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Experimental and simulation study on a novel uniform air/smoke exhaust device in subway

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Abstract. A novel π -shape device (π -D) was developed based on air full pressure supply theory to realize the uniform air/smoke exhaust for long duct with enormous vents in subway tunnel. To validate its performance, numerical simulation of internal flow field of the duct with π -D was conducted. Then an experimental 65-meter-long exhaust duct with π -Ds was set up in accordance with the real size. The air exhaust velocities of each vent and the total head losses along the main duct were measured. Both experimental and simulation results showed that the proposed new device could be designed and equipped flexibly into the long air/smoke exhaust duct. It would significantly enhance the ventilation uniformity, reduce the airflow resistance by 50%-65%, and achieve above 20% of distribution energy saving as well.

1. Introduction

With the flourishing development of subway construction, more and more attentions are paid to the ventilation for subway station tunnel [1, 2, 3]. Subway station is a typical long and narrow structure. The air/smoke exhaust system is generally divided into two symmetrical subsystems bounded with centerline of station. Each subsystem has exhaust ventilator, air duct, vents and so on. Each duct usually covers the length of about 50 to 70 meters with more than 30 exhaust vents. The vents at the end of station are nearer to exhaust fan and those at center are the end of the mechanical system. The main function of the exhaust system is to realize the heat emission of air conditionings of train compartments, heat discharge during the train braking process, as well as smoke extraction in case of fire. However, plenty of field tests prove that the air exhaust volume of each tuyere is quite different. The wind speeds flowing through the vents near exhaust fan are usually much greater than design value while those near the end of duct are almost zero [4, 5]. It really is a common and formidable problem of the uniform air exhaust for long ducts with enormous vents.

In fact, many investigations have been done on the uniform air distribution in duct ventilation. A design principle for uniform airflow distribution in duct ventilation is developed, the verification of which is conducted by the three-dimensional modeling with Finite volume method [6]. A simple 1D theoretical model is presented to provide uniform air distribution on the outlets of the ventilation ducts [7]. Optimal geometry for a rectangular duct is executed numerically. The airflow characteristic and air supply uniformity of four kinds of air ducts are discussed for a B car-type mode subway vehicle, which is validated by numerical simulation [8]. A kind of non-adjustment static pressure supply air duct is presented for the uniform air supply system of railway passenger cars [9]. The flow field



including air uniformity is studied inside an air-delivery duct of air conditioning system in subway compartments [10].

Although lots of work has been done on uniform air distribution, the design and research on uniform air distribution of long duct with numerous vents suitable for subway tunnel are relatively insufficient. Especially some kinds of practical engineering methods are necessary to handle the problem of non-uniform air exhaust for long ducts. In this paper, a novel π -shape device (π -D) was developed based on air full pressure supply theory to achieve the uniform air/smoke exhaust for a long duct. Its structure, characteristic, simulation and experimental validation were discussed as follows.

2. Structure and characteristic of π -D

In conventional air supply system, the air is always supplied theoretically from main duct to each outlet by static pressure, which based on two kinds of approaches, i.e. plenum chamber and static pressure regain. However, during the practical operation in subway, due to the duct inner resistance, non-uniform air velocity and environmental disturbance such as the piston-wind effect, the influence of airflow at entrance and existence of stairway, the static pressure inside the duct may usually be insufficient enough to overcome that outside the duct. Therefore cause the fact that the actual air supply through the duct could not reach the design value, and magnificent deviation of air velocity for each vent, sometimes air suction may even occur. There are similar situations for the air exhaust duct.

To mitigate and solve this uneven air supply/exhaust problem for long duct, a kind of air split/confluence-flow device was developed [11]. As shown in figure 1, it was a novel π -D to be installed inside the duct. One end of it would face at the airflow while another join to each air vent. Taking an air supply duct with π -D as an example, it was the full pressure near the vent converted by the static pressure or dynamic pressure of the airflow in main duct to produce the discharge driving force. For a long duct with these π -Ds, a certain amount of air would be diverged automatically from the main flow and distributed to each vent since the shunt effect of the upper baffles of π -D. Hence, the air flow turbulence would be slowed down and diverging flow resistance decreased. Considering the static pressure variation for outlets, the cross section of π -Ds perpendicular to the airflow should be designed in proportion to that of the variable cross-sectional main duct. Besides, the arc-designed rear end of π -D could further reduce the flow resistance. In this way, depending on the full pressure difference, the quasi-vertical air outlet flow would make the performance of uniform air distribution more self-tuning to some extent.

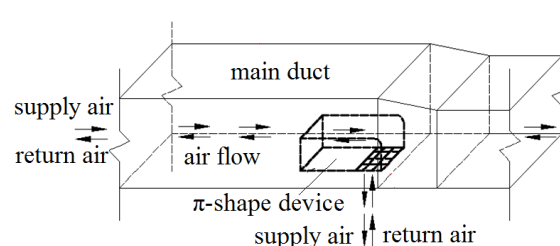


Figure 1. Diagram of π -D.

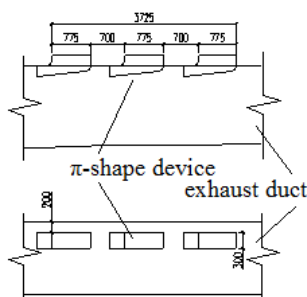


Figure 2. Front view and side view of air/smoke exhaust duct with π -Ds .

3. Simulation study on π -Ds

Taking an actual long air exhaust duct in a Shanghai subway tunnel as target, CFD simulation software was employed to validate the airflow characteristics and velocity uniformity of π -Ds. Parallel to the iron track, the 75-meter-long air/smoke duct was located on the lower side of the subway tunnel, with 36 of side exhaust vents. The cross section of main duct is rectangular with the maximum length of 1500mm and width of 1330mm respectively, which kept gradually decreasing during full length. Each vent has the size of $775 \times 300 \text{mm}^2$. Now suppose a total 36 π -Ds were designed to connect to the original vents. As shown in figure 2, the distances between every two draughts were 700 to 1000mm. A variable frequency exhaust ventilator with a maximum air volume of $43000 \text{m}^3/\text{h}$ was installed on the one end of the duct.

Take into consideration the incompressible airflow, the way of Euler conservation equation could be written as follows,

$$\frac{\partial(\rho\phi)}{\partial\tau} + \text{div}(\rho\vec{u}\phi) = \text{div}(\Gamma\text{grad}\phi) + S \quad (1)$$

Where ρ is the fluid density, ϕ is interchangeable variable, \vec{u} is velocity vector, Γ is general dispersion coefficient, S is general source item.

The standard k- ϵ model was employed to solve turbulent flow according to business code of Fluent. Some simplifications were made for the structure of duct and π -D during modeling with Gambit. Structured hexahedron grid technique was adopted for the inner space of π -Ds while unstructured tetrahedral grid for adjacent region of them and structured hexahedron grid for the rest part of main duct. The corresponding grid lengths were 2cm, 5cm and 5cm respectively. As to the boundary conditions, pressure-inlet for each π -D terminal vent since it was directly connected with the atmosphere while velocity-out for the exhaust fan at one end of the main duct. The relative field test is accomplished [12], which indicates that simulation result agrees with test well and the maximum derivation is less than 10%. Therefore, the numerical model can be used to study the airflow characteristic and the uniformity of the air/ smoke exhaust ducts with π -Ds.

During the steady state of air/smoke exhaust, the pressure distributions in duct with original vents and with π -Ds were given in figure 3 and figure 4. The first air tuyere on the left was closest to the exhaust fan, those behind were gradually far away. It could be seen that for original vents, the air suction pressures for No.1 draught and No. 5 draught were -37.64Pa and -5.38Pa respectively. The difference was even as high as seven times. While the suction pressures inside the five π -Ds were all -0.57Pa, which were nearly identical. This meant the pressure distribution was uniform in the regions near these π -Ds. On the other hand, in figure 3, the pressure difference in main duct between the vertical section of No.1 vent and No. 5 vent was 21.51Pa, which covered the length of about 6m. While the pressure difference counterpart in figure 4 was only 2.43Pa. This proved that compared with original vents, the flow resistance along the main duct with π -Ds was significantly decreased.

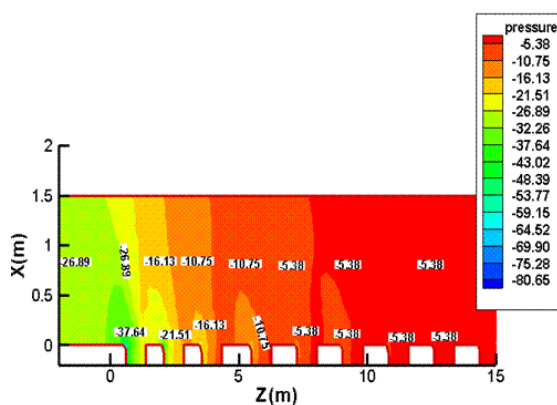


Figure 3. Pressure distribution for exhaust duct with original vents.

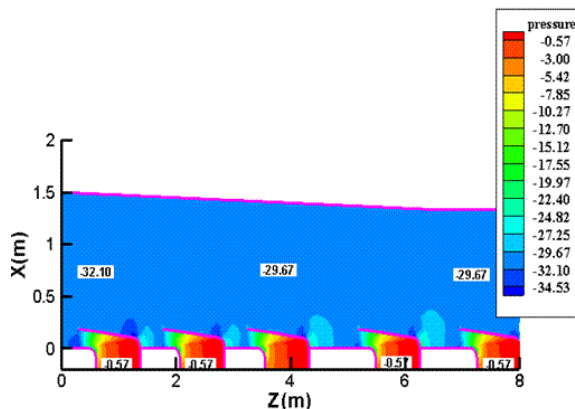


Figure 4. Pressure distribution for exhaust duct with π -Ds.

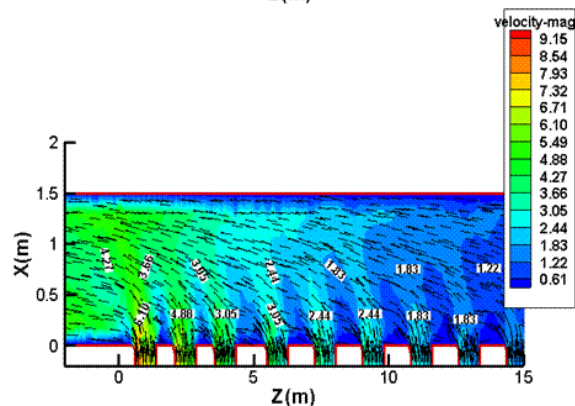


Figure 5. Velocity distribution for exhaust duct with original vents.

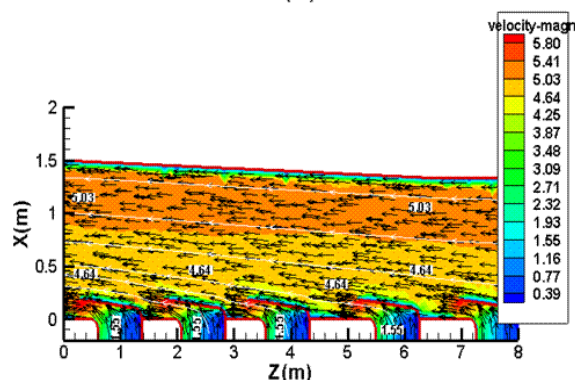


Figure 6. Velocity distribution for exhaust duct with π -Ds.

Similarly, there was a great uneven air exhaust velocity for each draught in the duct with original vents. As shown in figure 5, the speed at which the air was drawn in was 6.1m/s for No. 1 vent, then rapidly reduced by half for No.4 vent and attenuated to only 40% to 30% for the following several vents. Meanwhile, the average sectional velocity was 3 times different along the main duct. However, in a duct with π -Ds in figure 6, the air intake speeds for every vent was all about 1.55m/s and the average sectional velocities across the main duct were approximately equal. The velocity distribution was relatively uniform either at the front section of π -D or in the main duct.

4. Experimental study on π -Ds

The aforementioned simulation study showed that a long exhaust duct with π -Ds would have both uniform air velocities for each vent and low flow resistance across the whole duct. In order to validate further the effects of uniform air/smoke exhaust and the total pressure losses, an experimental 65-meter-long exhaust duct with 30 π -Ds was set up according to the real size. The cross section of main duct is rectangular with the maximum length of 1500mm and width of 1330mm respectively. In the full-length range, the main duct kept the height unchangeable while the width decreasing. All the π -Ds

were mounted on the sidewall of the duct, which would play the role of lower exhaust duct near the track area in subway tunnel. As shown in figure 7, each π -D had a rectangular vent with a size of $380 \times 150 \text{ mm}^2$ connected to it. A variable frequency exhaust fan with a maximum air volume of $36000 \text{ m}^3/\text{h}$ was installed on the one end of the duct (Figure 8)



Figure 7. Real size exhaust duct with π -Ds.



Figure 8. The exhaust fan for field test.

Let the frequency of variable speed fan started from 50Hz and decreased at the step of 5Hz until 25Hz. The field-test air velocities through π -Ds at different working conditions were given in figure 9. The smaller the number, the closer the π -D was to the exhaust fan. It could be observed that except for several air inlets further from the ventilator at the operation conditions with low frequencies, the air wind derivation of majority of tuyeres were less than 18%. For an exhaust long duct with enormous vents used in subway tunnel, this air confluent uniformity error was sufficient for engineering needs. Moreover, the exhaust air flow resistances along the entire duct at different frequency were also measured and listed in Table 1, which would be only one half to one third of the resistances for ducts with conventional vents in the same situation we actually tested in the subway tunnel. Comparing with the air/smoke exhaust duct with original vents, the duct with π -Ds could reduce the airflow resistance by 50%-65%, and achieve above 20% of distribution energy saving as well.

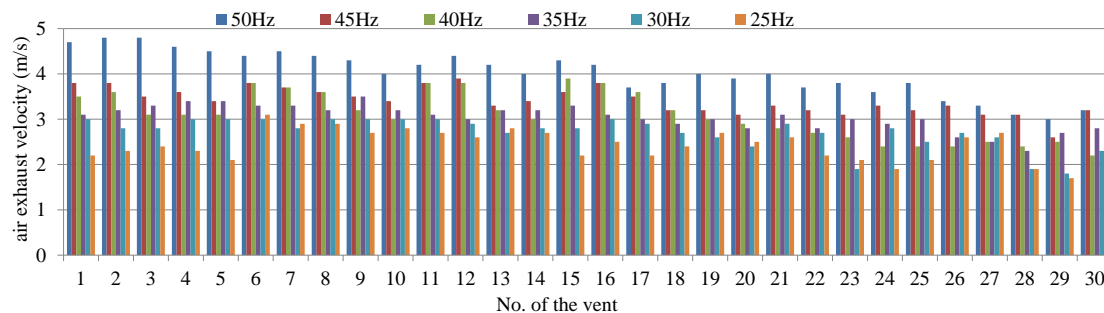


Figure 9. Exhaust velocities through each π -D at different working conditions.

Table 1. Airflow resistances long the duct at different frequencies.

Frequency (Hz)	50	45	40	35	30	25
Flow resistance (Pa)	43	34	20	16	8	7

5. Conclusions

This paper presented a novel π -shape device suitable for a long duct with enormous vents in subway tunnel, which changed the air distribution power from the traditional nearly static pressure to the full pressure. The device could self-distribute the air volume between main duct and each branch tuyere as needed and therefore make the shunt or confluence more reasonable. Both CFD simulation and real size experimental field test showed that the proposed new device could be designed and equipped

flexibly into the long air/smoke exhaust duct. Contrasting to the duct with traditional exhaust vents, it would significantly enhance the ventilation uniformity, reduce the airflow resistance by 50%-65%, and achieve above 20% of distribution energy saving.

Acknowledgments

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