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Reduced Scale Experimental Study and CFD Analysis on the Resistance Characteristic of Utility Tunnel's Ventilation System

Shu Li[a], Xuefeng Liu[a,*], Jiaxu Wang[a], Guanyu Fang[b], Wenjing Chen[b], Shiming Deng[b]

[a]South China University of Technology, School of Electric Power, Wushan RD., Tianhe District, Guangzhou, 510641, P.R. China
[b]The Hong Kong Polytechnic University, Department of Building Services Engineering, Hung Hom, Kowloon, 999077, Hong Kong

Abstract

An experiment model is established with the geometrical scale of 5:1 based on an actual utility tunnel engineering, and the air volume is deduced with Re similarity principle. Besides a corresponding numerical simulation model is set up. Through the comparison of the results of experiment and the numerical simulation, the errors are under the allowed error of engineering. The fitted formula between friction resistance and Re may help in the future design and type selection of utility tunnel's ventilation system.

Keywords: Utility tunnel; Reduced scale experiment; Numerical simulation; Resistance characteristic

Nomenclature

Re	Reynolds number	ΔP	Total pressure difference between two sections(Pa)
u	Velocity(m/s)	λ	Friction resistance coefficient
l	Length(m)	ζ	Local resistance coefficient
v	Kinematic viscosity(m^2/s)	d	Equivalent diameter(m)
C_u	Ratio coefficient of u	C_{Re}	Ratio coefficient of Re
C_l	Ratio coefficient of l	C_G	Ratio coefficient of G
A	Area of a section(m^2)	P	Perimeter(m)

* Corresponding author. Tel.: +86 13580456068
E-mail address: lyxfliu@scut.edu.cn

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1. Introduction

With the continuous improvement of the level of urbanization, the superiority of the utility tunnel has become increasingly prominent [1-2]. The ventilation system is related to the safety and economy of the operation of the utility tunnel. Thus, the acquisition of ventilation resistance coefficients is critical to the correct design and selection of the ventilation system [3-4].

For the study of the resistance coefficients of the utility tunnel's ventilation system [5], the measured data of a single case's utility tunnel cannot provide guidance for the design. At present, only the Technical code for urban utility tunnel engineering (GB 50838-2015) can be refer to the design of the utility tunnel's ventilation system, and the content does not involve resistance related [6].

For the theoretical study, Darcy came up with the Formula to calculate the total pressure loss. Carmen, Blachius, Nicholas et al have deduced empirical formulas in different values of Reynolds number (Re) according to lots of experiments. However, these formulas don't involve the condition that there existed pipes in the section, and the section area is much smaller than the section of utility tunnel. And for the study method, reduced-scale experiment according to the similarity theory is an important method. Reduced-scale experiment has been used on large space and long tunnel [7-10]. Zhou and Costantino used numerical simulation to research on large space and long tunnel [11-14].

In this paper, a reduced scale experiment model and the responding numerical simulation model are established. The similarity theory is used to derive the ratio coefficient. Under different air volume conditions, scale model experiments and numerical simulations were performed respectively. The errors were analyzed and the reliability of the numerical simulation results was verified. Then analyze the resistance characteristics of ventilation system of utility tunnel under different air volume conditions, and use polynomial regression to obtain the fitting formula between ventilation resistance coefficient and Re, thus providing theoretical basis for the design and later optimization of ventilation system.

2. Method

2.1. Experimental method

The reduced-scale experiment model is setup based on a pipeline compartment of a utility tunnel in an actual engineering with the geometrical scale of 5:1. The model is made up with three part of the inlet, the outlet and the main aside. There is a piece of water pipe, a piece of firefighting water pipe and 40 pieces of communication cables in 8 rows where each row includes 5 pieces. The geometrical size of the actual compartment and the reduced-scale experiment model is shown as Table 1. The geometrical structure and the sectional view are shown as Fig. 1 and Fig. 2.

Table 1. Geometrical size of the actual compartment and the reduced-scale experiment model

	width ×height /m×m	length /m	vertical length ×width /m×m	vertical height /m	communication cable	water pipe	firefighting water pipe
actual compartment	3×3	30	1×1	2	DN100	DN350	DN600
experiment model	0.6×0.6	6	0.2×0.2	0.4	DN20	DN70	DN120

P.S.: DN100 means the corresponding pipe's diameter is 100mm, etc.

The experiment model is made of galvanized steel. The model is sealed by the sealant to ensure the model in a good sealing performance. The outlet and the centrifugal fan are connected by PVC (Polyvinyl chloride) pipe. The centrifugal fan provides power to make the air move in the experiment model at a velocity. The inverter is used to control the frequency of the centrifugal fan. The measuring equipment include velocity sensor, pressure sensor and pitot tube which used to measure velocity in each section and the pressure difference between two sections. The experiment model system is shown as Fig. 3. The measuring equipment's full scale and accuracy are shown as Table 2.

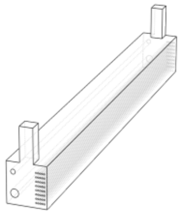


Fig. 1. Geometrical structure

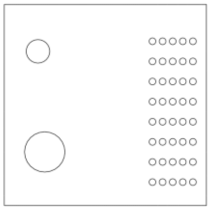


Fig. 2. Sectional view

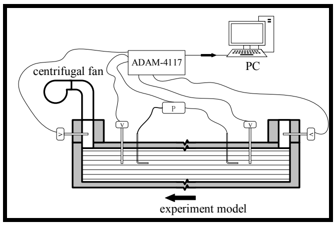


Fig. 3. Experiment model system

Table 2. Full scale and accuracy of sensors

	full scale	accuracy
velocity sensor	0~20m/s	±0.2m/s
velocity sensor	0~2m/s	±0.06m/s
pressure sensor	-50~50Pa	±0.25Pa

According to the Technical code for urban utility tunnel engineering (GB 50838-2015) announced in China, the maximum and minimum air change times in a compartment are twice and six times. The Reynolds number (Re) in the main aside is under 10^6 calculated with Eq. (1), which means it doesn't reach the second self-modeling region. So according to similarity theory, Re of actual compartment and experiment model should be equaled. That is shown in Eq. (2).

$$\mathrm{Re} = \frac{ul}{\nu} \tag{1}$$

$$f\left(\mathrm{Re}\right) = 0 \tag{2}$$

From Eq. (2), the relation of C_u and C_l can be deduced, shown as Eq. (3).

$$C_u = C_l^{-1} = \frac{1}{5} \tag{3}$$

And according to the Darcy-Weisbach Formula, shown as Eq. (4), C_{Re} and C_G are deduced, shown as Eq. (5) and Eq. (6).

$$\Delta P = \left(\sum \lambda_i \frac{l_i}{d_i} + \sum \zeta_i\right)\frac{1}{2}\rho u^2 \tag{4}$$

$$C_{\mathrm{Re}} = C_u C_l = 1 \tag{5}$$

$$C_G = C_u C_l^2 = C_l = 5 \tag{6}$$

Thus, by changing the inventor's frequency, the outlet velocity is controlled in a range where the air change times keeps from twice to 6 times in the experiment model. And among these conditions, 12 conditions are selected which shown as Table 3.

Table 3. Outlet velocity in each operating condition (unit: m/s)

operating conditions	1	2	3	4	5	6	7	8	9	10	11	12
outlet velocity	2.3	2.8	3.7	4.2	4.9	5.4	6.1	7.2	8.7	9.8	10.8	12.0

In each operating condition, corresponding measurements are conducted out. The measuring sections are shown as Fig. 4. Both inlet and outlet have a section respectively, and 9 sections at every 0.6m in the main aside marked with 1~9. In addition, each section has 9 measuring points marked with ①~⑨, which is shown as Fig. 5.

In the experiment procedure, first the centrifugal fan is turned on and running in a certain frequency set by the inventor. Then record the corresponding data of each measuring points after the air current is steady. And then change the frequency and repeat the steps above.

The formulas of friction resistance coefficient, local resistance coefficient at inlet and outlet are as follows. The friction resistance coefficient's formula is Eq. (7), and the local resistance coefficient at inlet and outlet are Eq. (8)

and Eq. (9), where ρ is 1.1614kg/m^3.

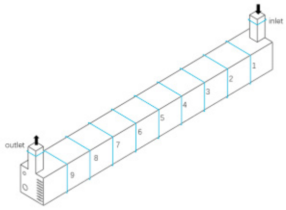


Fig. 4. Measuring sections

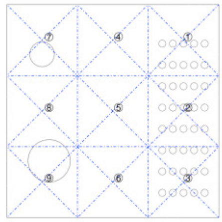


Fig. 5. Measuring points

$$\lambda = (P_4 - P_8) / \left\{ \frac{l}{d} \times \frac{1}{2} \rho \left[\left(\sum_4^8 u_\mathrm{i} \right) / 5 \right]^2 \right\} \tag{7}$$

$$\zeta_\mathrm{in} = (P_\mathrm{in} - P_4) / (\frac{1}{2} \rho u_\mathrm{in}^2) \tag{8}$$

$$\zeta_\mathrm{out} = (P_8 - P_\mathrm{out}) / (\frac{1}{2} \rho u_\mathrm{out}^2) \tag{9}$$

The formula of Equivalent diameter and Hydraulic radius are shown as Eq. (10).

$$d = 4 \times A / P \tag{10}$$

2.2. Numerical simulation method

A simulation model is built whose geometrical size is the same with the experiment model. In the process, the whole model's mesh is made of structured grid and the pipe and cable are made of O block. By checking the error due to the grid number, the number is determined with 1,080,000. In FLUENT, the calculation model is K-ε realizable model, and the accuracy is Second Order Upwind. The inlet is pressure-inlet and the total pressure is 0Pa. The outlet is velocity-outlet and the value is corresponding to the experiment's operating conditions, the detail values are shown as Table 4. The wall roughness is 1mm.

Table 4. Outlet air volume in each operating condition (unit: m^3/s)

operating conditions	1	2	3	4	5	6	7	8	9	10	11	12
outlet air volume	0.1	0.125	0.15	0.175	0.2	0.225	0.25	0.3	0.35	0.4	0.45	0.5

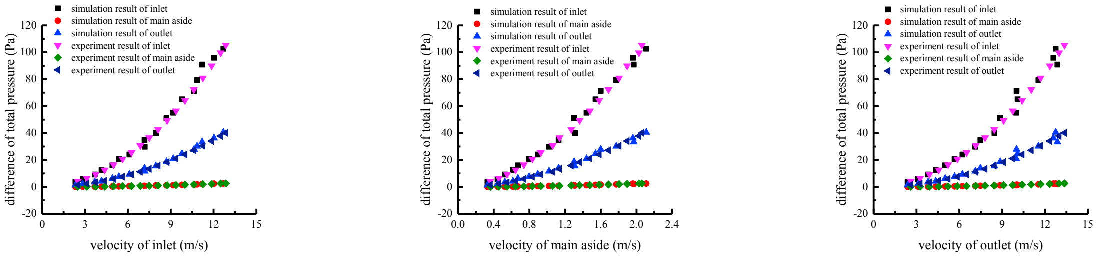
The calculation method of friction resistance coefficient, local resistance coefficient at inlet and outlet are the same as experiment model's formulas, which is shown above as Eq. (7)~(14).

3. Results and Discussion

3.1. Comparative analysis of experiment results and numerical simulation results

The result of experiment and numerical simulation are show as Fig. 6. Because the experiment operating conditions and numerical simulation operating conditions are not exactly alike in the air volume or the air change times, the results could not be compared directly. The total pressure difference of each part is related to the only one air volume in each operating condition both in experiment and numerical simulation. So The relation of total pressure difference of each part and air volume are shown as Fig. 6. (A), (B) and (C).

Due to the influence of the boundary condition, the calculation formulas and the residual error in the simulation, and also the influence of the outside environment and the limit of measuring equipment, deviation is existed between the experiment results and the simulation results. But the general tendencies are alike.



(A) (B) (C)

Fig. 6. The relation of total pressure difference of each part and air volume

From Fig. 6., it can be seen that the error is under ±10%, the allowed error of engineering, which can prove the reliability of the simulation.

3.2. Analysis of the resistance characteristic

The numerical simulation results of each operating condition are shown as follows. Velocity curves of each operating condition in each section are with air volume from 0.1m^3/s to 0.5m^3/s are shown as Fig. 7. It can be learnt that the velocity of inlet and outlet where the section area are smaller are larger than the velocity in the main aside. The velocity of each section grows with the growth of the air volume and the curves' tendency are consistent.

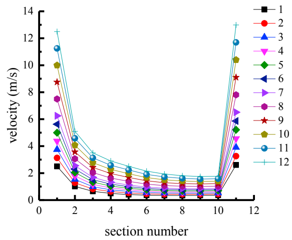


Fig. 7 Velocity of each section at different air volume

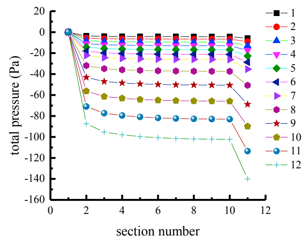


Fig. 8. Total pressure of each section at different air volume

Total pressure curves of each operating condition in each section are with air volume from 0.1m^3/s to 0.5m^3/s are shown as Fig. 8.

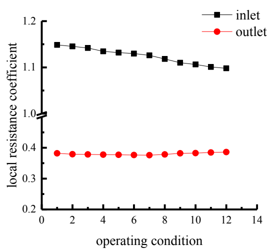


Fig. 9. Resistance coefficient of inlet and outlet at different air volume

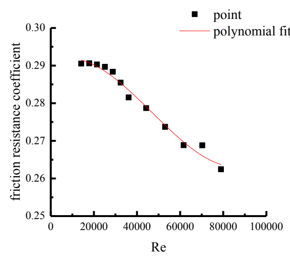


Fig. 10. Relation of Re and friction resistance coefficient

Local resistance coefficient of inlet and outlet with volume from 0.1m^3/s to 0.5m^3/s are shown as Fig. 9. In the inlet, the local resistance coefficient declines from 1.149 to 1.098 with the air volume grows. The relation of friction resistance coefficient and Re is shown as Fig. 10. Using polynomial regression, the polynomial regression model between friction resistance coefficient and Re is conducted out, which is shown as Eq. (11). The polynomial order is 3, and the R^2 (Coefficient of Determination) is 0.98344.

$$\lambda = 0.29064 + 2.89995^{-7}\,\mathrm{Re} - 1.81634^{-11}\,\mathrm{Re}^2 + 1.28879^{-16}\,\mathrm{Re}^3 \quad (11)$$

4. Conclusion

(1). Experiment of reduced scale model proved the reliability of the numerical simulation method. The data of experiment model and numerical simulation model are alike and the errors are under the allowed error of engineering. So numerical simulation method can be used to proceed related research on the resistance characteristic.

(2). The fitted formula between friction resistance coefficient and Re can be used to guide the design and type selection of utility tunnel's ventilation system and performance's management.

(3). Further research should be carried out such as the analysis of resistance characteristic influenced by in different section type (number of pipes, location of pipes, ratio of width to height of the section, and length of the main aside).

Acknowledgements

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