Effects of multi-orifice plate with different geometric parameters on flow distribution of plenum chamber for ventilation duct systems

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Abstract. Plenum chambers are common devices used for flow and pressure equalization in ventilation and air conditioning systems. Aiming for reducing energy consumption and improving ventilation performance, the optimal cross-sectional aspect ratio (*W/H*) and length (*L*) of the single-path unlined rectangular plenum chamber is obtained through the authors' preliminary research. In this study, based on the analysis of interior flow characteristics of single-path plenum chamber, it is shown that the traditional chamber configuration commonly used in engineering is not an ideal structure that can achieve uniform flow distribution. The multi-orifice plate is proposed to add inside chamber to improve flow uniformity. Under the two typical design schemes of *W/H*=1/1 and 5/1, the effect of multi-orifice plate with different geometric parameters on flow distribution of plenum chamber is investigated, and the optimal installation position and aperture rate of orifice plate is proposed. The optimized aperture ratio is designed to be 30% for both the two typical chamber configurations. When *W/H*=1/1, it is recommended to install the multi-orifice plate at the position of *y/L*=0.1, as for *W/H*=5/1, the *y/L*=0.3 is preferred. Besides, the fluid equalizing effect of the plenum chamber with multi-orifice plate is verified under four commonly used air ducts specifications in engineering.

1 Introduction

The single-path unlined rectangular plenum chamber has been widely used in the HVAC system for uniform and steady air distribution. The proper design of the chamber configuration is a key issue for the enhancement of uniform flow distribution. Due to the specific connection type of traditional chamber configuration with in-line upstream and downstream ducts, the plenum chamber could not exhibit uniformly distributed effectiveness sufficiently, even accompanied by large energy losses. Therefore, it is recommended to insert additional flow equalization components into the chamber to improve flow uniformity.

Recently, many previous experimental and numerical investigations have indicated that the uniform distribution in pipeline could be improved by appropriately decreasing the size and increasing the number of orifice plate [1, 2]. However, few studies pay attention to the combination of orifice plate and plenum to achieve uniform flow distribution. Besides, in terms of the geometric parameter of orifice plate and its position, the flow equalization effect still needs to be verified through extensive optimization and analysis. Therefore, in this study, the flow equalization plenum chamber with multi-orifice plate is proposed to improve flow uniformity, and the effects of multi-orifice plate with different geometric parameters on flow distribution are investigated.

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2 Figures and tables

2.1 Physical model

In this paper, the commonly used single-path unlined rectangular plenum chamber with parallel inlet/outlet axes in ventilation and air-conditioning system is taken as the object. Based on the optimization design method of the plenum chamber formed by the author's previous research, the main structure is designed with the optimal aspect ratio of the windward side (*W/H*) and chamber length (*L*), see **Fig. 1**. According to the relevant regulations for design of ventilation and air conditioning system in civil buildings [3], the inlet velocity of plenum chamber is equivalent to the outlet velocity of fan, which is recommended to be between 5 and 10 m/s. Therefore, the inlet velocity of plenum chamber is set as 8 m/s in this research.

Considering the performance of resistance reduction and flow uniformity of the plenum chamber, the segmented W/H is adopted to optimize the structure design. And the length of chamber is designed according to the jet development inside chamber [4]. In this study, the size of inlet/outlet of plenum chamber is the same and selected as $a \times b$=320×160 mm, and the structural design schemes under two typical ratios of *W/H*=1/1 and 5/1 are given respectively. The geometric parameters of the two chamber configurations are *W*=640 mm, *H* =640mm, *L*=1920 mm, and *W*=1011 mm, *H*=202 mm,

L=1271 mm, respectively. To ensure the flow is fully developed for the calculation of resistance loss, the upstream and downstream ducts have been prolonged to 18 m and 25 m, respectively.

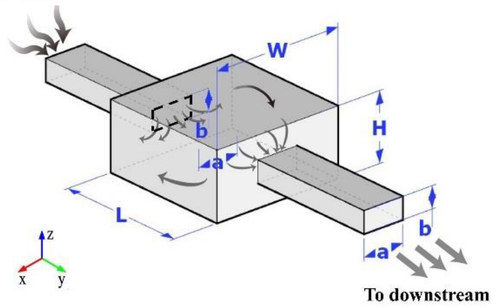

Fig. 1. Schematic diagram of three-dimensional flow in a plenum chamber with in-line upstream and downstream ducts.

2.2 CFD numerical method

In this study, ANSYS Fluent is used for the numerical simulation. The airflow is assumed as steady and incompressible flow, and the heat exchange is not taken into account. The governing equations of mass and momentum can be written in the following generic form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \quad (1)$$

The RSM turbulence model is employed to provide accurate predictions for flow distribution, which is applicable to the three-dimension pipe flow. The inlet boundary is set as velocity inlet, and the pressure outlet is adopted here, the gauge pressure is 0 Pa. The roughness height is 0.15 mm for galvanized steel. Moreover, the numerical method has been verified with the full-scale experiment, the details is shown in the author's previous research [4].

3 Analysis of interior flow characteristics of the plenum chamber

The interior flow characteristics of the plenum chamber under the above two typical design schemes are investigated respectively. For the chamber configuration with W/H=1/1 (see **Fig. 2**), due to the sudden expansion of the flow cross-section, the velocity of the mainstream fluid decreases continually along the way under the conversion of dynamic-static pressure. And in the process of jet movement, the surrounding air is constantly entrained, which drives the disturbance of the nearby low-velocity fluid and forms a high-velocity gradient region, corresponding to a large fluid energy dissipation. As the fluid continues to move toward the outlet until it hits the downstream end face of chamber, the boundary layer is separated, forming four groups of fluid vortices symmetrically distributed around the main flow. It is obtained that the local resistance coefficient of the plenum chamber (ζ) is 1.1031, and the turbulence intensity at outlet vent (I) is 23.33%.

As the W/H=5/1 is adopted for the chamber configuration, the flow field distribution is similar. Since the chamber height (H) is relatively close to the short side length of air duct (b), it is observed that the symmetrically distributed vortices generated around the mainstream fluid are "compressed" along the height direction of chamber, and are mainly distributed in the horizontal direction, as shown in **Fig. 3**. The local resistance coefficient is 0.2946, and the turbulence intensity at outlet vent is 11.22%. There is still uneven flow distribution after optimizing the main structural parameters of the traditional chamber configuration. The dynamic and static pressure of fluid particles could not be fully conversed, and the uniformity of flow field needs to be further improved.

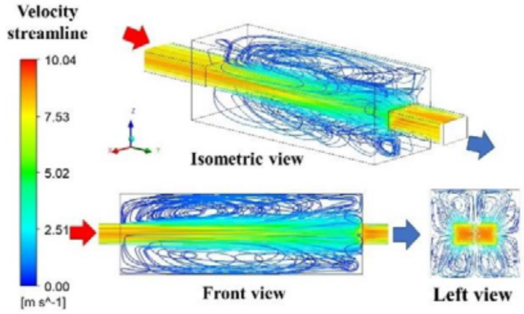

Fig. 2. Velocity streamlines of the traditional chamber configuration with W/H=1/1.

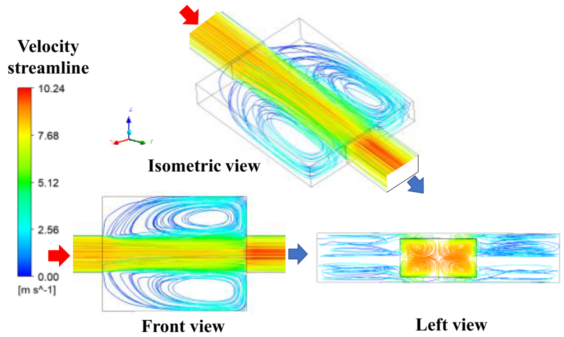

Fig. 3. Velocity streamlines of the traditional chamber configuration with W/H=5/1.

4 Results and discussion

4.1 Optimization of flow distribution in plenum chamber based on multi-orifice plate

In order to further improve the flow uniformity of the traditional chamber configuration, it is proposed to add flow equalization components inside the chamber to achieve uniform flow distribution. As a common throttling element, the multi-orifice plate is simple in structure and easy to manufacture, which is widely used in the transmission and distribution ductwork of ventilation and air conditioning system. The principle of flow equalization is that after the fluid passes through the orifice whose flow cross section is suddenly reduced, the outlet velocity of the orifice is increased, while the static pressure is decreased. The diffusion and disturbance of fluid is formed to the downstream of orifice plate, and finally the uniform flow distribution is achieved. Ideally, the fluid flows out at the same velocity under the action of the equalizing orifice. The larger the aperture diameter is, the lower the outflow velocity will be, which is more conducive to the uniform distribution of the downstream flow field.

Furthermore, different geometric parameters of multi-orifice plate directly determine the adjustment effect of flow distribution. The aperture ratio (ε) of the orifice plate is an important factor affecting the air attenuation, which is defined as the ratio of aperture area to the entire orifice plate area. **Fig. 4** shows that the geometric parameters such as the aperture diameter (d) and the net distance (l) between each hole are directly related to ε. The optimal parameter value needs to be determined. However, it is inevitable to an increase in resistance loss using multi-orifice plate to achieve uniform flow distribution. Therefore, a reasonable design of the multi-orifice plate should increase the aperture ratio as much as possible to reduce the flow resistance without affecting the dynamic-static pressure conversion.

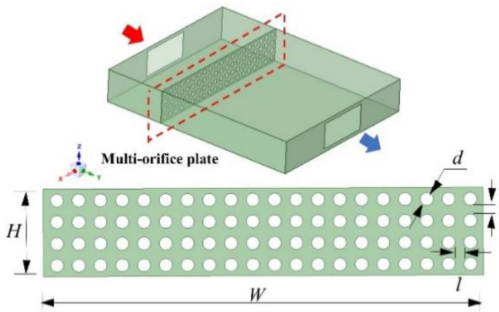

Fig. 4. Schematic diagram of the flow equalization plenum chamber with multi-orifice plate.

4.2 Effects of multi-orifice plate with different geometric parameters on flow distribution

Based on the traditional chamber configuration which optimizes the main structural parameters, a multi-orifice plate is added inside the chamber to further uniformize the flow field. The multi-orifice plate with uniform holes arrangement is adopted, ignoring the influence of the orifice plate thickness. For the two typical aspect ratio design schemes of W/H=1/1 and 5/1, the opening diameter is initially selected as 30 mm, the net distance between holes is 20 mm, and the corresponding opening ratio is 24.85%, 27.69%, respectively. The influence of five dimensionless installation positions of orifice plate on the flow distribution was compared, which is y/L=0.1、0.3、0.5、0.7、0.9.

As shown in **Fig.5 (a)**, with the same geometric parameters of the orifice plate, as the y/L goes on along the chamber length, the local resistance coefficient first decreases slightly and then increases, which is higher than that of the traditional chamber configuration. The minimum value of ξ reaches at y/L=0.5. For the turbulence intensity of outlet vent, the flow uniformity is significantly improved and generally shows an upward trend. The minimum value is obtained at the position of y/L=0.1, and the flow uniformity is improved by about 29.66%. Considering both resistance reduction and flow uniformity performance, for the chamber configuration with W/H=1/1, it is recommended to install the multi-orifice plate at the position of y/L=0.1.

Then, based on the optimized dimensionless installation position y/L=0.1, the effect of aperture diameter on the flow and resistance characteristics is investigated when the l=10 mm. The aperture diameter d=8, 10, 15, 20, 30 mm are selected, corresponding to the aperture ratio ε=15.03, 18.43, 26.96, 30.68, 44.18%. It is indicated from **Fig. 5 (b)** that when the l is constant, with the increasement of d, the aperture ratio increases correspondingly. The ξ value of chamber decreases sequentially, while the I value at outlet vent first decreases and then increases. When the d is too small, the fluid is mostly blocked by the wall surface of plate, and the flow rectification effect is diminished. When d=20 mm, corresponding to ε=30.68%, the I value is reduced to 17.47%. The outlet uniformity is improved by about 25.12%, achieving a comprehensively better flow distribution.

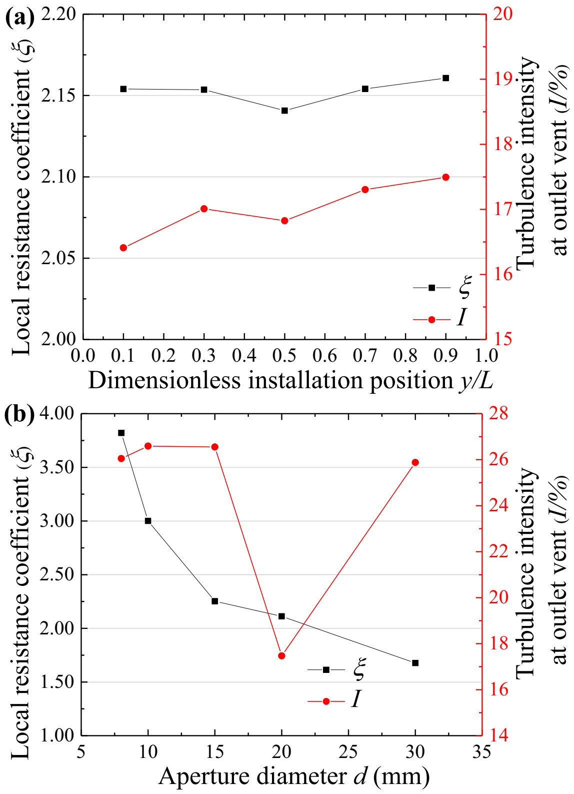

Fig. 5. Comparison of flow distribution of the flow equalization plenum chamber (W/H=1/1): (a) with varied y/L, (b) with varied d.

For the chamber design with W/H=5/1, the effect of y/L and d on flow distribution presents similar tendency as the chamber configuration with W/H=1/1. As shown in **Fig. 6**, as the y/L continues to move along the chamber length, the ξ value shows a trend of first decreasing and then increasing, and reaches the minimum at y/L=0.5. For the I index at outlet vent, the closer the orifice plate is installed to the outlet, the less obvious the flow equalizing effect will be. Considering the above two aspects, it is recommended to install the orifice plate at the position of y/L=0.3. Based on the optimal y/L, the effect of different aperture sizes on flow distribution are compared. It is obtained that when d=20 mm (corresponding to ξ=30.46%), the I value achieves the minimum value, and the uniformity of outlet vent is improved by about 61.94%.

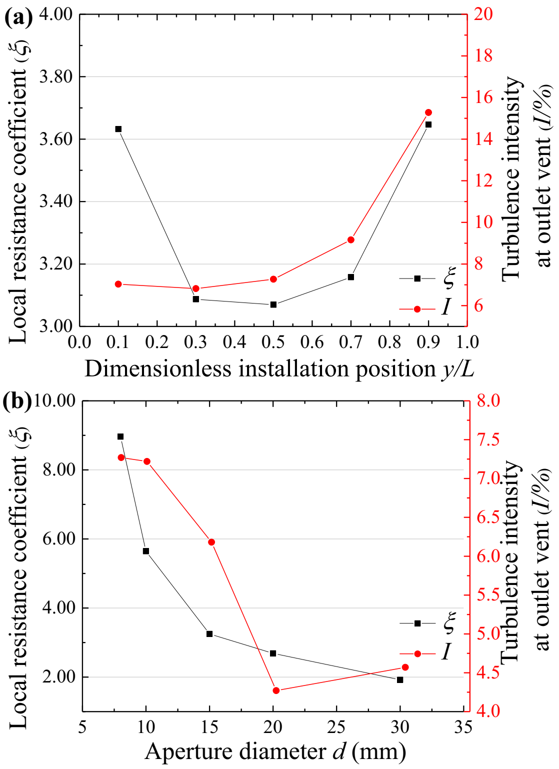

Fig. 6. Comparison of flow distribution of the flow equalization plenum chamber (*W/H*=5/1): (a) with varied *y/L*, (b) with varied *d*.

4.3 Verification of the flow equalization effect of the plenum chamber with multi-orifice plate

The applicability of the flow equalization effect of the plenum chamber with multi-orifice plate has been verified. Four commonly used sizes of air ducts in engineering are selected under the aspect ratio *a/b*=1/1~4/1 (see **Table 1**). For the two typical ratios of chamber configuration with *W/H*=1/1 and 5/1 at v_{in}=8 m/s, the flow and resistance characteristics of the plenum chamber with multi-orifice plate at the *y/L*=0.1 and 0.3 are compared respectively, corresponding to the aperture rate of 30%. Generally, comparing with the traditional chamber configuration, the ξ of flow equalization plenum chamber at each case has increased significantly, and even doubled, while the I at outlet vent has been reduced by nearly 70% at the maximum. Therefore, the effect of flow equalization is based on the premise of increasing the flow resistance loss. A reasonable design of the multi-orifice plate should increase the aperture rate as much as possible to reduce the flow resistance loss without affecting the flow equalization effect. So far, the optimization design method for the uniform flow distribution of the single-path plenum chamber with multi-orifice plate has been obtained.

Table 1. Verification of the flow equalization effect of the flow equalization plenum chamber with multi-orifice plate.

W/H	*y/L*	*a*×*b* (mm)	*d/l/ε* (mm/mm/%)	$\zeta_{\triangle}$ (%) ↑	$I_{\triangle}$ (%) ↓
1/1	0.1	200×200	20/10/30	79.97	69.30
		320×160	20/10/30	91.43	25.12
		500×160	20/10/30	61.04	50.26
		800×200	20/10/30	15.83	52.39
5/1	0.3	200×200	20/10/30	238.40	57.58
		320×160	20/10/30	812.25	61.94
		500×160	20/10/30	254.11	68.23
		800×200	20/10/30	261.61	67.04

Note: The aperture ratio *ε* of the orifice plate in the table is approximately 30%, and jointly determined by the aperture diameter *d* and the net distance *l* between each hole.

5 Conclusions

In this study, based on the chamber configuration with the optimized main structural parameters, the flow equalization plenum chamber with multi-orifice plate is proposed to further optimize the flow distribution. The effects of multi-orifice plate with different geometric parameters on flow characteristics of plenum chamber are investigated. The main conclusions are summarized as follows:

Through the analysis of interior flow characteristics of the plenum chamber, it is observed that the jet flows directly to the outlet vent and the chamber does not exhibit uniformly distributed effectiveness. The resulting vortexes are distributed on both sides of the mainstream, accompanied by large energy losses.

For the two typical chamber configurations with *W/H*=1/1 and 5/1, the recommended aperture ratio of the orifice plate and the dimensionless installation position are obtained. The optimized aperture ratio is 30%. When *W/H*=1/1, it is recommended to install it at the position of *y/L*=0.1, if *W/H*=5/1, it should be installed at the position of *y/L*=0.3.

Moreover, the applicability of flow equalization effect of the plenum chamber with multi-orifice plate has been verified under four commonly used duct size. The turbulence intensity of outlet vent can be reduced by up to 70%. It can provide reference and guidance for the optimization design of the single-path plenum chamber in ventilation and air conditioning systems.

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