Optimization Analysis of Coupling of Natural Ventilation and Mechanical Ventilation in Office Buildings Based on CFD

Jinge Zhang
INFINAIR Tongren Fan Co., Ltd., Shanghai, China

Abstract: Aiming at the problems of high energy consumption and poor indoor air quality in modern office buildings, this study uses computational fluid dynamics (CFD) technology to numerically simulate and optimize the coupling system of natural ventilation and mechanical ventilation in a typical high-rise office building. By establishing a three-dimensional model and using the standard k-ε turbulence model to solve the flow field inside and outside the building, the ventilation effect of the building in different seasons and at different times is analyzed. The research results show that a reasonably designed coupling system of natural ventilation and mechanical ventilation can effectively improve the indoor air quality and significantly reduce the energy consumption of the building. In the transition season, making full use of natural ventilation can reduce the operating time of the air-conditioning system by more than 30%; in summer and winter, the total energy consumption of the building can be reduced by 15%-20% by optimizing the ventilation strategy. This study provides an important reference for the design and operation optimization of the ventilation system of office buildings.
***Keywords*:** office building; natural ventilation; mechanical ventilation; CFD; energy consumption optimization

1. Introduction

With the acceleration of urbanization and the rapid development of the economy, the number of office buildings has increased sharply, and the problem of building energy consumption has become increasingly prominent. According to statistics, the energy consumption per unit area of office buildings is 2-3 times that of ordinary civil buildings, of which the energy consumption of air conditioning systems accounts for 40%-50% of the total energy consumption[1]. At the same time, due to the increased airtightness of buildings, the indoor air quality problem caused by the accumulation of indoor air pollutants has become increasingly serious, and has become an important factor affecting the health and work efficiency of workers. In this context, how to reduce building energy consumption while ensuring the quality of the indoor environment has become an important research topic in the field of building energy conservation.

In recent years, domestic and foreign scholars have made significant progress in the study of building ventilation systems. In terms of foreign research, the Lawrence Berkeley National Laboratory in the United States has carried out a large number of experimental studies on natural ventilation in buildings, confirming the important role of natural ventilation in building energy conservation[2]. Through long-term follow-up research, the University of Cambridge in the United Kingdom found that a reasonably designed natural ventilation system can reduce the cooling energy consumption of buildings by 30%-50%. Tokyo Institute of Technology in Japan proposed a CFD-based building ventilation optimization method, which provides new ideas for ventilation system design. In terms of domestic research, Tsinghua University, Tongji University and other institutions have conducted a lot of exploration in the field of building ventilation energy conservation and have achieved rich research results. However, there are currently few systematic studies on the optimization of coupling natural ventilation and mechanical ventilation, especially special research on high-rise office buildings, which needs to be deepened.

2. Research methods

2.1 Research object

This study selected a 20-story office building as the research object, with a building height of 80 meters, a standard floor area of 1,200 square meters, and a total construction area of 24,000 square meters. The building adopts a double-layer glass curtain wall facade design, and the openable area of the exterior windows accounts for 30% of the curtain wall area. The building is equipped with an atrium natural ventilation shaft with a cross-sectional area of 100 square meters. The mechanical ventilation system includes a fresh air system and an air conditioning system, and each floor is equipped with an independent air conditioning unit and a fresh air unit. The cooling capacity of the air conditioning system is 2000kW, and the total air volume of the fresh air system is 100,000 m^3/h.

2.2 Numerical simulation method

ANSYS Fluent software is used for CFD numerical simulation. The simplification and meshing of the building geometric model are the key links to ensure the calculation accuracy. On the basis of retaining the main structural features, this study appropriately simplifies the non-critical components inside the building. The meshing adopts a structured and unstructured hybrid mesh, and key areas such as window openings and air outlets are locally encrypted. After grid independence verification, the number of grids was finally determined to be 5.2 million, and the minimum grid size was 0.05 meters.

The choice of turbulence model has an important influence on the simulation results. By comparing the calculation results of different turbulence models with the measured data, the standard k-ε turbulence model was selected for solution. This model achieves a good balance between computational efficiency and accuracy, and is suitable for simulation analysis of building ventilation flow fields. The wall treatment adopts the standard wall function method, the inlet and outlet boundary conditions are set according to the actual meteorological parameters, and the solid wall adopts the no-slip boundary condition.

In terms of boundary condition setting, the inlet boundary adopts the velocity inlet condition, and the inlet velocity is determined according to the wind speed data of the meteorological station. The outlet boundary is set as a pressure outlet with a relative pressure of 0. The building surface is set as a solid wall boundary with a roughness of 0.001m. Considering the influence of the external space of the building on ventilation, the calculation domain size is set to: 5 times the building height upstream, 15 times downstream, 5 times on both sides, and 5 times on the top.

During the verification of the turbulence model, the standard floor of the building was selected for actual measurement experiments. On a typical working day, 15 measuring points were arranged to measure indoor and outdoor temperature, wind speed, CO_2 concentration and other parameters at the same time. The measured data were compared with the simulation results of different turbulence models to evaluate the applicability of the model. The results show that the average error between the simulation results of the standard k-ε model and the measured data is 12%, which meets the requirements of engineering applications.

3. Simulation results and analysis

3.1 Analysis of natural ventilation effect

The natural ventilation effect of the standard floor of the building was simulated and analyzed. The characteristics of indoor airflow organization under different wind speeds and wind directions were studied[3]. The results show that under the outdoor wind speed of 5m/s, when the dominant wind direction is at an angle of 45° with the windward surface of the building, the indoor airflow organization is most ideal. At this time, the natural ventilation volume of the standard floor can reach 30,000m^3/h, and the ventilation frequency can reach 4 times/h. As the building height increases, the natural ventilation effect gradually weakens due to the decrease in wind pressure difference, and the ventilation frequency in the top floor area of the 20-story building drops to 2.5 times/h.

The atrium natural ventilation shaft plays an important role in building ventilation. The simulation results show that a stable updraft is formed inside the atrium under the action of thermal pressure, and the vertical wind speed reaches 0.8-1.2m/s. This "chimney effect" can effectively drive the air flow of each layer and improve the ventilation effect. By optimizing the opening form of the top of the atrium and adopting the guide cap design, the suction effect of the atrium can be improved by 20%. At the same time, the synergy between the atrium and the external windows can form a stable air flow path inside the building, significantly improving the natural ventilation effect.

The opening method of the external window has a significant impact on the natural ventilation effect. The study compared the ventilation effects of three types of top-hung windows, sliding windows and blinds at different opening angles. The results show that under the same opening area conditions, the top-hung window has the best ventilation effect, and the ventilation volume is 15% higher than that of the sliding window. This is mainly because the top-hung window can form a diversion effect and improve the air intake efficiency. At the same time, the top-hung window has a better effect on rainy days, which is conducive to expanding the use time of natural ventilation.

For high-rise office buildings, the coupling effect of wind pressure and thermal pressure is a key factor affecting the natural ventilation effect[4]. The simulation analysis shows that in the low-rise area (1-7 floors), the wind pressure effect is dominant, and the ventilation effect is mainly affected by the outdoor wind speed. In the middle-rise area (8-14 floors), the wind pressure is equivalent to the heat pressure effect, and the ventilation effect is relatively stable. In the high-rise area (15-20 floors), the heat pressure effect is enhanced, but due to the external air flow disturbance, the ventilation effect fluctuates greatly. In view of this feature, a regional window opening control strategy was formulated to improve the utilization efficiency of natural ventilation.

3.2 Analysis of mechanical ventilation system

The performance of the mechanical ventilation system directly affects the indoor environmental quality and building energy consumption. The CFD simulation was used to analyze the impact of different air supply parameters on the indoor environment, and the optimal operation plan was obtained. In terms of fresh air volume control, combined with the indoor CO_2 concentration simulation results, the optimal fresh air volume was determined to be 30m³/(h·person). Considering the dynamic changes in the density of office buildings, the variable air volume technology can realize the on-demand adjustment of the fresh air volume, which can save 25% of the fan energy consumption compared with the fixed fresh air volume method.

The choice of air supply method has a significant impact on airflow organization and temperature distribution. The effects of mixed ventilation and displacement ventilation were simulated and compared. The results show that the vertical gradient of indoor temperature under displacement ventilation is 1.2°C/m, which is 33% lower than 1.8°C/m of mixed ventilation. At the same time, displacement ventilation can form a relatively ideal piston flow pattern, which is conducive to the removal of pollutants. By adjusting the position and size of the air outlet, the optimized displacement ventilation method can reduce the indoor sensible heat load by 15% and the airflow dead zone area by 40%.

In terms of air supply parameter optimization, the effects of air supply temperature, air supply speed and air supply angle on the indoor environment were studied through orthogonal experiments. The results show that the air supply temperature has the greatest impact on the uniformity of the indoor thermal environment, followed by the air supply angle. The optimized air supply parameters are: air supply temperature 18°C, air supply speed 2.5m/s, and air supply angle 15° upward. This set of parameters can achieve the best energy utilization efficiency while ensuring thermal comfort.

The fresh air volume control strategy adopts a dual control mode based on CO_2 concentration and personnel density. In areas where the personnel density changes drastically, such as conference rooms, CO_2 concentration control is the main focus, and the start threshold is set to 700ppm and the target control value is 900ppm. In open office areas with relatively stable population density, population density prediction control is mainly used, and fresh air volume adjustment strategies are formulated in combination with historical data. This dual control mode can make the operation of the fresh air system more accurate and efficient.

4. Ventilation strategy optimization

4.1 Seasonal ventilation strategy

Based on the analysis of meteorological data throughout the year, differentiated seasonal ventilation strategies are formulated. In the transition season (March-May, September-November), the outdoor temperature and humidity conditions are suitable, and the natural ventilation mode is preferred. Through statistical analysis of two-year operation data, the natural ventilation time that can be used in this season accounts for 65% of the total working time, which correspondingly reduces the air conditioning system operation time by 1,200 hours. On the premise of ensuring that the indoor temperature and humidity parameters meet the design requirements, making full use of natural ventilation can save about 35% of the energy consumption of the air conditioning system.

In summer, the composite operation mode of "nighttime natural ventilation + daytime mechanical ventilation" is adopted. The outdoor temperature is lowered at night, and the use of natural ventilation for building pre-cooling can effectively reduce the heat storage of the structure. The simulation results show that the adoption of the night ventilation strategy can delay the start-up time of the air conditioner the next day by 1-2 hours and reduce the peak load by 20%. At the same time, optimizing the operation strategy in advance according to weather forecast data can further improve the energy saving effect. In extremely hot weather, switch to full mechanical ventilation mode in time to ensure a stable indoor environment.

4.2 Intelligent control strategy

Develop an intelligent control strategy based on CFD simulation to achieve coordinated operation of natural ventilation and mechanical ventilation. Arrange a sensor network of temperature, CO_2 concentration, wind speed, etc. in the building to monitor indoor and outdoor environmental parameters in real time. The control system automatically adjusts the opening of the openable window, the fresh air volume and the operating parameters of the air conditioning system according to the monitoring data and the CFD simulation prediction results to achieve a dynamic balance between the best ventilation effect and the lowest energy consumption.

5. Economic and environmental benefit analysis

5.1 Economic benefit evaluation

After implementing the natural ventilation and mechanical ventilation coupling optimization scheme for a 20-story office building, a two-year operation effect tracking analysis was conducted. The results show that the annual operating time of the building air conditioning system has been reduced from the original 3,600 hours to 2,400 hours, a decrease of 33%. The annual electricity consumption is saved by about 420,000 kWh. According to the local electricity price of 0.8 yuan/kWh, the annual electricity bill expenditure is saved by 336,000 yuan. The annual operating time of the fresh air unit is reduced by 800 hours, saving 52,000 yuan in electricity bill expenditure.

The investment cost of the ventilation optimization system mainly includes automatic control systems, sensor networks, actuators, etc., with a total investment of about 1.2 million yuan. Considering that the equipment maintenance cost is about 50,000 yuan per year, the investment payback period is about 3.6 years. Compared with the traditional single mechanical ventilation system, this solution has significant economic advantages. Long-term operation data show that the system is stable and reliable, with low maintenance costs and good economic benefits.

5.2 Environmental Benefit Analysis

The optimized ventilation system significantly improves the indoor air quality. By comparing and analyzing the indoor environmental parameters before and after optimization, the peak CO_2 concentration dropped from 1500ppm to 800ppm, and remained below 1000ppm throughout the day. The indoor PM2.5 concentration was 40% lower than before optimization, and the concentrations of pollutants such as formaldehyde and TVOC were also significantly reduced. The improved indoor environment has a positive effect on improving the work efficiency of office staff.

The questionnaire survey results show that more than 90% of office staff are satisfied with the renovated indoor environment. Especially in areas with high population density such as conference rooms and open office areas, the air quality improvement effect is more obvious. At the same time, due to the full use of natural ventilation, the discomfort caused by long-term use of air conditioning is avoided, and the employee complaint rate is significantly reduced.

6. Conclusion

The coupling system of natural ventilation and mechanical ventilation in office buildings was optimized and analyzed by CFD numerical simulation technology, and a series of important conclusions were obtained. A reasonably designed natural ventilation system can achieve a ventilation rate of 4 times/h in the transition season, which basically meets the requirements of sanitary ventilation in office buildings. The synergy between the atrium ventilation shaft and the external windows can significantly enhance the natural ventilation effect, and the vertical wind speed in the atrium can reach 0.8-1.2m/s. By optimizing the fresh air volume control and air supply mode of the mechanical ventilation system, the use of variable air volume technology can reduce the energy consumption of the fresh air system by 25%. The displacement ventilation method has better ventilation effect than the mixed ventilation method, and the vertical temperature gradient is reduced by 33%. In terms of ventilation strategy, the ventilation strategy formulated based on seasonal differences can effectively reduce the energy consumption of buildings. In the transition season, making full use of natural ventilation can reduce the operating time of the air conditioning system by 33%. In summer, the use of natural ventilation strategy at night can reduce the peak load by 20%. The intelligent control system realizes the coordinated operation of natural ventilation and mechanical ventilation. The actual operation results show that the optimization scheme saves 420,000 kWh of electricity per year, with an investment payback period of 3.6 years. At the same time, it significantly improves the indoor air quality and has good economic and environmental benefits. This study used CFD technology to deeply analyze the optimization potential of office building ventilation systems and established a feasible optimization plan, which can provide an important reference for energy-saving renovation of similar buildings. Subsequent research will further explore ventilation optimization strategies in different climate zones and different building types, expand the scope of application of the research results, and combine building information modeling (BIM) technology to deepen the research on intelligent control strategies and improve system operation efficiency.

References

[1] Ke Rui, Huang Xiaoping. Simulation analysis and evaluation of the contribution of internal wind corridors to natural ventilation in high-rise office buildings[J]. China New Technologies and New Products, 2024, (04): 74-77.

[2] Pan Renying. Discussion on optimization strategy of natural ventilation design for an office building in Hefei[J]. Anhui Architecture, 2023, 30(07): 23-24+48.
[3] Yang Qianmiao, Sun Zhizhong, Zheng Huanqi. Study on window opening behavior of natural ventilation in transition season of an office building in cold regions[J]. Building Energy Conservation (Chinese and English), 2023, 51(06): 57-64.
[4] Xiong Haiyue. Study on natural ventilation control strategy of office buildings in cold regions during air conditioning season[D]. Shijiazhuang Railway University, 2023.