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Numerical Simulation Of Thermal Pressure Ventilation In Building Atrial: A Case Study

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Abstract. Over one-third of China's total energy usage can be attributed to buildings, of which 50% is consumed by HVAC systems. Natural ventilation is an effective approach to increase the quality of indoor air and maintain a comfortable temperature. In order to provide a higher ventilation rate, a stack ventilation system with an auxiliary heat source of solar energy was proposed in this research. Taking the main building of the School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, as an example, the ventilation efficiency of the system was evaluated by using the software of Fluent. The results show that using a stack ventilation system with an auxiliary heat source of solar energy in the lower part of the chimney increases the ventilation capacity by 738% over the unheated case and reduces the average room temperature by 1.7°C compared to the unheated. The proposed system could be orientated to improve natural ventilation for public buildings.

1 Introduction

Human production and living activities are seen to be inextricably linked to energy. Primary energy sources are irrevocably depleted as a result of economic and social growth, and global energy shortages and environmental issues are becoming more prominent. The construction industry is considered to be an important area of end-use energy consumption and CO_2 emissions, which has been suffering from high resource consumption and high emissions. It is shown in China Building Energy Consumption Annual Report 2020 [1] that in 2018, the proportion of energy consumption in the whole process of China's buildings accounted for 46.5% of the total national energy consumption and 51% of CO_2 emissions in the proportion of national carbon emissions. Therefore, it is important to make full use of renewable clean energy such as solar energy in building design and HVAC systems to reduce building energy consumption and to achieve the goal of "carbon peak, carbon neutral".

Natural ventilation is an effective way to improve the indoor thermal environment. Omrani et al.[2] developed a numerical model to investigate the influence of balconies on natural ventilation performance and concluded that the addition of balconies to single-sided ventilated buildings could improve ventilation performance. Fan et al.[3] examined the natural ventilation model of the office with single-side ventilation and cross-ventilation using CO_2 gas tracing technique to improve the natural ventilation model. Frattolillo et al.[4], experimented to examine indoor air exchange rate by using a blower test and tracer gas acid-base test method for several rooms. The findings suggested that when occupancy density is consistent, natural ventilation wind speed determines the rate of indoor air exchange. Solar energy, which is increasingly being utilized to power buildings, is a hot subject of discussion these days. Vazquez et al.[5] carried out a computational experiment to determine the heat transmission and ventilation in a room with heated walls and a two-channel vertical roof solar chimney. The findings indicate that heated walls generate more heat and produce more air changes per hour. However, there are fewer cases of building ventilation chimney walls heated to enhance the effect of building chimney ventilation.

Natural ventilation based on the chimney effect is considered to be an effective passive energy conservation approach. In this paper, the atrium of the main building of the School of Human Settlements and Civil Engineering, Xi'an Jiaotong University was used as an example to strengthen the natural ventilation of the building by using the thermal energy of the sun to heat the air in the building chimney, and a solar thermal storage coupling-driven chimney enhanced building ventilation system was proposed. Photovoltaic-thermal collectors are placed on the roof of the building. The water heated by solar heat is stored in a thermal storage tank, when reaches a certain temperature, the hot water is passed to the heat dissipation end of the capillary network laid on the inner wall of the chimney, after which the exhaust air temperature is raised. Natural ventilation under the action of thermal pressure is enhanced by the increased difference in air density between inside and outside the building, which forms a pressure difference and thus strengthens the chimney effect and reinforces natural indoor ventilation.

2 Method

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2.1 Case description

An architectural model of an atrium passive ventilation system based on the No.1 and No.2 chimneys is simulated in this paper. The total area of the exhibition hall and the surrounding corridor is 840m^2. The roof of the exhibition hall is pitched, with a minimum of 6 m and a maximum of 9 m. On the east and west sides of the exhibition hall, there are chimneys for the building's ventilation system. And the size is, the height is 26 m, and there is an air inlet connected to the room. The height of the air inlet of No.1 and No.2 chimneys are 3.1 m and 7 m respectively. The number of grids of the building model is 8,914,270, which has been validated by grid independence and is capable of meeting the required accuracy levels. The architectural rendering is shown in Fig 1.

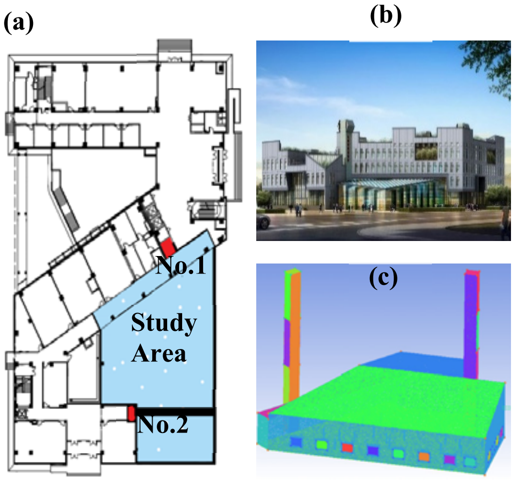

Fig. 1. (a) depicts the building plan, with the blue area representing the simulated building atrium, the red area representing the building ventilation chimneys No.1 and No.2, and the white dots representing 21 individuals; (b) depicts the building effect; (c) shows the building model grid.

2.2 Mathematical model

The governing equation of the variants to be solved can be written as follows:

$$\underbrace{\frac{\partial(\rho\phi)}{\partial t}}_{\text{Transient term}}+\underbrace{\operatorname{div}(\rho U\phi)}_{\text{Convection term}}=\underbrace{\operatorname{div}(\Gamma_{\phi}\operatorname{grad}\phi)}_{\text{Diffusion term}}+\underbrace{S_{\phi}}_{\text{Source term}} \quad (1)$$

where, denotes the general variable of velocity, temperature, and turbulent kinetic energy; and denote the generalized diffusion coefficient and source term, respectively. The finite volume method was adopted to discretize the governing equation. The discretization schemes of the implicit Euler, the second-order upwind difference, and the central difference are used for the transient term, convection term, and the diffusion term of the governing equations, respectively. The governing equation was solved using the commercial software Fluent 17. Coupled algorithm for coupling pressure and velocity was adopted and a Realizable two-equation turbulence model was adopted for the turbulence model.

2.3 Simulated cases and boundary conditions

As per the climatic conditions of Xi'an, the average annual temperature is 13.1~13.4°C. Generally, natural ventilation is adopted during the summer and transitional seasons when the outdoor thermal environment parameters are pleased over the indoor ones. For the simulation, a typical weather day was chosen at 13:00 on June 10, 2020, with a temperature of 24°C.

The room’s outer wall is no-slip. Due to the uncertainty of the wind speed of the natural wind in the numerical model, the inlet boundary condition is taken as “pressure-inlet”, and the “pressure-outlet” boundary is chosen to simulate the free flow assuming that the flow is fully developed [6], given the static pressure as the outlet at ambient pressure at the outlet. The human body is the source of heat dissipation, and the floor and ceiling are considered as the planar heat source.

In the simulation, the three windows were kept open according to the actual usage. At the same time, the area above the air inlet of chimneys No. 1 and No. 2 were both divided into three parts, and the indoor airflow condition was simulated by modifying the location of air heating in the chimneys.

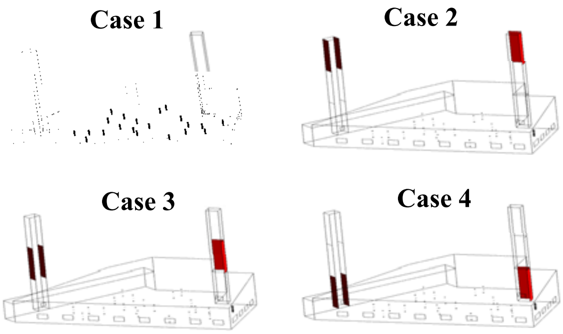

Fig. 2. The simulated working condition of chimney heating position

3 Results

Simulation results for the four operating conditions were obtained after running the building passive ventilation system, and ventilating the building chimney interior for several minutes without heating and with heating. The temperature distribution clouds of the building model sectional passing through the air shaft No.2 of the exhibition hall to the open window and the temperature contours of the 0.5 m and 1.3 m height planes are intercepted and presented below.

As the result, for Case 1, the average temperature is 27.7 °C, there is a lot of backflow of air, and wind speed is too small, resulting in poor indoor air quality and waste heat that is difficult to remove from the outdoor environment. The indoor temperature is high at this time, heating surfaces with a temperature of 50°C are installed in various places of chimneysNo.1 and No.2 in order to improve the ventilation of the building. The simulation results of Case 2 were obtained when the upper part of the chimney was heated when the average room temperature was 27.5°C. Air return is reduced, the airflow rate in the chimney is significantly increased, and fresh air with

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lower outdoor temperature enters the room, but at this time the indoor temperature is slightly lower than the room temperature of case 1, and the overall economy is not efficient. The simulation results of Case 3 were obtained by heating in the middle of the chimney, at which the room temperature was 26.7°C. Compared with Case 2, the temperature was reduced by 0.8°C. In the profile with a height of 0.5m, the temperature was still high at the profile of 0.3m due to the lower sink temperature of the incoming cold air, and the overall ventilation effect was better than that of Case 2. Simulation results of Case 4 were obtained when the lower part of the chimney was heated, the heated air was close to the chimney inlet, the average indoor temperature was 26°C, and the air with lower outdoor temperature entered the room in large quantities and mixed fully with the indoor air, and the ventilation and cooling effect were relatively satisfactory.

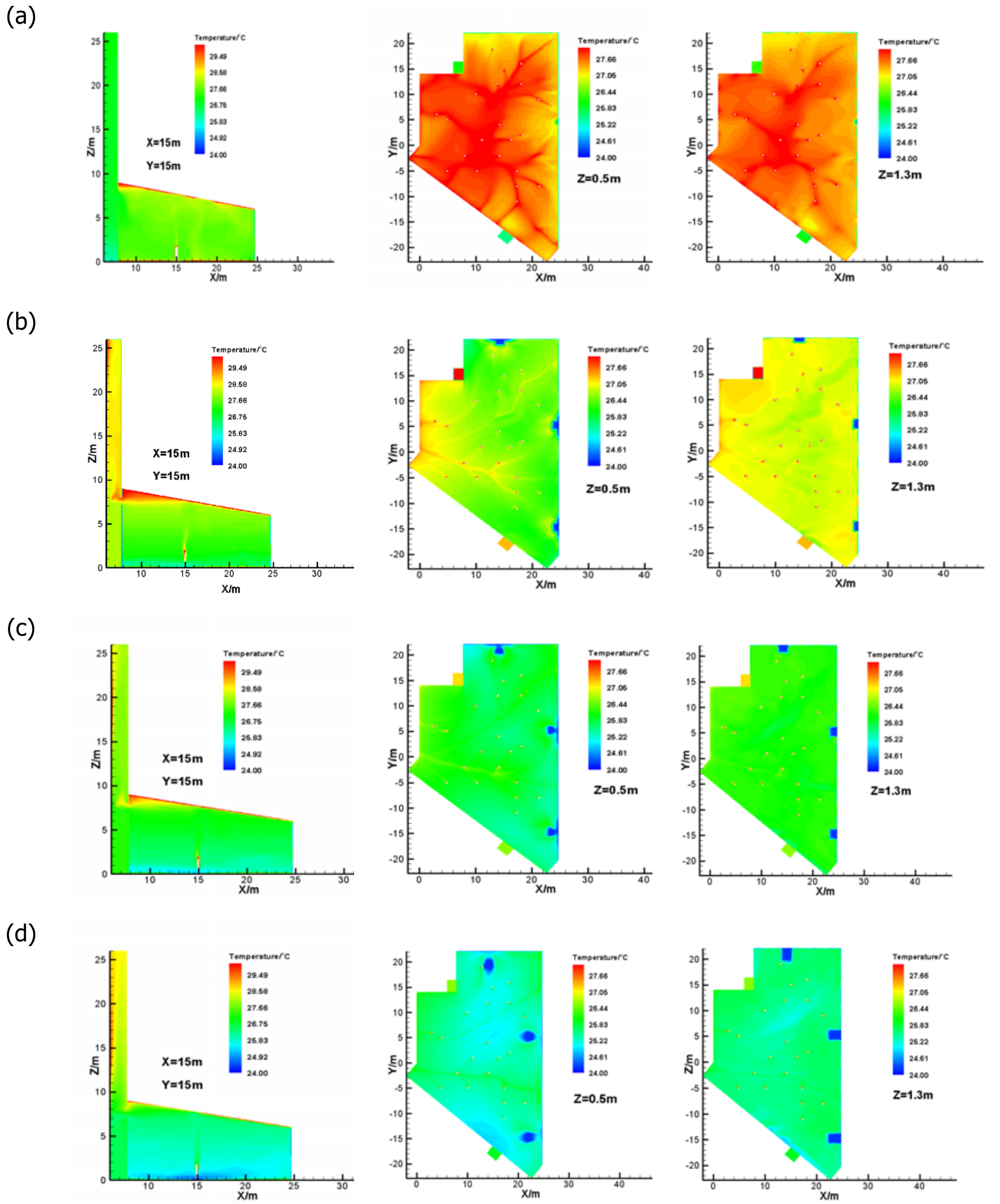

Fig. 3. Temperature distribution in preservation area for cases C1 to C4: a) Case 1, b) Case 2, c) Case 3, and d) Case 4

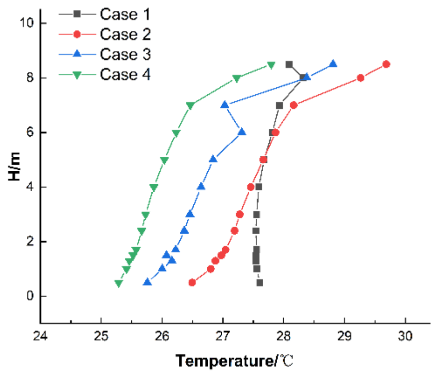

Fig. 4. Temperature distribution curve at different heights

In order to conduct a more in-depth investigation of the temperature distribution in the vertical space, several different heights were specifically selected to plot the average temperature distribution curve, as shown in Fig.4. The floor of the building is taken as the reference window height of 1.2m, the indoor temperature is relatively low near the window and increases with height, and there is a source of heat dissipation at the ceiling, with the temperature being greater towards the ceiling. In Case 1, the variation of upper and lower temperatures in the natural state is small, and the overall temperature is high. In other operating conditions, Case 2 is affected by the passive ventilation system of the chimney, and the temperature from the ground to 5m is lower than Case 1. However, the remaining heat is still difficult to dissipate and tends to congregate near the ceiling level. In comparison to the normal operating conditions of Case 1, the ventilation in Case 3 and Case 4 is significantly improved, particularly in Case 4. The temperature at the bottom of the human activity area is much lower, and the thermal comfort of the room is improved. As a result, it is more effective to enable the heating chimney passive ventilation system to cool down the air, and it is better to heat the exhaust air near the chimney inlet.

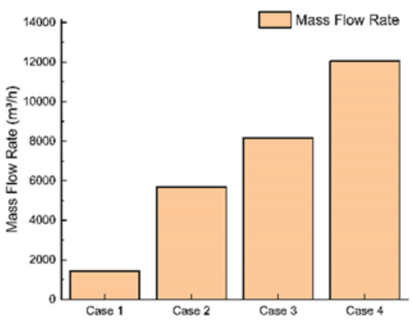

Fig. 5. The ventilation of the chimney

As shown in Fig.5, comparing the ventilation capacity of the four working conditions, the ventilation capacity is only 1440m³/h in Case 1, yet the Case 2 ventilation capacity increases after heating the exhaust air in the chimney. In Comparison to the unheated condition, Case 4 has 738% higher ventilation capacity, and heating at the chimney inlet doubles the heating at the chimney exhaust. The results show that after heating the exhaust air in the chimney, the ventilation volume is considerable and the natural ventilation effect is obvious, and the use of building chimneys coupled with solar heat to improve the chimney effect is found to be very effective in natural ventilation.

4 Conclusion

The influence of various heating zones on the natural ventilation effect of building chimneys was investigated in this research and the following results are obtained:

A ventilation chimney with a heated inner surface could significantly enhance the natural ventilation efficiency. Compared with the case without a heating surface, a 1.7°C decrease in the room temperature was observed. The arrangement of the heating surface in the chimney has a remarkable influence on ventilation rate. The ventilation rate of the lower heating mode is 50% higher than that of the upper heating mode.

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