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Analyses of the improvement of subway station thermal environment in northern severe cold regions

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ABSTRACT

Currently, subway lines are being increasingly constructed in the northern severe cold regions of China. The average ambient temperature in this region is below −10 °C during winter. Therefore, the extreme climate and piston effect impose challenges for designers for enhancing the thermal environment of a metro station in severe cold season. In this study, one-dimensional modelling is developed using the IDA Simulation Environment (IDA) based on an actual metro line, and the results are validated by experimental data. Moreover, the thermal environment of a typical metro station in the control group, two traditional optimisation measures, and one new method are investigated in severe cold regions. The results indicate that the primary heat loss during winter is attributed to the cold air invasion caused by the piston effect from the entrances. The addition of a warm-air curtain individually at the entrance may not effectively prevent the intrusion of cold air. Furthermore, adding a door curtain can reduce the inlet air volume of the entrance, but reduce the outlet air volume of the entrance. Thus, the heat of the train brake cannot be effectively utilised to improve the station temperature. In addition, one new method using the piston wind principle was presented, and it can effectively prevent the cold wind and more effectively utilise the train braking energy to improve the temperature of the metro station. It serves as a guideline for subway environmental control system (ECS) design.

1. Introduction

For decades, the regional landscape of China has been urbanised to a major extent. Thus, subway projects have developed rapidly during this period. More than 32 cities of mainland China established subway lines by the end of 2017, including a total length 3168.7 km [1]. Most of the subway lines are built in regions with an average air temperature in winter ranging from −10 °C to 10 °C. However, in recent years, an increased number of subway lines without heating systems have been built in the northern severe cold regions, where the average ambient temperature is below −10 °C during winter [2,3]. If the air temperature in the subway station and tunnel is extremely low, it becomes uncomfortable for the passengers. Additionally, the hazardousness of the freezing equipment and water pipes is increased, thus affecting the regular operation of the subway line. Hence, improving the thermal environment of subway stations in northern severe cold regions has received intense attention, and effective measures have been considered in recent years.

As a train moves through a tunnel, the piston effect occurs, which refers to the strong airflow brought via the rapid movement of the train in the tunnel [4]. Many research studies have investigated the piston effect, which is an important characteristic for metro environmental control systems. Wang [5] established a theoretical method to study the piston effect. Kim [6] implemented a numerical analysis of the effects of duct location on the ventilation performance in a subway tunnel. In addition, scaled experimental models [7,8] were also established to investigate the pressure variations and unsteady tunnel flow during the train movement. González [9] employed numerical modelling to analyse the effect of the piston effect in the longitudinal ventilation system of metro tunnels.

Piston effect has a significant effect on the environment of a subway station. Yuan and Xue [10,11] applied computational fluid dynamics (CFD) to analyse the effect of piston wind on a metro station environment. Liu and Lee [12,13] concentrated on the improvement of the indoor air quality (IAQ) and decrease in the energy consumption using ventilation control strategies at a metro station. Furthermore, numerous studies [14–16] have been conducted on the optimisation of the environmental control system design for metro stations. The results

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Nomenclature

u	Velocity vector (m/s)
P	Static pressure (Pa)
ϑ	Kinematic viscosity (m^2/s)
S	Source terms (W/m^3)
μ	Air viscosity ($kg/(m{\cdot}s)$)
k	Thermal conductivity ($W/(m{\cdot}°C)$
f_x	Body force (m/s^2)
Q_{in}	Energy of entering the control body (W)
Q_{out}	Energy leaving the control body (W)
Qin_{PBD}	Heat flow from the tunnel to the station (W)
Qin_{en}	Heat flow from the entrance to the station (W)
Q_{eq}	Heat from the equipment (W)
Q_{occ}	Heat from the occupants (W)
Q_{siol}	Heat exchange through soil (W)
$Qout_{en}$	Heat leaving through the entrance (W)
$Qout_{PBD}$	Heat leaving through the PBD (W)
c_p	Specific heat of air ($J/kg{\cdot}°C$)
T	Temperature (°C)
t	Time (s)
V	Volume of the station (m^3)
ΔP	Pressure difference with respect to the atmospheric level (Pa)
G_{in}	Inlet air volume through the entrance (m^3)
G_{out}	Outlet air volume through the entrance (m^3)
dE	Increment of energy in the control body (W)
ζ	Local resistance coefficient
Q	Heat (W)
υ	Velocity (m/s)
α	Opening angle of the door curtain (°)
θ	Opening angle of small pieces of the door curtain (°)
M	Weight (kg)
g	Acceleration of gravity (m/s^2)
S	Area of door curtain (m^2)
ρ	Air density (kg/m^3)
v_{iin}	Inlet velocity of the $i-th$ entrance (m/s)
A_i	Area of the $i-th$ entrance (m^2)
MBE	Mean bias error
E_i	Value of test
S_i	Value of simulation
N	Total number of tests and simulations
L	Length (m)
W	Width (m)
H	Height (m)

indicated that the piston ventilation shafts position, train velocity, and type of platform edge door (PED) had remarkable effects on the subway environment.

Significant heat is generated when a train begins to accelerate and brake, which comprises approximately 70% of the air-conditioning cooling load at a metro station during summer. To save energy, numerous studies focused on systems for converting the kinetic energy into electrical energy, which are called regenerative braking systems (RBSs). An RBS can reach up to more than 30% of the traction energy and it has been widely introduced in the metro lines in China [17–19]. Few studies concentrated on directly using the braking heat to improve the station thermal environment. Zhang [20] employed experimental and numerical methods to study the more efficient use of the braking heat to improve the temperature of the metro station. However, the hall and platform average temperatures were only increased by 0.21–1.3 °C by using a distinct ventilation mode when the outdoor temperature was −5.4 °C.

With the development of numerical modelling, the dynamic mesh technology of CFD is being widely used in the research on the thermal environment and unsteady airflow at metro stations. Based on a dynamic mesh, Peng [11] employed a CFD model to study whether the unsteady airflow at a subway was affected by the piston effect. Fernando [21] established a CFD model to build a complex station set to analyse the subway airflow. Marta [9] also used a CFD model to simulate and analyse the flow patterns in longitudinal ventilation systems in detail. Using a dynamic layering method, Huang [22] developed the train-induced unsteady airflows in a subway tunnel with natural ventilation ducts through numerical simulations. However, subway stations and their ventilation and air-conditioning systems are highly complex, and the dynamic mesh method requires excellent computer performance and a long computing time. Generally, dynamic mesh method-based research practically constructs a single model of the metro station. As such, the pre-tunnel and post-tunnel interference effects of a train are not considered. Literally, a single metro line includes many subway stations, whereas the trains come through the station sequentially. One-dimensional numerical modelling has the advantages of simple modelling and a short computing time. Previous research using a 1D model was capable of considering directly the problems related to subway piston wind [9,23,24]. Therefore, 1D numerical modelling can manage an entire subway line and establish a combined solution.

Although numerous researchers have investigated the piston effect and analysed the effect of the piston wind on the metro station environment, most of these focussed on the metro station IAQ and thermal environment during the summer and transition seasons, whereas the focus on the severe cold winter conditions was limited [16]. Furthermore, the heat generated by the braking of the train can provide a gratis heat for the metro station during winter, particularly in a severe cold winter. The current research aims to directly use the braking heat to improve the thermal environment in metro stations in the northern severe cold regions in China. In this work, a 1D numerical model was created based on an actual metro line, and the simulation results were demonstrated by the field measured data. Subsequently, the verification model was employed to analyse the effectiveness of the passive improvement of the subway station thermal environment by using the train breaking heat in the northern severe cold regions.

2. Modelling and experimental verification

2.1. 1D modelling

A metro line model with seven underground platform screen door (PSD) metro stations is constructed based on the actual metro line information using the IDA [25]. The total length of the line is 11.28 km. Fig. 1 illustrates the line information concerning the tunnel length and a typical station of the subway line. The typical station is a double-decker island station, with a hall size of 75.5 m (L) × 16.8 m (W) × 4.4 m (H), and the platform size is 114 m (L) × 10 m (W) × 4.5 m (H). Four entrances are connected to the station hall floor. Each entry includes one abrupt contraction, abrupt expansion, and rectangular elbow. In the1D model, the resistance components, such as the stairs, entrances, and vent shafts are computed based on the experiential values provided in the relevant literature. The total local resistance coefficient of the entrances is 6.15 [26,27]. A schematic of the three-dimensional (3D) model is presented in Fig. 1. The train type is type B, with a size of 117 m (L) × 2.8 m (W) × 3.8 m (H) according to the actual metro line information. The front area of the train is 10.64 m^2, and the total mass of the train is 215000 kg. The regenerative braking efficiency (RBE) of the train is approximately 38%. More detailed parameters are included in Table 1.

The PSD remains closed until the immobilisation of the train at the