Research on spatial local resistance characteristics in a plenum space for an exhaust fan room

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Abstract. The local resistance loss is of great importance to the structural design of the exhaust room and the selection of fan equipment. In this study, the resistance characteristics of isotropic multi-inlet and single-outlet plenum spaces are investigated using numerical simulations. Orthogonal experiment method was used to determine the key influencing factors. An empirical formula for the local resistance loss law was proposed and the internal flow characteristics of the plenum space were analysed. Results show that the fan interaction rate is an important factor for the drag loss and that the vortex zone is closely related to the magnitude of the local drag loss. The results can provide a theoretical basis for the structural design of the plenum space and the selection of fan equipment.

1 INTRODUCTION

The energy consumption of building ventilation systems is a mandatory consideration in building design. Relevant studies have shown[1,2] that the energy consumption of fans due to resistance losses accounts for about 30-50% of the total building energy consumption. Therefore, reducing fan resistance loss is of practical significance for building energy consumption and sustainable development.

Plenum space is essentially a large space with multiple inlets and one outlet. In a confined chamber with a sufficiently large cross-sectional area, the air velocity is reduced to near zero. It can convert dynamic pressure to static pressure to the maximum extent. The plenum space has a significant effect on the airflow organization and conveying resistance in the exhaust system.

Several domestic scholars have carried out research in areas related to plenum space air supply. Wang et al.[3] studied the law of static pressure distribution in plenum chamber without barriers using the model experiment method. Fulpagare et al.[4] investigated the effect of obstructions on the flow rate of a plenum chamber. And it showed that the placement of obstacles in the plenum chamber was an important factor in the performance of the air conditioning. Nada et al. [5] investigated the effect of the depth of the plenum chamber on the airflow characteristics and thermal performance. Zhang et al.[6] conducted numerical simulation to study the internal flow characteristics of a single-in-single-out plenum space and identified significant influencing factors through orthogonal experiments.

However, there are few researches on the airflow characteristics and the key parameters affecting the resistance in the plenum space of the exhaust system. In this study, plenum space with single outlet is taken as the research object. And orthogonal test is adopted to determine the relationship between the pressure loss and the key design parameters of structure and study the internal flow characteristics. It is hoped that the study could provide a theoretical basis for the structural design of the plenum space and the selection of fan equipment.

2 METHODS

2.1 Physical model

In the model, the plenum space is simplified to a multi-inlet plenum space with dimension of 26.7m×4.1m×10.5m. Five air supply outlets and one exhaust outlet are arranged along the streamline direction of the plenum space, all of which are rectangular in shape. The size of the air supply port is 1.4m×1.4m and the size of the air exhaust outlet is 6.2m×6.2m. Figure 1 shows the schematic diagram of the model for this study.

Fig. 1. Geometric model of plenum space
2.2 Numerical methods

Numerical simulations were carried out using ANSYS Fluent commercial software, the Navier-Stokes equations were solved using the finite volume method. In this study, air is assumed to be calculated as an ideal incompressible fluid. The governing equations for mass and momentum are expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u_i) = 0$$  \hspace{1cm} (1)

$$\frac{\partial (\rho u_i)}{\partial t} + \nabla \cdot (\rho u_i u_i) = -\nabla p + \rho g_i + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) - \rho \varepsilon_i$$  \hspace{1cm} (2)

To ensure the accuracy of the prediction, reynolds stress model (RSM) is used to solve the transport equation and dissipation rate equation of reynolds stress. The transport equation of reynolds stress is given by:

$$\frac{\partial \mu_{ij}}{\partial t} + \nabla \cdot (\rho \mu_{ij} u_i) = -2D_{ijkl} \frac{\partial u_j}{\partial x_l} - \rho \varepsilon_{ij}$$  \hspace{1cm} (3)

Where $\mu_{ij}$ is the Reynolds stress, $D_{ijkl}$ represents turbulent diffusion and molecular diffusion, $P_i$ is pressure generation, $G_i$ is buoyancy generation, $\varphi_i$ is the pressure strain, $\varepsilon_i$ is the dissipation term.

2.3 Validation

Due to the limitation of the experimental conditions, the internal resistance losses in the plenum space would be analyzed by numerical simulations. In order to ensure the accuracy of the simulations in practical application engineering, this study performs a comparative validation work according to the small-scale experiments of Wang et al[3].

Fig. 2. comparative validation

Wang et al. proposed the relationship between pressure distribution and air supply flow rate of orifice plate side-fed plenum space side-wall air supply using the model test. The experiments were conducted using a plenum space model of 700mm x 700mm x 200mm, in which the hole space is 100mm and the hole diameter is 10mm. Six sets of numerical simulation experiments were conducted by varying the air supply from 3.0m/s to 3.5m/s. Fig. 2 represents the comparison of the experimental results with the simulation results. The results show that the relative error of the mean pressure is less than 5%, which proves the feasibility of numerical simulation.

2.4 Orthogonal experimental design

Orthogonal experimental design is an efficient, rapid and economical experimental design method based on orthogonal tables. According to orthogonality, the points that meet the conditions are selected from the overall experiment. The following pressure loss factors were identified through qualitative analysis of this exhaust mode.

The space geometry of plenum space includes length L, width D and height H. The average air velocity of plenum space $\bar{V}_{in}$ is as follows:

$$\bar{V}_{in} = \frac{Q}{A_{in}} \text{ (m/s)}$$  \hspace{1cm} (4)

Where Q is total air supply volume in plenum space (m³/s), $A_{in}$ is total area of fan inlets (m²).

The average air velocity of plenum space exhaust $\bar{V}_{out}$ is as follows:

$$\bar{V}_{out} = \frac{Q}{A_{out}} \text{ (m/s)}$$  \hspace{1cm} (5)

Where $A_{out}$ is exhaust air outlet area(m²).

The wall opening ratio $k$ is as follows:

$$k = \frac{A_{out}}{A_k}$$  \hspace{1cm} (6)

Where $A_k$ is total area of the wall where the fan is located (m²).

The fan interaction ratio $\lambda$ is as follows:

$$\lambda = \frac{d_m}{l}$$  \hspace{1cm} (7)

Where $d_m$ is air supply opening equivalent diameter(m), $l$ is distance between the centres of adjacent air supply outlets(m).

The exhaust air outlet Reynolds number is as follows:

$$Re_{out} = \frac{\rho d_m}{\mu}$$  \hspace{1cm} (8)

Where $\rho$ is fluid density(kg/m³), $v$ is characteristic velocity of the flow field(m/s), $d_m$ is characteristic length of the flow field(m), $\mu$ is fluid dynamic viscosity coefficient (kg/m s).

The position unbalance rate is as follows:

$$\eta = \frac{\Delta d}{l}$$  \hspace{1cm} (9)

Where $\Delta d$ is the relative position difference between the center of the fan group and the center of the exhaust air outlet in the length direction(m).

Through the above qualitative analysis, the resistance expression can be expressed as:

$$\frac{AP}{\rho \bar{V}_{out}^2} = \left[ \frac{L}{D} \cdot \frac{L}{H} \cdot \frac{\bar{V}_{in}}{\bar{V}_{out}} \cdot k \cdot \lambda \cdot Re_{out} \cdot (1 - \eta) \right]$$  \hspace{1cm} (10)

In this study, the local resistance loss of the plenum space is used as the test index. Due to the large number of changing parameters, the research uses an orthogonal
table to examine the relationship between local resistance loss and other factors. The level of each factor refers to the actual structure of the exhaust fan room of the hydropower station, and the fluctuation range is 20%.

3 Results and discussion

3.1 Fitting empirical equation

For the results of orthogonal working conditions obtained by CFD method, the Nlinfit algorithm is used for fitting calculation. The empirical formula for the local resistance loss obtained by fitting is shown below:

\[
\frac{\Delta P}{\rho V_{out}^2} = 12.7233 \times \left( \frac{L}{D} \right)^{0.488} \times \left( \frac{L}{H} \right)^{1.047} \times \left( \frac{V_{in}}{V_{out}} \right)^{0.0473} \times (k)^{0.4556} \times (\lambda)^{0.3256} \times (1-\eta)^{2.931} \times (Re)^{0.0227}
\]

(11)

Where \( \Delta P \) is the average value of the pressure at the supply air inlet.

Eq.(11) in the factors are expressed in a power function, the designer should take into account their influence factors and theoretical calculations.

In the experimental range, \( V_{in} \) takes the value of 4-6m/s according to the engineering application range. It is found that the dimensionless volume \( V_{in}/V_{out} \) of the average wind speed of air supply and exhaust in the plenum space, and the Reynolds number of the exhaust port has no significant effect on the local resistance loss of the plenum space.

From the empirical formula, the fan interaction rate \( \lambda \) is one of the important factors affecting the local resistance loss, and \( \Delta P/\rho V_{out}^2 \) is a single-valued decreasing function of \( \lambda \). A decrease in \( \lambda \) will lead to an increase in the local resistance loss. The \( \lambda \) can be increased by increasing the equivalent diameter of the air outlet or reducing the distance between the centers of adjacent air outlets.

There is little difference between the \( Re_{out} \) of the air outlet and the geometric eigenvalue \( L/D \) of the plenum space on the resistance loss. There are many ways to increase \( L/D \). There are two specific aspects. On the one hand, it is to increase the length of the plenum space,
and on the other hand, it is to reduce the maximum range of the air supply airflow in the plenum space.

### 3.2 Key factors on flow characteristics

From Eq.(11), it can be seen that fan interaction rate is a major factor that lead to the outstanding performance of local resistance loss. In Fig.3, the velocity vector diagrams of the spatial Y-Z section of the plenum space for three fan interaction rates ($\lambda_1=27.8\%$; $\lambda_2=29.8\%$; $\lambda_3=35.9\%$) are obtained by changing the size of the air supply opening. It can be seen from the figure that the airflow organization inside the plenum space is complex, and there are multiple vortex regions, which is also an important reason for its local resistance loss.

The comparison of the three shows that with the increase of the interaction rate, the vortex area of the confined space jet becomes significantly smaller. The interaction rate is positively correlated with the wind speed along the centerline of the fan. When the interaction rate gradually tends to 1, the multi-inlet and single-out plenum space will become a single-inlet and single-out plenum space, which will greatly reduce its resistance loss.

In Fig.4, due to the blocking by the wall, the pressure of the wall where the outlet is located increases and also causes the loss of the kinetic energy of the gas. It can be seen from the pressure distribution cloud map that with the increase of the interaction rate, the pressure distribution inhomogeneity in the plenum space also increases. The picture shows that the key to the local resistance loss is the formation of the vortex region, and the number and size of the vortex region also affects the uniformity of the pressure distribution in the plenum space. The local resistance loss can be effectively reduced by reducing the size of the eddy current region. When designing the structure of the machine room, the designer should appropriately reduce the interaction rate of the fan, and at the same time determine the reasonable fan equipment, the construction cost can be minimized.

### 4 Conclusion

In this paper, numerical simulation is used to simulate the working conditions determined by the orthogonal test. The law of local resistance loss in multi-input and single-out barrier-free plenum space is studied. The main findings are described as follows:

1. An empirical formula for the law of local drag losses is presented. The fan interaction rate $\lambda$ is found to be an important factor affecting the local resistance loss.
2. The wall opening ratio $k$ and the geometrical characteristics of the plenum space $L/D$ have no significant effect on the resistance losses.
3. Three kinds of plenum space with different interaction rates are analyzed. The results show that the vortex region is the main factor of the space resistance loss of the plenum space. Reducing the size of the vortex region is the main means to decrease the local resistance loss.

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