A review on available energy saving strategies for heating, ventilation and air conditioning in underground metro stations

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Abstract

Due to the increasing number of underground metro stations worldwide and the great energy consumption of heating, ventilation and air conditioning (HVAC) systems in underground stations, reducing the HVAC energy consumption while maintaining a hygienic and acceptable environment in underground stations is becoming an ongoing research challenge. This paper presented an overview of the strategies available for HVAC energy saving in underground stations. Firstly, the design features of the HVAC systems are summarized and issues affecting the HVAC systems' energy efficiency are identified. Then, a thorough review of the energy-efficient HVAC strategies is presented. For each strategy, the principal application and the effect on energy saving are described, and the limitation is also analyzed. Lastly, the strategies are classified and compared from different perspectives and upcoming challenges are proposed. The authors hope that this study can promote the reasonable adoption of different energy-efficient HVAC strategies in underground stations, which could reduce the energy consumption of the HVAC systems in the long run.

Highlights

Design features of the HVAC system in underground stations are summarized.
Issues affecting HVAC systems' energy efficiency in existing stations are identified.
Various strategies for HVAC energy saving in underground stations are reviewed.
The novel HVAC strategies are classified and compared from different perspectives.
Applicability and upcoming challenges of the HVAC strategies are discussed.

Keywords

Energy-saving, underground stations, ventilation, air-conditioning, strategies

Word count

7527 words (excluding title, author names and affiliations, keywords, abbreviations, table/figure captions, acknowledgments and references)

Abbreviations

UMSs	Underground Metro Stations	DX A/C	Direct expansion Air-Conditioning
HVAC	Heating, Ventilation, and Air Conditioning	ICAE	International Conference on Applied Energy
ISHVAC	International Symposium on Heating, Ventilation and Air Conditioning	ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
IAQ	Indoor Air Quality	ASHPs	Air Source Heat Pumps
RWI	Relative Warmth Index	GSHPs	Ground Source Heat Pumps
CO_2	Carbon Dioxide	WSHPs	Water Source Heat Pumps
PM	Particulate Matter	SES	Subway Environment Simulation
UPE	Under Platform Exhaust	IDA	IDA tunnel simulation software
PSDs	Platform Screen Doors	PID	Proportional Integral Derivative
APGs	Automatic Platform Gates	MPC	Model Predictive Control
PBDs	Platform Bailout Doors	TRNSYS	Transient System Simulation Tool
AVPDs	Adjustable Ventilation Platform Doors	STESS	Subway Thermal Environment Simulation Software
CoP	Coefficient of Performance	CFD	Computational Fluid Dynamics
VFDs	Variable Frequency Devices		

1. Introduction

By the end of 2017, metros were available in 178 cities of 56 countries, responsible for delivering around a total of 168 million passengers per day [1]. Comparing with other over-ground transportations, such as buses and trams, metros can efficiently use underground space to share the high burden of transportation in major cities [2,3]. Underground metro stations (UMSs) are the basic entrance of occupants to the metro services and they are a special kind of buildings built beneath the ground. Because these stations are built under the ground, their indoor environment and energy efficiency are more difficult to maintain than traditional buildings [4–6].

To provide metro passengers with a healthy, comfortable and safe environment, heating, ventilation and air conditioning (HVAC) systems are available in almost every UMS used for regulating indoor environmental parameters, such as air temperature, humidity, air speed and particle concentrations [7,8]. However, when doing this work, they are consuming high-level energy as well [9–11]. In 2015, the energy consumption from the HVAC systems available in all metro stations in Beijing, China, was approximately 490 GWh, which can power nearly 255,500 families for a year [12]. In Barcelona, Spain, 84.2 MWh/year was used in one of their oldest underground stations for ventilation only [13]. Comparison between continents also revealed that the energy demand by HVAC systems may be geography dependent, as Asia requires more energy than Europe, North America and Latin American [14,15].

Due to the high demand of HVAC energy in UMSs, it is essential to develop energy efficient strategies for them. Zhang et al. [16] have investigated the energy performance of an innovative environmental control system in a UMS and identified an energy saving potential of 20.6-60.4% under different situations. Yang et al. [17] have tried to use frequency conversion technology for the operation of pumps and fans in UMSs and suggested a total power saving ratio ranging between 59.5-73.4%. Besides these, there were also some other studies that have identified an energy saving potential over 30% when applying energy efficient solutions to existing systems [18–20].

Despite various studies have been proved the energy saving potential of the HVAC systems by conducting on one specific technology or individual solution (such as platform screen door systems, variable frequency devices, direct expansion air-conditioning, artificial intelligent ventilation, etc.) while maintaining an acceptable environment, but a comprehensive study that summarizes a wide range of different strategies and technologies for HVAC energy savings is still lacking. Furthermore, the energy demand and performance of the HVAC systems in UMSs are influenced by different influential factors. Finding the most suitable energy saving strategy that can properly handle various factors and achieve the overall optimization of the entire HVAC system in UMSs is an ongoing challenge for current research community.

Therefore, the objectives of this review are (i) to summarize the design features of the existing HVAC systems used in UMSs to help researchers/designers identify the most relevant variables of the station environment and major issues that can affect the system's energy efficiency; (ii) to investigate the characteristics and compare the performances of different energy saving HVAC strategies; and (iii) to analyze the applicability and upcoming challenges of the energy saving HVAC strategies for achieving low-energy underground stations.

2. Materials and methods

The research methodology was composed of three primary steps:

First, a keyword-based search of research articles was conducted using major international online databases, such as Web of Science and Scopus. Examples of the keywords used were listed in Table 1. Based on the research theme, the keywords were divided into three categories (site, HVAC strategy, and energy) and the keywords belonging to each category were cross-used in the literature search.

Table 1

Keywords used in searching relevant literature.

Subject categories	Keywords
Site	Metro, subway, underground, station, tunnel urban, rail
HVAC strategy	Ventilation, air conditioning, system, environment, technology, strategy
Energy	Energy saving, consumption, efficiency, efficient, management, optimization

Notes: The articles were screened for the relevance of the research subjects, and the articles that cited or were cited by an article that passed the screening test were further identified as additional candidate articles.

Second, related articles were screened based on the following criteria: (1) the scene must be the built environment of UMSs; and (2) the purpose must be to save energy of the HVAC system. The materials, such as journal articles, conference articles and reports used were all published within the past 20 years. Major journals covering this topic included Energy and Buildings, and Renewable and Sustainable Energy Reviews, and major conferences included the ISHVAC conference and the ICAE conference. In the following sections, a total number of 109 publications were used, with 87% journal articles, 7% conference articles, and 6% books or reports.

Third, all relevant articles were classified and analyzed to identify the research gaps in the field of metro station HVAC energy saving. The review results were analyzed to provide cutting-edge knowledge of this research topic and highlight future research directions.

To guide the future development of energy efficient HVAC strategies for UMSs, this paper has reviewed existing solutions, through a thorough review of the relevant literature. The remainder of this paper is divided into five major sections. Section 2 describes the methodology used in this study. Section 3 summarizes the major design features of HVAC systems in UMSs. Section 4 presents a detailed overview of existing strategies developed for saving HVAC energy consumption in UMSs, with their basic theories, advantages, and disadvantages. Section 5 compares these strategies in terms of their operational mechanisms and energy saving potential, and discusses the direction of future improvements. A thorough conclusion of the paper is provided in Section 6.

3. Design features of HVAC systems in UMSs

Because UMSs are built under the ground, they have special requirements that need to be considered when designing and operating their HVAC systems. An in-depth understanding of these requirements/design features is important for developing energy efficient solutions. This section, therefore, has described these requirements by answering the following three questions:

1. What are the environmental requirements (design conditions) in UMSs (Section 3.1)?
2. What are the major influential factors on stations' indoor environment (Section 3.2)?
3. What HVAC systems are available for UMSs (Section 3.3)?

3.1 Environmental criteria in UMSs

3.1.1 Thermal comfort inside metro stations

Environmental requirements in UMSs can be mainly divided into thermal comfort and indoor air quality (IAQ). According to standard ASHRAE 55 [21], thermal comfort is 'that condition of mind which expresses satisfaction with the thermal environment'. Thermal environment represents the characteristics of the environment, which affect the heat exchange between the human body and the environment. Currently, it is widely acknowledged that people's thermal comfort/sensation is affected by four environmental parameters, namely, air temperature, mean radiant temperature, relative humidity and air velocity, and two personal parameters, namely, metabolic rate and clothing insulation, defined by Fanger's predicted mean vote model [22], which has been adopted in many major building design standards, such as ISO 7730 [23], EN 15251 [24] and ASHRAE 55. Among these parameters, mean radiant temperature is defined as 'the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure'; the metabolic rate is defined as 'a conversion of chemical into mechanical and thermal energy, measures the energetic cost of muscular load and gives a numerical index of activity (such as it is 54 Btu/h.ft^2 at the entrance and 39 Btu/h.ft^2 at the platform in UMSs)'. For the remaining parameters, please also refer to [22].

In UMSs, indoor air temperature and relative humidity are the two main parameters used to control the indoor thermal environment [25,26]. For example, according to [27], in China, it is recommended to maintain indoor temperature ⩽30°C for station halls and ⩽29°C for platforms, with relative humidity between 40% and 70% for both of them, in summer. In winter, the temperature should be maintained ⩾12°C for both of them, but without any specific requirement on humidity.

For UMSs, there is another index called relative warmth index (RWI) [28] that is commonly used in studies to evaluate indoor thermal comfort level. The RWI is developed by ASHRAE, and can be used to determine how warm a person feels in UMSs. It is a dimensionless parameter, considering parameters like temperature, air velocity, clothing insulation and metabolic rate. This parameter has considered the impact of transient effect on occupants' thermal sensation in the station design, which often gives a higher design temperature (3-5°C) in summer than that decided by the steady-state method, resulting in reduced cooling load of air-conditioning systems [28]. According to [25], RWI can be calculated by Equations 1 and 2 for different ambient vapor pressure conditions.

$$RWI = \frac{M(I_{cw} + I_a) + 1.13(t - 95) + RI_a}{70(1.73 - P)} \quad (P > 0.67 \text{ in Hg}) \tag{1}$$

$$RWI = \frac{M(I_{cw} + I_a) + 1.13(t - 95) + RI_a}{74.2} \quad (P \leq 0.67 \text{ in Hg}) \tag{2}$$

where M is metabolic rate (Btu/h.ft^2); I_{cw} is wet clothing insulation (clo); I_a is air boundary insulation (clo); t is dry bulb temperature (F); R is mean incident radiant heat from sources other than walls at room temperature (Btu/h.ft^2), and P is vapor pressure of water in air (inch of mercury, in Hg).

Table 2 relates RWI and the ASHRAE comfort classification, the acceptable range of RWI values is between 0 and 0.15 [25].

Table 2

ASHRAE comfort classification using RWI [25].

ASHRAE comfort classification	RWI
Warm	0.25
Slightly warm	0.15
Comfortable	0.08
Slightly cool	0.00

ISO 7726 [29] has given a detailed technical description about the measurement of these thermal factors used to evaluate indoor thermal environment, including air temperature, mean radiant temperature, relative humidity and air velocity. According to the standard, air temperature should be measured by a thermocouple or a thermistor, at a height of abdomen level for homogeneous environment or at heights of head level, abdomen level and ankle level for heterogeneous environment. Mean radiant temperature should be measured by a black globe thermometer, only at the height of abdomen level. Humidity should be measured by a psychrometer or a whirling hygrometer, only at the height of abdomen level. Air velocity should be measured by a hot-wire/sphere anemometer, at the same height(s) as temperature. For metabolic rate and clothing insulation, ISO 7730 [23] has given useful checklists based on people's activities (to decide metabolic rate) and combination of garments (to decide clothing insulation). In UMSs, temperature and humidity sensors are commonly installed to reflect the thermal environment of the station [24], with other parameters, such as air velocity [30,31] and mean radiant temperature [32,33], were also measured in some research studies.

3.1.2 IAQ inside metro stations

According to CIBSE KS17 [34], IAQ is 'the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants, and good IAQ can be defined as air with no known contaminants at harmful concentrations'. Common indoor contaminants or pollutants include carbon dioxide

(CO_2), volatile organic compounds, odors and particulates. In UMSs, indoor CO_2 [35] and particulate matters (PMs) concentration [5,36] are major environmental parameters linked with IAQ:

CO_2 concentration: a widely used parameter to decide ventilation rate in buildings (i.e. the demand control ventilation), including metro stations, because of its good reflection of occupancy levels indoors [37]. The limit of CO_2 concentration in metro stations may be different between countries, such as 1000 ppm in Korea and 1500 ppm in China [38].

PM concentration: another important parameter used to control IAQ, mainly focusing on $PM_{2.5}$ and PM_{10} concentrations. In metro stations, these particles come from 1) mechanical wear and friction processes between rails and wheels or between pantographs and trains; 2) erosion of construction materials, and 3) particles brought from outdoors by piston wind [4,5]. Because $PM_{2.5}$ is included in PM_{10}, the official limitation set for PM_{10} is always higher than that for $PM_{2.5}$. For example, for UMSs in Korea, the upper limitation for $PM_{2.5}$ is set as 40 $\mu g/m^3$ and for PM_{10} the value is 150 $\mu g/m^3$ [39].

3.2 Influential factors of stations' indoor environment

When designing UMSs, the most challenging part is for their public areas (halls and platforms), due to their high population and complex internal environment [28]. Figure 1 has shown possible factors that may influence the indoor thermal environment of UMSs, with heat gains for public areas coming from 1) outdoor air; 2) tunnel air; 3) passengers; 4) station devices; 5) mechanical fresh air, and 6) earth. Little effect is coming from external solar radiation, but strong dependencies exist to piston effect and heat sink effect [25]. The piston effect enables stations exchange heat with both outdoor environment and tunnel environment, and the heat sink effect has an influence on the heat exchange between stations/tunnels and earth. Due to this complexity, most studies in UMSs focused on developing energy efficient strategies for public areas.

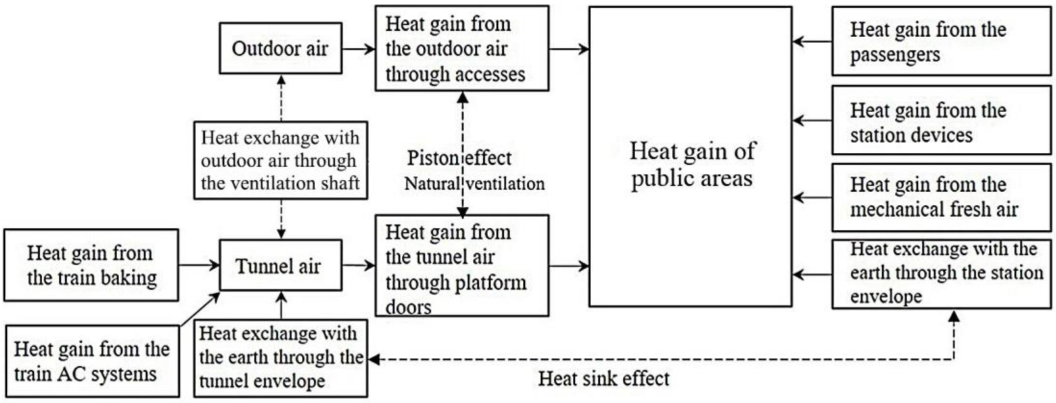

Figure 1: Schematic of heat gains for the public areas of typical underground stations.

In terms of IAQ, the influences are mainly determined by pollutant sources and propagation (including driving force and the route). In UMSs, the main source of CO_2 is metro passengers, but for PMs, their sources are more complicated, as mentioned in Section 3.1 and shown in Figure 2. The propagation of pollutants is mainly driven by piston wind, and natural ventilation when there is no mechanical ventilation. It is also affected by the layout of stations, such as the number and length of accesses, the volume of public areas, the form of platform doors, and the location of ventilation shafts, etc.

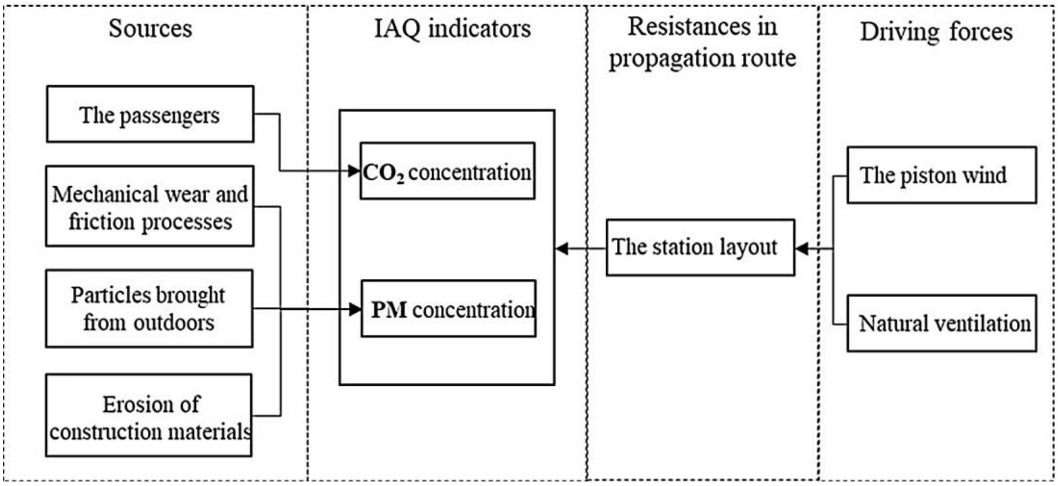

Figure 2: Schematic of IAQ influential factors for the public area.

3.3 HVAC systems in UMSs

Due to the complexity of the environment of UMSs, various systems have been developed to suit different function requirements. These systems can generally be classified into 1) public areas HVAC system [40,41], 2) under platform exhaust (UPE) system [42], and 3) tunnel ventilation system [43,44].

Public areas HVAC systems: with main functions to 1) control the indoor environment; 2) ensure enough fresh air; and 3) remove smoke in case of a fire. The primary air return system, as shown in Figure 3, is a common form used in the station where cooling is needed [45], such as in most countries in Asia [14,15]. In Europe, the major system form is mechanical ventilation systems equipped with variable frequency drives to regulate the fan speed under various environmental conditions [13]. When using these systems in UMSs, there are some major issues that can affect the system's energy efficiency: 1) the impact from train-induced airflow on HVAC load [13,40]; 2) a high proportion of energy consumption on moving mediums, including both air and water, in the system due to the large volume of stations [46]; 3) potential influential factors, such as outdoor environment and occupancy level, affecting the system performance [18].

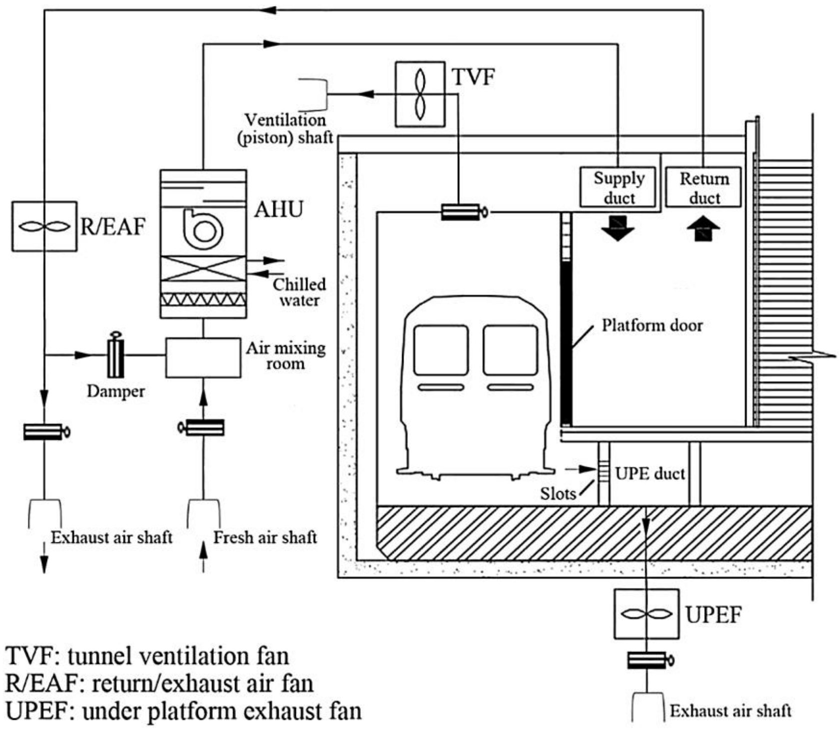

Figure 3: Schematic of a typical HVAC system in UMSs.

Under platform exhaust (UPE) systems: with a main function to remove heat generated from train braking before it enters the platform [47]. The UPE duct is installed beneath the platform, with many slots on it to capture heat, as shown in Figure 3 as well. It links to exhaust air shafts at both sides, exhausting hot air from tunnels to outdoors, driven by UPE fans. When using this system in UMSs, there are some major issues that can affect the system's energy efficiency: 1) high energy demand from fans [42,47]; 2) extracting conditioned air from the platform, leading to energy waste [48].

Tunnel ventilation systems: with main functions to 1) keep an acceptable environment in tunnels under normal circumstances; 2) control air and smoke movement in emergency, such as a fire, happening in tunnels [49]. This system usually includes tunnel ventilation fans, ventilation (piston) shafts and dampers installed on the tunnel, as indicated in Figure 3. Besides ventilation, the ventilation shaft can also attenuate possible pressure fluctuations originating from the piston effect when the fan is off [49]. When using this system in UMSs, there is one major factor that can affect the system's energy efficiency: the design of ventilation shafts on ventilation efficiency, for example, changing the location or the cross-sectional area of shafts would affect the air exchanging rate between tunnels and outdoors, which indirectly influence the energy consumption of ventilation systems [49,50].

4. Overview of the energy saving HVAC strategies for UMSs

Figure 4 has listed the available strategies that can help to achieve higher energy efficiency of HVAC systems in UMSs, grouped for the three systems classified in Section 3.3. Apparently, as mentioned previously, most attentions have been put into the public areas of UMSs, with eight available solutions. According to the review results in this study, only one kind of solution has been proposed for each of UPE systems and tunnel ventilation systems to improve their performance.

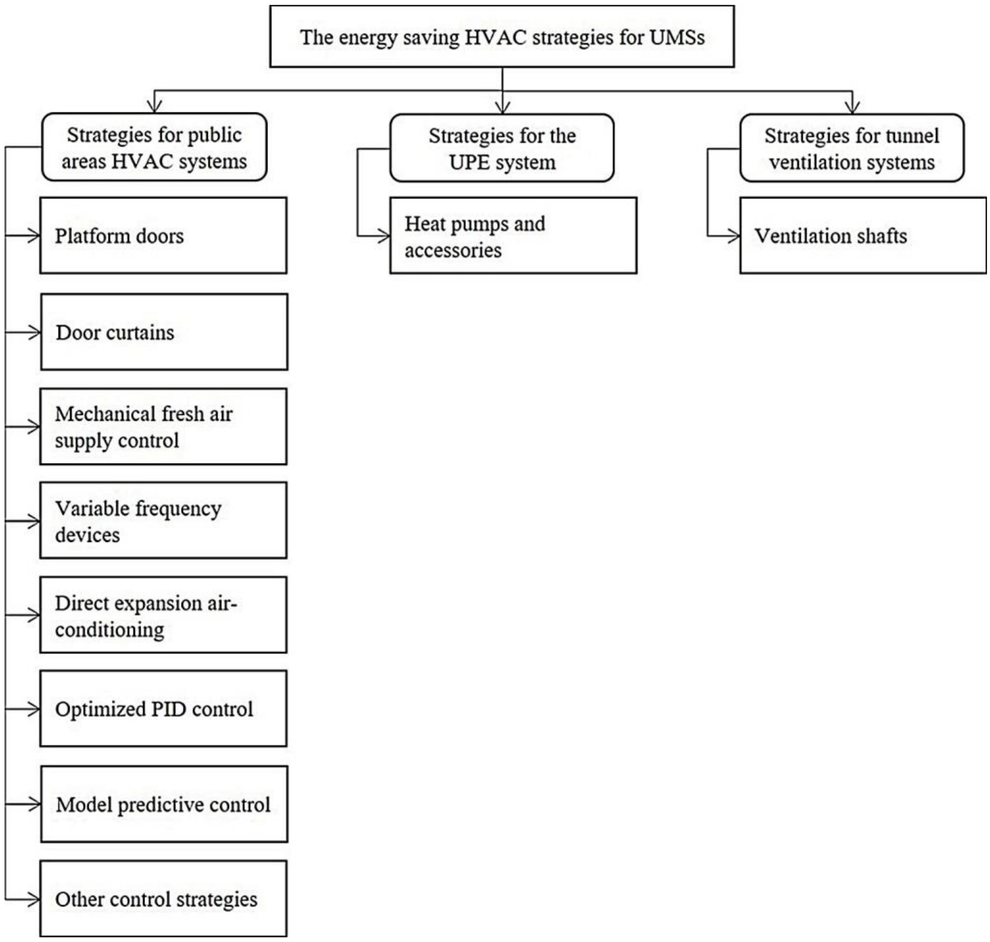

Figure 4: The energy saving HVAC strategies for UMSs.

4.1 Energy saving strategies for the public areas HVAC system

When developing energy saving solutions for public areas in UMSs, a major issue to tackle is the piston effect which causes the train-induced airflow. This has a significant impact on the energy efficiency of systems [51]. Figure 5 has shown the different air flow conditions when trains entering the station and when they are leaving the station. When the train is moving, positive pressure realized at the front by pushing air, and the negative pressure developed at the rear, due to the lack of air pushing away from the train [52]. When the train enters the station, air in the tunnel will be pushed into the station, and when the training leaves the station, air in the station will be sucked into the tunnels to fill the vacuum zone behind trains.

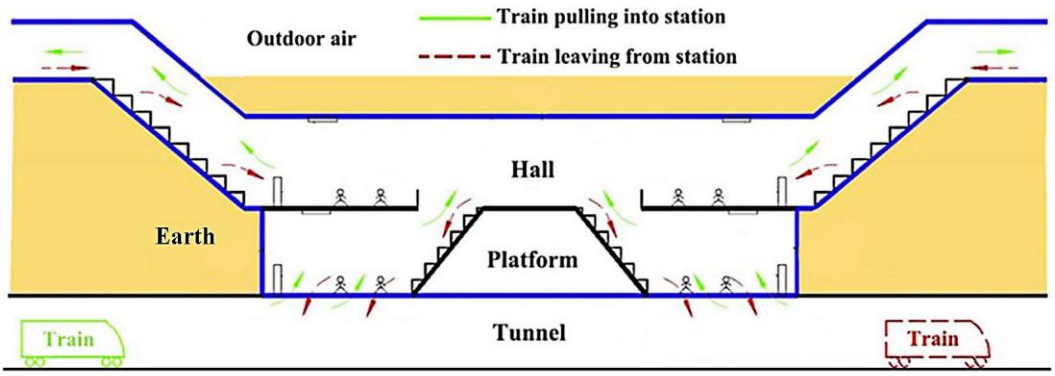

Figure 5: Air flow schematic of the piston effect in an island-type station (adapted from [53]).

4.1.1 Platform doors

Platform doors are a device installed on the side edge of rails in UMSs to prevent people from falling to tracks. Meanwhile, it can also help to minimize the impact of piston effect on the overall efficiency of HVAC systems in stations [42,51]. Generally, there are four types of platform doors in the market, namely, platform screen doors (PSDs), automatic platform gates (APGs), platform bailout doors (PBDs), and adjustable ventilation platform doors (AVPDs), as demonstrated in Figure 6.

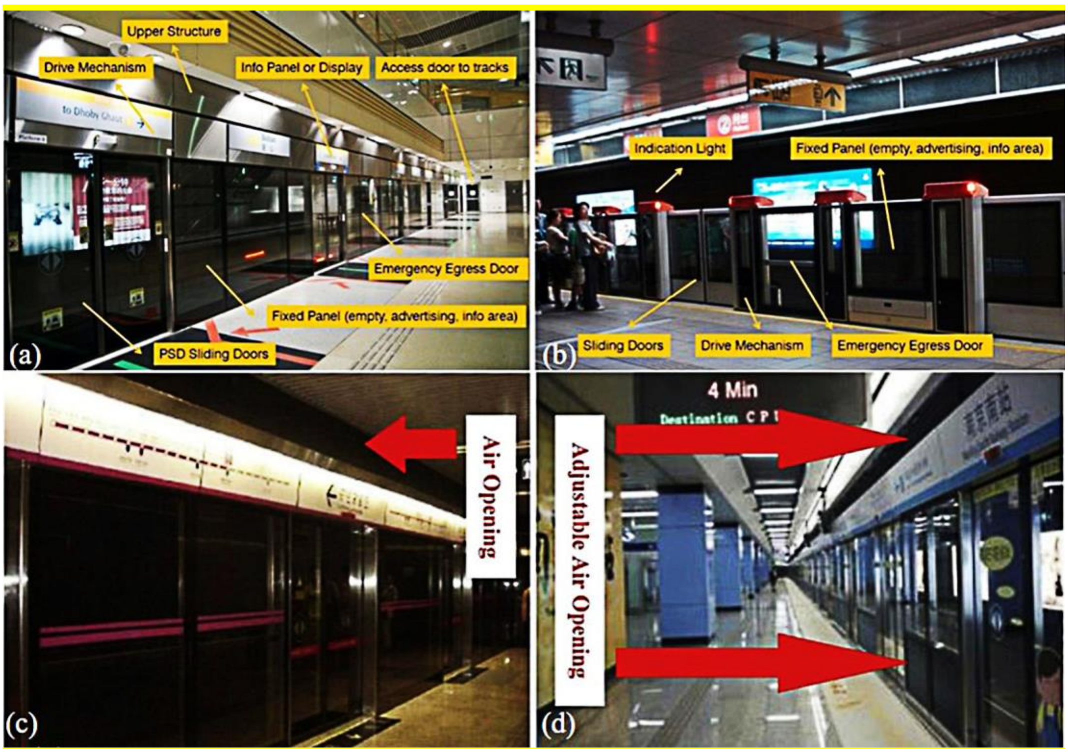

Figure 6: Platform doors in UMSs (a: PSDs; b: APGs; c: PBDs and d: AVPDs).

PSDs are full-height glass partitions with sliding doors, which completely isolate the platform from tunnels. The contribution of PSDs to system energy efficiency mainly happens in cooling seasons, by effectively separating the platform environment from heated tunnels. When using PSDs, Hu and Lee [42] have carried out a simulation study on Taipei metro stations and observed a reduction of peak load in public areas by around 50%, comparing to that without PSDs. This system, however, will increase the energy consumption of UPE fans, as the heat generated in the tunnels cannot be efficiently exhausted by the piston effect. Additionally, in non-cooling seasons, the energy consumption for station ventilation will also increase, as the airflow induced by trains cannot be utilized to provide fresh air.

APGs are chest-height sliding doors, usually with a height between 1.2-1.5m. The height of PBDs is often somewhere between PSDs and APGs. As both of them have the space above the door, they have the same effect on the piston wind. Their contribution to system energy efficiency is mainly by using the airflow induced by trains to cut down mechanical fresh air supply in non-cooling seasons. In northern China, the annual HVAC energy consumption of stations equipped with APGs has been found to be lower than that of PSDs by 6.4%, when UPE systems operate [54].

Recently, more studies have been carried out for a new type of platform doors, namely, AVPDs. AVPDs are also full-height doors, but with adjustable air outlets at either the upper or lower part. The air outlets of AVPDs will be closed in cooling seasons to reduce heat gain from tunnels, and they will be reopened in non-cooling seasons to make full use of the airflow induced by trains for ventilation. Yang et al. [55] have created a numerical model of AVPDs and proposed an operating scheme to analyze this solution's energy saving potential in eight cities in China. Their results showed that the energy-saving rate was ranging between 7.8-31.6%. Zhang et al. [56] used computational fluid dynamics (CFD) to analyze the position, size and open angle of air outlets for optimizing the performance of AVPDs, and found that optimized AVPDs could save 20.6-60.4% of energy compared to PBDs. Although AVPDs have been proven of having better energy performance than PSDs and PBDs, their energy performance was markedly influenced by local climatic conditions. For example, a study has found that the energy-saving rate of AVPDs was only 1% better than PSDs in places with hot climate and high passenger flow [57].

4.1.2 Door curtains

Although for most places there is no need for heating metro stations in cold seasons [18], its indoor temperature still needs to be maintained at appropriate levels [58]. This can be achieved by taking the heat released by train braking in tunnels by piston effect [59]. Adding door curtains can help to reduce the amount of cold air outdoors coming into stations from entrance. Meanwhile, it can also help to trap warm air inside stations. Ma et al. [53] have proposed a new type of door curtain with small rotation pieces, which can rotate automatically and harvest more heated air when trains drive in, as depicted in Figure 7. Their results given by the experimental model indicated that the hall temperature could be increased by 2°C when using this type of door curtain, compared to traditional door curtains.

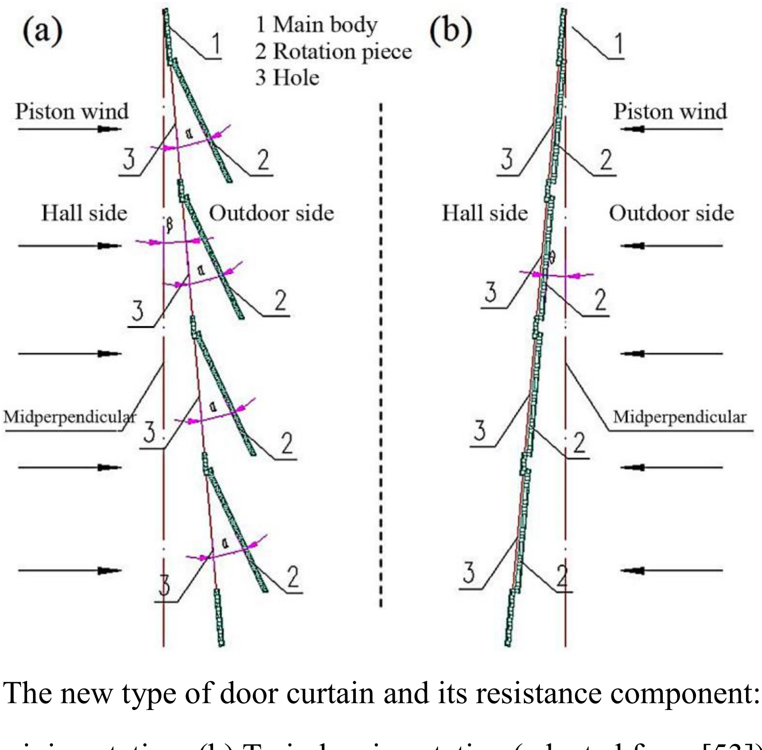

Figure 7: The new type of door curtain and its resistance component: (a) Train arriving station, (b) Train leaving station (adapted from [53]).

4.1.3 Mechanical fresh air supply control

Many studies have proven that an optimal control of mechanical fresh air supply can significantly reduce the ventilation load, due to the existence of airflow induced by trains [60–63]. By field experiments, Yang et al. [60] have found that the airflow induced by trains can help to keep CO_2 concentration in an appropriate range in most cases. Wang and Li [12] have proposed a method to simulate train-induced airflow, with a calculated airflow rate between 4.1-13.2 m^3/s under a resistance coefficient of PSDs between 0.11-0.35. Based on these results, they suggested that most UMSs in China no longer require mechanical fresh air if train-induced airflow can be used effectively. And this could help to save 3-23% energy consumption by the HVAC systems [64]. Guan et al. [38] have suggested to use a return air alone condition for ventilation, as illustrated in Figure 8. Under this condition, the outdoor air fan would be switched off but with damper V3 on, damper V1 off and damper V2 off, to utilize train-induced air for fresh air supply. When using this solution, the electricity consumption of the ventilation system was reduced by 10-20% in cooling seasons, compared to normal ventilation conditions. Similarly, in Nobosibirsk, Russia, Krasyuk [65] mentioned that the piston effect allowed effective ventilation of shallow stations without switching on fans when the outdoor air temperature was lower than 8ºC.

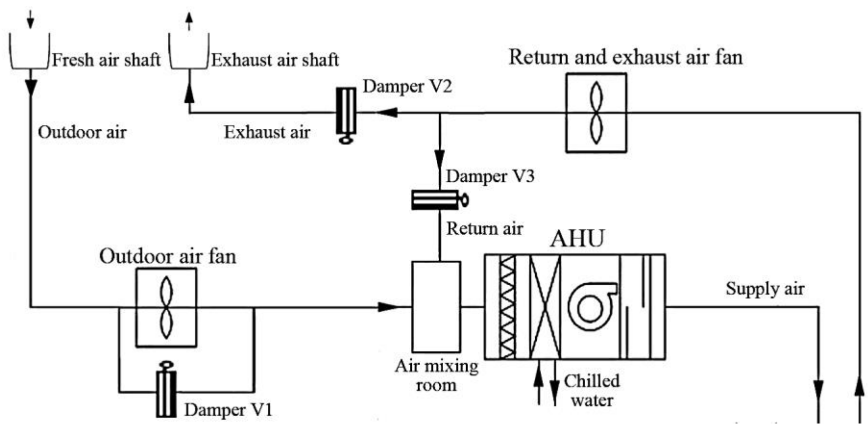

Figure 8: Air flow pattern in ventilation systems.

The mechanical fresh air supply control using piston wind to reduce the energy consumption of the mechanical ventilation system is easy to implement and can bring reliable energy-saving benefits. However, it is also a need to guarantee the train-induced air quality when using the piston wind to save energy from the mechanical ventilation system.

4.1.4 Variable frequency devices (VFDs)

Reducing the transportation energy required in HVAC systems is also one way of getting better energy performance. A field investigation in ten stations in Beijing has shown that the coefficient of performance (CoP) of refrigerators in the monitored stations were at 4.4 in average. However, due to the energy consumed by fans, pumps and cooling towers, the average energy efficiency ratio and the seasonal coefficient of performance were 27% and 48% respectively lower than the average CoP [46]. Yang et al. [17] have analyzed the operation condition of chilled-water pumps and fans with frequency conversion technologies and observed total power saving ratios ranging from 59.5-73.4%. Motors with inverters to enable variable speed operation of fans, as shown in Figure 9, have been suggested as an alternative to enhance the performance of ventilation systems [66]. Hu et al. [47] performed a study based on simulation for using variable frequency control for UPE fans in tropical climate, and obtained results showing that this solution could save 70-83% of electricity consumption, comparing to traditional control methods. The VFDs have been proven to be a reliable means of energy saving, with economic advantages in the long run, but the premise is based on a stable control strategy.

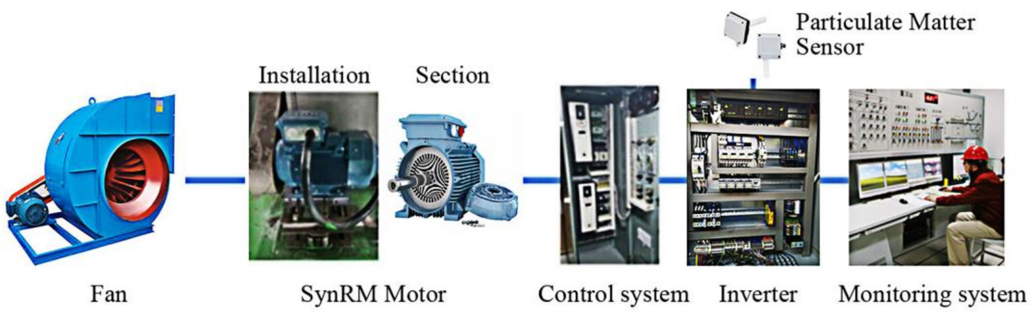

Figure 9: Ventilation system with inverter equipped in metro stations (adapted from [66]).

4.1.5 Direct expansion air-conditioning (DX A/C)

Figure 10 has shown the schematic diagram of another solution, called direct expansion air-conditioning system. In this solution, the refrigerant is evaporated in the cooling coils by absorbing heat in the supply airflow instead of chilled water. This system eliminates chilled water systems and relevant pipes, helping to save initial cost and operating energy consumption.

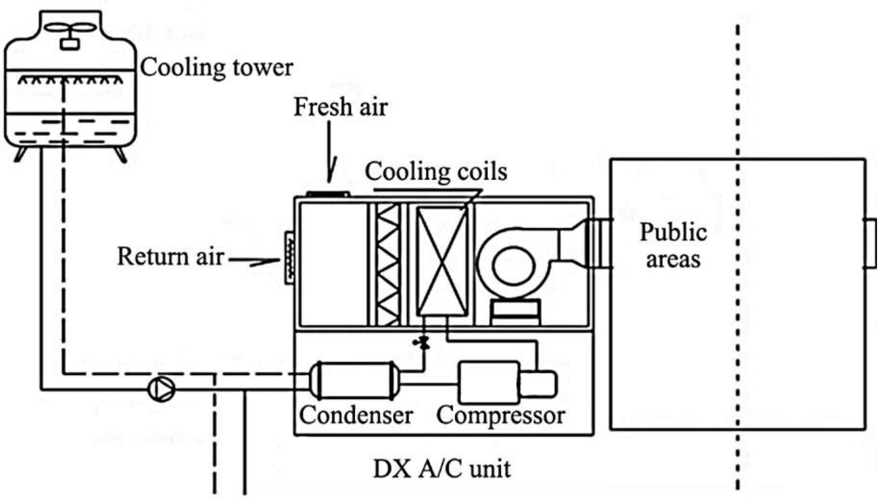

Figure 10: A schematic diagram for DX A/C systems.

A recent study has used DX A/C and evaporative condensers together in UMSs [67], the evaporative condenser of the system is working collaboratively with the fan installed on the wall to ensure the condensation effect. Comparing to traditional systems, the novel system is a refrigerant direct-expansion system, which can save both energy and space. Due to the removal of cooling towers, this system can also solve issues in terms of both noise and water leakiness. Additionally, the condensing temperature can be decreased due to direct expansion, hence increasing the system's CoP. An economic model has been applied to analyze the effect of using this solution in Beijing, and the results showed that it saved energy by up to 81,022 kWh annually, equaling to 11% of the energy consumption by conventional systems [67]. However, the operation performance of this system is affected by the changing external conditions, such as the air relative humidity and velocity on the condenser side, which limits its operational stability.

4.1.6 Optimized proportional-integral-derivative (PID) control

It has been well proven that implementing advanced control strategies can promote the performance of HVAC systems, in terms of both energy and occupant comfort [68,69].

Therefore, many studies have devoted to developing optimized PID control strategies for UMS ventilation systems. Their solutions mainly considered error dynamics and modulated controlled variables to understand the dynamically changing indoor environment in UMSs. Kim et al. [70] have compared the performances of four PI (proportional-integral)-based control strategies, namely, 1) feedback (FB) control only, 2) combining one FB and one feedforward (FF_1) control (used to control the disturbance effects of the subway schedule), 3) combining one FB and one feedforward (FF_2) controls (used to control disturbance effects of the outdoor PM10 by handling the ventilation inverter frequency) and 4) combining one FB and two FF controls. The FB controller controlled PM_{10} concentration by regulating the frequency of ventilation inverters to meet the set points. The results indicated that the solution with one FB and two FF controls gave the best energy saving performance. With further tuning of control parameters [71,72], the improved gain scheduling control system, as depicted in Figure 11, was proven to reduce energy consumption by up to 9% when compared to traditional control methods. Upon this solution, Li et al. [73] added an FF controller to consider the influence of passengers and a multi-objective genetic algorithm for automatically updating the system optimal set-points, with an noticed 10.3% reduction in ventilation systems.

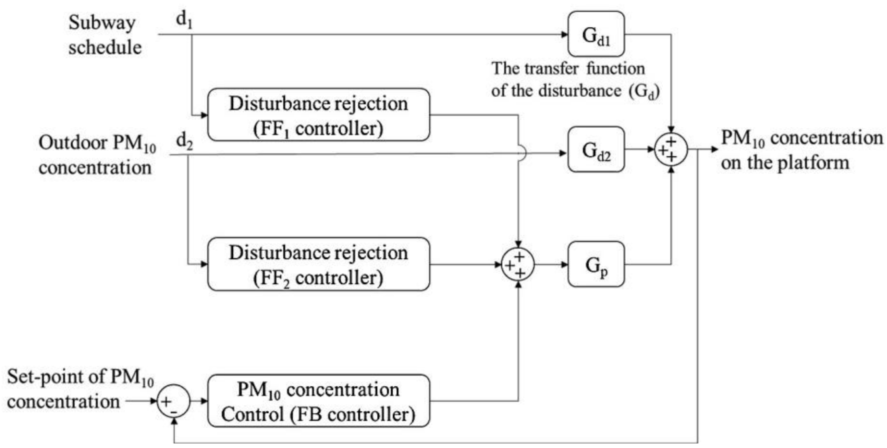

Figure 11: Block diagram of the ventilation control system for the metro station (adapted from [72]).

Lee et al. [74] have also developed a ventilation control algorithm based on PID control.

After re-tuning the proportional gain of PID controllers by a line-searching algorithm, the optimized control structure showed a 36% reduction in energy demand when compared to the open-loop structure. Kim et al. [75] implemented iterative dynamic programming into the control of ventilation systems to decide the optimal set-points, and the system reduced the energy consumption by 4.6% comparing to schedule-based systems. According to these studies, the optimized PID control for ventilation systems can be classified into three categories, namely, adding control modules for different disturbances, tuning the control parameters, and optimizing the control set-points. These optimization measures are universal and can be extended to different types of public infrastructures including airports and coach stations, without a priori knowledge and human intervention.

4.1.7 Model predictive control（MPC）

MPC is a promising control approach for HVAC systems, because of its ability of optimizing both linear and non-linear multi-input/multi-output processes, with explicit consideration of potential constraints [69]. In 2011, one European Union project (Sustainable energy management for underground stations, SEAM4US) developed an intelligent energy management system to reduce electricity consumption of metro stations [18,76–80]. This system is based on an MPC algorithm coupled with a monitoring network. The MPC algorithm was based on a Bayesian environmental prediction model (using weather data predicted by a weather forecast web service), an occupancy detection system, and schedule-based determinations of train arrivals and fan operations. As the MPC approach allows earlier actions to change system settings, in a case study carried out in Barcelona, it helped to achieve an energy saving greater than 30%.

Rigaut et al. [81] have presented an MPC-based strategy for the optimal management of a microgrid, which connects regenerative braking energy sources, HVAC systems and electricity storage systems in metro stations. Liu et al. [19] utilized a multi-objective genetic algorithm to optimize MPC setpoints and achieved a 24% energy saving compared to schedule-based control. Nevertheless, the stability of these MPC systems may become difficult to maintain with more complex control algorithms [69]. For example, the predictive model in the MPC is usually a grey box system based on both simulation model and field tests. If the real situation is beyond its design conditions, such as in cases of extreme climate or building retrofitting, the control accuracy will lose guarantee. Thus, the system needs updating control models at certain time intervals.

4.1.8 Other control strategies

Other control strategies, such as adaptive control and reinforcement learning control, [82,83] have also been applied in existing studies. Wang et al. [84] retrofitted HVAC control systems in UMSs based on distributed control architecture with centralized management. Both adaptive control and schedule-based policies were developed according to the components of HVAC systems, and helped to reduce the energy consumption of stations between 20-38%. Heo et al. [82] have proposed a data-driven approach for a ventilation control system based on a deep reinforcement learning algorithm. The algorithm agent was trained in a virtual environment developed based on a gray-box model, and their results showed that the control system could reduce the energy consumption by up to 14.4% for the validation dataset. The deep reinforcement learning algorithm, however, took an unacceptably long time to learn the data and therefore was difficult to ensure stability and efficiency in real practice.

It should be noted that the operation of these intelligent control systems is based on a large-scale monitoring system, which contains various sensors and actuators. The wireless sensor network has been increasingly used in UMSs for connecting a control system with different devices, and this will increase both initial investment and maintenance costs [18,85,86].

4.2 Energy saving strategies for the UPE system

For underground metro networks, the heat absorbed by the earth surrounding an underground tunnel can account for 30% of the total heat lost [87,88]. The heat energy provided by tunnels could potentially be captured, transferred, and utilized by heat pumps. The use of heat pumps may lead to energy conservation in heating as they can perform between 2-4 times more efficiently than electrical resistors [20]. Moreover, heat pumps can help cool the tunnel and reduce the UPE energy consumption as well.

Common sources of heat for heat pumps used for UMSs include air, ground, and water. The work done by Ninikas et al. [89] found a relatively stable temperature (average temperature during winter = 15°C, annual variation = 2.6°C) and enough air movement inside the tunnels of the metro system in Glasgow through field tests, and decided to use this character to collect heat from tunnel air for space heating and domestic hot water. The energy consumption of air source heat pumps (ASHPs) is expected to be 75% less than existing electric fired heating systems. Davies et al. [90] have proposed an air source recovery method through the ventilation shafts of London underground tunnels (see Figure 12 left), and this system can simultaneously provide 900 kW cooling to the tunnel and 1.1 MW heat for local district networks.

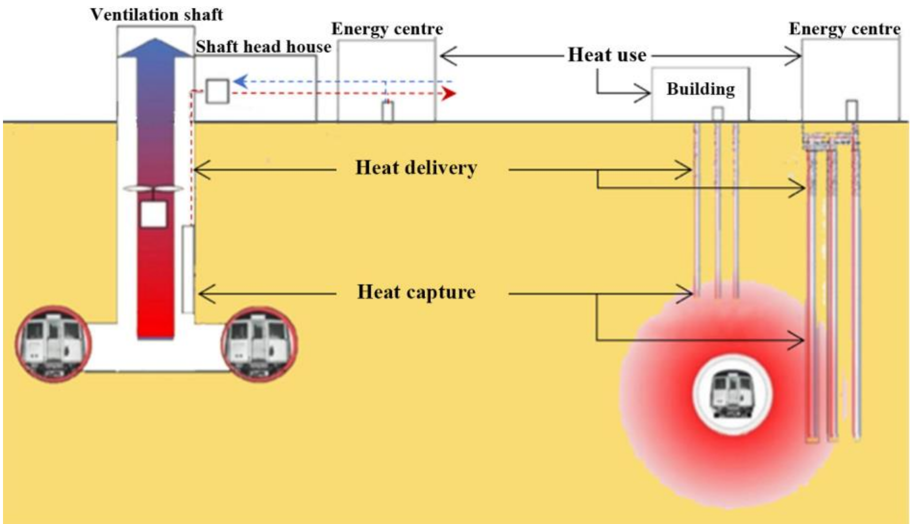

Figure 12: Heat recovery from tunnel air (left) and ground (right) (adapted from [87]).

Besides recovering heat from tunnel air, energy has been recovered by external ground loops as well, as shown in Figure 12 (right). Revesz et al. [87] have reviewed the interactions between ground source heat pumps (GSHPs) and urban underground tunnels, and pointed out that underground tunnels were appropriate heat sources for nearby heat pumps. Mortada et al. [91] presented a simulation framework for quantifying the amount of heat that can be extracted from overheated subway tunnels using geothermal heat exchangers. Their results showed that the depth of 15 m below the tunnel was sufficient for vertical closed-loop heat exchangers to yield a temperature drop of 4°C in the metro stations in London, and a single tunnel bore-hole's annual heat extraction could be about 9336 kWh, equaling to the average annual heat demand of one UK household.

There are also attempts to use groundwater as a direct cooling source for stations [92] and water source heat pumps (WSHPs) to recovery heat energy from tunnel waste water for heating and domestic hot water [93–95]. Ninikas et al. [95] installed a WSHP at St. George's Cross station in Glasgow, using subsurface wastewater to heat all offices at the station. In the study, they realized a 60% energy usage reduction of the heating system, against the value of the old heating system. Although the use of WSHPs and GSHPs can recovery a great amount of heat, these systems are more complex and expensive than AHSPs, and their applications are restricted by geographical conditions.

Meanwhile, some researchers also tried to promote terminal heat exchangers to enhance the overall performance of GSHPs. Thompson et al. [96] have evaluated the possibility of strengthening ground cooling using heat pipes for UMSs using a model experiment. This was further explored by Brandl [97], who combined heat pipes with heat pumps for heating and cooling stations in Vienna, as shown in Figure 13. Similar studies were carried out in northern China as well [98–100], where Zhang et al. [98] conducted an experimental study on the thermal performance of tunnel lining ground heat exchangers. They indicated that the inlet temperature and the flow rate of heat exchange medium and heat exchange pipe distance were important parameters affecting the heat exchange rate of heat exchangers. Capillary heat exchangers have also been used in underground tunnels to promote heat exchange recently, and their performance has been investigated in some numerical studies [101–104]. These studies simulated the heat transfer performance of the capillary with different influencing factors, including water flow velocity, initial temperature of surrounding rock and tunnel air temperature, etc., but the energy-saving potential of this heat exchanger has still not been quantified.

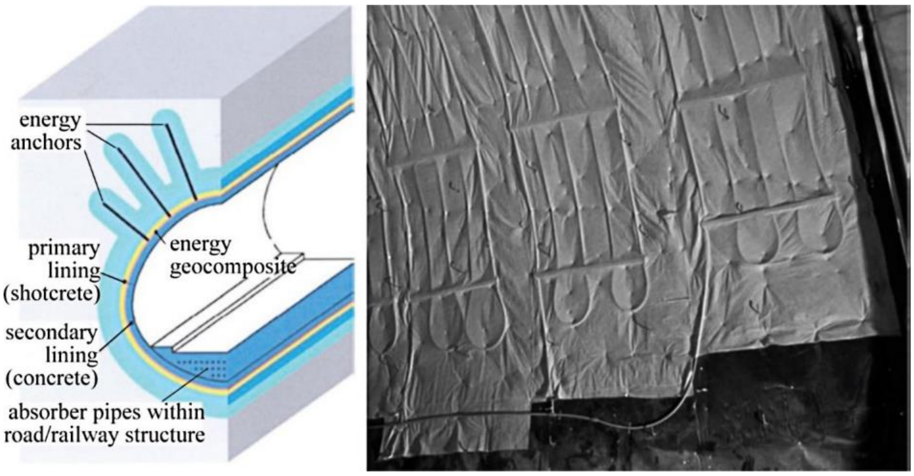

Figure 13: Schematic of an energy tunnel (adapted from [97]).

4.3 Energy saving strategies for the tunnel ventilation system

Since a large part of the cooling load in stations is from the train movement in tunnels, cooling tunnel environment will effectively reduce the burden of HVAC systems in UMSs [105]. A reasonable design of ventilation shafts can help to improve tunnel ventilation with minimized energy input.

Ke et al. [50] have explored the impact of various ventilation operating strategies in metro environment for optimizing the design of HVAC systems. From the study, they concluded that the cross-sectional area of ventilation shafts was quite more effective on ventilation volume than length, with 40% more airflow rate achieved by doubling cross-sectional area. González et al. [49] presented a numerical study based on a dynamic mesh technique to simulate the influence of piston effect in longitudinal ventilation systems of metro tunnels, with an estimated overall energy saving between 2.5-3.0%, taking into account the airflow caused by train movement. Using a three-dimensional numerical analysis, Kim and Kim [106] analyzed the effect of duct location on the ventilation performance in one metro tunnel and evaluated the ventilation efficiency of PSDs. From the study, they suggested the optimum location of the vent shaft giving maximum ventilation performance lies near the upstream of the station.

5. Discussion and future work

Although current existing HVAC systems in UMSs can exhaust redundant heat and provide fresh air, it is not enough to achieve metro environmental control solely based on providing adequate capacity to satisfy given criteria [25,107]. On the contrary, it is necessary to achieve the overall optimization of the entire HVAC system. The design objectives ought to be geared to obtain the most efficient utilization of economic and natural resources. Existing studies have designed or developed various HVAC strategies to meet these goals and each HVAC discipline has specific design requirements and presents opportunities for saving energy. To promote their applications in UMSs, this section has compared the mechanisms and the energy saving potential of these strategies, and proposed future research directions based on this analysis.

5.1 Classification based on operational mechanisms

The use of platform doors, door curtains and ventilation shafts are mainly based on changing the geometry (resistance) of the piston airflow path, and thus to control the airflow rate of piston wind in public areas or tunnels. To avoid energy waste, mechanical fresh air supply control, VFDs, optimized PID control, MPC and other control strategies are mainly based on demand control strategy. DX A/C uses refrigerant to directly absorb heat from fresh air and save cost in the cooling part by changing configurations. ASHPs use the relatively stable environment inside tunnels to improve systems' CoP. GSHPs and WSHPs recover heat energy from ground and subsurface water around metro tunnels, respectively. Heat pipes and capillary heat exchangers enhance the heat exchange between tunnels and earth by increasing heat exchange area.

In the view of building energy conservation, platform doors, door curtains and ventilation shafts can be considered as passive strategies because they use energy in natural environment (train-induced airflow) to air-condition the indoor environment of stations, so should be preferred in real applications [108]. Active strategies, which consume energy to satisfy the needs of cooling/heating buildings, can be classified into two classes: 1) energy-efficient HVAC equipment, such as VDFs, DX A/C and heat pumps; and 2) advanced control systems, like the system based on the demand control strategy.

5.2 Comparison of energy performance

Finding out the most appropriate HVAC system for a given UMS is a complex evaluation process that requires a detailed analysis on energy considering various influential factors. Table 3 lists three aspects relevant to evaluating the energy saving potential of reviewed strategies. For the environmental criteria, only the MPC can control temperature, CO_2, and PM concentration simultaneously. Additionally, most control strategies aim at controlling ventilation systems to regulate temperature, rather than controlling air conditioning systems. It can also be seen that when passive strategies are used, there is usually a lack of control on the concentration of PMs. For study methods, the simulation method is dominantly used, with validation against field measured data. This is excusable as full-scale experimental models are generally costly in both finance and time [109]. However, in terms of simulation, the main simulation tool is design for the station thermal environment rather than systems' energy consumption. For energy performance, the energy-saving potentials of these strategies showed great differences, and the same strategy even performed differently in different studies. A possible explanation is because of the various influential factors and different benchmarks in complex metro systems.

5.3 Future work

According to the review work carried out in this study, some notes have been proposed for saving HVAC energy demand in UMSs, to better underpin future energy analysis. They include 1) when using train-induced air for ventilation, it is necessary to consider the impact of both tunnels and outdoor air quality on stations' IAQ; 2) energy models or evaluation systems for underground stations are still needed for evaluating the energy performance of each strategy under standard conditions; 3) with energy recovery when running metro trains, such as using regenerative braking and energy-saving slope technologies, the amount of heat dissipated in tunnels will be reduced, affecting the environments both in tunnels and stations; 4) since most studies on energy conservation strategies are still in pilot or a modelling stages, more studies are needed to justify their actual impact in real situations.

Table 3

Energy saving potential of the reviewed strategies for UMSs.

Category	**Environmental criteria**	**Study methods**	**Energy saving rate**	**Ref.**
PSDs	Temperature, CO_2	Simulation (SES, carrier E20-II) with on-site measurements	The peak load for the case with PSD is only around 50% of that for the case without PSD	[42]
APGs and PBDs	Temperature, CO_2	Simulation (Energy Plus) with on-site measurements	The annual air conditioning and ventilation energy consumption of APG is lower than that of PSD system by 6.4%	[54]
AVPDs	Temperature, CO_2	Simulation (CFD, STESS, IDA) with on-site measurements	1-20% compared with PSD system 7.8-31.6% compared with PSD system 20.64-60.43% compared with PSD system	[57] [55] [56]
Door curtains	Temperature	Simulation (IDA) with on-site measurements	The hall temperature would increase 2°C	[53]
Mechanical fresh air supply control	CO_2	Simulation (STESS) with on-site measurements	9.9% and 19.6% in two stations under the return air alone condition If the mechanical fresh air supply is abandoned, there would be 3-23% energy saving of the HVAC system	[38] [64]
VFDs	Temperature, CO_2, PM	Theoretical calculation and simulation	59.5-73.4%	[17]
DX A/C	Temperature	On-site measurements	11% when combined with the evaporative condenser	[67]

Optimized PID control	PM	Simulation (MATLAB) with on-site measurements	4.6-36%	[73–75]
MPC	Temperature, CO_2, PM	Simulation (MATLAB, CFD) with on-site measurements	24-33%	[18,19]
ASHPs	Temperature	On-site measurements	75% less compared with the existing electric fired heating system	[89]
GSHPs	Temperature	Simulation (MATLAB, IDA) with on-site measurements	The heat from the tunnel per meter is 3100 kWh/m	[91]
WSHPs	Temperature	Theoretical calculation and on-site measurements	60% energy input reduction for the heating system	[95]
Heat pipe	Temperature	Theoretical calculation	Reduction natural gas costs on 34,000 m^3 per year	[97]
Capillary heat exchanger	Temperature	Simulation (MATLAB, TRNSYS)	The heat transfer characteristics are studied but no energy saving results	[101,104]
Ventilation shafts	Temperature	Simulation (CFD, STESS, SES)	2.5-3%	[49]

6. Conclusions

UMSs are rapidly developing, and their energy consumption is considerably growing. The HVAC systems used in UMSs are key energy consumers, so have received increasing attention from researchers in the world. This review work has summarized major design features of HVAC systems in UMSs and identified issues affecting their energy efficiency. A systematic review on recent novel energy saving HVAC strategies for UMSs has been presented in this paper, with a total number of ten different strategies. From the review work, main conclusions have been drawn as followings:

(1) Platform doors, ventilation shafts and door curtains are classified as passive strategies related to using the train-induced air, and they are preferred for designing energy efficient UMSs. From the aspect of active strategies, heat pumps used to recover heat from the UMSs are becoming a trend in the research community, especially geothermal technologies. The DX A/C is another promising option for air conditioning energy saving. However, the actual energy performance of these two types of technologies is usually greatly affected by the actual operating conditions. In comparison, the application of VFDs is one of the most reliable energy-saving ways among the active strategies.

(2) For the existing HVAC systems in UMSs, the implementation of operational measures is normally preferred to the introduction of new technologies, as significant energy savings can be achieved with relatively low investment costs and minor modifications. Thus, adopting advanced control strategies have been identified as the most promising solutions for those systems. Currently, these strategies are continually being proposed for their vital ability to reduce the energy use of HVAC systems in long-term running. Among them, the algorithm-based approaches are effective based on the careful design and maintenance of the system. On the other hand, reducing the mechanical fresh air supply has been proved an easy-to-operate control strategy with appropriate cost and it is recommended along with the passive strategies and VFDs.

(3) Although various energy saving strategies have been proposed for the HVAC systems of underground stations, there are still limitations identified in the study for different reasons. To better underpin the future energy analysis of the reviewed strategies, four suggestions were proposed for the future evolution of the HVAC system. Additionally, based on the proved energy-saving potential of existing strategies, it can be inferred that the continuous improvement of the HVAC energy-saving strategies will make greater contributions to the reduction of energy consumption and carbon emissions of the ever-expanding urban metro networks.

Declarations of interest

None.

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