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Performance investigation of outdoor air supply and indoor environment related to energy consumption in two subway stations

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ABSTRACT

On-site measurements of the outdoor air supply and indoor environment in the public area (hall and platform) in two subway stations have been conducted in cooling season in this study. The result revealed that the outdoor air intake through entrances was enormous and played an important role in outdoor air supply. Influencing factors have been discussed and negative effects of mechanical outdoor air supply and train interval are revealed. The total outdoor air involved in by both infiltration and mechanical ventilation was far greater than the demand of occupants in public area under the normal condition, with indoor CO_2 concentration only 399 ~ 670 ppm. Return air alone (RAA) condition for ventilation with no mechanical outdoor air supply was then proposed, utilizing the air infiltration through entrances to meet outdoor air demand and reduce the cooling load in public area. Under the proposed condition, similar indoor thermal performance could be realized, and enough outdoor air could be supplied through entrances even for expected maximum passengers. Electricity consumption of VAC systems reduced by 10% ~ 20% compared with the normal operation condition in cooling season.

1. Introduction

Rail transit is a kind of important urban infrastructure and it has been in a fast development driven by the rapid urbanization in China. There have been more than 30 cities with established subway systems in China by the end of 2016, and the total route length has been over 4000 km (China Association of Subways, 2016). Ventilation and air-conditioning (VAC) systems are important sections to guarantee the normal operation of a subway station. Electricity consumed by VAC systems may account for 30% ~ 50% of the total energy consumption, even higher than the energy for train traction in some cities (Anderson, Maxwell, & Harris, 2009). Therefore, improving the performance of VAC systems is a key issue for energy conversation in subway stations.

Entrances in subway stations are connections between the station and outdoor environment. Outdoor air could be involved in the station either by mechanical ventilation system or by infiltration through entrances. Indoor CO_2 concentration could be a visual indicator reflecting the outdoor air intake and mechanical ventilation rate, which has been concerned in lots of standards. The limit 1000 ppm has been set in Korea by the Korea Ministry of Environment (ECOREA, 2015) and 1500 ppm in China (GB 50157, 2013). It has been revealed that there are close links between indoor CO_2 level and passenger volume in subway stations (Cheng & Yan 2011). The on-site measured CO_2 concentration in public area of subway stations has been revealed ranging from 383 to 832 ppm in different stations in Seoul (Bong, Kim, Song, Oh, & Kim, 2013; Hong and Kim, 2014; Kim et al., 2016), whereas 391–561 ppm in Barcelona (Moreno et al., 2014), 427–919 ppm in Taipei (Chen, Sung, Chen, Mao, & Lu, 2016) and 390–905 ppm in Beijing (Wang, Feng, & Xi, 2017). There is usually excessive outdoor air provided in subway stations, leading to a low CO_2 concentration level, compared with guidelines. Besides indicator CO_2, description of air volume is direct to characterize ventilation between indoor and outdoor in a subway station. Some studies have used computational fluid dynamic (CFD) to simulate the velocity and pressure distribution in the subway station when a train passing (Jia, Huang, & Li, 2006; Wang & Li, 2007). However, there have been limited on-site measurements conducted to quantitatively estimate the ventilation, especially outdoor air intake through entrances (Perna, Carbonari, Ansuini, & Casals, 2014; Wang & Li, 2017).

Some studies have focused on key parts of VAC systems and investigated the effectiveness of different designs for ventilation, such as the setting of platform screen doors (Han, Lee, & Jang, 2015; Zhang, Gong, Kang, & Han, 2011; Zhong, Yang, Pei, & Niu, 2011; Zhu et al., 2016), ventilation shafts (Kim & Kim, 2009; Lin, Chuah, & Liu, 2008) and under platform exhausts (Ke, Cheng, & Wang, 2002). In the design stage, Hu and Lee (2004) and Cao, You, and Dong, (2009) have demonstrated that platform screen doors affect the energy consumption of the VAC systems obviously. Effect of other designs like the number of

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Nomenclature

AHU	Air handling unit
C_{out}	Outdoor CO_2 concentration (ppm)
C_{∞}	Indoor equilibrium CO_2 concentration (ppm)
CFD	Computational Fluid Dynamic
G	Outdoor air supply per person (m^3/h)
$\dot{m}$	CO_2 generation rate of the body (g/h)
N_{en}	Passenger number flowing into the station
N_{ex}	Passenger number leaving the station
N_s	Staff number in public area
P	Statistical significance
PM	Particulate matter
Q_D	Total outdoor air demand of occupants in public area of the station (m^3/h)
q_D	Outdoor air demand per person (m^3/h)
RAA	Return air alone
RH	Relative humidity
VAC	Ventilation and air-conditioning

Greek symbols

A	Confidence level
P	Air density (g/m^3)
τ_{en}	Average dwell time for entry (s)
τ_{ex}	Average dwell time for exit (s)

entrances on energy consumption have also been analyzed by Hong and Kim (2014). As for performance of VAC operation strategy, Domingo et al. (2011) has applied five different VAC strategies to determine the best one to control pollutant concentration and thermal comfort. Different design solutions and operation strategies directly influence the energy consumption of the subway station, and it has been declared in previous studies (Zhang et al., 2017; Yang, 2018).

Most of the current researches have focused on controlling indoor CO_2 concentration to ensure enough outdoor air intake into the subway station. However, there have been limited on-site measurements about the actual outdoor air flow rate, especially the outdoor air flow rate through entrances. In the present research, monitoring devices will be deployed in two subway stations to describe the outdoor air flow rate by air infiltration and mechanical ventilation respectively. Volumes of outdoor air intake through entrances in normal ventilation condition and return air alone (RAA) condition (without mechanical outdoor air supply) will be compared, and the influencing factors of the outdoor air intake will be discussed. Indoor thermal environment, CO_2 concentration, particle concentration as well as energy consumption of VAC systems will be tested under different ventilation conditions to prove the feasibility of the RAA condition. It's hoped that the present investigation will be beneficial to optimize the ventilation strategy and energy conservation in subway stations.

2. Station information and methodology

2.1. Station information

Line 1 and Line 2 are two main subway lines in a city, located in the middle of the Yangtze River Delta in hot summer and cold winter zone in China. 86% of the 73 stations in Line 1 and Line 2 are underground without transfer function, and platform screen doors are installed in all these underground non-transfer stations. In order to find a station that was representative of all these stations, an analysis of the main characteristics was conducted, in terms of annual passengers and main physical characterization parameters. The analysis revealed two stations with typical values, shown in Table 1a and b. In light of their representativeness, Station A and Station B were selected as case study stations for the on-site measurement.

Station A and Station B have been coming into service since December 2013 and April 2017 respectively. Either of the two monitored subway stations is a 2-layers underground non-transfer station with platform screen doors, served by double tracks with an island platform. Sketch of the public area (platform and hall) in these two stations is depicted as Fig. 1. Two trains run underground in opposite directions, at a depth of 15 m below the ground surface. The hall and platform of Station A cover an area of 2239 m^2 with four entrances. And station B is about twice as large as Station A with two entrances. As for the tunnel ventilation system, double piston air shafts are used at both ends of the station. Air shafts are turned into natural ventilation mode when the station in the normal operation condition in cooling season, with the trackway exhaust system never used. And there are no bypass ducts installed in both stations.

2.2. Measurement methodology

2.2.1. Measurements of outdoor air supply

On-site measurements in Station A was from July 1st to July 7th, while the measurements in Station B from July 17th to 23rd in 2017. Outdoor air is involved into the station both by mechanical ventilation and by infiltration through entrances. The measurement of outdoor air flowrate by mechanical ventilation is relatively simple. The air speed in the outdoor air duct was measured at a fixed frequency of the outdoor air fan. And the outdoor air flowrate was obtained according to the air speed and the size of the duct.

As for air infiltration, air velocity and flow direction measurements were carried out at entrances in both stations. Wind parameters were tested with a high frequency (every 5 s) for 3 h every day, i.e. 7:30–8:30, 11:30–12:30 and 17:30–18:30. Nine measuring points were performed in the intersecting surface of every entrance to describe the air velocity distribution. And the positions of anemometers in entrance 1# are depicted in Fig. 2. In order to guarantee the effective traffic capacity of entrances, a single device for air velocity and flow direction

Table 1
a) Selection of the sample underground non-transfer station in Line 1. b) Selection of the sample underground non-transfer station in Line 2.

(a)

	Line 1			Case study
	Mean	Lower quartile	Upper quartile	Station A
Annual passengers (million)	1.0	0.3	3	1.6
Hall floor area (m^2)	1969	1356	2407	1454
Platform floor area (m^2)	934	635	1489	785
Number of layers	2	2	2	2
Number of entrances	4	3	5	4

(b)

	Line 2			Case study
	Mean	Lower quartile	Upper quartile	Station B
Annual passengers (million)	1.3	0.5	3.1	2.5
Hall floor area (m^2)	2108	1446	3105	3070
Platform floor area (m^2)	1024	795	1566	1467
Number of layers	2	2	2	2
Number of entrances	4	3	5	2

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