A review of piston effect and energy saving of subway environmental control system

Jialu Jin[1], *Huixingi* Li[1*], *Xinyi* Liu[1], and *Luoxin* Feng[2]

[1] College of Municipal and Environmental Engineering, Shenyang Jianzhu University, Shenyang 110168, China
[2] College of Civil Engineering, Shenyang Jianzhu University, Shenyang 110168, China

Abstract. The piston effect and piston wind generated by subway train operation are closely related to the energy consumption of subway environmental control system. With the rapid development of subway industry, under the premise of meeting the needs of passengers, using piston wind to reduce station energy consumption has become one of the focuses of current research. This paper collects and sorts out the domestic and foreign literature related to the piston effect. Firstly, the relevant information of piston effect and subway environmental control system is summarized and analyzed. Secondly, the utilization strategy of piston wind is emphasized in this paper. These strategies are mainly related to the design of ventilation shaft, the speed of train, the selection of platform door and the installation of door curtain. Reasonable use of these strategies can reduce energy consumption for the station. Finally, the utilization principle of piston wind was proposed in this review. When the piston wind meets the demand, the piston ventilation should be a priority choice, compared with mechanical ventilation. Evaluating whether the piston wind meets the needs of use, mainly through these parameters as the judgment basis, such as air volume, temperature and humidity, carbon dioxide concentration and particle concentration.

1 Introduction

By the end of 2020, 45 cities in China had rail transit systems with 244 operating lines and the total length of 7969.7 km. The length of subway line is 6280.8 km, accounting for 78.8 % of the total length of rail transit (China Urban Rail Transit Association, 2020). Compared with other modes of transportation, subway has the advantages of green, environment-friendly, comfort and safety. In China's 14th Five-Year Plan, it is proposed to increase the operating mileage of urban rail transit by 3000 kilometers. With the development of urbanization, metro is known as the lifeline of urban development [1].

Subway brings convenience to people's travel, but also accompanied by huge energy consumption. An energy survey in South Korea found that the average annual energy consumption of subway stations in four cities was 645 MJ/(m^2 · year) [2]. Lin et al. conducted a sample survey on the energy consumption of three public transport buildings (airport terminal, railway station and subway station) in China. Their results showed that the average annual energy consumption of subway station was 124.9 kWh/(m^2·year), which ranked second among the three transport buildings [3]. According to statistics in 2014, the national urban rail transit electricity consumption accounted for 1.7‰ of the total electricity consumption of the whole society, accounting for 14‰ of the tertiary industry [4]. Searching some ways to reduce energy consumption has become an urgent problem. In the subway energy consumption system, the energy consumption of ECS (environmental control system) is particularly prominent, accounting for about 30%-50% of the total energy consumption of the subway [5,6]. ECS has great energy saving potential, reducing energy consumption of ECS is the key to realize energy saving of subway.

In the study of environmental control system energy saving, the piston wind caused by train operation has attracted many researchers' attention. Piston wind is considered to be one of the main factors affecting subway energy consumption [7]. The unsteady airflow induced by train will make the ventilation and heat transfer of station more complex [8]. The piston wind entering the station in hot summer will greatly increase the load of the station refrigeration unit [9]. In the transitional season, piston wind is a well wind resource, which promotes the natural ventilation in the public area of the station. The idea of using piston wind to replace the station fresh air unit was proposed in some articles. They studied a subway station in Wuxi, their results showed that piston ventilation could meet the fresh air demand of passengers [10]. In addition, some studies explored measures to improve the thermal environment of the station in winter. They found that train braking would emit a large amount of heat in the tunnel, the piston wind carrying part of the heat into the station could increase the temperature of the public area of the station by about 1 °C [11]. Therefore, making full use of

* Corresponding author.
Email address: lihuixing07@163.com.

piston wind is an effective measure for energy saving of subway environmental control system.

2 Piston Effect and ECS in Subways

The relationship between piston effect and subway energy consumption is complex. The first work we did is to study the formation mechanism of piston effect.

2.1 Formation mechanism of piston effect

Due to the space constraints formed by the tunnel wall, when the train runs in the tunnel, a part of the air driven by the train will surround the tail of the train. The other part of the air will be pushed forward by the train and discharged from the tunnel openings. Inhaling air from the openings in the negative pressure zone formed at the tail of the train [12]. The phenomenon that the train pushes the airflow forward in the tunnel is called the piston effect, and the driving airflow is called the piston wind.

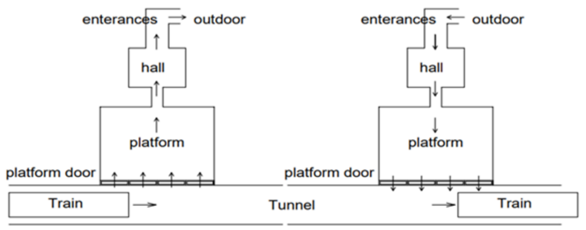

Fig. 1. Schematic diagram of the piston airflow when the train enters and leaves the station.

The station environment, tunnel environment and outdoor environment are interrelated because of the existence of platform doors, entrances and exits and ventilation wells. Fig. 1 shows the piston effect occurred at the subway station. When the train enters the station, the tunnel airflow driven by the positive pressure in the front of the train enters the platform and finally flows from the exit to the outside. When the train leaves the station, the negative pressure at the rear of the train inhales the outdoor air into the station hall through the entrance and exit channels, then flows to the platform, and finally flows into the tunnel [4]. With the arrival and departure of the train, periodic airflow movement occurs at the platform door and entrance, which has an important impact on the environmental maintenance and energy consumption of the station.

2.2 Environmental Control System of Subway

In subway engineering, ventilation and air conditioning system is also called environmental control system. The ECS aims to exclude humidity and heat, create a transitional and comfortable environment for passengers to and from the ground streets and subway trains, and provide necessary safe, sanitary and comfortable environmental conditions for staff, and also provide good working conditions for the operation of trains and equipment. In case of an accident inside the local railway, the system shall create favorable conditions for the evacuation of passengers [13].

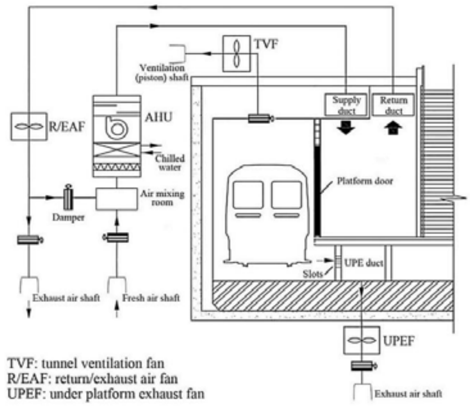

Fig. 2. Schematic of ECS at a typical station [14].

As shown in Fig. 2, the ECS of a typical station usually includes the station ventilation and air conditioning system, the heat exhaust system under the platform and the tunnel ventilation system. The ventilation and air conditioning system in public area is responsible for the environmental control of the station hall, platform and entrance and exit channels. The air conditioning system adopts the whole air system with one return air to deal with the air in the station. The ventilation and air conditioning system of station equipment and management room is responsible for the environmental control of subway station equipment and management room. The main function of the under platform exhaust (UPE) systems is to eliminate the heat generated by the brake before the train enters the platform. The main function of the tunnel ventilation system is to ensure the ventilation and ventilation of the tunnel environment, and to control the flow of air and smoke in emergency situations such as tunnel fire [14].

3 Utilization Strategies of Piston Wind

In this paper, the utilization strategies of piston wind in tunnel and station are reviewed. The principles and characteristics of these strategies are described, their energy-saving effects are also analyzed.

3.1 Utilization Strategies of Tunnel Piston Wind

Ventilation shaft plays an important role in tunnel ventilation as a connection channel between tunnel and external environment. Researchers tried to use piston wind to increase tunnel ventilation efficiency by optimizing ventilation shaft design. Kim and Kim optimize the location of tunnel ventilation shaft by three-dimensional numerical simulation to improve the efficiency of natural ventilation. They found that the best location of ventilation shaft is near the station [15]. In the numerical simulation of Xue et al., the ventilation shaft located in front of the station is found to be more effective than the ventilation shaft located behind the station [16]. Yan et al. studied the influence of the location and number of ventilation shafts on the natural ventilation system. Their results showed that the dual ventilation shaft system could significantly improve the air exchange efficiency [17]. González et al. used CFD software to establish two typical station models. The influence of ventilation shaft on the piston air volume of the station was analyzed. The results show that the amplitude of the piston effect is affected by the central mechanical ventilation shaft. The instantaneous flow driven by the piston effect can reach 50 % of the total flow generated in the ventilation system [18].

Some researchers have studied the influence of train-related operation on piston effect. Based on three-dimensional simulation and experimental research, Liu et al. proposed that the best train speed is 30 m / s. The train running at the optimal speed can simultaneously meet the minimization of carbon dioxide concentration and heat release in the tunnel. The study also finds that the energy saving potential of piston wind in different climate zones is about 13%–32% [19]. In order to enhance the tunnel piston effect, Cross et al. proposed to install an airfoil with a fixed angle of 10° on both sides of the train, as shown in Fig. 3. Their results show that the maximum air displacement can be increased by 8 % by adjusting the angle of the airfoil at different stages of the train operation [20].

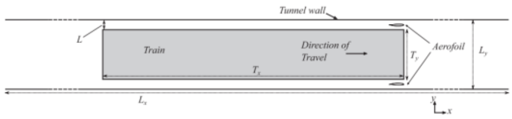

Fig. 3. Diagram of fixed angle airfoil on both sides of train [20].

3.2 Utilization Strategies of Station Piston Wind

Under the traction of the train, the piston wind enters the station from the entrance and exit and the platform door respectively, which leads to different utilization strategies.

3.2.1 How to use piston wind from platform doors

The utilization of the platform piston wind mainly relies on the platform door, which is a safety device located between the platform edge and the tunnel. The platform doors are mainly divided into: platform screen doors (PSDs), platform bailout doors (PBDs), and innovative platform doors with adjustable vents.

PSDs completely separate the platform from the tunnel, which minimizes the impact of piston wind on the ECS and reduces the load of air conditioning and refrigeration units in summer. Hu et al. used SES (Subway Environment Simulation) to simulate the subway station in Taipei. Their research shows that installation of PSD can reduce the energy consumption of station air conditioning units compared with non-PSD stations [21]. Another study also proved that the PSDs improved the platform air quality [22]. But the station with PSDs cannot use piston ventilation in transition season, the fresh air load of the station is large. A survey by Yin et al. found that the fresh air load at the station was as high as 34%–37% [23]. It should be noted that the PSD has air leakage problem, because it is not completely sealed [24]. The PBD does not completely separate the station from the tunnel. The ventilation outlet above the fixed door can make full use of piston ventilation.

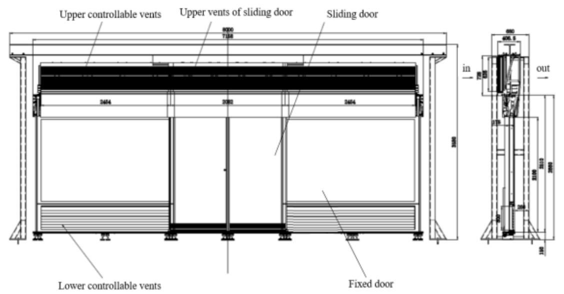

Fig. 4. Platform door schematic with adjustable vent[25].

Combining the advantages of the PSD and PBD, Li first proposed the idea of an innovative platform door with adjustable vent, and successfully produced this new type of platform door product [25]. As shown in Fig. 4, the innovative platform door is equipped with adjustable vents above or below the fixed door to control the inlet and outlet of the piston wind. The innovative platform door system can realize the flexible switching between the PSD and the PBD. The closing of the vent in summer can play the role of the PSD, and the opening of the vent in the transition season and winter can also realize the function of the PBD, so as to make full use of the piston wind in different seasons.

Table 1. Operation mode of ECS for the innovative platform doors.

Ventilation modes	Conditions	Vents	Use of piston wind
Mechanical ventilation	$t_w<12℃$	Close	No
Small piston wind ventilation		Open(30°)	Yes
Piston ventilation	$12℃<t_w<t_1$	Open	Yes
Mechanical and piston ventilation	$t_1<t_w<t_2$	Open	Yes
Mechanical ventilation	$t_2≤t_w≤t_3$	Close	No
Return air ventilation air conditioning	$h_a>h_i$	Close	No
Full fresh air ventilation air conditioning	$h_a<h_i$	Close	No

The following are the formulas of t_1 , t_2 and t_3 :

$$t_1=\frac{\rho c(V_{h1}+V_{h2})t_n-3600Q_i-\rho cV_{h2}t_t}{\rho cV_{h1}} \quad (1)$$

$$t_2=\frac{\rho c(V_{h1}+V_{h2})t_n-\rho cV_{h2}t_t}{\rho cV_{h1}} \quad (2)$$

$$t_3=t_n-\frac{Q_i}{\rho cV_{AUHmax}} \quad (3)$$

where ρ is the density of air, m^3/kg; c is specific heat of air; t_w is outdoor air temperature, °C; t_1 is upper limit of outdoor temperature for piston wind ventilation model, °C; t_2 is upper limit of outdoor temperature for mechanical and piston wind ventilation model, °C; t_2 is upper limit of outdoor temperature for mechanical ventilation model, °C; t_n is station air temperature, °C; t_t is tunnel air temperature, °C; V_{h1} is the amount of piston wind entering the station per hour, m^3/h; V_{h2} is the amount of air entering the station from the platform door per hour, m^3/h; V_{AUHmax} is air flow rate when air handing units fan reaches upper limit, m^3/h; Q_i is heating load in the station; h_a and h_i are outdoor air enthalpy and return air enthalpy, respectively.

The opening and closing of vents are usually judged by the temperature of the outdoor air, as shown in table 1. When the outdoor temperature is low (t_w <12℃), the piston wind is unfavorable to maintain the thermal environment of the station, and the vent should be closed. However, Zhang et al. believed that when the vent opened at a small angle (30°), an appropriate amount of piston wind entered the station not only met the demand for fresh air, but also brought the heat released by train braking into the station to improve the temperature of the station [26]. When the outdoor temperature increases (12℃< $t_w < t_1$), all the heat load generated by the station can be eliminated by piston ventilation. When the piston ventilation cannot eliminate all the heat load ($t_1 < t_w < t_2$), the station fan is opened, the mechanical ventilation and piston ventilation operate together. When the outdoor temperature is high ($t_2 \leq t_w \leq t_3$), the piston wind will increase the thermal load of the station, and the vent should be closed.

The energy-saving benefits of the innovative system are proved in the following studies. Through numerical simulation, Yang et al found that the energy-saving potential of different cities is different under five operating modes. The longer the non-air conditioning season, the more obvious the energy-saving effect of the new system [27]. Zhang et al. conducted numerical simulation on the position, opening size and angle of the vent. Their research found that the new system could meet the requirements of fresh air and comfort in different seasons by adjusting the opening angle of the vent. The new system has remarkable energy saving effect in temperate zone, and the energy saving rate is 20.64%-60.43% in different climatic zones [26]. In the simulation study of He et al., it is found that the new system has remarkable energy saving effect in temperate cities, with the maximum energy saving rate of 42.71%, while in cold regions, the minimum energy saving rate is only 9.67%. One possible reason for the large difference in energy saving rate is that the energy saving effect of the new system is the most obvious in the transition season, but the transition season length is different in different regions [28]. Li et al. compared PSD, PBD and PSD-PBD， their results showed that PSD-PBD could indeed achieve energy saving, but the energy saving effect was only 1%–8% [29].

Presently, there are few practical cases of the innovative adjustable vent platform door in China, only used in Shanghai Yunjin Railway Station. Li et al. investigated the thermal comfort and energy saving effect of Yunjin Road Station. Their measurement results showed that the average temperature in the station was 16.5-28°C. The estimated electricity savings for one station using such an innovative ventilation system can reach 275,785.71 kWh per year, indicating a great energy saving potential [30].

3.2.2 How to use piston wind from entrances

With the arrival and departure of the train, a large number of piston wind will flow from the entrances to the station. A survey found that the average volume of piston wind was 2.5×104~3.5×104m^3/h . They put forward that the piston wind volume from the entrances can meet the needs of passengers under the condition of return air alone (RAA) without mechanical ventilation. Energy consumption of ECS can be reduced by 10%-20% [31]. Perna et al. proposed using automatic control system to control mechanical ventilation in station. According to the air volume of piston wind, automatically adjusting the air supply volume of mechanical ventilation seems to reduce energy consumption [32]. Ma et al. found that 64.4% of heat loss in winter was due to cold air intrusion caused by the piston effect in northern cities. Setting only warm air curtain cannot effectively prevent cold wind intrusion, installation of automatic adjustment curtain seems to be an effective way [33].

4 Discussions

From the perspective of utilizing the piston effect, these utilization and control strategies can be divided into three angles: source, path and direct utilization. Train operation is the cause of the piston effect. Some measures can be taken to increase the strength of the piston effect, including taking the optimal train speed (30 m/s), installing fixed angle airfoils on both sides of the train. The use of platform doors, door curtains and ventilation shafts mainly control the air volume of piston wind in public areas or tunnels by changing the geometric shape (resistance) of piston airflow path [14]. The piston wind from the entrances and exits can be used directly. The environmental control system of the station cannot set up fresh fan, set up return air condition alone, or automatically control mechanical ventilation according to the piston air volume.

How to use the piston wind in tunnel, the existing research mainly focuses on the design optimization of ventilation shaft, such as the location, number and size of ventilation shaft. Obviously, these research results should be used as an important reference in the future subway tunnel design. For the subway lines in operation, some measures to increase the tunnel piston ventilation can also achieve the purpose of energy saving.

Installation of platform door is an effective control strategy for piston wind entering station from tunnel. Combined with the advantages of traditional PSD and PBD, an innovative platform door with adjustable vent is proposed. In different seasons, opening or closing the vent on the platform door and adjusting the opening angle and size can achieve accurate and flexible control of piston wind. The reference index of regulating the vent is often the relevant parameters of the outdoor environment (temperature and enthalpy, etc.). In fact, the relevant parameters of tunnel environment should also be considered, but the importance of tunnel parameters is ignored in the existing research. It is worth noting that most of the research on the energy saving potential of the innovative system is based on the calculation of the simulation method, the measured research on the operation data of the new system is less, which is unfavorable for the popularization and application of the innovative system. Although studies have shown that climate characteristics can affect the energy-saving potential of the innovative system, it is undeniable that the innovative system still has much room for development in the future. Some studies have found that the friction between the train and the track is the main source of particulate matter at the station. The piston effect makes the concentration of particulate matter at the station change with the train entering and leaving the station, and even greater than the concentration of outdoor particulate matter [34]. Therefore, whether the piston wind from the tunnel can be directly used is worthy of consideration and research. Air filters for subway stations and train braking heat recovery systems have been proposed in some articles, which seem to offer more possibilities for using tunnel piston winds [35,36]. Relatively speaking, it is acceptable and reasonable that the piston wind from outdoor can be directly used.

5 Conclusions

It is found in this paper that the piston wind can not only provide free ventilation for the station, but in some cases, the cold or heat carried by the piston wind enters the station and improves the cold and hot environment of the station. The utilization principle of piston wind was proposed in this review. When the piston wind meets the demand, the piston ventilation should be a priority choice, compared with mechanical ventilation. The equipment such as fans and air conditioners that the environmental control system needs to consume energy should be used as a supplement, when the piston wind cannot meet the needs. When the environment changes and the piston wind is unfavorable to the station environment, some measures should be taken to prevent or reduce the intrusion of the piston wind and reduce the load of the environmental control system. Evaluating whether the piston wind meets the needs of use, mainly through these parameters as the judgment basis, such as air volume, temperature and humidity, carbon dioxide concentration and particle concentration.

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