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VENTILATION SOLUTIONS SIMULATION FOR URBAN RESIDENTIAL AREAS

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Abstract
Rapid urbanization intensifies air quality and ventilation challenges in densely populated areas, impacting residents' health and comfort. While healthy ventilation systems regulate airflow, temperature, humidity, and pollutants, their design remains complex due to space constraints, dense structures, and climate variability. This study addresses two aspects: (1) evaluating ventilation effectiveness across diverse conditions using airflow analysis, and (2) proposing a multi-objective optimization framework integrating air quality, energy efficiency, and comfort metrics. Results show optimized strategies enhance environmental performance while maintaining energy savings and comfort. The research provides actionable insights for adaptive ventilation design and advances sustainable urban planning frameworks. By merging practical challenges with data-driven optimization, this work offers scalable solutions to improve living conditions in dense cities.

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Key Words: Urban Densely Populated Residential Areas, Healthy Ventilation, Airflow Organization, Multi-Objective Optimization, Architectural Design

1. INTRODUCTION

With the acceleration of global urbanization, urban densely populated residential areas have become an important part of modern urban construction [1-4]. However, as the population density increases, the quality of the living environment has become one of the key factors affecting residents' quality of life [5-7]. In this context, how to provide a healthy living environment in limited space, particularly ensuring effective airflow in urban densely populated residential areas, has become an important challenge in urban residential design [8, 9]. Healthy ventilation in urban densely populated residential areas can not only improve air quality, reduce the accumulation of harmful substances, but also effectively regulate temperature and humidity, providing residents with a comfortable living experience [10-13]. Therefore, studying healthy ventilation solutions for urban densely populated residential areas and exploring optimization strategies is of great practical significance for improving the quality of life for urban residents.

Although some studies have made progress in areas such as airflow organization and ventilation efficiency, most of the research methods have certain limitations. First, many studies are based solely on single building designs or ventilation forms, without fully considering the impact of different climate conditions, urban layouts, and varying residential densities on ventilation effects [14-17]. Secondly, existing optimization methods mostly focus on a single optimization objective related to ventilation effects, neglecting other factors that may affect health, such as temperature and humidity, air quality, and noise in urban densely populated residential areas [18-21]. These shortcomings make it difficult for existing ventilation design solutions to achieve ideal results in practical applications, thus necessitating a more comprehensive and systematic multi-objective optimization method to address this issue.

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The research in this paper mainly includes two aspects. First, by conducting a detailed evaluation of airflow organization in urban densely populated residential areas, this study explores the impact of different design solutions on healthy ventilation to identify the optimal airflow pattern. Second, based on a multi-objective optimization method, this research proposes a healthy ventilation solution that takes various factors into account to achieve a comprehensive balance between air quality, comfort, and energy efficiency within residential areas. Through this study, it is hoped to provide guidance for practical building design and offer theoretical foundations and practical experience for optimizing the healthy ventilation system of future urban densely populated residential areas, thus contributing to the improvement of the living environment for urban residents.

2. AIRFLOW EVALUATION FOR URBAN RESIDENTIAL VENTILATION

Urban densely populated residential areas are a typical product of the modern urbanization process, facing the dual challenges of high population density and limited space. In such living environments, poor airflow often leads to the deterioration of air quality, which in turn affects the physical health of residents. Due to factors such as dense buildings, limited green spaces, and restricted wind corridors, urban densely populated residential areas commonly suffer from insufficient natural ventilation, leading to the accumulation of harmful substances such as carbon dioxide, formaldehyde, and volatile organic compounds. In severe cases, this may cause respiratory diseases, allergic reactions, and other health issues. Furthermore, the impact of climate change has gradually highlighted the influence of temperature and humidity fluctuations on the airflow within these residential areas. Therefore, ensuring healthy ventilation in urban densely populated residential areas is not only a necessary measure to protect residents' health, but also a critical factor in improving living quality and increasing comfort.

Against this backdrop, studying the healthy ventilation issues of urban densely populated residential areas becomes particularly urgent. Firstly, due to the high building density and layout, these areas are often unable to solve the airflow problem through traditional natural ventilation methods, especially in high-rise buildings or areas with narrow building spacing. Secondly, the complexity of the urban environment makes it difficult to rely solely on external climatic conditions to regulate ventilation efficiency. As a result, exploring effective ventilation airflow organization schemes and precisely controlling airflow paths becomes key to improving air quality. On the other hand, with the increasing demand for building energy efficiency, healthy ventilation designs must not only consider the flow of air in urban densely populated residential areas, but also balance energy efficiency and comfort, avoiding excessive reliance on mechanical ventilation systems. Therefore, it is essential to develop a healthy ventilation solution that adapts to the characteristics of urban densely populated residential areas, combining building forms, surrounding environmental conditions, and the needs of residents. This will not only effectively optimize the air quality in these residential areas but also reduce energy consumption to some extent and improve the sustainability of the buildings.

In the study of healthy ventilation in urban densely populated residential areas, the evaluation of airflow organization is a critical link to ensuring air quality and comfort. The uniformity of airflow organization directly affects the ventilation effect, especially in dense urban environments where the concentration of buildings and the complexity of layouts often lead to uneven airflow distribution. Thus, the unevenness coefficient becomes an important evaluation index, used to measure the degree of variation in airflow temperature and speed. Specifically, the unevenness coefficient reflects the imbalance in the distribution of air movement in space, indicating the degree of variation in airflow within a certain area. A higher unevenness coefficient usually indicates uneven air movement, leading to poor ventilation in certain areas, imbalanced temperature and humidity, and the potential for localized overheating or air stagnation, which may affect residents' comfort and health. On the other hand, a lower unevenness coefficient indicates more uniform airflow distribution across the space, helping to maintain good air quality in urban densely populated residential areas. Specifically, within the region of the urban densely populated residential area, v measurement points are selected, and the temperature (s) and wind speed (i) at each point are measured. Assuming the average temperature is represented by $\bar{s}$, the average speed by $\bar{\imath}$, the root mean square deviation (*RMSD*) of temperature by δ_s, the *RMSD* of speed by δ_i, the temperature values at each point by s_u, and the wind speed values at each point by i_u, the total number of points in the region is represented by V. The temperature unevenness coefficient is represented by j_s, and the speed unevenness coefficient by j_i. The arithmetic mean is calculated as:

$$\bar{s} = \frac{\sum s_u}{v} \tag{1}$$

$$\bar{\imath} = \frac{\sum i_u}{v} \tag{2}$$

The *RMSD* is:

$$\delta_s = \sqrt{\frac{\sum (s_u - \bar{s})^2}{v}} \tag{3}$$

$$\delta_i = \sqrt{\frac{\sum (i_u - \bar{\imath})^2}{v}} \tag{4}$$

The Unevenness Coefficient is:

$$j_s = \frac{\delta_s}{s} \tag{5}$$

$$j_i = \frac{\delta_i}{i} \tag{6}$$

In urban densely populated residential areas, due to dense buildings, limited space, and complex and changing airflow paths, the study of air age is particularly important. A lower air age indicates that the air in the urban densely populated residential area is being refreshed rapidly, with lower concentrations of harmful substances and better air quality. Conversely, a higher air age suggests that the air is stagnant for longer periods, potentially leading to the accumulation of harmful substances, which affects residents' health. The air age at a specific point, π_o, is the mean air age of all the microcells at that point. The expression for air age is:

$$\pi_o = \int_0^o z d(\pi) f(\pi) \tag{7}$$

There are two main methods for calculating air age: the tracer gas method and numerical solution method. The tracer gas method is an experimental approach, where a tracer gas, easily detectable, is released in the residential area. The concentration changes at different locations are monitored to calculate the air age. The numerical solution method typically uses computational fluid dynamics (CFD) simulation techniques. A 3D model of the residential area is constructed, and ventilation systems and airflow are simulated numerically, allowing air age to be calculated in a virtual environment. The specific numerical solution formula is:

$$\frac{\partial}{\partial a_k}(\vartheta i_k \pi_o) = \frac{\partial}{\partial a_k}\left(I_\pi \frac{\partial \pi_o}{\partial a_k}\right) + \vartheta \tag{8}$$

In urban densely populated residential areas, due to dense building layouts and limited space, airflow may be obstructed, making it difficult to effectively renew the air. In such cases, the efficiency of the ventilation system is crucial. If the exhaust system's pollutant removal efficiency is low, harmful substances such as carbon dioxide, formaldehyde, and volatile organic compounds can accumulate in the residential area, severely affecting residents' health. Insufficient heat removal efficiency may lead to excessively high temperatures in the summer, negatively impacting living comfort. Specifically, let the pollutant concentration at the exhaust outlet be represented by $Z_r(\infty)$, the pollutant concentration at the supply outlet by $Z_t(\infty)$, and the pollutant concentration at point O by $Z_o(\infty)$. The ventilation efficiency at any point O in the urban densely populated residential area can be expressed as:

$$R_O^e = \frac{Z_r(\infty) - Z_t(\infty)}{Z_o(\infty) - Z_t(\infty)} \tag{9}$$

Supply air accessibility not only involves the airflow path but also concerns whether the air can flow smoothly to all corners of the urban densely populated residential area, particularly in high-density, limited-space urban residential areas. Due to small building spacing and complex layouts, certain areas may face airflow obstruction, leading to poor ventilation and even localized air stagnation. Let the tracer gas concentration at point O at time s in the urban densely populated residential area be represented by $Z(s)$, the concentration of tracer gas in the supply air be represented by Z_t, and the time elapsed since the start of the supply air be represented by π. The supply air accessibility can be expressed as:

$$X_{TX}(\pi) = \frac{\int_0^\pi Z(s) fs}{Z_t \pi} \tag{10}$$

The evaluation of pollution source accessibility not only involves whether the ventilation system can identify the location of pollution sources in urban densely populated residential areas, but also whether the airflow can directly contact and eliminate these pollutants through a reasonable path. In urban densely populated residential areas, there are often multiple pollution sources, such as kitchens, bathrooms, and gas appliances, and the locations of these pollution sources are closely related to the design and layout of the ventilation system. Therefore, assessing the accessibility of pollution sources is crucial for ensuring the air quality and health of the residents in such areas. Let the mean pollutant concentration at the return air outlet under steady state be represented by Z^{-}. The pollutant accessibility at a point at time π can be expressed as $X_{ZT}(\pi)$, and the pollutant concentration at point s is represented by $z(s)$. The time elapsed since the pollutant began to diffuse is denoted by π, and the supply air mass flow rate is represented by W, then the mathematical expressions are:

$$X_{ZT}(\pi) = \frac{\int_0^\pi Z(s) fs}{\overline{Z}_\pi} \tag{11}$$

$$\overline{Z} = \sum \frac{l_u}{W} \tag{12}$$

The air distribution characteristics index primarily focuses on the relationship between wind speed and effective temperature difference. This index is designed to evaluate whether the ventilation system can provide sufficient airflow to ensure the air quality and thermal comfort of urban densely populated residential areas without causing discomfort. The relationship between wind speed and effective temperature difference directly impacts residents' comfort and health. In urban densely populated residential areas, due to the small distance between buildings, the external environment has a significant effect on the air distribution within the area. Therefore, evaluating the reasonableness of wind speed and temperature differences is crucial. High wind speeds may result in uncomfortable airflow, while very low wind speeds may lead to poor air circulation and pollutant accumulation, affecting air quality. At the same time, the effective temperature difference refers to the temperature difference between different locations within the residential area, and excessive temperature differences can lead to thermal discomfort, negatively impacting the living experience. Let the air temperature, wind speed, and specified temperature at a point in the residential area be represented by s_u, i_u, and s_v, respectively. The relationship between indoor wind speed and effective temperature difference can be expressed as:

$$RFS = (s_u - s_v) - 7.66(i_u - 0.15) \tag{13}$$

The air distribution characteristics index can be defined as:

$$XFOU = \frac{\text{Number of measurement points for} - 1.7 < RFS < 1.1}{\text{Total number of measurement points}} \times 100\ \% \tag{14}$$

Under normal circumstances, *XFOU* should be greater than 80 %, and the larger the value of *XFOU*, the more people feel comfortable in the urban dense residential area.

Due to dense buildings and limited air flow in urban dense residential areas, it is easy to lead to the accumulation of pollutants, including dust, PM 2.5, and other particulate matter in the urban dense residential area. The evaluation index of the average concentration of particulate matter in the breathing zone aims to determine the potential health risks to the residents by evaluating the distribution of these pollutants under the action of the ventilation system. Low concentrations of particulate matter help improve the health of the living environment, while high concentrations may lead to respiratory diseases and other health problems.

In order to effectively assess the average concentration of particulate matter in the breathing zone, this paper combines numerical simulations, experimental monitoring, and other methods to analyse how particulate matter in the air of residential areas is distributed and flows between rooms under different ventilation conditions. Simulation studies can predict the dilution and discharge effects of the ventilation system on particulate matter by calculating the air flow paths and evaluate the impact of different ventilation methods, such as natural ventilation and mechanical ventilation, on particulate matter concentration.

3. OPTIMIZING VENTILATION IN DENSELY POPULATED URBAN AREAS

Factors influencing the organization of healthy ventilation airflow mainly include building density, wind speed, the distribution of pollution sources, the layout of urban densely populated residential areas, external environmental conditions (such as climate, wind direction, etc.), and the type and design of the ventilation system. Firstly, the building layout in urban densely populated residential areas is often relatively compact, and the density and height differences of surrounding buildings affect airflow, causing poor ventilation in certain areas and creating air stagnation zones or pollution accumulation zones. In addition, the location and distribution of various pollution sources within the urban densely populated residential area directly impact the efficiency of airflow organization, especially when multiple pollution sources coexist. Organizing the airflow reasonably to avoid cross-contamination and improve airflow efficiency becomes a key challenge in designing a healthy ventilation system. At the same time, external climate conditions and wind speed also affect the ventilation effect. When wind speed is too low, the ventilation effect may be unsatisfactory, while excessively high wind speed may cause discomfort or unstable airflow distribution, affecting the temperature and air quality of the urban densely populated residential area.

Based on these influencing factors and the previous evaluation indicators, healthy ventilation solutions for urban densely populated residential areas should include optimizing the external wind environment of buildings, designing ventilation paths reasonably, and effectively utilizing a combination of natural and mechanical ventilation. In terms of ventilation design, the use of natural ventilation can be improved by increasing building gaps and improving the exterior facade structure, thereby enhancing the effect of natural ventilation. At the same time, the design of the ventilation system in urban densely populated residential areas should focus on improving the uniformity of airflow, ensuring that air flows effectively to all key areas, especially near pollution sources, to avoid pollutant retention. In terms of system type, combining natural ventilation and mechanical ventilation can be flexibly adjusted based on climate conditions and the needs of different seasons.

To achieve the optimal healthy ventilation solution for urban densely populated residential areas, this paper constructs the corresponding multi-objective optimization model, which mainly includes decision variables, objective functions, and constraints. These parts are set based on the specific needs of the urban densely populated residential area. The decision variables may involve ventilation duct locations, the number of ventilation openings, airflow distribution parameters such as wind speed and air flow paths, as well as the ratio of natural to mechanical ventilation. These decision variables need to be optimized under given constraints to achieve the best ventilation effect and optimal energy efficiency. The objective functions usually include multiple aspects, such as: maximizing air quality in the urban densely populated residential area, minimizing energy consumption, and maximizing thermal comfort. These objective functions are often in conflict with each other. For example, increasing airflow may increase energy consumption, while excessively low wind speed may lead to poor air circulation in the urban densely populated residential area. Therefore, it is necessary to balance the contradictions between the objectives through multi-objective optimization methods. Let the F-dimensional decision variables be represented by a, the objective function by b, the total number of optimization objectives by V, the v^{th} sub-objective function by $d_v(a)$, the J inequality constraints by $h(a)$, and the feasible domain formed by the constraints by $g(a)$. The upper and lower bounds of the vector search are represented by $a_{f\text{-}MIN}$ and $a_{f\text{-}MAX}$. The multi-objective optimization mathematical description of the healthy ventilation solution for urban densely populated residential areas is as follows:

$$\begin{aligned}
&MIN(\&)B = MAXd(a) = [d_1(a), d_2(a), \dots, d_v(a)]\ (v = 1, 2, \dots, V)\\
&T.s{:}\, h(a) = \left[h_1(a), h_2(a), \dots, h_j(a)\right] \le 0; g(a) = [g_1(a), g_2(a), \dots, g_l(a)]\\
&a = \left[a_1, a_2, \dots, a_f, \dots, a_F\right]; a_{f-MIN} \le a_f \le a_{f-MAX}\ (f = 1, 2, \dots, F)
\end{aligned} \tag{15}$$

4. SIMULATION RESULTS AND ANALYSIS

Fig. 1 presents a schematic diagram of the simulation layout for an urban densely populated residential area, showing the building layout and related dimensional information. The simulation model adopts a regular grid layout, with buildings distributed at the grid intersections. The horizontal dimensions are labelled from left to right as 7.2 m, 5 m, 10 m, 10 m, 10 m, 10 m, 5 m, and 30 m; the vertical dimensions are labelled from top to bottom as 6 m, 10 m, 10 m, 10 m, 10 m, and 6 m. These dimensions represent the inter-building spacing, road width, or other spatial distances, which are used to accurately construct the simulation model and simulate the spatial scale relationships of the residential area. The dashed box in the figure represents the key research area or specific simulation range.

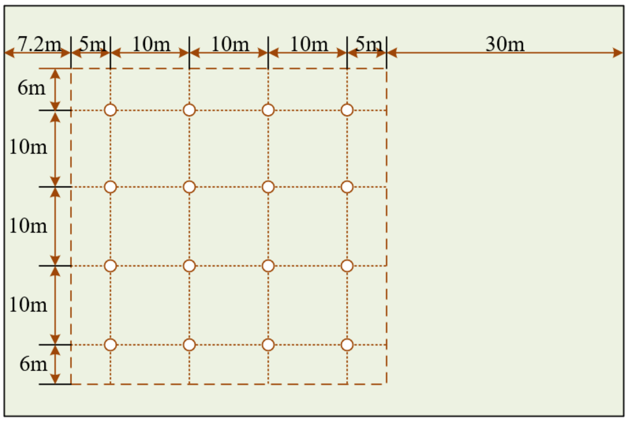


Figure 1: Schematic diagram of the simulation layout for urban densely populated residential areas.

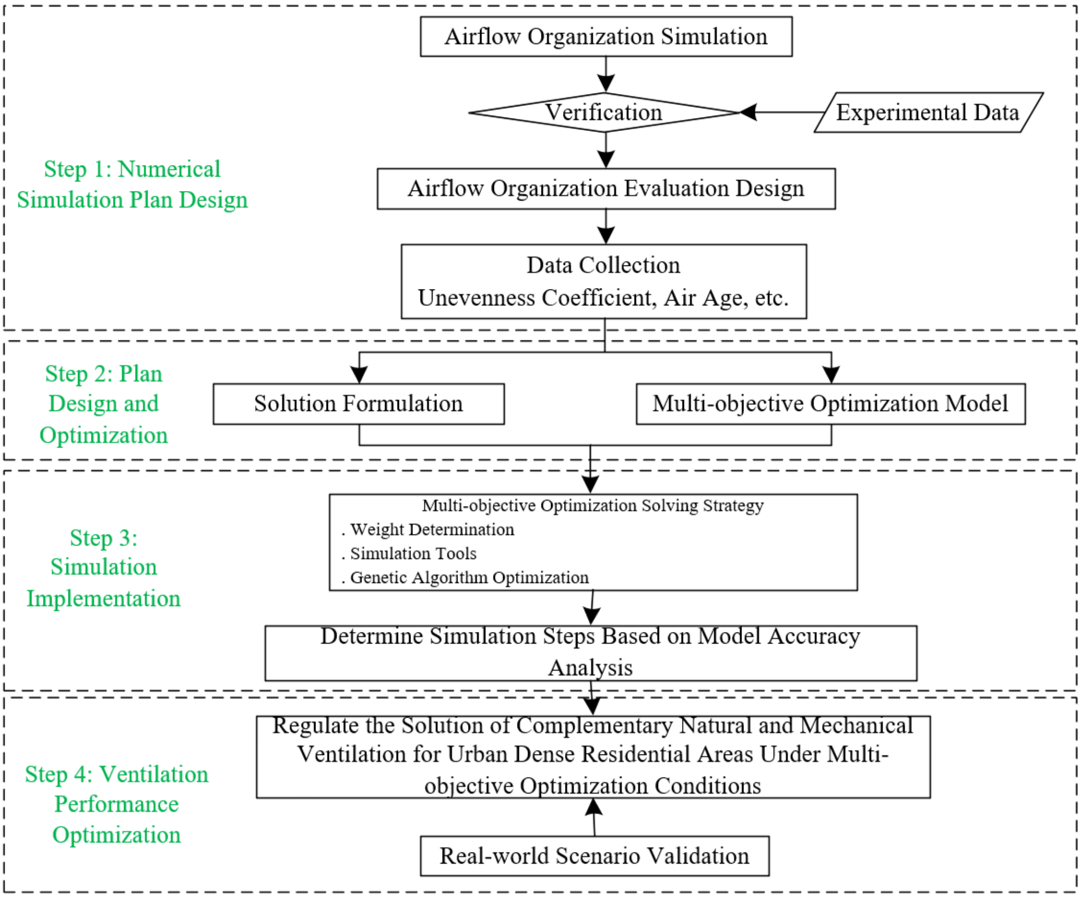


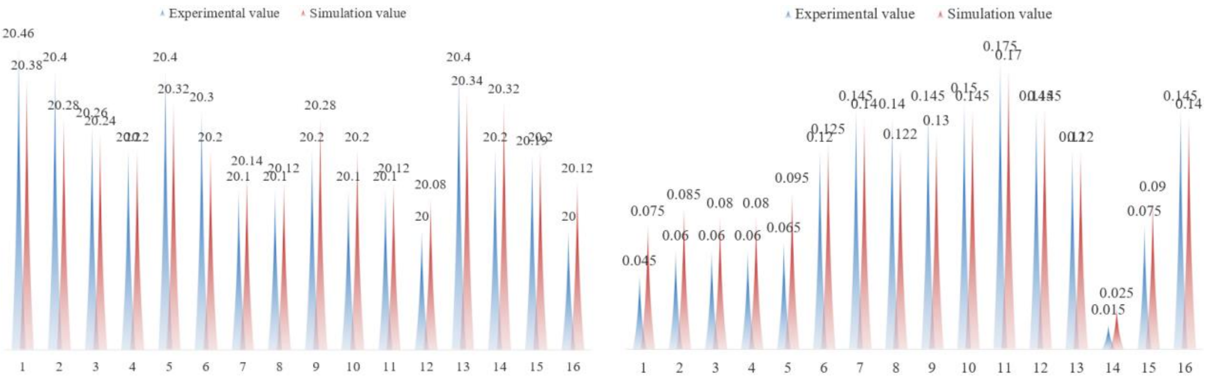
Figure 2: Simulation research flowchart.

Fig. 2 presents the simulation research flowchart. The simulation experiment in this paper is divided into four steps: Step 1, numerical simulation plan design, which involves first performing airflow organization simulation, comparing and validating the simulation results with experimental data, then conducting airflow organization evaluation design, and collecting data such as unevenness coefficient, ventilation volume, air age, etc.; Step 2, plan design and optimization, which involves formulating a solution and constructing a multi-objective optimization model; Step 3, simulation implementation, which involves determining the multi-objective optimization solving strategy, including weight determination, simulation tools, and genetic algorithm optimization, and determining the simulation steps based on model accuracy analysis; Step 4, ventilation performance optimization, which involves regulating the complementary solution of natural and mechanical ventilation for urban dense residential areas under multi-objective optimization conditions and verifying through real-world scenario validation.

Table I: Ventilation efficiency calculation values for urban densely populated residential areas.

Case	**Ventilation temperature**	**Area number**						
		1	2	3	4	5	6	7
A	17.8	21	22.4	22.4	22.4	22.6	22.8	23.5
B	17	22.8	22.3	22.6	21.6	21.5	22.6	22.4
C	17.9	21.8	22.8	22.1	22.8	22.8	22.1	21.8

Based on the data shown in Table I, the ventilation temperatures in various areas exhibit different variations. Area 1 (strong ventilation open-type area) has relatively low ventilation temperatures: 17.8°C, 21°C, 22.4°C, 22.4°C, 22.4°C, 22.6°C, and 22.8°C, indicating better airflow performance with smaller temperature fluctuations, demonstrating superior ventilation efficiency. Area 2 (plate-type building with good ventilation) shows relatively balanced temperature variation across different area numbers, with temperatures of 17°C, 22.8°C, 22.3°C, 22.6°C, 21.6°C, 21.5°C, and 22.6°C, indicating good ventilation performance, particularly in terms of maintaining temperature stability. Area 3 (point-type building with staggered ventilation) has a small temperature variation range across different area numbers, with temperatures of 17.9°C, 21.8°C, 22.8°C, 22.1°C, 22.8°C, 22.8°C, and 22.1°C, presenting a more uniform temperature distribution, indicating good ventilation effectiveness, especially in improving dead spots. Other areas, such as Area 4 (column-type semi-permeable ventilation area), Area 5 (enclosed weak ventilation area), and Area 6 (mixed complex ventilation area), exhibit greater temperature differences, indicating relatively poor ventilation efficiency, with noticeable dead spots in certain areas.

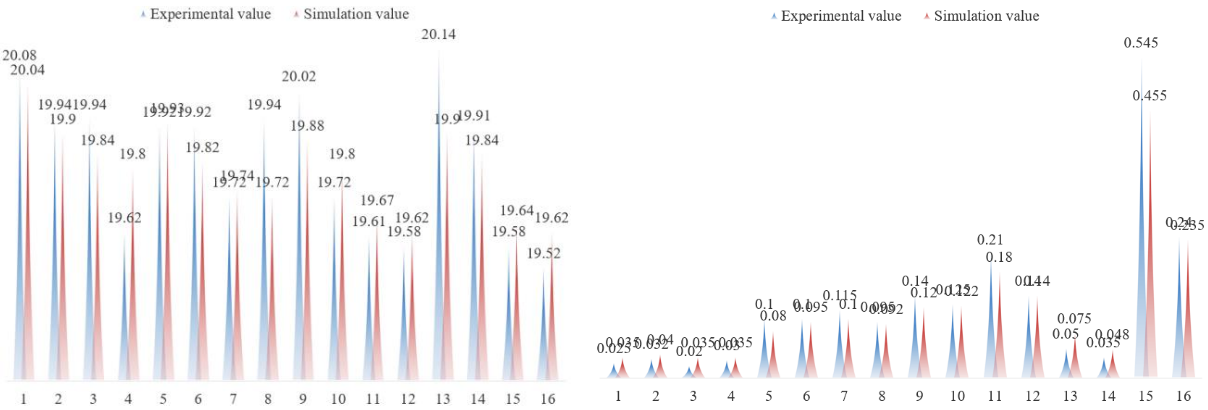


1) Objective function value

2) Ventilation speed

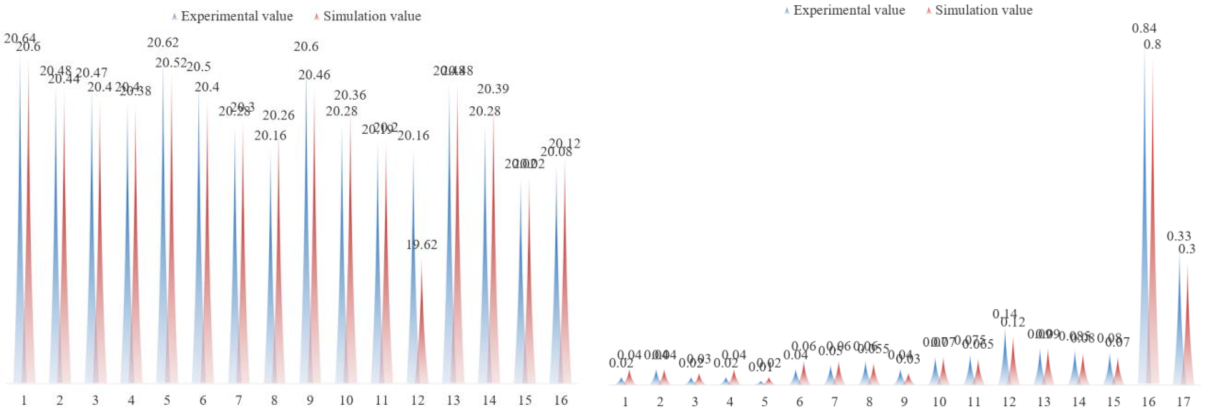
Figure 3: Ventilation airflow organization simulation results at 5 m height plane in urban dense residential area.

Based on the Table I, several conclusions can be drawn. First, the strong ventilation open-type area (Area 1) demonstrates the best ventilation effect, with relatively low and stable temperatures, making it suitable for residential designs that require significant airflow. Second, the plate-type building with good ventilation (Area 2) has relatively uniform temperatures but the overall ventilation effect has not reached its optimal level, mainly showing slightly higher temperatures in some local areas. The point-type building with staggered ventilation (Area 3) can effectively reduce ventilation dead spots, with small temperature variations, making it suitable for residential areas with complex layouts. The column-type semi-permeable ventilation area (Area 4) and enclosed weak ventilation area (Area 5) show poor ventilation performance, especially in the enclosed areas, where noticeable ventilation dead spots exist. The mixed complex ventilation area (Area 6) shows some fluctuation in ventilation performance, indicating that its design complexity leads to poor airflow in some areas.



1) Objective function value 2) Ventilation speed

Figure 4: Ventilation airflow organization simulation results at 15 m height plane in urban dense residential area.



1) Objective function value 2) Ventilation speed

Figure 5: Ventilation airflow organization simulation results at 25 m height plane in urban dense residential area.

Based on the experimental data in Figs. 3, 4, and 5, the variation trends of the objective function values and ventilation speeds at different height planes can be observed between the experimental values and the simulated values. Regarding the objective function values, the difference between the experimental and simulated values is small, indicating that the simulation results are relatively accurate. For example, the experimental value of the objective function at measuring point 1 is 20.46, and the simulated value is 20.38; at measuring point 2, the experimental value is 20.4, and the simulated value is 20.28. The differences are small, showing that the simulation model performs well in predicting the objective function values. In terms of ventilation speed, the simulated values are generally higher than the experimental values, but the overall trends are consistent. For example, at measuring point 1, the experimental value is 0.045 m/s, and the simulated value is 0.075 m/s; at measuring point 5, the experimental value is 0.065 m/s, and the simulated value is 0.095 m/s. This indicates that the simulation model is able to accurately predict the variation of ventilation speed at different height planes, although there is a slight overestimation. Overall, the differences between experimental and simulated values for both objective function values and ventilation speeds are within a reasonable range, suggesting that the simulation model has high predictive accuracy.

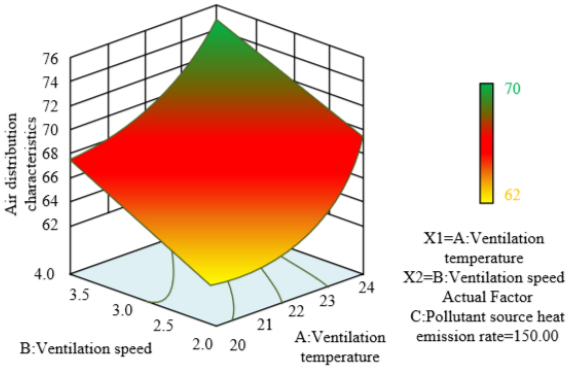


Figure 6: Response surface analysis graph showing the effect of ventilation temperature and ventilation speed on air distribution characteristics.

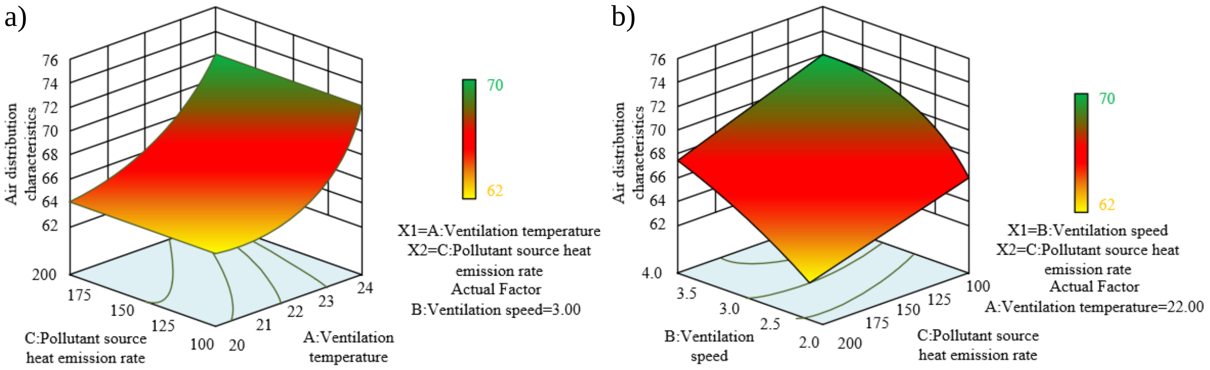


Figure 7: Response surface analysis graph showing the effect of ventilation temperature (a) / speed (b) and pollution source heat emission rate on air distribution characteristics.

This study conducts a detailed analysis of the airflow organization in urban dense residential areas, considering the mutual influence of factors such as ventilation temperature, ventilation speed, and heat emission rates from pollution sources, and further reveals the impact of these factors on air distribution characteristics. In Fig. 6, the experimental results show that when both ventilation temperature and ventilation speed increase, the air distribution characteristic indicators show a significant increase, indicating that appropriate ventilation speed and temperature can effectively improve air distribution and enhance overall airflow and comfort. Fig. 7 a shows the positive correlation between ventilation temperature and pollution source heat emission rate, meaning that when ventilation temperature increases, the effect of the pollution source heat emission rate on improving air distribution also strengthens. This indicates that ventilation temperature has an important impact on air quality, and an appropriate ventilation temperature helps to effectively dilute and remove pollutants. Fig. 7 b further confirms the positive correlation between ventilation speed and pollution source heat emission rate. When both increase, the air distribution characteristic indicators also tend to increase, indicating that higher ventilation speed and more heat emission help to improve airflow, thereby improving air quality and comfort in the residential area.

5. CONCLUSION

This paper investigated the optimization design of airflow organization in urban dense residential areas, focusing on the impact of different design schemes on healthy ventilation, and proposed a health ventilation solution based on multi-objective optimization. The study systematically evaluated the impact of factors such as ventilation temperature, ventilation speed, and pollution source heat emission rate on air distribution characteristics and indoor air quality through a combination of experimental data and simulation results. The experimental results show that increasing the ventilation speed and temperature significantly improves airflow and comfort, and that an increase in the pollution source heat emission rate also positively impacts the improvement of airflow and air quality. These findings provide a scientific basis for the airflow organization in urban dense residential areas, revealing how to achieve a comprehensive balance between air quality, comfort, and energy efficiency while ensuring healthy ventilation.

However, this study also has some limitations. First, although the simulation results and experimental data show good agreement, they are still influenced by complex factors such as local building structures and environmental conditions. Therefore, the universality of the results and potential deviations in practical applications need further verification. Second, the study mainly focuses on factors such as wind speed, temperature, and heat emission, while in complex urban environments, other factors such as air humidity and the thermal conductivity of building materials also significantly affect ventilation effectiveness. Including these factors would help further refine the research model.

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