Column-Attached Airflow Fields Created by Multi-slot in Single Ring

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Abstract. Researchers have shown increasing interest in attachment ventilation due to its high ventilation efficiency and good thermal comfort. To meet the ventilation performance and engineering design challenges of Circular Column Attached Ventilation (CCAV) mode due to low ventilation rates, large-diameter cylinders, and installation too high at the top of large spaces. This paper proposes a novel ventilation mode known as Column-attached ventilation with Multi-slot in Single Ring (MCAV). Through measurement of air velocity and computational fluid dynamics simulation, the air distribution characteristics of the MCAV were studied. The findings show that MCAV and CCAV have similar trends of maximum velocity decay in the vertical attachment region. The MCAV has a 10.48% higher average value of dimensionless axial velocity in the horizontal air reservoir region than the CCAV. Besides, the flow pattern envelope surface and the velocity non-uniform coefficient were introduced to verify ventilation performance. The current study helps understand a new air distribution and is used as a reference for Attachment Ventilation design.

1 Introduction

Effective utilization of underground space will promote the sustainable development of humans. Subway is an urban transportation mode designed to carry large passenger volumes in dense urban areas. Since the 21st century, the subway system has grown popular [1]. Published research on the subway system indicates that the concentration of pollutants in subway stations is higher than in the outdoor environment [2–4]. Therefore, the subway station may become one of the hot spots of viral disease [5]. Indoor airflow plays an essential and direct role in affecting indoor air quality (IAQ), the distribution of pollutants in the occupied zone, and even human health. Appropriate air distribution should improve IAQ, create a comfortable and healthy environment for indoor residents and reduce energy consumption [6,7].

In recent years, Li and Yin proposed the Circular column-based attachment ventilation (CCAV) mode [8,10], widely used in large-space buildings such as subway stations, shopping malls, exhibition centers, and train waiting rooms with many columns exist. The CCAV mode mainly aims to eliminate the cooling/heating load in the occupied zone, and the air supply volume is lower than that of the mixing ventilation, which reduces the energy consumption of the air-conditioning system operation. The airflow is attached to the column surface and flows downward, showing the phenomenon of radial radiation diffusion along the circumference of 360° in the horizontal air reservoir region [8–11]. However, the utilization of CCAV in large spaces remains a significant challenge. The CCAV mode is affected by various factors, such as the column diameter, air diffuser size, and installation height [8]. In practical engineering, columns are often constructed due to their functional and aesthetic needs. Therefore, the air diffuser is not installed arbitrarily and should be installed according to the actual installation height. Suppose the installation height of the air diffuser is too high. In that case, the jet body entrains surrounding air, the velocity decays significantly, and the fresh air arriving at the occupied zone decreases, although reducing the air diffuser width probably improves the air delivery speed. Nevertheless, this will accelerate jet velocity decay and cause poor ventilation performance. [8].

Fig.1. Airflow schematic of Column-attached ventilation with Multi-slot.

To improve the manifestation, reasonable improvement of ventilation performance in tall spaces. A novel air supply pattern named Column-attached ventilation with Multi-slot (MCAV) mode was proposed based on the study of attachment ventilation. The probable
airflow patterns of MCAV in rooms are presented in Fig. 1. Under isothermal conditions, the flow field characteristics of MCAV were studied by combining velocity measurement with numerical simulation. This research provides a basis for further design and optimization of the MCAV mode and is helpful to improve the air distribution of the building.

2 Methods

In this study, a full-scale experiment is used to verify the accuracy of the numerical simulation and the effect of air supply after installing the column-attached ventilation with a multi-slot device. The numerical simulation compares the ventilation performance of CCAV and MCAV with 45°open-angle under the same air volume (Table 1). Combining the two methods makes this research more comprehensive.

2.1 Experimentation

The velocity field was measured in a full-size space (10.0 m × 10.0 m × 6.0 m), with the dimensions of the room shown in Figure 2. The air supply device was located in the center of the test room, mounted on a 6 m high column, with a 45° opening angle of the equally spaced air diffuser and a width of 0.03 m.

Fig.2. Schematic diagram of the full-scale experimental model.

The distributions of the measurement points are also shown in Fig. 3. In order to study the airflow characteristics of the MCAV, the velocity field tests were carried out throughout two regions: the horizontal air reservoir region and the vertical attachment region. Non-uniform intervals are used to measure each cross-section.

Fig.3. The layout of velocity measurement points: (a) the vertical attachment region; (b) the horizontal air reservoir region.

Use the Tsi-8386 model multi-parameter ventilation tester to measure the air supply velocity, with an accuracy of 0.01 m/s and an error of ±3.0% of the measured value.

2.2 Numerical simulations

2.2.1 Physical model

As shown in Fig. 4, the software ANSYS ICEM™ was adopted to create the physical model and construct structured grid. Fig. 4 shows the layouts of the model studied here. The room dimensions are 10.0 m × 10.0 m × 6.0 m. A circular column with a radius of 0.7 m is located at the center of the room. The annular spaced slot inlet with a width of 0.03 m and an opening angle of 45° was located in the upper part of the column.

Fig.4. Three-dimensional geometric grids of the column-attached ventilation with multi-slot.

2.2.2 CFD method

Five commonly used turbulence models (i.e., Standard k-ε, RNG k-ε, Realizable k-ε, Standard k-ω, and SST k-ω) were employed to perform the simulations by commercial ANSYS FLUENT™ software (version 19.0) [12]. The calculation is carried out in the Reynolds number (Re) range from 3353 to 8383, where Re is defined according to the air supply speed \( U_0 \) and the slot inlet b. The air outlet is specified as the pressure-outlet boundary. The room's periphery is assumed to be solid walls and insulated boundaries.

During the numerical simulation process, the equations of pressure, momentum, turbulence, and energy are discretized by second-order upwind scheme, and the pressure and velocity are coupled by SIMPLE algorithm. In all simulation calculations, the converged residuals of the continuity and momentum equation were less than \( 10^{-3} \), the converged residuals for \( k \) and \( \varepsilon \) were less than \( 10^{-4} \). The net imbalance of the inlet flow rate and outlet flow rate is less than 0.2%, also demonstrating the computation's convergence [13].

Table 1. Boundary conditions of the numerical simulations

| No. | Supply air velocity (m/s) | Open-angle (°) | Width of the slot inlet (mm) | Size of the air outlet (mmxmm) | Reynolds number |
|-----|--------------------------|---------------|------------------------------|-------------------------------|----------------|
| 1   | 3                        | 45            | 30                           | 200×200                       | 5030           |
| 2   | 3.5                      |               |                              |                               | 5868           |
| 3   | 4                        | 45            | 30                           | 200×200                       | 6706           |
| 4   | 4.5                      |               |                              |                               | 7545           |
| 5   | 5                        |               |                              |                               | 8383           |
| 6   | 2                        | 90            |                              |                               | 3353           |
2.2.3 Validation of the CFD method

The values of the dimensionless maximum velocity obtained from the experiments were used to verify the accuracy of the turbulence model. As shown in Fig.5, the predicted velocity values had similar trends as the experimental results. In terms of absolute error values, the results of the RNG k-ε model best fit the experimental data. Therefore, the RNG k-ε turbulence model was selected for subsequent numerical simulations.

Fig. 5. Turbulence model verification.

3 Results and discussion

3.1 Maximum jet velocity decay

This section investigates the dimensionless axial velocity decay distribution to provide a theoretical basis for the design and engineering application of MCAV mode.

Fig. 6(a) shows the maximum jet velocity decay of MCAV at different velocities in the vertical attachment region and CCAV proposed by Li [8] and Yin [10]. The MCAV has a similar velocity decay trend for each air supply velocities. However, the velocity decay of the attached jet is faster at y*/b<40, a possible explanation for these results may be affected by the Extended Conda Effect (ECE) [14]. With the distance between the air supply inlet and the column surface, the jet body is gradually deflected to adhere to the column surface and flows downward. The ECE will make the jet decay too fast in the initial section. At y*/b>40, the velocity decay becomes slower and correlates well with the empirical equation.

Fig. 6(b) shows that the maximum jet velocity decay obtained at different velocities in the horizontal air reservoir region is also very close. The dimensionless maximum velocity is negatively correlated with the dimensionless distance. Meanwhile, Figure 6(b) data indicates that the MCAV has a 10.48% higher average value of dimensionless axial velocity in the horizontal air reservoir region than the CCAV, demonstrating that MCAV has acceptable ventilation performance.

3.2 Flow pattern envelope surface

The flow pattern envelope surface is used to describe the boundary interface formed by the equal velocity points on the contour of the air supply jet, and the air velocity on the boundary surface is the allowable velocity value specified by the design [8]. Figure 7 presents velocity distribution contours at 0.1 m above the floor. Under the same air supply volume, the envelope formed by CCAV at 0.3 m/s accounts for 26.54% of this level, while MCAV accounts for 46.38%, the airflow of MCAV maintenance was enhanced, the air supply range is extensive. Furthermore, the percentage of envelope area increases is achieved by increasing air supply velocity for MCAV.

Fig. 7. Velocity Distribution Contours at 0.1 m above the floor under the same air volume: (a) MCAV; (b) CCAV.

3.3 Velocity uniformity analysis

This section uses the velocity non-uniform coefficient to evaluate the uniformity of the velocity profile. The non-uniform coefficient formula is illustrated in equation (1). The smaller the value, the more uniform the airflow profiles.

\[
K_v = \frac{\sqrt{\frac{1}{n} \sum (u_i - \bar{u})^2}}{\bar{u}}
\]  

(1)
where \( n \) is the number of measured points, \( u_i \) is the local air velocity, and \( \bar{u} \) represents the local average velocity.

![Image](https://example.com/image.png)

**Fig.8.** The layout of measurement points at 0.1 m above the floor.

**Table 2.** Numerical results in the two ventilation modes

|                      | CCAV | MCAV |
|----------------------|------|------|
| Average velocity (m/s) | 0.28 | 0.35 |
| Velocity non-uniform coefficient \( K_u \) | 0.17 | 0.24 |

ASHRAE 55-2020 defines the occupied zone, which is to be between the floor and 1.8 m above the floor and more than 1.0 m from outside walls or air-conditioning equipment [15]. Figure 8 shows the layout of measurement points. The calculation results are shown in Table 2, the average air velocity of both CCAV and MCAV meet the airflow velocity requirements of temporary stay zones such as subway stations under the identical air supply volume [15], and the average air velocity is higher when MCAV air supply mode was used. The velocity non-uniformity coefficients of MCAV and CCAV are within the acceptable range, indicating that a uniform velocity field distribution may be realized in the horizontal air reservoir region using MCAV mode.

**4 Conclusions**

The research shows that MCAV mode can be applied to the air conditioning system in large spaces. Full-scale velocity measurements and numerical simulation methods were combined to examine the ventilation performance of the MCAV mode, and some conclusions can be obtained as follows.

The MCAV has a 10.48% higher average value of dimensionless axial velocity in the horizontal air reservoir region than the CCAV, demonstrating that MCAV is more suitable for high spaces.

The flow envelope and velocity non-uniformity coefficient were introduced to evaluate the MCAV mode. MCAV creates a more comprehensive air supply range. The envelope surface area formed by MCAV at the height of 0.1 m above the floor with a boundary velocity of 0.3 m/s is 1.75 times larger than that of CCAV at the same air supply volume.

Multi-slot diffuser design conducive to realizing the uniform velocity field environment. The average air velocity was higher when MCAV air supply mode was used under the identical air supply volume. This study indicates that MCAV mode has a larger capacity for building cooling load than CCAV mode.

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**References**

1. G. Monchambert, D. Hörrcher, A. Tirachini, N. Coulombel, International Encyclopedia of Transportation (Elsevier, 471–478, 2021).
2. W. Ji, Z. Liu, C. Liu, C. Wang, X. Li, Build. Environ. 188 (2021).
3. D.-U. Park, K.-C. Ha, Environ. Int. 34, 629 (2008).
4. C. Colombi, S. Angius, V. Gianelle, M. Lazzarini, Atmos. Environ. 70, 166 (2013).
5. A. Passi, S.M. Shiva Nagendra, M.P. Maiya, Atmospheric Pollut. Res. 12 (2021).
6. B. Yang, A.K. Melikov, A. Kabanshi, C. Zhang, F.S. Bauman, G. Cao, H. Awbri, H. Wigō, J. Niu, K.W.D. Cheong, K.W. Tham, M. Sandberg, P.V. Nielsen, R. Kosonen, R. Yao, S. Kato, S.C. Sekhar, S. Schiavon, T. Karimipanah, X. Li, Z. Lin, Energy Build. 202 (2019).
7. G. Cao, H. Awbri, R. Yao, Y. Fan, K. Sirén, R. Kosonen, J. Zhang, Build. Environ. 73 171 (2014).
8. A. Li, Attachment Ventilation Theory and Design (China Architecture & Building Press, Beijing, 2020).
9. H. Yin, A. Li, Z. Liu, Y. Sun, T. Chen, Build. Environ. 109,112 (2016).
10. H. Yin, R. Wu, T. Chen, Y. Sun, A. Li, Procedia Eng. 205,3511 (2017).
11. O. Han, A. Li, H. Yin, Energy Build. 231 (2021).
12. Ansys Fluent User's Guide, Southpointe, ANSYS, Inc., (2019).
13. O. Han, A. Li, Build. Environ. 194 (2021).
14. A. Li, Indoor Built Environ. 28,437 (2019).
15. ANSI/ASHRAE Standard 55-2020, Thermal Environment Conditions for Human Occupancy, American Society of Heating, Refrigerating, and Air Conditioning Engineers Inc, Atlanta, (2020).