DYNAMIC EVOLUTIONS OF TRAFFIC WIND INFLUENCED BY AMBIENT WIND FOR URBAN ROAD TUNNEL WITH SHAFTS

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Abstract. Urban road tunnels with shafts have been applied in some cities in China. Field measurements of Mofan Road Tunnel show that ambient wind is widespread and its influence on the ventilation efficiency of shaft is unclear. In this paper, the physical model of a three-lane 210 m (length) *12 m (width) *6 m (height) tunnel is studied, with three vehicles in each lane and a speed of 60 km/h. Three-dimensional CFD simulations on a 210 m long tunnel with double shafts is carried out by Fluent 6.3.26. Momentum equation and k-ε equation turbulence model are used for simulation analysis and dynamic grid technology is used to simulate vehicles driving. It is found that the ambient wind in tunnel has great influence on the flow field in tunnel and shaft. Number *Ri* is defined as the ratio of horizontal inertia force to vertical inertia force, revealing the conversion of horizontal inertia force to vertical inertia force.
Key words: urban road tunnel with shafts; ambient wind; traffic wind; dynamic grid; ventilation efficiency

1 Introduction

In recent years, with the improvement of urbanization in China, more and more urban road tunnels have emerged for relieving traffic congestion. In Nanjing, the Urban Rapid Inner Ring consists of several naturally ventilated urban road tunnels with shafts including Mofan road tunnel (length of 1444 m), Tongjimen road tunnel (length of 1400 m), etc. For such urban road tunnels with multiple shafts, airflow induced by moving vehicles (piston effect) is expected to force vehicle emissions to exhaust out of the tunnels through shafts. In short one-way tunnels, the piston effect combined with nature ventilation, is usually sufficient to drive fresh air in and to push polluted air out of the tunnel[1]. Wang[2] using one-dimensional models and computational fluid dynamics (CFD), concluded that increasing the number and speed of vehicles increases traffic force. Tong[3] established a network model of traffic wind based on mass and energy conservations for naturally ventilated urban road tunnels with shafts, also carried out real tests on the Nanjing Urban Rapid Inner Ring with its findings that shafts weaken the traffic winds compared to that of the mechanically ventilated tunnels without shafts. Also, in Tong's[4] full-scale fire experiments on Xianmen tunnel, a steady longitudinal ambient wind inside the tunnel was tested out to be in range of 0.9~1.5 m/s when there was no vehicle movement. Jin[5] revealed that the vehicle speed has more influence on air velocity than the vehicle spacing. Chen[6] found that the piston effect mainly existed at the bottom of tunnel. In simulation, Marta[7] carried out a dynamic mesh method to simulate the train displacement between two subway stations by using commercial code FLUENT, and addressed the impact of the piston effect on the global ventilation performance. Wang[8] conducted dynamic mesh technique to investigate the effects of traffic force.

In this paper, field measurements of ambient wind are performed, and the effect of ambient wind on the air flow field inside the tunnel are simulated by FLUENT. Reveals the influences of shaft ventilation efficiency and height of backflow occurring of tunnel with double shafts under different ambient winds.

2 Field measurements in real tunnels

Mofan road tunnel is a type of naturally ventilated urban road tunnel with multiple shafts. Its general layout is shown in Fig.1. Two kinds of testing were conducted in Mofan road tunnel. Table 1 lists sizes of several naturally ventilated urban road tunnels with shafts in city Nanjing.

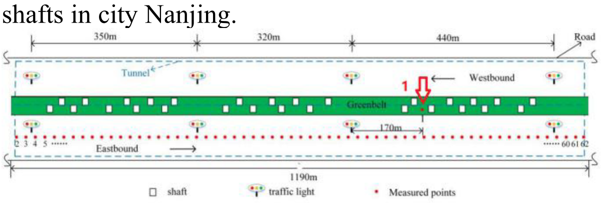

Fig. 1. Layout of urban road tunnel with multiple shafts

Test 1 was on the external ambient wind near top opening of a shaft being denoted as point 1 (as shown in Fig.1). Air velocities of point 1 were tested one day every week lasting for 5 months from August to November in 2019, and there were a total of 11 tested days. During each test, velocities were collected every 6 seconds and there were a total of 880 recorded values respectively for the three times (9:30~9:38 in the morning, 3:30~3:38 in the afternoon, and 9:30~9:38 in the evening), and its wind direction frequencies are summarized in Fig.2. Occurrences of the different

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tested values during each time are listed in Table 2. The results present that during any time the tested velocities varied in range of 0~4 m/s; the most frequencies occurred in range of 0~1 m/s reaching up to 700.

Table 1. Sizes of urban road tunnels with shafts

Tunnel	Hole size (*L***W***H*) (m)	Shaft size (*L***W***H*) (m)	Shaft group		
			Shaft number /group	Spacing (m)	Number
Mofan Road	1136*12.5*5.7	4.4*3.0*(1.1~4.5)	2	41~177	15
Xianmen	1720*12*6	3.2*2.6*(4.9~7.8)	4	24~240	24
Tongjimen	1340*10.5*6	3.2*2.6*(6.0~7.6)	4	23~116	14
Shuiximen	1280*11.5*6	(3.1~3.2)*3.0*(4.2~11.0)	2/3/4/5/6/7	10~275	10
Qingliangmen	1655*11.5*6	3.4*(1.9~3.0)*(1.8~4.8)	4/5/6	26~233	14
Wutang	1590*11.75*6	3.31*3.0*(4.1~9.2)	3	40~120	21

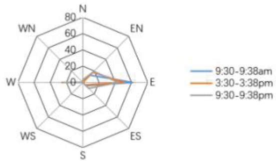


Fig. 2. Measured wind direction frequency of point1

Table 2. Measured air velocity during three periods in test 1

velocity(m/s)	0~1	1~2	2~3	3~4	total
morning	715	134	24	7	880
afternoon	713	139	25	3	880
evening	710	157	12	1	880

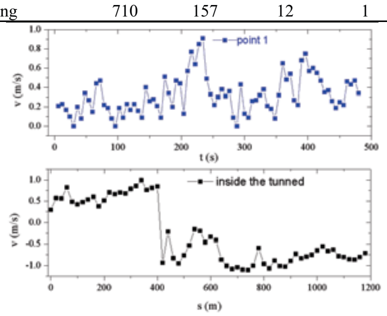


Fig. 3. Measured air velocities inside and outside the tunnel

Test 2 was on the internal and external ambient winds when off-run (no vehicle moving) at midnight on 12/09/2019. Air velocities of point 1 were collected every 15 seconds lasting for 8 minutes. Air velocities inside the tunnel were collected along the longitude at 1.5 m high above the ground in an interval of 20 m with its points shown in Fig.1. The measured air velocities inside and outside the tunnel during midnight in test two are depicted in Fig.3 in which the positive signal represents the east direction towards the exit and the negative signal represents the west direction towards the entrance. It was found out that the external air velocities of point 1 were always less than 1.0 m/s indicating its weak street canyon wind during midnight which was similar to that of the test 1; when without vehicles moving, the internal ambient winds existed still and varied in range of 0.1~1.2 m/s.

3 Methodology

3.1 Physical model

In order to investigate on the flow fields induced by vehicles moving in tunnels with shafts, a physical model tunnel is established which is unidirectional and has a size of 210 m in length and 12 m in width with three-lanes. Fig.4 shows the schematic views of the physical model. A shaft group is built over the tunnel ceiling, and consists of shafts with each size being 4.4 m (length)*3 m (width)*3.5 m (height). There is no need to focus on details of flow fields of vehicles arounds, so shape of every vehicle is simplified to be cubic in order convenience, and each vehicle size is 4.2 m *1.7m *1.4 m. A flow extended region is added over the shafts' top opening so as to facilitate mass transfer existing between inside and outside tunnel, and size of the region is 40 m *18 m *5 m. All vehicles move from the tunnel inlet to the outlet with a same speed 60km/h with an interval of 4 m in every vehicle. For the studied 210m long tunnel, a total crossing time is 12 s for one car, and the simulation time is also set to be 12 s.

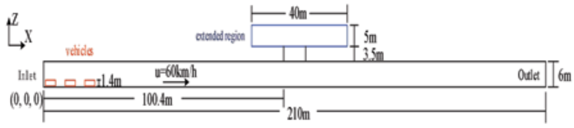


Fig. 4. Schematic views of the physical model established

3.2 Controlling equations

The flow around the crossing vehicles is one type of three-dimensional unsteady viscous incompressible flow. Reynolds Averaged Navier–Stokes method offers a good compromise between accuracy of result and computational cost. Moreover, the standard k–ε turbulent model has the advantage of being extensively used in simulation of vehicle-induced turbulence and tunnel ventilation and has been validated against experimental data[9][10].

3.3 Dynamic mesh updating method

A dynamic grid method is used to simulate and obtain instantaneous information about the air flow induced by vehicles moving. In this study, vehicles movement is technically implemented via the user-defined function (UDF) in Fluent 6.3.26, so as to significantly enhance its capabilities. Computational time step has to be kept small enough to avoid the presence of negative volume for the upgrade of dynamic meshes, resulting in a typical time step of 0.01 s.

4 Simulated cases

Based on the real tests, ambient winds vary in range of -1~1m/s (*V1*, take a positive sign if it is in the same direction as the vehicle) for inside and 0~3m/s (*V2*) for outside tunnel in the following simulation.

Different combinations of *V1* and *V2* will affect the air flow field in tunnel and shafts. As shown in Table 3, 39 cases are adopted to study the flow field of tunnel and shafts.

The momentum source term (MST) is used as the driving force of the fluid in the tunnel, and values in this model are shown in Table 4. By using momentum source term as driving force, air velocity in the tunnel can be stable, as shown in Fig.5.

Table 3. Simulated cases

Cases	1	2	3	4	5	6	7	8
V1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5
V2	0	0.5	1.0	1.5	2.0	2.5	3.0	0
Cases	9	10	11	12	13	14	15	16
V1	0.5	0.5	0.5	0.5	0.5	0.5	-0.5	-0.5
V2	0.5	1.0	1.5	2.0	2.5	3.0	0	0.5
Cases	17	18	19	20	21	22	23	24
V1	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0
V2	1.0	1.5	2.0	2.5	3.0	0	0.5	1.0
Cases	25	26	27	28	29			
V1	-1.0	-1.0	-1.0	-1.0	0			
V2	1.5	2.0	2.5	3.0	0			

Table 4. Values of momentum source in cases

Cases	1	2	3	4	5	6	7
MST	0.0064	0.0091	0.0103	0.0106	0.0109	0.0112	0.0113
Cases	8	9	10	11	12	13	14
MST	0.0017	0.0028	0.0030	0.0031	0.0032	0.0033	0.0034
Cases	15	16	17	18	19	20	21
MST	-0.0014	-0.0020	-0.0023	-0.0026	-0.0028	-0.0029	-0.0030
Cases	22	23	24	25	26	27	28
MST	-0.0060	-0.0078	-0.0083	-0.0088	-0.0093	-0.0098	-0.0103

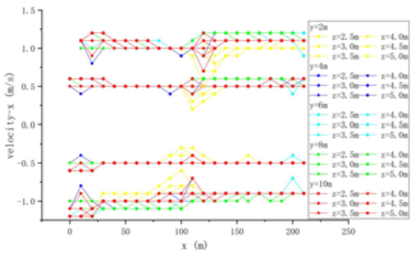


Fig. 5. Values of air velocity at different measuring points

The shaft volume flow rates reflect the ventilation capacity of the shaft. In order to reflect the ventilation capacity more intuitively, the ventilation efficiency of shaft η is defined to describe the values of the shaft ventilation as a percentage of the tunnel air exchange, calculated according to equation 1.

$$\eta = \frac{|2Qs|}{|Q1|+|Q2|+|Q3|+|Q4|} \quad (1)$$

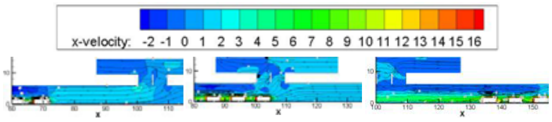
where: Q_s is the shaft volume flow rates, m^3/s; Q_1 and Q_2 are inlet and outlet volume flow rates of tunnel, m^3/s; Q_3 and Q_4 are volume flow rates of two shafts, m^3/s.

5 Results

5.1 Occurring height of backflow

Air velocity contour in X-direction at plane of Y=10m respectively when t=3s (not yet reach the shafts), t=5s (reach the shafts) and t=8s (already through the shafts) under case 29, as shown in Fig.6. After the vehicles leaving, the flow field in the Z-direction is divided into two obviously different upper and lower parts, with a small backflow speed at the top and a high forward speed at the bottom which reaches a maximum of 6 m/s.

Three monitoring surfaces (Y=6m, X=52.5/105/157.5m) were selected to monitor the air velocities distribution of the flow field in the X-direction of the tunnel. A measuring point is taken every 0.1m in Z-direction from 1.8m to 5.8m.



(a) t=3s (b) t=5s (c) t=8s

Fig. 6. Air velocity contour in X-direction at plane of Y=10m

Occurring height of backflow refers to the lowest height of the fluid in the tunnel where the air velocity is in the opposite direction as the vehicles. Backflow appears in the height of 2.5m ~ 6.0m and the maximum backflow velocity appears in the height of 5.0m ~ 5.5m. It is found that ambient wind *V2* outside the tunnel has little influence on the backflow height. Fig.7 shows backflow height measured at each measuring point at x=52.5m, x=105m and x=157.5m under different *V1*. When *V1* is in the same direction as the vehicle, with the increase of *V1*, backflow height is higher; when *V1* is opposite to the direction of the vehicle, with the increase of V1, height of backflow is lower. Therefore, *V1* in the same direction as the vehicle will weaken the backflow effect, while *V1* in the opposite direction as vehicle will enhance the backflow effect.

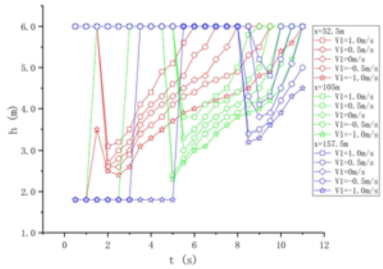
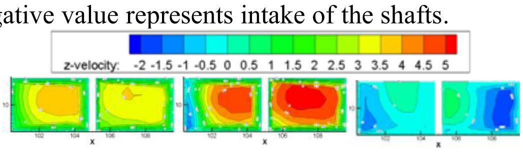


Fig. 7. Occurring height of backflow in main body

5.2 Shaft ventilation efficiency

The distribution of piston wind in the shafts is changing every moment. Air velocity contour in the Z-direction inside the shafts respectively when t=3 s, t=5s and t=8 s under case 29, as Fig. 8. A positive value of air velocity represents exhaust of the shaft, while a negative value represents intake of the shafts.



(a) t=3s (b) t=5s (c) t=8s

Fig. 8. Air velocity contour inside shafts

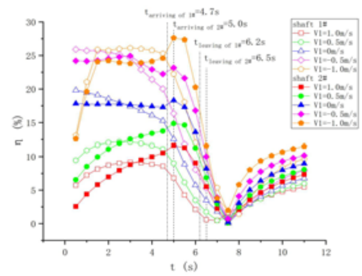


Fig. 9. Ventilation efficiencies of two shafts

The variation of *V2* has little influence on the shaft ventilation efficiency, which is mainly affected by the variation of *V1*. As seen in Fig. 9, when *V1* is in the same direction as vehicle, the shaft ventilation efficiency decreases with the increase of V1; when *V1* is opposite to the direction of vehicle, the ventilation efficiency of the shaft increases with the increase of *V1*. Therefore, *V1* in the same direction as the vehicle will decrease the shaft ventilation efficiency (the maximum value reaches 15%); *V1* in the opposite direction will improve the ventilation efficiency of the shaft (the maximum value reach 27%).

5.3 Number *Ri*

The fluid in tunnel is affected by horizontal inertia forces as well as vertical inertia forces. The fluid moves under the action of vertical inertia force caused by the pressure difference between inside and outside the shafts. The main driving force of horizontal inertia force is the combined effect of traffic wind and ambient wind (*V1*) in the tunnel. Based on the force analysis of the ventilation process, a dimensionless number Ri is used to judge the motion state of the fluid, whose physical meaning is the ratio of vertical inertia force (F_v) to horizontal inertia force (F_h), calculated according to equation 2 :

$$Ri = \frac{F_v}{F_h} \quad (2)$$

F_v is calculated according to equation 3:

$$F_v = \pm \frac{1}{2}\rho {v_0}^2 + \varphi \frac{1}{2}\rho {V_2}^2 \quad (3)$$

where ρ is the air density, kg/m^3; v_0 is the average air velocity of the shaft, m/s;φ is the proportion of air flow outside the tunnel into the shaft; V_2 is the ambient wind speed outside the tunnel, m/s; when the shaft exhaust, take positive.

F_h is calculated according to equation 4 :

$$F_h = \frac{A_{cs}\xi}{A_r}\frac{\rho}{2} n_c {v_t}^2 \pm \frac{1}{2}\rho {V_1}^2 \quad (4)$$

where v_t is the speed of a vehicle, m/s; V_1 is the ambient wind speed in tunnel, m/s; A_r is the size of tunnel cross section, m^2; n_c is the number of vehicles in the tunnel; A_{cs} is front projection area of vehicles (=2.13m^2); ξ is air drag coefficient of vehicles in tunnel (=0.35); For $\pm\frac{1}{2}\rho {V_1}^2$, its value should be positive, when the direction of the ambient wind is the same as the direction of the vehicles.

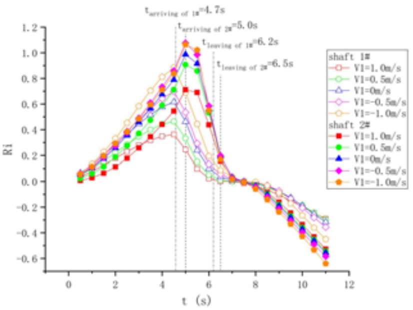


Fig. 10. Number *Ri* of two shafts in cases of *V1*

The values of number Ri with the variation of *V1* is shown in Fig.10, when *V1* is same to the direction of the vehicle, number *Ri* decreases as *V1* increasing (the maximum value reaching 1.0); when *V1* is opposite to the direction of vehicle, number *Ri* increase as *V1* increases.

6 Conclusions

In the real tunnel, the ambient wind speed inside and outside the tunnel is measured, with the range of 0-1.2m/s and 0-4m/s respectively. A physical model of a 210 m (length) * 12 m (width) * 6 m (height) tunnel with nine vehicles, three vehicles per lane, uniformly arranged, and a vehicle speed of 60 km/h was established to simulate the piston wind evolution caused by the vehicle motion. For a vertical shaft type naturally ventilated urban highway city road tunnel, this study uses a standard k- ε two-equation turbulence model in the Fluent software environment, and a dynamic grid technique to simulate vehicle motion. A total of 29 working conditions were simulated for the cases with ambient wind and it was found that:

(1) *V2* has little influence on the flow field changes in the tunnel and the shaft. That is, it has little influence on ventilation efficiency and backflow height.

(2) *V1* in the same direction as the vehicle will weaken the backflow effect, while *V1* in the opposite direction will enhance the backflow effect.

(3) The ventilation efficiency of the shaft will be decrease when the vehicle group passes through the shafts. *V1* in the opposite direction of the vehicles will improve the shaft ventilation efficiency (reaching 27%), while *V1* in the same direction will decrease the shaft ventilation efficiency.

(4) *V1* is same to the direction of the vehicle, number *Ri* decreases with the increase of *V1* (reaching 1.0); when *V1* is opposite to the direction of vehicle, number *Ri* increases as *V1* increase.

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