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REVIEW OF PASSIVE STRATEGIES FOR VENTILATION AND AIR-CONDITIONING ENERGY SAVING IN UNDERGROUND METRO STATIONS

Yanzhe Yu[1,2], Shijun You[1,2], Huan Zhang[1,2], Tianzhen Ye[1,2*] Xuejing Zheng[1], Yaran Wang[1]
1 School of Environmental Science and Engineering, Tianjin University, Tianjin 300350, China
2 National Engineering Laboratory for Digital Construction and Evaluation Technology of Urban Rail Transit, Tianjin 300072, China
* Corresponding author. Email address: tzhye@tju.edu.cn.

ABSTRACT

This paper presented an overview of the passive strategies for ventilation and air-conditioning energy saving in underground metro stations. The strategies were relevant to building envelopes, piston effect and natural cold sources. This review found that the building envelopes had made minimal contribution to the research literature and might not be applicable to the underground stations. The piston effect was the most popular passive strategy in research community for its great energy saving potential. The ground cooling strategy was another promising option for air-conditioning energy saving but it was often overlooked due to its high R&D costs. The authors hope that this study can promote the adoption of different passive strategies for the ventilation and air-conditioning energy conservation in underground metro station buildings.

Keywords: Underground; Metro station; Energy-saving; Passive strategies; Ventilation; Air-conditioning

1. INTRODUCTION

To build a safe, hygiene and comfortable underground environment, ventilation and air-conditioning (VAC) systems are used in metro stations and found to be high energy-consuming [1,2]. In fact, the VAC systems have become one of the largest energy consumers for non-traction usage in metro stations, especially in Asia cities, which usually accounted for 30%-50% of the total energy consumption [3,4]. For instance, the energy consumption of VAC systems in Beijing metro networks was approximately 490 million kWh in 2015, which was equivalent to the electricity consumed by 255,500 families in one year [5]. Another study reported that the ventilation electricity consumption of one of the oldest underground metro stations in Barcelona was 85.62 MWh /year [6] .Furthermore, as the expansion of metro networks over the world, it is essential to develop flexible strategies to reduce the VAC energy consumption in metro stations.

Over the past few decades, passive energy saving strategies, such as advanced building envelops, passive cooling and thermal energy storage, have been the preferred technologies in energy-efficient buildings design because of their eco-friendliness and cost saving. Until now, some strategies have been introduced in underground metro station, which is one special type of the underground buildings. However, there remains a gap in the existing work on comprehensive study that describes and compares the passive strategies used in underground metro systems.

This paper intended to present an overview of the passive strategies used in the underground metro stations and demonstrate their performance in the energy saving of the VAC systems. Various passive strategies in different configurations and mechanical designs were discussed. For each strategy, a brief description was firstly presented and then the influence of the method on VAC energy saving was investigated. Finally, a statistical analysis on these approaches was carried out.

2. OVERVIEW OF PASSIVE STRATEGIES FOR VAC ENERGY SAVING IN UNDERGROUND METRO STATIONS

The implementation of passive strategies is a fundamental way to improve building energy efficiency. Following the classification used in aboveground buildings, we discussed the passive strategies in

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underground metro stations relevant to building envelopes, piston effect and natural cold sources, and conducted literature review (a total of 59 articles) in the past two decades in major English language journals.

2.1 Building envelope

The envelope of underground metro stations is made up by concrete and shotcrete, and the heat transfer through the envelope is different from the aboveground buildings, which can be ascribed to the prominent heat gain and the heat sink effect. As the indoor air in the station is significantly heated (approximately 8-12 ℃ above the outdoor air [7]) by tremendous heat gain during station operation, the heat transfer direction through the building envelop is from station to the earth in summer daytime, which is opposite from aboveground buildings (outside environment to indoor air). Specifically, the metro structure and surrounding earth have a moderate effect on metro air temperature variation because the temperature of the earth is almost stable. As metro air temperature rises, heat is transferred from station air into tunnel and station walls, tending to reduce the magnitude of the temperature rise, and vice versa. This phenomenon has come to be known as the heat sink effect [7,8].

A study conducted by Alkaff et al. [9] pointed out that the earth is a very capacitor to store heat and moderate heat at different meteorological conditions as shown in Fig. 1 [10]. The thermal energy performance criteria used in underground buildings design include design typology, earth depth, earth thermal properties, insulation and ventilation system. Furthermore, Liu et al. [11] calculated the cooling load in underground metro stations by using various earth thermal properties and conducted the sensitivity analysis. They found that the cooling load changes between 0.5% and 1.5% with variation of the earth thermal conductivity and heat capacity within ±20%, respectively.

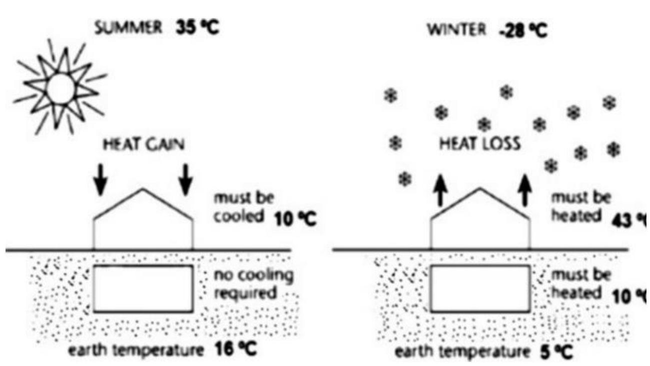

Fig. 1. Earth as heat capacitor which absorbs heat during summer and released heat during winter [10].

In the context of insulation, Shi et al. [12] investigated the influence of thermal performance of envelopes on energy consumption in underground buildings in different climate zones of China. The results indicated that the relationship between the energy consumption and the thermal transmittances of envelopes for underground buildings is different with those for aboveground buildings. Improving thermal performance of exterior walls cannot reduce energy consumption, which may result in more energy costs contrarily. Staniec and Nowak [13] simulated the cooling energy demand of underground buildings with different thermal insulation thicknesses, and suggested that thinner thermal insulation results in better cooling effect gained from soil.

2.2 Piston effect

The piston effect refers to the effect of a moving train on the air in a tunnel, analogous to a piston pushing air ahead as it moves through a cylinder. Fig. 2 shows the impact of the piston effect on the airflow of an island-type station. When a train enters a station, positive pressure in front of the train pushes the air in the tunnel flow into the platform, which is then exhausted to the outdoors. When the train leaves the station, the negative pressure behind the train sucks outdoor air into the tunnel in the opposite direction. The piston effect can exhaust air from the tunnel to outside and introduce fresh air into the station, resulting in a “cross ventilation” effect, which usually occurs in aboveground buildings [14].

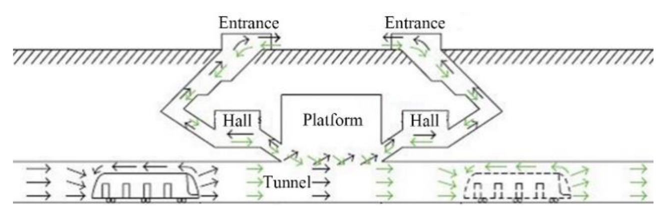

Fig. 2. Air flow schematic of the piston effect in an island-type station [14].

Recently, numerous investigations have proven that the piston wind has obvious impact on the energy consumption of metro VAC system. For instance, Yang et al. [15] developed a set of methods to measure the airflow rate generated by piston effect in the station and found that the fresh air induced by train movement might always keep the CO_2 concentration in an appropriate range. Thus, the mechanical ventilating energy will be saved though reasonable operation mode. Furthermore, Guan et al. [16] proposed a return air alone condition (the outdoor air fan is switched off, with V3 on, V1 and V2 off, as illustrated in Fig. 3.) for ventilation with no mechanical outdoor air supply, utilizing the air infiltration through the entrances to meet the fresh air demand and reduce the cooling load in public area. Under the proposed condition, electricity consumption of the VAC systems in cooling season could be declined by 10%-20% compared with the normal operation condition. Similarly, Krasyuk [17] calculated the tunnel fan capacity of shallow subways and revealed that the piston effect allowed effective ventilation of subways without switching on the fans at the outdoor air temperature lower than 8 ℃ in Russia.

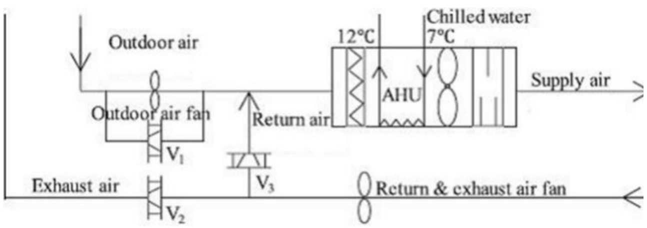

Fig. 3. Air flow pattern in VAC systems under the normal condition [16]. (Outdoor air fan is switched on, with V3 on, V1 and V2 off)

2.2.1 Platform door

In order to take advantage of the piston effect, some studies focus on the optimization of equipment, such as the platform door, ventilation shaft and door curtain. Nowadays, the platform screen doors (PSDs) are widely used in underground stations in Asia. When PSDs are used, heat inside the tunnel is kept away from platform effectively, reducing the air-conditioning energy consumption in cooling seasons [18]. However, in non-cooling seasons, the piston wind cannot be utilized and air ventilation will be ineffective without using proper mechanical equipment, which will increase station energy consumption. Zhang et al. [19,20] proposed an innovative platform door with controllable vents (the adjustable ventilation platform doors, AVPDs), as shown in Fig. 4, and used experimental measurement and computational fluid dynamics (CFD) simulations to analyze the thermal environment of the station for optimizing the platform door including position, size and open angle. The results showed that the AVPDs could save 20.6%-60.4% of energy compared with the traditional platform bailout doors (PBDs) under the same thermal environment. The AVPDs have also been proven to be the most energy-efficient among the tradition platform doors (PSDs and PBDs) in Ref. [21], and its energy saving performance was markedly influenced by the climate condition.

Fig. 4. (a) Platform Bailout Doors system (PBDs). (b) Adjustable Ventilation Platform Doors system (AVPDs) [20].

2.2.2 Ventilation shaft

Since a large part of the cooling load in stations is from tunnel, cooling the tunnel environment will effectively reduce the VAC demand in stations [22]. In this respect, a reasonable design of ventilation shafts is rewarding as it permits the evacuation of heat gains with no energy costs. The variations in size and configuration of these shafts are almost infinite, which leave the opportunity for improvement. Huang et al. [23] numerically investigated the effects of the ventilation shaft number and geometry on shaft ventilation performance in a metro tunnel. The results showed that for a given total area of openings, the shaft number has little influence on the total mass flow of the air sucked into the tunnel through the shafts and it is proportional to the total mass flow of the air pushed out of the tunnel through the shafts. Kim and Kim [24] carried out a numerical analysis of the effects of duct location on the ventilation performance in a metro tunnel, and evaluated the PSDs ventilation efficiency. The optimum location of the vent shaft with respect to maximizing ventilation performance is found lies near the station. Zhang et al. [25] employed IDA Tunnel software to calculate the air inflow rate at the entrances of a PSD metro station in severe cold area in winter, and found that the air inflow rate could be reduced by 29.2–93.8% under different traffic densities when turning on the piston vent shaft at the station downstream location.

2.2.3 Door curtain

Despite that there is no need for heating in most stations in winter [26], we still hope to improve the station temperature appropriately in severe cold area. The piston effect takes the heat released by the train braking from tunnel into the station and offer an opportunity to improve the temperature. At this point, adding a door curtain can reduce the inlet and outlet air volume of the entrance. Ma et al. [27] compared the effect of warm-air curtain and traditional door curtain, and proposed a new resistance component including small pieces which can be rotated automatically under the action of the piston wind, as shown in Fig. 5. The results from the experimental model indicated that the hall temperature increased by 2 °C compared to the traditional door curtain when the resistance coefficient was 300.

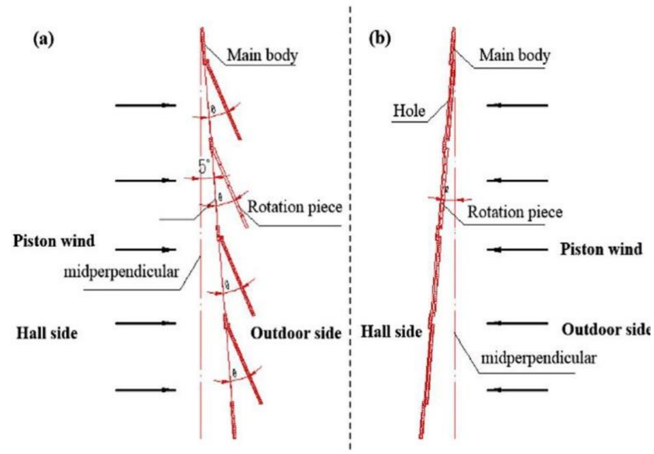

Fig. 5. The new resistance component and its resistance coefficient. (a) Train arriving station (b) Train leaving station [26].

2.3 *Natural cold sources*

Another low-energy cooling strategy that proved highly effective for underground metro system is ground cooling. Ampofo et al. [28] found that the cooling provided by the heat sink effect could account for approximately 30% of the cooling load in the London underground railway. Thompson et al. [29] proved the possibility for enhancing ground cooling using heat pipes for underground stations by a model experiment. Brandl [30] described a combined heat pipe and heat pump system using geothermal energy for heating and cooling urban undergrounds in Austria. Additionally, the use of groundwater [22] and the phase-change materials (PCMs) [7] to absorb heat from metro system were also considered, but these approaches were theoretical and not validated by experiments.

3. DISCUSSION

The major targets of VAC system are exhausting redundant heat and providing fresh air in underground stations. This section discussed the pros and cons of the passive strategies used to achieve these goals.

The envelope insulation is the main passive strategy in aboveground buildings, but it does not seem to work in underground stations under most circumstances. The studies showed the limited influence of ground depth and soil thermal properties on the heat transfer through underground building envelop, and negative effect of thermal insulation on underground building cooling. Fig. 6 shows that about 6% of the publications on Elsevier about this topic were related to the envelope insulation, which also proved its low value in related research. So, this method could not be considered as an energy-efficient way for underground stations as it need to strengthen the heat transfer rather than insulation, however, it is still essential for another purpose for protecting equipment from moisture erode.

The piston effect is probably the bread and butter way for achieving the built environment goals in underground stations. It accounts for 80% of the related studies published in the past two decades as shown in Fig. 6. The piston effect generated by train driving not only bring in the outside fresh air and save the mechanical ventilation energy, but also provide free heating opportunities. Besides, some reports [31,32] proposed to use piston wind to support advertising lighting in stations, as the velocity of airflow can reach 6-8 m/s in tunnel.

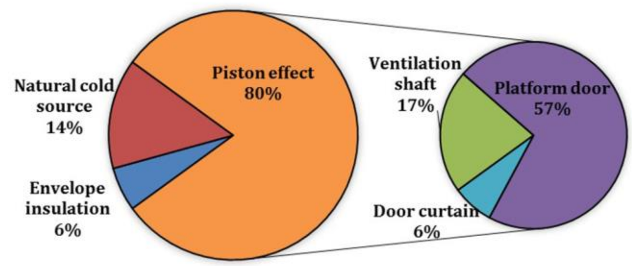

Fig. 6. The share of different passive strategies for VAC in underground metro stations.

With the reasonable VAC design, such as choosing proper platform doors and optimizing ventilation shafts setting, researchers proved appreciable energy savings can be obtained by taking advantage of the piston effect. It should be noted that the effects of these strategies are highly sensitive to local climate conditions, for example, the AVPDs only get 1% energy saving rate more than PSDs in hot climate zone in China [22]. Nevertheless, most of existing researches have not consider the deliverability of the fresh air to the transfer station, as well as the air quality of the train introduced air, both from the outdoor and the tunnel. In addition, the use of nighttime ventilation cooling has also likely been neglected, partly due to the lack of appropriate mathematical models which can be applied to the underground stations environment.

The ground cooling strategies appears to be another promising option after piston effect. The implication of these strategies can save significant amount of energy when compared with under platform exhaust fan. However, the utilization of the heat sink effect may be more complex than piston effect, as the installation of heat pipes or PCMs dedicated derived more devices and initial costs [30]. Moreover, the underground soil will absorbs a lot of heat after several years of station operation, these geothermal heat also can be used for stations cooling/heating by heat pumps [33].

Table 1 summarized the strategies aforementioned in this section. The costs are estimated category-specifically and subject to change in different situations.

Table 1
Summary of the reviewed passive strategies.

Strategy	Principle	Advantages	Disadvantages	Cost	Projected improvement
Building envelopes	Insulation and waterproof	Waterproof	Insulation	Low	Better no insulation when considering energy saving
Piston effect	Gain fresh air for free	Reduce the energy consumption of mechanical ventilation	The air quality of the fresh air is not guaranteed	Low	Can be improved according to the main needs
PSDs	Separate platform from hot tunnel air	Reduce cooling loads	Cannot use the piston wind to ventilation	Medium	As AVPDs
AVPDs	Separate platform from hot tunnel air	Reduce cooling loads in cooling-season and use the piston wind in transition-season	Limited effect in hot climate zone and required extra control	Medium	Combined with automatic control system
Ventilation shafts	Enhance the flow rate into the station	Reduce the energy consumption of mechanical ventilation	Take up more of the underground space	Low	Simulation should be done to optimize the arrangement
Door curtain	Prevent indoor and outdoor air exchange	Increase station temperature in winter	Hinder the passengers in and out	Low	Charge resistance as needed
Heat pipe	Strengthen the heat sink effect	Reduce cooling loads and keep the soil heat balance	High implementation requirements	High	Combined with heat pump systems

4. CONCLUSIONS

This study contributes to the current literature by providing a comprehensive overview on passive strategies for VAC energy saving in underground metro stations. The strategies have been grouped by the strategy types, their principal benefits and drawbacks, costs and projected improvement. It is found that the building envelopes had made minimal contribution to the research literature. The piston effect was the most popular passive strategy in research community. The ground cooling strategies appear to be another promising option but with few measured results. Based on the review of these passive energy saving strategies, there should be further development of the utilization of natural cold sources, combing the strengths of active strategies, advanced control strategies and etc., to achieve sustainable underground metro stations.

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