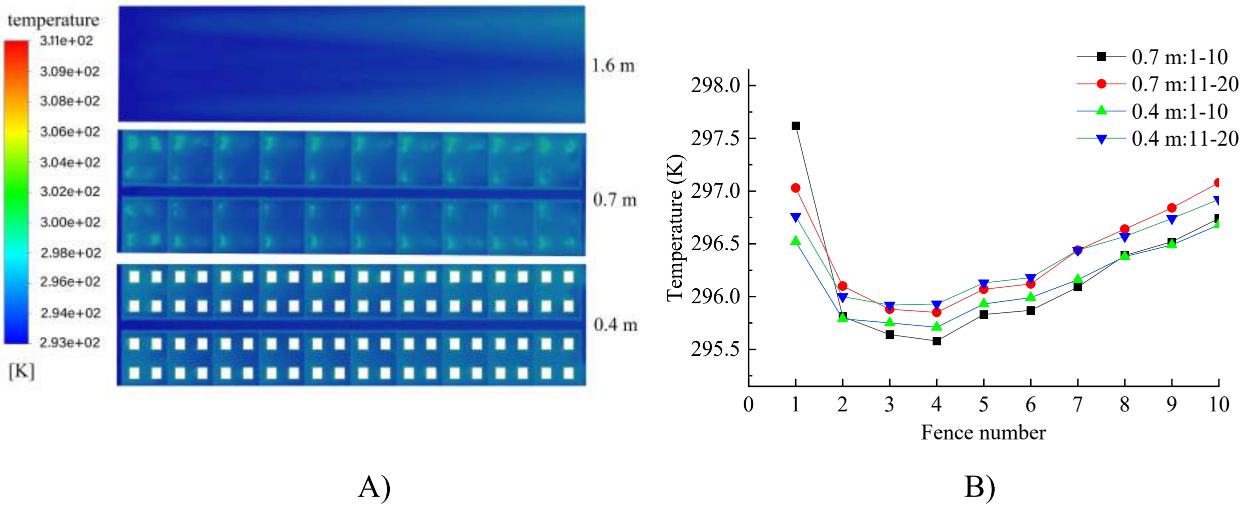


Figure 6. Comparison of temperature cloud chart and average temperature of pig pens. A) Temperature change diagram; B) Comparison of average temperatures in pig pens.

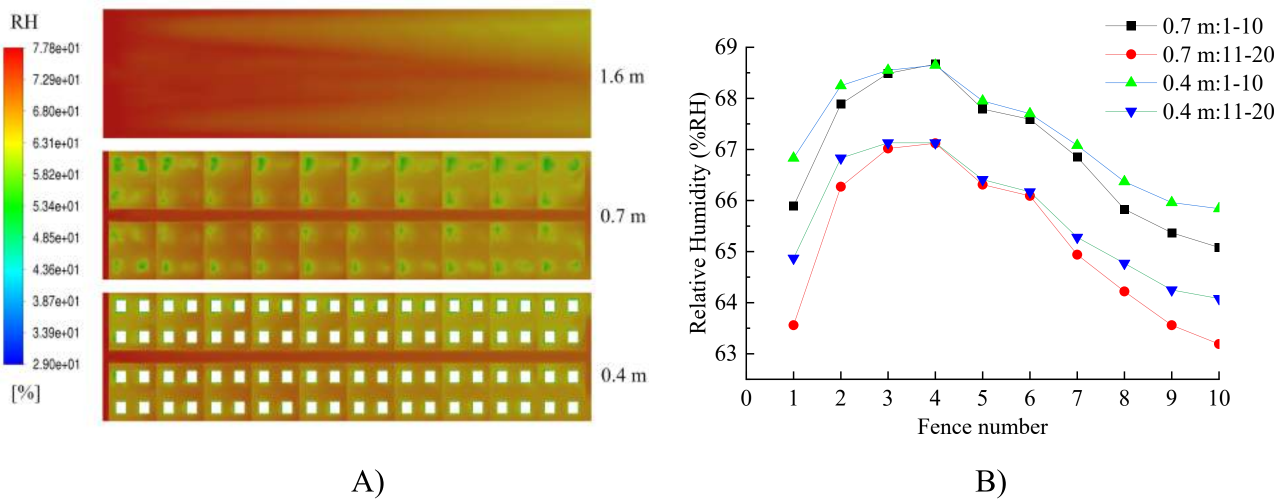
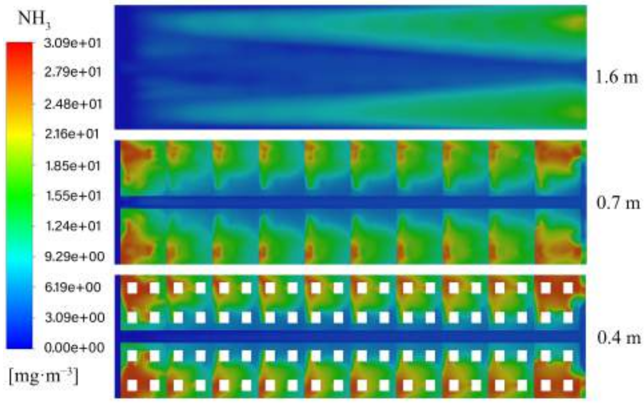
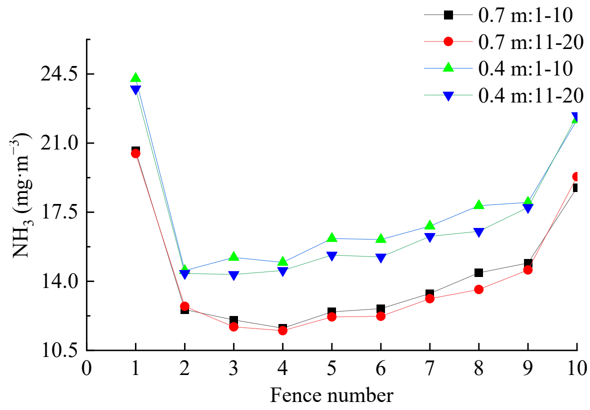


Figure 7. Humidity change chart and comparison of average humidity in pig pens. A) Humidity change chart; B) Comparison of average humidity in pig pens.



A)



B)

Figure 8. NH_3 change chart and comparison of average NH_3 concentration in the pig pen. A) NH_3 change chart; B) Comparison of average NH_3 concentration in pig pens.

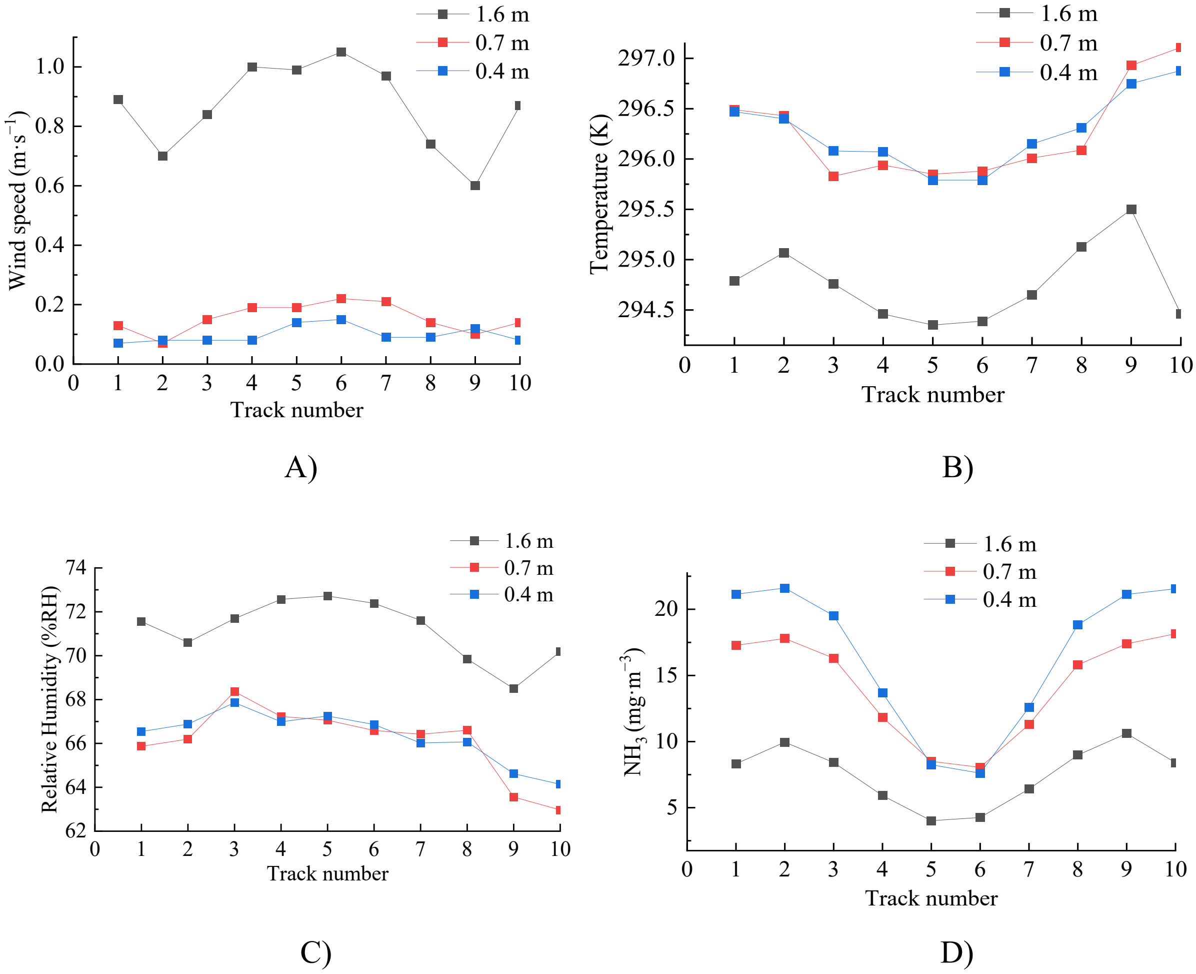


Figure 9. Comparison of average environmental parameters of orbits y_1~y_{10}. A) Comparison of average wind speed; B) Comparison of average temperature; C) Comparison of average humidity; D) Comparison of average NH_3 concentration.

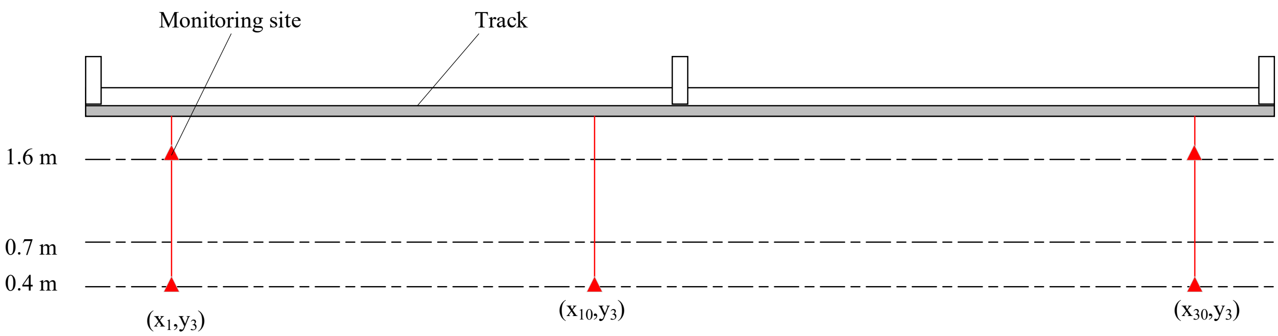


Figure 10 Schematic diagram of HTIR operation trajectory.

Table 1. Environmental data collection equipment.

Environmental parameter	Device name.	Model	Measuring range	Measurement accuracy	Factory
Air temperature and humidity	Temperature-humidity transmitter.	VMS-WS	0~100%RH,−313.15~+353.15K;	±3%RH,±273.65K.	VEMSEE
	Temperature-humidity detector	THM-01	0~100%RH,-293.15~+333.15K;	±3%RH,±273.45K	DELIXI ELECTRIC
Wall temperature	Infrared thermometer	ST590C	−323.15~863.15K	±275.15K	SMART SENSOR
Building dimensions.	laser rangefinder	DB50	0~50 m	±1.5 mm	DELIXI ELECTRIC
Wind speed	Anemometer	AS816	0.3~30 $m \cdot s^{-1}$	±5%	SMART SENSOR
	Air volume sensor	D6F-V03A1	0~3 $m \cdot s^{-1}$	±10%F.S.	OMRON
NH_3	NH_3 transmitter	VMS-NH3	0~70 $mg \cdot m^{-3}$	±8%	VEMSEE

Note: All equipment has been calibrated before leaving the factory.

Table 2. Environmental parameter management standards for nursery piggeries.

Environmental parameter	Standard
Temperature (K)	Comfort range:293.15~298.15 Critical value:289.15~301.15
Wind speed ($m \cdot s^{-1}$)	Winter:≤0.2 Summer:≤0.6
Humidity(%RH)	Comfort range:60~70 Critical value:50~80
NH_3($mg \cdot m^{-3}$)	≤20

Table 3. Boundary condition settings.

Boundary	Boundary type	Options		Numerical value
Fan	Velocity-inlet	Wind speed ($m \cdot s^{-1}$)	1.5×1.5 m	−1.5
			1.1×1.1 m	−1.4
			0.8×0.8 m	−1.5
Wet curtain	Pressure-inlet	Temperature(K)		293.15
		Humidity (%RH)		75
Pig	No-slip	Temperature(K)		311.35
Building envelope		Temperature(K)		Right wall: 296.15
				Left wall: 295.25
				Front wall: 296.95
				Back wall: 294.35
				Rooftop: 298.05
				Ground: 296.65
Solid panels		Temperature (K)		24
Septic tank wall		NH_3 concentration ($mg \cdot m^{-3}$)		30.1

Note: All values in the table are the average of multiple sampling results.

Table 4 Comparison of differences in environmental parameters of each plane.

Flat	The average difference of environmental variables in each plane				p			
	Wind speed ($m\cdot s^{-1}$)	Temperature(K)	Humidity(%RH)	NH_3($mg\cdot m^{-3}$)	Wind speed	Temperature	Humidity	NH_3
α−β	0.709	−274.593	5.079	−3.92	0.000**	0.000**	0.000**	0.000**
α−γ	0.771	−274.585	4.661	−9.87	0.000**	0.000**	0.000**	0.000**
β−γ	0.062	273.158	−0.419	−3.08	0.001**	0.915	0.144	0.000**
α(left) −α(right)	0.040	−273.404	1.321	0.343	0.051	0.004**	0.000**	0.468
β(left) −β(right)	−0.020	−273.444	1.716	0.203	0.327	0.001**	0.000**	0.727
γ(left) −γ(right)	−0.014	−273.373	1.667	0.784	0.632	0.085	0.000**	0.338

Note：*p<0.05; **p<0.01.