Optimization analysis of air-conditioning duct structure of high-velocity train

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Abstract. In order to improve the comfort of the air conditioning system in the driver's cabin of a high-velocity train and advance the distribution of air supply, a 3D simulation software is used to establish the model of the air supply pipeline of the driver's cabin. The air flow field and the rationality of the air distribution are analysed accordingly. The results indicate that the structure of the air supply pipe is optimized and the air flow rate in the left and right air chambers is solved and air flow rate in each outlet of the air supply pipe are achieved.

1. Introduction

With the progress and improvement of science and technology, high-velocity trains have become an important means of transportation in people's lives. A comfortable environment plays a vital role for divers to ensure the safety of train operation. However, due to limited the space inside the cabin of the high-velocity train and the strict tightness. Since it is hard to adjust the air flow and temperature of the room, it is necessary to adjust the temperature of the cabin through the air conditioning system by the organization and air supply of air conditioning system.

Many scholars have made a lot of researches and contributions to the air conditioning system. Yu Fengjiao¹ used Fluent to calculate and simulate the air supply duct of the air conditioning system. Through the detection of the air volume and pressure drop of the air outlet, optimization analysis for the optimization of air supply uniformity is proposed. Liu Zhongqing² compared the experimental data of fixed-velocity air conditioners and variable-frequency air-conditioning with inverter air conditioners based on the comfort of subway train . He also tested the temperature, air velocity, passenger operation. The comfort of air conditioning of variable-frequency is better than that of the fixed velocity. Wang Shukun³ used Hypermesh software and Star-CCM+ to simulate the air flow about the air duct structure. The uniformity of the air volume of the air outlet was improved by optimizing the bending length of the central air duct, and the comfort of the cabin is improved. W. Khier⁴ studied the friction between high-velocity trains and air, and proposed the resistance impacts of air conditioning installation and deflectors in different aerodynamic environments. Boon Chiang Ng⁵ proposed a nonlinear autoregressive neural network to simulate the dynamic characteristics of the air conditioning system. Through the optimization and data comparison of different types of neural network data, it played a role in promoting the development of intelligent control. Youjun Wang⁶ took a B-type subway as an example to discuss the influence of four types of air ducts on the air flow characteristics and proved by adding a spoiler which can effectively improve the uniformity of air...
supply. Abbas Taheri\textsuperscript{[7]} studied the air distribution of the air conditioning system with different factors such as wall curvature, and analysed the turbulent boundary layer.

Because the front space of high-velocity trains cabin is very limited and air-conditioning systems cannot be installed there, the driver's cabin is supplied with air from left and right sides on the top. The air supply and the temperature of original system is unreasonable. This paper carried out a series of structural optimization and analysed two typical optimization schemes based on the design requirements of the air flow of the main driver of the train which should be about 55% of the total air volume.

2. Simulation analysis method

2.1 Basic theory of simulation

In the CFD calculation of the air duct in the train driver's cab, the volume flow rate of air volume at each outlet and the flow state of air in the duct are mainly concerned. The compressibility, viscosity and thermal conductivity of air are ignored in the calculation. Therefore, the fluid model should be incompressible and ideal gas in mathematical modeling. The governing equation is as follows:

The equation of continuity is as follows:

\[ \rho \frac{\partial p}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]  \hspace{1cm} (1)

\( \rho \), the fluid density; \( \mathbf{u} \), the velocity of a fluid particle; \( t \), time.

The momentum conservation equation of \( x \), \( y \) and \( z \) is as follows:

\[ \frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{U}) = - \nabla p + \nabla \cdot \mathbf{T} + \mathbf{F} \] \hspace{1cm} (2)

\[ \frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{U}) = - \nabla p + \nabla \cdot \mathbf{T} + \mathbf{F} \] \hspace{1cm} (3)

\[ \frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{U}) = - \nabla p + \nabla \cdot \mathbf{T} + \mathbf{F} \] \hspace{1cm} (4)

\( p \), pressure on a fluid microelement; \( F_x, F_y, F_z \), the physical strength of a microelement. If gravity is the only force on the element and the axis is straight up. Then \( F_x \) and \( F_y \) are zero and \( F_z = -pg \).

2.2 Mathematic model

From the above, it can be seen that the alternative fluid model is an incompressible, gas-viscous, adiabatic fluid. Therefore, the standard K-Epsilon model was selected.

The standard k-Epsilon is a semi-empirical formula based on turbulent kinetic energy and diffusion rate. In the standard K-Epsilon model, turbulent kinetic energy \( K \) and turbulence dissipation rate are two basic unknowns, and the corresponding transport equation is as follows:

Turbulent kinetic energy \( K \) equation is as follows:

\[ \rho \frac{dK}{dt} = \frac{\partial}{\partial x_i} \left[ (\mu + \frac{\mu_k}{\sigma_k}) \frac{\partial K}{\partial x_i} \right] + G_k + G_{\nu} - \rho \varepsilon \] \hspace{1cm} (5)

The equation of turbulence dissipation rate \( \varepsilon \) is as follows:

\[ \rho \frac{D \varepsilon}{Dt} = \frac{\partial}{\partial x_i} \left[ (\mu + \frac{\mu_k}{\sigma_{\varepsilon}}) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_{\nu}) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \] \hspace{1cm} (6)
\( \mu_l \), laminar viscosity coefficient; \( \mu_t \), turbulent viscosity coefficient; \( G_k \), turbulent kinetic energy generated by laminar velocity gradient; \( G_b \), turbulent kinetic energy generated by buoyancy.

Turbulence viscosity can be expressed as a function of \( K \) and \( \varepsilon \).

\[
\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}
\]  

(7)

\( C_{1g}, C_{2g}, C_{3g}, \sigma_\varepsilon, \sigma_k \), empirical constant.

Model constants are obtained from the basic turbulence test of air and water, and generally take the following values:

\( C_{1g} = 1.44; C_{2g} = 1.92; C_{3g} = 0.99; \sigma_\varepsilon = 1.00; \sigma_k = 1.30. \)

3. Model establishment of air supply duct

3.1 Original air duct model and meshing

The air duct of a high-velocity train air-conditioning model was selected as the research object. The original air duct structure of the air-conditioning system, the driver's cabin, and the number of each air outlet is shown in Fig. 1(a). The division is shown in Fig. 1(b).

The area of each air outlet of the original air duct is shown in Table 1:

| Inlet 7 (m²) | Air outlet 1, 4 (m²) | Outlet 2, 3, 5, 6 (m²) |
|-------------|----------------------|------------------------|
| 0.025       | 0.005                | 0.041                  |

Taking the original air supply duct as the research object, it is pre-processed and meshed by CFD software. The number of meshes after division is 713606, as shown in Fig. 2.

(a) Relative location of air duct and train cabin  
(b) Air duct structure

1-side air outlet in front of the co-pilot; 2, 3-top air outlet in the area of co-pilot; 4-side air outlet in front of the main driver; 5, 6-top air outlet in the area of the main driver; 7-inlet of air supply.

Fig. 1. Original air duct and train cabin

Fig. 2. Meshing of original duct structure
3.2 Boundary conditions

The air velocity is high, so the wall surface is set as adiabatic wall surface. The specific boundary conditions are set as follows:

- Inlet: velocity inlet, 9m/s (design requirement).
- Outlet: pressure outlet, 0 MPa.

4. Analysis of the original air duct of the train

4.1 Performance analysis of the original duct

Fig. 3 shows the distribution characteristics of the air flow field in the air duct, and the volume flow of each air outlet (Table 2) was monitored.

It can be seen from the velocity distribution of the original train air ducts in Fig. 3 (a) and Fig. 3 (b) that there are strong air vortex movements in the left and right air chamber. These vortexes will interfere with the air around and normal flow, therefore cause momentum losses and it also cause noise. It can be seen from the velocity profile of the original train air ducts in Fig. 3 (c) and Fig. 3 (d) that due to the air inlet angle and the small cross-sectional area of the circular duct inlet, the air volume of the circular air outlets of the left and right air chambers is much smaller than that of other air outlets.
The calculation of the air volume distribution of each outlet of the original structure is shown in Table 2:

**Table 2. The volume flow of each air outlet**

| Left air outlet number | 1      | 2      | 3      | Left air chamber total air volume | Air volume percentage (%) |
|------------------------|--------|--------|--------|-----------------------------------|---------------------------|
| Volume flow (m³/h)     | 47.189 | 161.91 | 247.183| 456.282                           | 56.9                      |
| Right air outlet number| 4      | 5      | 6      | Right air chamber total air volume | Air volume percentage (%) |
| Volume flow (m³/h)     | 38.269 | 128.942| 178.427| 345.638                           | 43.1                      |

The results indicate that the total air volume of the right air chamber is less than the total air volume of the left air chamber, which does not meet the design requirements (the ratio of the total air volume of the left and right air chambers equal to about 45%:55%). The air flow rates of the four air outlets of the air chamber on the left and right sides is not uniform, and the air output of the two circular air outlets (1, 4) is significantly lower than that of the other four air outlets (2, 3, 5, 6) in the same air chamber (The air volume at outlet 1 only accounts for 10.3% of the total air volume at left air chamber, and that at outlet 4 only accounts for 11.1% of the total air volume at right air chamber).

5. **Optimization of train air duct structure**

5.1 **Optimal structure of deflector**

Because the cross-sectional area of the air flow from the left and right air chambers to their corresponding circular outlets is too small, most of the vortex exists in the left and right air chambers. In order to reduce the loss of vortex kinetic energy and noise, the structure of the connecting part between the left and right air chambers and their circular air outlets should be optimized. The optimized section is the cross-sectional area which is shown in Fig.4(a).

It can be seen from table.2 that since the left air chamber is close to the inlet, there is a large amount of air entering the left air chamber (as shown by the arrow in Fig.4(a). In the original air duct structure, the air volume distribution of the left isn’t as same as that of the right chambers. Therefore, in the optimization, arc air deflectors are added in the connection duct between the air inlet 7 and air chambers, and the cross-sectional area from the left and right air chambers to the circular air outlet 3 and outlet 4 is increased, which is rectangular, as is shown in Fig.4(b), it can achieve the uniformity of air volume at each outlet, and the total air output of the left and right air chambers can be adjusted.
5.1.1 Optimization analysis of the diversion structure of the deflector

The velocity profile and the volume flow of each outlet after the arc deflectors are shown in Fig. 5 and Table 3.

![Fig. 5. Velocity profile of the deflector optimization structure](image)

The air volume distribution of each outlet of the arc deflector optimization structure is shown in Table 3:

| Left air outlet number | 1  | 2  | 3  | Left air chamber total air volume | Air volume percentage (%) |
|-----------------------|----|----|----|----------------------------------|---------------------------|
| Volume flow (m³/h)    | 47.189 | 161.91 | 247.183 | 456.282 | 56.9 |
| Optimized volume flow | 82.047 | 129.392 | 125.009 | 336.448 | 41.9 |

| Right air outlet number | 4  | 5  | 6  | Right air chamber total air volume | Air volume percentage (%) |
|------------------------|----|----|----|----------------------------------|---------------------------|
| Volume flow (m³/h)     | 38.269 | 128.942 | 178.427 | 345.638 | 43.1 |
| Optimized volume flow  | 153.289 | 187.477 | 124.621 | 465.387 | 58.1 |

By comparing the volume flow data of each outlet before and after optimization, it can be found that: the arc deflector structure improves the distribution of the total air volume in the left and right air Chambers design requirements that the air volume in the left chamber is adjusted from 56.9% to 41.9%, and the air volume in the right chamber is adjusted from 43.1% to 58.1%. By adding a curved deflector structure in the left air chamber and increasing the cross-sectional area of the left and right air chamber branches, the dynamic pressure of the air in the left room is reduced, which not only has a good drainage distribution effect on the air distribution in the air room. Not only does it have a good drainage distribution effect on the air distribution in the air chamber, but also reduces the vortex phenomenon in the air chamber, and ultimately the uniformity of the air volume of the air outlet of each wind chamber is significantly improved.

5.2 Optimal structure of fractal

Different shape of the shunt pipe is simulated in order to study the influence of the deflector on the flow.

The structure of fractal mainly connects the air inlet to the left and right air chamber. The structure of fractal retains the position and size of the inlet and outlet, the left and right air chambers and the left
and right air chambers to the connection part of the circular air outlet. This structure avoids the difficulty of adding deflectors in actual machining.

For the original structure, it can be seen that the uneven distribution of air volume in the left and right air chambers may be caused by the position of air inlet and the "N-type structure" and "inverted Y-type structure" entering the connecting part of the left and right air chambers which are shown in Fig.6(a). Therefore, the structure is optimized to "n-type structure" in the structure of fractal which is shown in Fig.6(b).

(a) N-type inverted Y-type structure  (b) n-type structure

Fig.6. Comparison before and after the optimized structure of fractal

5.2.1 Optimization analysis of the structure of fractal

The velocity profile and the volume flow of each outlet after the fractal are shown in Fig. 7 and Table 4.

Fig.7. Velocity profile of the fractal optimization structure

The air volume distribution of each outlet of the fractal optimization structure is shown in Table 4:

| Table 4. The volume flow of each outlet of the fractal optimization structure |
|---------------------------------------------|-----------------|-----------------|-----------------|
| Left air outlet number | 1 | 2 | 3 | Left air chamber total air volume | Air volume percentage (%) |
| Volume flow (m³/h) | 47.189 | 161.91 | 247.183 | 456.282 | 56.9 |
| Optimized volume flow | 114.54 | 119.777 | 122.231 | 356.548 | 44.4 |
| Right air outlet number | 4 | 5 | 6 | Right air chamber total air volume | Air volume percentage (%) |
| Volume flow (m³/h) | 38.269 | 128.942 | 178.427 | 345.638 | 43.1 |
| Optimized volume flow | 143.081 | 150.33 | 152.178 | 445.589 | 55.6 |
By comparing the air volume of each outlet before and after optimization, it can be found that: by optimizing the "N-type" and "inverted Y-type structure" into "n-type structure" in the original structure, the air flow in the original structure into the left and right air chambers through the "inverted Y-type structure" was changed, and the velocity direction of air flow from the air inlet into the left and right air chambers was changed (in the direction is 45° that the air enters the left and right air chamber in the original structure is optimized to 90°). At the same time, it also reduces the dynamic pressure of the air in the left and right air chambers. The optimized structure improves the eddy current in the left and right air chamber and the air volume of each outlet is effectively regulated. Finally, it makes the air volume deviation of each air chamber outlet less than 10%.

5.3 The effect of rounded corners in the "n-type structure"

In "n-type structure", the rounded corners structure plays an important role in the air motion in the air duct. With or without rounded corners and outlet Numbers are shown in Fig.8(a),(b).

![Comparison with and without rounded corners](image)

**Fig.8.** Comparison with and without rounded corners

5.3.1 Optimization analysis of the structure of corner

The velocity profile and the volume flow of each outlet in the structure with or without rounded corners are shown in Fig.9(a),(b) and Table5.

![Comparison velocity profile of with and without rounded corners](image)

**Fig.9.** Comparison velocity profile of with and without rounded corners

The air volume distribution of each outlet of with and without rounded corners structure are shown in Table 5:
Table 5. The volume flow of each outlet of with and without rounded corners structure

| Outlet number | No round corner transition Volume flow (m³/h) | With rounded corners Volume flow (m³/h) |
|---------------|---------------------------------------------|----------------------------------------|
| 1             | 89.454                                      | 114.54                                 |
| 2             | 94.099                                      | 119.777                                 |
| 3             | 112.724                                     | 122.231                                 |
| 4             | 166.096                                     | 143.081                                 |
| 5             | 200.8                                       | 150.33                                  |
| 6             | 138.717                                     | 152.178                                 |
| Left air chamber total air volume | 296.277 | 356.548 |
| Right air chamber total air volume | 505.613 | 445.589 |

There is a no air region in the no rounded corners structure which is shown in the circular region in Fig. 9(a). The region caused unnecessary losses such as uneven air flow in each outlet.

By comparing the air volume of Table 5, it can be found that: the maximum deviation of air output from each outlet reaches 30% in the no rounded corners structure, but the air volume of each outlet is more uniform, and the air volume deviation of each air chamber is less than 10% in the rounded corners structure.

6. Conclusions

Through the above analysis, the following conclusions can be drawn.

1. Through the simulation of the original air duct of the air conditioner of a high-velocity train, it can be obtained that the air volume distribution of the left and right air chambers of the original structure cannot meet the design requirements (total air volume of the left air chamber: total air volume of the right air chamber = 45%: 55%), The air flow distribution of each air outlet is uneven and the vortex phenomenon is generated inside the left and right air chambers, which cannot meet the use requirements.

2. An arc deflector is added in the left chamber as a optimization scheme. It can effectively adjust the distribution of left and right air volume and the uniformity of air volume at each air outlet problem.

3. Adopt the fractal and shunt optimization plan for the original air duct. By adopting the "n-type structure" between the air inlet and air chambers and adjusting the position of the air inlet into the left and right air chambers, the air vortex phenomenon in the air chamber can be effectively reduced. The total air volume of the left and right air chambers and the uniformity of the air volume at each outlet can meet the design requirements.

4. By setting a rounded transition structure at the bend, it can effectively improve the air motion in the air duct and reduce the internal vortex.

The optimization design of the air-conditioning duct structure is a fractal and shunt optimization scheme. This scheme is not only simpler and easier to manufacture than the optimized structure of arc air deflector, but also the air volume error of each outlet of the left and right air chambers is less than 7%, which has better uniformity and can more accurately achieve the ratio of the total air volume of the left and right air chambers equal to about 45%: 55% of design requirements.

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