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Numerical investigation of unsteady airflow in subway influenced by piston effect based on dynamic mesh

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ABSTRACT

The piston effect has a significant influence on unsteady airflows in subway stations and tunnels. This study uses in situ experimental data and a computational fluid dynamics (CFD) method to analyze the three-dimensional unsteady air flow in a subway station and tunnel. An experimental analysis of train-induced unsteady flow was measured in an actual station with platform bailout doors (PBD), and air velocity variations were recorded at regular time intervals. The unsteady numerical analysis uses a dynamic mesh method for the full-scale model. The results indicate that Standard $k–\varepsilon$ and RNG $k–\varepsilon$ equations are both appropriate for simulating the high Reynolds numbers in tunnel and station airflow because these equations coincide with the experimental data. Specific diversion and suction ratios exist in each channel of the airflow for piston wind. The proportions between bypass ducts and platforms are stable no matter in open or close systems. And the draught relief shaft located before station plays more important role for piston wind than the one located after the station.

1. Introduction

With the rapid development of the subways, more people are paying attention to subway station environmental conditions, such as air temperature, humidity, air velocity, pressure, air quality and noise. Environmental Control Systems (ECS) in subway stations are responsible for delivering a comfortable and healthy station environment (Yuan and You, 2007; Wang and Li, 2007), but train-induced unsteady airflows in the subway tunnels have a great influence on the subway station environment.

Many researchers have focused on the issue of unsteady airflow. A theoretical research method was used by Wang et al. to study the piston effect (Wang et al., 2009). In addition, CFD technology has been widely utilized to analyze the airflow in subways. Haitao had validated the formation of piston wind by using FLUENT (Haitao, 2010). Kim and Kim employed PSD (Platform Screen Doors, which gets tunnels and platform apart) to carry out a numerical analysis of the effects of duct location on the ventilation performance in a subway tunnel (Kim and Kim, 2007, 2009). Lin et al. discovered that the length of the draught relief shaft is an important parameter for tunnel ventilation. Analysis using SES (Subway Environmental Simulation) produced results that agreed well with the measured values, but the sectional area of the draught relief shaft was not the factor for increasing the piston effects and effective air exchange (Lin et al., 2008). Juraeva et al. used CFX to locate better installation locations for tunnel air-curtains (Juraeva et al., 2011). Huang and Gao conducted a numerical study of the train-induced unsteady airflows in a subway tunnel with natural ventilation ducts using the dynamic layering method by FLUENT. And the numerical results from the RNG $k–\varepsilon$ model agree quite well with the experimental results (Huang and Gao, 2010). Then he revealed the duct number and duct geometry on duct ventilation performance in a subway tunnel (Huang et al., 2011). In 2012, he investigated numerically the characteristics of train-induced unsteady airflow in a subway tunnel in Seoul by using the Standard $k–\varepsilon$ model. And the results are closer to experimental results than those from Kim (Huang et al., 2012). However, the experimental data used for validating these numerical results were obtained by performing a 1/20 scale experiment. It is difficult to obtain the same Reynolds and Grashof numbers, which are necessary to achieve flow similarity between a small-scale experimental model and a complex actual subway station (Chen, 2009). Thus, in situ measurement data must also be used to validate the numerical models, especially CFD models.

In most cities of northern China, platforms typically have PBD (platform bailout doors) system, which leaves an area 0.5 m in height area where the air can flow between the tunnel and platform. When a train moves through the tunnel, a piston effect will form. The increasing pressure becomes a compression wave and the piston wind will propagate down to the next station (Ogawa and Fujii, 1997). Jia et al. performed numerical simulations of the flow characteristics in a subway tunnel and station (Jia et al.,

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2006, 2009). Ke et al. combined the SES program with the PHOENICS to carry out simulations for optimizing the design of a subway environmental control system (Ke et al., 2002). Numerical methods are useful in both investigating and validating the characteristics of train-induced unsteady airflows in subway tunnels with both ventilation ducts and PBD.

This study aims to measure and evaluate the effect of train-induced unsteady airflows in a subway tunnel on a subway station environment. In this paper, a full-scaled geometrical model of a subway station is created based on an existing subway station. A transient simulation of the process of subway trains pulling in and out of the station is carried out through CFD. We adopt two turbulence models to find the difference in simulating the high Reynolds numbers in tunnel and station airflow between them. The airflow measured in both the subway station and the related subway tunnel in the existing subway station could be used for validation of the CFD method. We can then study the diversion and suction ratios of the piston wind in the connections linking the tunnel, draught relief shaft and bypass duct. In this way, we lay foundation for the next step of analyzing the thermal field in subway.

2. Methods

2.1. Experimental method

2.1.1. Experimental setting

The underground stations of the Shenyang subway network adopt a close system (with draught relief shaft dampers closed) in winter and an open system (with draught relief shaft dampers open) in summer. This study conducted several field measurements for the Tai Yuanjie (TYJ) station while operation. The purpose was to investigate the ventilation influence of piston effects on the station exits and draught relief shafts. The field measurement results for TYJ station are presented in Section 2.2.4.

The TYJ station is in the middle of the line and represents a typical station. The net dimensions of the platform layer box are 114 m (*L*) 9.8 m (*W*) 5 m (*H*). The net dimension of the station hall layer (upstairs of the platform layer) box is 94 m (*L*) 17.3 m (*W*) 5 m (*H*). The track rail is 3.75 m wide in the station and 5.4 m wide in the tunnel. A Shenyang subway train has six cars with a total length of 118 m. The front area of the train is 8.82 m^2 (2.8 m wide, 3.15 m high). The inner diameter of the bored tunnel is 5.4 m, and the net area of the bored tunnel is 22.9 m^2. The TYJ station has two draught relief shafts. The dimensions of the relief shaft are 5 m (*H*) 5.2 m (*W*). The area of the external louvers for each shaft is 20 m^2. The bypass ducts under the draught relief shafts link the two tunnels, and balance the pressure as diversion channels. The dimensions of the bypass duct are 5 m (*H*) 5 m (*W*). The height of the PBD is 2.5 m, and the dimension of the exits depends on the engineering drawing. Fig. 1 shows the model of the entire TYJ station.

The dampers for the draught relief shafts were opened when the field measurements were conducted. The air velocity in the shaft and at the exits was measured using a high accuracy multi-functions TSI Q-Trak with a hot bulb type sensor capable of achieving ±0.02 m/s of accuracy. The air direction was verified by a slip of paper during the field measurements. The measurements were recorded at one second interval.

2.1.2. Test procedure

The distance from the tunnel damper to the external louver of the draught relief shaft is 82 m. Fig. 1 also shows the layout of shaft 1 and the location of measuring point 3. The measuring point was placed in a straight section of the shaft 30 m from the tunnel damper. The distance from the station hall layer to the exit is 65 m for both exits A and exit B. Measuring points 1 and 2 were placed in the flow path at 30 m from the exits, as shown in Fig. 1. These locations were chosen to avoid flow vortices near the corners and minimize unnecessary interference factors. The measurement setup is shown in Fig. 2.

Before collecting data, the station's environmental system was engaged for approximately 8 h to ensure a stable airflow and temperature distribution. Because this test concerns about the piston effect which is caused by the train, the computation will be divided into three parts according to the train's deceleration, stopping and acceleration. The time train stops in the station is defined as the arrival time, and the time when the train starts to move is defined as the departure time. All devices were calibrated before the test. Four groups were required to simultaneously record all the measurements: two groups operated at the exits A and B, one group worked in the draught relief shaft 1, and the other recorded the arrival time and departure time.

2.2. Numerical method

2.2.1. Presumptions

Because piston wind is the primary force of the air flow from the tunnel, the turbulence on the platform is transient and complex. Therefore, some presumptions must be made for quantitative analysis:

(1) In this simulation, we only consider a case where a train is running in one direction and there is no train arriving or departing in the other direction.
(2) The train's movement is the only factor affecting the flow field of the station, and the influences of mechanical ventilation and pedestrian behavior are not considered. This is because few pedestrian passed when measuring and they were 3 m away from the instruments. The force of ventilation in the hall also depends mainly on piston effect when train decelerates and accelerates.
(3) To ensure the efficiency and reduce the huge computational time, the train remains stopped in the simulation only lasts for 8 s, which is convergence and sufficient to stabilize the airflow. In fact the stopping time lasts more than 1 min in the test (the test data are constant enough, and we cut off the data from the stopping time as shown in Fig. 3).

2.2.2. Numerical model

This study adopted FLUENT6.3.26 to calculate velocity and pressure while the train is moving. Some researchers used continuity equation, Reynolds-averaged Navier–Stokes (RANS) equations with standard k–ε turbulence model (Kim and Kim, 2007, 2009; Huang et al., 2012; Jia et al., 2006; Ke et al., 2002) to predict the airflow. And some other researchers used renormalization group k–ε (RNG k–ε) turbulence model (Haitao, 2010; Huang and Gao, 2010; Huang et al., 2011) for prediction. The corresponding governing transport equations for the k–ε turbulence model can be generalized as Eq. (1):

$$\frac{\partial(\rho\Phi)}{\partial t} + div\left(\rho\,\vec{u}\,\Phi - \Gamma_{\Phi,eff}\,grad(\Phi)\right) = S_\Phi \tag{1}$$

where ϕ represents the time averaged velocity components $\vec{u}$, k the turbulent kinetic energy and ε the dissipation rate of turbulent kinetic energy. ρ is molecular density, Γ is the diffusion coefficient, and S_Φ is the source term of Φ .The difference between two mathematical models is ε equation.

$$\rho\frac{\partial\varepsilon}{\partial t} = \frac{\partial}{\partial x_i}\left(X\frac{\partial\varepsilon}{\partial x_i}\right) + G_{1\varepsilon}\frac{\varepsilon}{\kappa}(G_{3\varepsilon} + G_\kappa G_b) - G_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa} - R \tag{2}$$