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Case study of train-induced airflow inside underground subway stations with simplified field test methods

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ABSTRACT

With the rapid development of subway construction in developing countries like China, energy conservation in subway stations is gaining popularity within society. Generally, ventilation and air-conditioning play important roles in the total energy consumption. As a major feature of subway stations, the train-induced airflow (TIA) driven by moving trains has been recognized for years, having a great influence on indoor environment and energy consumption. However, there is a lack of case study on real amount of train-induced airflow inside stations. In order to get extensive knowledge of the real situation, this paper proposes a set of simplified methods to measure and calculate train-induced airflow rates. Using these methods, field tests were conducted in several typical underground subway stations in China during the spring of 2016. This paper presents the basic situation of train-induced airflow in these stations and the influence of different ventilation modes. Based on the fact that there exists unneglectable amount of train-induced airflow, and considering the demand-supply analysis of fresh air, the potential for high levels of energy savings could be identified in the mechanical ventilation systems of these stations. These new findings are of great benefit for energy-efficient operation of existing stations.

1. Introduction

Till now, rail transit exists in approximately 330 cities of 50 countries worldwide, reaching tens of thousands of kilometers in length (Li, 2011). In recent years, subway construction is rapidly growing in China. Based on information till the end of 2014, there are 22 Chinese cities running 95 subway lines, with a total distance of 2933 km and 1947 subway stations (China Rail Transit, 2015). Moreover, the total distance is expected to reach 13000 km in the near future, according to development plans in the country.

On the other hand, the rapidly growing rail transit industry is also consuming more and more energy, which draws attention from society. According to official statistics (China Association of Metros, 2015; National Energy Administration, China, 2015), the rail transit system in China consumed 9.4 billion kWh of electricity in 2014, accounting for 1.7‰ of the total electricity consumption in the country. Therefore, energy savings of rail transit has become a crucial issue in China for the purpose of energy conservation and CO_2 emission reduction.

In terms of subway energy consumption, besides train traction, the environment control system (ECS) in subway stations is a major consumer, accounting for one- third to one-half of the total energy consumption of the subway (Li, 2011).

The subway stations in most parts of China are equipped with centralized ECSs for space cooling in summer, which usually includes chillers, pumps, cooling towers, supply air fans, return/exhaust air fans, fresh air fans, etc. This leads to more energy consumption and higher expenditure on the ECSs in Chinese subways (Anderson, Maxwell, & Harris, 2009; Casals, Gangolells, Forcada, Macarulla, & Giretti, 2014). Therefore, ECSs are crucial to subway energy savings in China.

Generally, the ECS of an underground subway station can be classified into two major types: platform screen doors (PSDs) system and non-platform screen doors (non-PSDs) system. For a station that has PSDs along its platform edge, the public area of the station, including the hall and platform, is separated from the tunnel by the screen doors. Thus, the public area has its own ECS, while the tunnel air is connected with outdoor air through the piston shafts at both ends of the station. On the other hand, for a station that has no screen doors, the ECS is responsible for both the public area and tunnel air, while the piston shafts are either closed or do not exist. The lack of PSDs makes it easier for the air to flow between the public area and the tunnel.

Besides mechanical ventilation in ECS, the train-induced airflow (TIA), is indispensable in subway station. As trains move in the underground tunnel, regular air movement is generated by the piston effect. The periodic TIA exists not only in the tunnel but also in the public area when there are no PSDs; thus, it has a strong influence on the indoor environment of non-PSD stations. Specifically, when a train

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Nomenclature

ECS	Environment control system
PSD	Platform screen door
TIA	Train-induced airflow
EEP	Entrance/exit passages
D	Damper
IFA	Infiltrated fresh air
ITA	Infiltrated tunnel air
NMIA	Net mechanical inward air
MFA	Mechanical fresh air
MEA	Mechanical exhaust air
IAT	Indoor air temperature
OAT	Outdoor air temperature
BJA, BJB, BJC, SHA, and SZA	Five typical stations in this study
$\dot{G}$	Airflow rate, m^3/s
V	Accumulative flowrate, m^3
V_0	Air volume of the EEP, m^3
ε	Hourly bypass factor

Subscript

A, B, C, D	Entrance/exit passages
τ	Serial numbers of the semi-cycles
f	Fresh air
in	Hourly inward airflow
s	Supply air of the mechanical ventilation system
r	Return air of the mechanical ventilation system
m	Net mechanical air

Superscript

+	Positive semi cycle
−	Negative semi-cycle

moves toward the station, the air in the tunnel will be partly pushed into the station, from the platform to the hall, and finally to the outside through the entrance/exit passages (EEPs). On the contrary, when a train leaves the station, the outdoor air will be sucked into the station through the EEPs, from the hall to the platform, and finally into the tunnel. The fluctuation period of TIA is decided by train movement and schedule, which is around 3 min and can be changed according to actual situation.

Apart from the discussion on ECS operation modes in many studies (Thirumal, Amirthagadeswaran, & Jayabal, 2014; Yuan & You, 2007; Zhu, Zhu, & Xiao-Feng, 2004), TIA has been a popular topic among researchers for many years. First, the flowrate and pressure of the airflow in the tunnel was the focus of many studies through field tests, simulations, or wind tunnel experiments (Huang, Hong, & Kim, 2012; Kim & Kim, 2007). Both field model and network model were adopted to simulate the distribution and variation pattern of the wind speed and temperature and to analyze the influential factors of the TIA in the tunnel (Ke, Cheng, & Wang, 2002; Li, 2011; Lin, Chuah, & Liu, 2008; Xue et al., 2014). Using the SES (Subway Environmental Simulation) software, Wang et al. (2011) developed the network model of a station in Shanghai and found the blockage ratio and speed of the train had a significant influence on the piston airflow speed. Furthermore, some studies have indicated that the TIA had a significant influence on indoor environment and energy consumption of ECSs and tried to identify methods for alleviating the negative effects and recommendations for future design and operation (Guang, 2006; Li, 2011). Wang et al. (2017) established a simulation method to predict CO_2 concentration in a subway with PSDs and conducted field tests to verify the simulation results.

Besides the non-PSD station, local air infiltration of PSDs is also discussed in some research investigations (Xiang, 2007; Zhang et al., 2013). To monitor the TIA inside stations, Di Perna, Carbonari, Ansuini, and Casals (2014) proposed a series of methods, including field tests of air speed and pressure in EEPs as well as simulation methods; however, there were few applications or further analysis of the airflow pattern in actual stations.

Since PSD systems are gaining popularity in newly built stations, many researchers have tried to compare PSD stations and non-PSD stations in terms of the indoor environment and energy consumption. As PSDs separate the public area from the tunnel, one of their advantages is that they reduce the heat gain from tunnel in cooling season, while one disadvantage is that a high level of mechanical ventilation is required in non-cooling season. Some studies have proven that PSD systems are more appropriate for stations in regions having hot and humid climates, while others held different opinions (Ding, Zhu, Ye, & Bu, 2006; Feng, 2002; Hu & Lee, 2004; Hu, Zhao, Li, Guo, & Deng, 2015).

However, there are still some key points that have been overlooked in previous research. Firstly, owing to the difficulty of conducting field tests in operating stations, the TIA rate is usually obtained by simulation tools or wind tunnel experiments; thus, there is a lack of empirical results obtained from actual stations. Next, attention was paid to air movement in the tunnel, and the TIA in the public area was largely ignored. More importantly, although the TIA inside non-PSD stations has been well studied, attentions should be payed that TIA also exists in PSD stations owing to the regular opening of PSDs when trains stop and different levels of PSD leakage. Combined with mechanical ventilation, some stations could potentially have an extra amount of fresh air during operation. Finally, even though the infiltrated air is recognized, there is still a lack of discussions on how to take advantage of its benefits and avoid its negative impacts under different conditions, which are crucial to the energy efficient operation of the ECS. Therefore, this industry and research field are in desperate need of a practical method of measuring the actual amounts and basic patterns of TIA in real stations, especially in PSD stations.

Based on the above discussion, this study attempts to elucidate the pattern of TIA inside subway stations, particularly PSD stations, with a set of simplified methods for measuring and calculating the airflow rate and then to come up with some useful recommendations for ECS operation. The second section of this paper introduces the mechanical ventilation system of a typical subway station. The third section carefully describes the simplified methods used to conduct field tests and the corresponding calculations. The forth section shows the main results from the field tests in several typical underground subway stations in China during the spring of 2016. Here, the basic patterns of TIA are presented for these stations, the influence of different ventilation modes is analyzed, and the difference between PSD stations and non-PSD stations are investigated. Based on these facts and the demand-supply analysis of fresh air, an energy efficient ventilation mode is discussed preliminarily. The last section concludes the major findings in this study, which are expected to benefit energy efficient operation of the existing stations and help enable a better design of future stations.

2. Ventilation system

Fig. 1 shows the mechanical ventilation system for the public area of a typical subway station. Since the station and the system are symmetrical, the other half is omitted in this figure. Generally there are two major ventilation modes in a typical underground subway station. In cooling season, when the chillers are running, the mechanical fans are operated at minimum-fresh-air mode: supply air fans, return/exhaust air fans, and fresh air fans running; minimum-fresh-air damper (D1)