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Train-induced unsteady airflow effect analysis on a subway station using field experiments and numerical modelling

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ABSTRACT

In recent years, subway systems (rail transit) have become an increasingly significant means of urban transportation. Platform screen doors (PSDs) can play an important role in enhancing the thermal environment in subway stations. However, train-induced unsteady airflow results in unorganised ventilation at the entrances (supplying fresh air and causing heat exchange) and air infiltration at the PSDs (causing heat exchange) in subway stations with PSDs. In the present study, field experiments (in Xi'an, China) and numerical modelling were conducted to investigate the rate of air inflow at the entrances and the PSDs of subways. The accuracy of the model was verified using the results from field experiments. In addition, the effects of various factors such as the traffic density, the piston vent shaft at the station downstream location (PVSASDL), and the season were analysed. The simulation results showed that turning on the PVSASDL could reduce the rate of air inflow at the entrances to 29.2–93.8%, while that at the PSDs could be enhanced to 121.8–126.3% under different traffic densities. In addition, to explore appropriate control of the PVSASDL in winter, different outdoor temperatures were simulated for a traffic density of 12 pairs/hour. It was found that the temperature in the station could meet the standard requirements when outdoor temperatures were greater higher than −5 °C with either open or closed PVSASDL conditions.

1. Introduction

As an important means of urban transportation, subways (rail transit) have developed rapidly owing to their advantages of convenience, speed, and punctuality. Nevertheless, the large number of passengers and existence of long narrow tunnels have resulted in various factors such as security issues, passenger comfort, and the energy consumption of subway stations attracting significant research attention. Some studies have reported that the energy consumption for non-traction requirements is of the same magnitude as that for moving rolling stock [1]. Furthermore, more than 70% of the non-traction energy consumption is attributed to environmental control systems in subway stations, of which the ventilation system consumes more than 75% of the energy [2,3]. Based on these statistics, research on energy conservation mechanisms for ventilation systems in subway stations is quite important.

Based on intense research, a Platform Screen Door (PSD) system has been suggested as a novel technology. PSDs are typically constructed of glass and a stainless steel or aluminium framework and can separate the platform area from the tunnel area (see Fig. 1) [4]. PSDs reduce the flow of warm air from the tunnel into the platform in the summer, thereby reducing the energy consumption of the air-conditioning system. PSDs also protect passengers and objects from falling onto the track [4]. As a result, PSD systems are increasingly being installed in subway stations across the globe.

Although PSDs are installed to reach from the platform floor to the ceiling, the inherent design of the doors is not completely airtight [5]. There are gaps along the sliding door rails and at the joints between the PSDs and the ceiling. In addition, the sliding doors open when the train stops at the station to let passengers get on and off the train. Therefore, PSDs cannot completely eliminate heat and mass transfer between the tunnel and the platform areas. However, the airflow through PSDs has some positive effects. One problem is that the air temperature in subway stations can become too low for passenger comfort in the northern cities of China during the winter. As the train brakes near the subway station generate a large amount of heat, the resulting warm air infiltrating the platform from the tunnel area may be beneficial to achieve the designed conditions of the subway station in winter. Therefore, research on the use of heat produced by the brakes on the train in winter is of significance [6,7]. In addition, the airflow through PSDs

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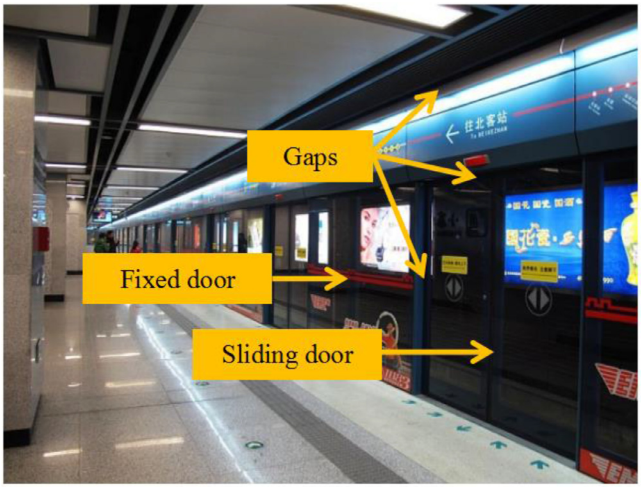

Fig. 1. Platform Screen Doors (PSDs) in a subway station.

induces a large amount of unorganised ventilation at the station entrances [5]. This unorganised ventilation at the station entrances supplies fresh air to the station, and thus it can reduce the energy consumption of fresh air fans in subway stations. Therefore, analysing the rate of air infiltration (caused by the train-induced unsteady airflow) through the station entrances and the PSDs and investigating the factors that influence this airflow are also important.

So far, most of the investigations regarding PSDs in subway stations have focused on three areas. The first research area is related to the indoor air quality in subway stations, and the indoor air quality, occupant comfort, and new ventilation methods in subway stations have been explored [8–11]. The second research area focuses on tunnel ventilation and the smoke exhaust effect, which are strongly influenced by the train-induced unsteady airflow. Both experiments and numerical modelling have been carried out to analyse the features and effects of train-induced unsteady airflow on tunnel ventilation [12–16]. In addition, improved ventilation approaches with high-efficiency smoke exhaust have been proposed to ensure passenger safety [17–19]. The third research area concerns the thermal environment in subway stations. The air temperature and velocity in subway stations have been previously analysed [20,21]. The factors affecting the thermal environment in a subway station have also been investigated, and include the under-platform exhaust (UPE) system and the ventilation shaft [22,23]. However, there are few studies on the rate of airflow through the entrances and PSDs in a station along with the factors that influence that rate. In the literature, studies on the airflow through subway stations have generally been carried out with either mechanical ventilation or air-conditioning systems [20,24–27]. Additionally, air infiltration at PSDs is generally ignored when the PSDs are closed. Li reported a rate of air inflow at a station's entrances of 17.2 m^3/s, while the air leak rate at the PSDs was 29.2 m^3/s. These values were obtained when a train was present at the station with a mechanical fresh air rate of 11.8 m^3/s [20]. Gong proposed an air inflow rate through PSDs of 1.8 m^3/s, whereas the air leak rate at the PSDs was 23.9 m^3/s. These values were obtained for an exhaust air rate of the trackway exhaust fan of 45.0 m^3/s and a mechanical fresh air rate of 6.0 m^3/s [25]. Chen performed field tests on four subway stations with mechanical ventilation and reported that the air inflow rate at the station's entrances was approximately 20.0–30.0 m^3/s [26]. In these previous studies, analysis of the influencing factors and patterns of change in the airflow rate at station entrances and PSDs was rarely performed. In summary, previous studies have various limitations, and the role of unorganised ventilation in subway stations due to train-induced unsteady airflow has yet to be adequately investigated.

On-site tests in subway stations are generally carried out under limited conditions. However, numerical modelling can be used to carry out systematic analyses under various conditions. Three-dimensional (3D) numerical methods can simulate a subway station to obtain detailed information. However, these methods are difficult to apply to large-scale subway systems owing to the resulting large calculation time and computational costs [28]. One-dimensional (1D) numerical methods are suitable for modelling subway ventilation systems on the large scale of a subway line [14].

Therefore, this study aims to measure and evaluate the rate of air inflow at the entrances and PSDs of a subway station, caused by the train-induced unsteady airflow through the subway station PSDs. A one-dimensional subway network model is established using IDA Tunnel software to investigate the influence of various factors, such as traffic density, the piston vent shaft at the station downstream location (PVSASDL), and season. In addition, appropriate control of the PVSASDL in winter is also analysed.

2. Explanation of terms used in this study

2.1. Traffic density

Traffic density is generally defined as the number of trains passing through a certain section of a railway per unit time. For an island subway station, there are tunnels on both sides of the platform, through which trains travel in opposite directions. Therefore, in this case, the traffic density is generally described as one half of the number of trains passing through the subway station through the two tunnels in an hour. The unit used for traffic density is pair per hour (pair/hour).

2.2. Arrival time interval

As shown in Fig. 2, the arrival time interval represents the time between two consecutive trains arriving at the subway station from the two tunnels.

3. Methodology

3.1. Field experiments

3.1.1. Setting for the field experiments

The Xi'an subway station in China has adopted the PSD system. In this study, several field measurements were conducted at the BY station, which is a typical island station. Fig. 3 shows a model of the BY station. The testing points were located at the hall, platform, station entrances, and outdoors. These measurements were intended to explore the unorganised ventilation at the entrances and the air temperature in the subway station.

The dimensions of the occupied zone in the hall are 70.0 m (length) × 16.8 m (width) × 4.4 m (height), and the dimensions of the occupied zone on the platform are 113.0 m (length) × 9.6 m (width) × 4.5 m (height). Entrances (named B, C, and D) connect the station to the outdoor environment, and have lengths of 61.1 m, 54.7 m, and 47.8 m, respectively. The cross-sectional area of each entrance is 14.1 m^2. A piston vent shaft is located at each end of the station. The dimensions of each piston vent shaft are 12.6 m (width) × 4.7 m (height). The BY station also has two bypass ducts, which have dimensions of 5.0 m (width) × 5.0 m (height). The inner diameter of the bored tunnel is 5.4 m, and the net area of the bored tunnel is 20.6 m^2. A Xi'an subway train consists of six cars, and has a total length of 118 m. The area of the front of the train is 10.64 m^2, and it has dimensions of 2.8 m (width) × 3.8 m (height).