Thermal Performance of an Atrium with Hybrid Ventilation and cooled air supply

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Abstract. A reduced-scale model of an atrium with displacement ventilation and natural exhaust in the ceiling was applied in experimental investigation, where its air velocity field was measured by particle image velocimetry (PIV). By computational fluid dynamics (CFD) method, the indoor airflow in both the reduced-scale and real-size atrium model with hybrid ventilation under cooling conditions was simulated. The experimental and calculated results show that the hybrid ventilation that coupled natural exhaust with mechanical air supply of air conditioning can satisfy the thermal environments requirements. Moreover, with the same heat gain and supply air parameters, space cooling load of the atrium can be a little less when applying displacement ventilation. In addition, the vertical temperature gradient in the atrium, the cooling load of handling return air and the temperature difference between supply and exhaust air decrease with the increase of exhaust air rate. An optimal exhaust-supply air ratio for the minimum cooling load of the air conditioning system in the atrium was obtained under a given heat gain and fresh air parameters.

Key Words. Atria; Hybrid ventilation; Exhaust air rate; Particle image velocimetry(PIV); Computational fluid dynamics (CFD)

1. Introduction

Atria have a long history and were already applied in Ancient Rome buildings as early as the 19th century. With atria widely applied in buildings at present, it’s not only simply as a buffer zone to improve nearby room microclimate, but also as a function space. Therefore, in order to satisfy the needs of health, comfort and energy saving, higher requirements on environmental control of atria are put forward.

For high atria, natural ventilation based on stack effect is applied to improve their indoor environments because of zero energy consumption. Thermal environments of atria under natural ventilation have been investigated in many literatures [1-4]. However, the indoor air environments of atria cannot be satisfied only by natural ventilation, present research discovered that using the system coupled mechanical and natural ventilation, i.e. Hybrid Ventilation is a good strategy. Hybrid ventilation can effectively reduce building energy consumption while ensure the quality of indoor air environment. Main researches of hybrid ventilation currently involve ventilation control strategies, indoor thermal comfort and indoor air quality evaluation of functional rooms in buildings [5-8]. The study on thermal environment control with hybrid ventilation in atria is limited. To the office building in Montreal, Canada, the reference [9] investigated the thermal environment
characteristics of the atrium with mixed-mode cooling strategies and the proportion of hybrid ventilation system operating time during the cooling season by experimental measurement. Then, Hussain, et al. [10] used FLUENT software to simulate the thermal environment of the atrium in reference [9] and the accuracy of different turbulence models was discussed. Yuan, et al. [11] focused on the atrium in a 17-story institutional building with a hybrid ventilation system in Canada, the lower limit of outdoor air temperature allowed to enter the building through the motorized inlets was proposed to ensure indoor thermal comfort, and the effect of night hybrid ventilation on reducing cooling load during the summer was estimated.

The hybrid ventilation mode in recent study is that outdoor air enters naturally and moves due to wind and buoyancy forces with fan-assistance through the rooftop outlet. In order to achieve the thermal environment control, more and more atria adopt heating, ventilation and air conditioning (HVAC) system. The air supply modes are displacement ventilation and nozzle outlet air supply, and to eliminate the high temperature air, the exhaust outlet is set up at the top of atrium. No similar study was found that combines natural exhaust with mechanical air supply of air conditioning in atria. In this paper, in order to analyze the influence of two mechanical ventilation forms on indoor environment under hybrid ventilation, the characteristics of thermal environment in atria under displacement ventilation and nozzle outlet air supply will be investigated by both CFD and reduced-scale model experiment. And the influence of different exhaust-supply air ratios will be further discussed, which can help the design and control of HVAC system in atria.

2. Research Methods

2.1. Experimental Method
Considering the prototype size of a real atrium, 20 m×20 m×27.2 m, and the measurement conditions of particle image velocimetry (PIV), a reduced-scale model, 1 m×1 m×1.36 m, was set up, as shown in Figure 1(a). Two local heat sources are inside the model. The atrium adopted hybrid ventilation which is coupled mechanical air supply cooled by air conditioning system with natural exhaust. The air inlets and return air outlets are located at lower part of same wall of the model, and the exhaust outlets with adjusted open size are located at the ceiling of the model.

The supply air parameters and heat sources were controlled under various experiment conditions. The temperatures of indoor air and internal walls of the model are measured by thermocouples (T-type, copper-constantan) and monitored by a data acquisition system. Figure 1(b) shows three measuring bars arranged in the model. The velocity of indoor airflow was measured by PIV, where smoke was chosen as the tracer gas. The return and exhaust air rates were measured by hot-wire anemometers.
2.2. CFD Method
Both of a real atrium model (20 m×20 m×27.2 m) and its reduced-scale model (1 m×1 m×1.36 m) were all simulated by Fluent. Boussinesq hypothesis was made, and RNG k-ε turbulence model and DO (Discrete Ordinates) radiation model were applied. The interval of grids in regions close to the inlets and heat sources was 0.2 m in the real atrium model and 0.01 m in the reduced-scale model. The upper regions were meshed by structured grids with the interval of 0.3 m in the real atrium model and 0.015 m in the reduced-scale model.

2.3. Experimental and calculated Conditions
Usually only lower space of atrium is the occupied zone, so the mode of nozzle outlet air supply at the upper of the occupied zone or displacement ventilation is used for high atrium. Here, some conditions were set for the experiment and calculation to discuss the characteristics of thermal environment in the atrium. According to similarity theory, Condition 1 and Condition 2 are made for the reduced-scale model of experiment, which are similar with Condition 3 and Condition 4 for the real atrium model. Nozzle outlet air supply was adopted only in Condition 4, and the others were displacement ventilation. Table 1 gives the detailed parameters of the four conditions. Beside the above four conditions, different exhaust air rates in Condition 3 were also numerically simulated.

Table 1. Conditions for experiment and calculation.

| Condition | Model size       | Airflow form          | Supply air temperature / °C | Supply air rate /m³·h⁻¹ | Return air rate /m³·h⁻¹ | Exhaust air rate /m³·h⁻¹ | Local Heat Source /W |
|-----------|------------------|-----------------------|----------------------------|------------------------|-------------------------|-------------------------|----------------------|
| 1         | 1000 mm×1000 mm×1360 mm | Displacement ventilation | 20                         | 5.4                    | 4                       | 1.4                     | 44×2                 |
| 2         | 1000 mm×1000 mm×1360 mm | Displacement ventilation | 25.4                      | 5.4                    | 3.6                     | 1.8                     | 44×2                 |
| 3         | 20 m×20 m×27.2 m  | Displacement ventilation | 18                        | 6700                   | 5245                    | 1455                    | 5090×2               |
| 4         | 20 m×20 m×27.2 m  | Nozzle outlet air supply | 18                        | 6700                   | 5245                    | 1455                    | 5090×2               |

3. Analysis of Experimental and Calculated Results

3.1. Comparison of Experimental and Calculated Results
The airflow velocities in the experimental atrium model under Condition 1 were measured by PIV, and part of their results are shown in Figure 2(a). The numerical results of velocity were compared with the experimental results as shown in Figure 2(b). It shows that the streamlines of the numerical results are consistent with the experiment data, and the relative error of velocity is less than 11.5%.
Figure 2. Velocity comparison between the numerical and experimental results under Condition 1 (Section 1).

Both experiment and numerical calculation were also carried out under Condition 2. The temperature comparison between experimental and numerical results is shown in Figure 3, and the trends of temperature variation are basically same at measuring bar 1 close to air supply outlets. The maximum temperature difference is less than 1.0 °C, and the corresponding relative error is less than 5.0%.

Figure 3. Temperature comparison between experimental and numerical results under Condition 2 (Bar 1).

3.2. Comparison of different air supply forms
Figure 4 shows the velocity fields on typical section in the calculated model under Condition 3 and Condition 4 when the air cooled by air conditioning system is supplied to the atrium in summer, noting that y=5.52 m is the vertical section across the heat source 1. Under displacement ventilation, the lake of cold air appears in the bottom of the atrium, and the velocities in the lower zone are less than 0.1 m/s. Buoyancy plumes are driven by heating sources, and its velocity is up to 0.34 m/s, as shown in Figure 4(a). Under nozzle outlet air supply, large eddies appear in the lower zone, and the velocity is up to 0.60 m/s which may lead to draft sensation and is larger than that under displacement ventilation, as shown in Figure 4(b). Besides, no obvious buoyance plumes appear above the heat sources.

Figure 4. Comparison of velocity field on y=5.52 m (m/s).
The calculated temperature distributions in the location of three measuring bars under Condition 3 and 4 are shown in Figure 5. The temperature of upper zone in the atrium under displacement ventilation is 1 °C higher than that under nozzle outlet air supply condition. Under Condition 3 (displacement ventilation), indoor air is affected by both the inlets and heat sources, and the horizontal temperature difference is larger near the floor. The temperature on measuring bar 1 close to air supply outlets is the lowest among the three measuring bars, while the temperature on measuring bar 2 close to heat sources is the highest. The temperatures above the 10 m height of three measuring bars are almost consistent, that is, the horizontal temperature distribution is uniform. Under Condition 4 (nozzle outlet air supply), the temperature at the 4.5 m height of measuring bar 1 is lower due to the effect of jet flow, and the horizontal temperature difference among the three measuring bars is small and less than 1 °C in other locations. Overall, the hybrid ventilation forms aforementioned can satisfy the thermal environments requirements at the working area.

3.3. Influence of Exhaust air rate
The thermal performances of the atrium were further simulated when the air volume ratio of exhaust to supply was changed to be 0, 20%, 40% and 60%, respectively, but other conditions were same as Condition 3. The calculated results display that the trend of velocity and temperature distribution is similar under different exhaust-supply air ratios, but the temperature difference between supply and exhaust air changes, given in Table 2. The vertical temperature gradient and the temperature difference between supply and exhaust air decrease with the increase of exhaust air volume and the decrease of return air volume. More calculated results discover that the amount of indoor sensible heat removed by exhaust air increases, so space or return air sensible cooling load can be decreased with exhaust-supply air ratio, however its fresh air load increases with the increase of fresh or exhaust air volume, shown in Figure 6. Therefore, the optimal exhaust-supply air ratio need be decided to achieve the minimum system cooling load. For the summer design parameters of fresh air in Xi’an and the heat gain in the atrium, the optimal exhaust-supply air ratio is 20%.

| Exhaust-supply air ratio | 0      | 20%    | 40%    | 60%    |
|-------------------------|--------|--------|--------|--------|
| Supply and exhaust air temperature difference (°C) | 24     | 21     | 18     | 16     |

Table 2. Supply and exhaust air temperature difference under various exhaust-supply air ratios.

![Figure 5. Comparison of temperature under Condition 3 and 4.](image1)

![Figure 6. Influence of exhaust air rate.](image2)

4 Conclusions
In this paper, thermal performances in an atrium under various conditions were investigated by experimental and numerical methods. Some results can be found as follows.

1. Under the same heat gain and supply air conditions, the exhaust air temperature under displacement ventilation is a little higher than that under nozzle outlet air supply, which indicates space cooling load of the atrium can be a little less when applying displacement ventilation.

2. For the atrium with displacement air supply and natural exhaust, both the supply and exhaust air temperature difference and the vertical temperature gradient in the atrium decrease with the increase of exhaust air rate.

3. For the summer design parameters of fresh air in Xi’an and 25.5 W/m² indoor heat gain in the atrium with displacement air supply and natural exhaust, the optimal exhaust-supply air ratio to achieve the minimum cooling load is 20%.

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