Energy Consumption of the VAC System for Subway Stations: A Model Based on Theoretical Analysis and its Engineering Application

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Abstract. With the continuous expansion of the subway scale, the amount of energy consumed by subway stations has become a concern, among which the energy consumption of ventilation and air-conditioning (VAC) system takes a large proportion. There are many former studies concentrated on this topic. However, the problems of previous studies are obvious, such as time-consuming and unclear practical meaning of the energy model. This study has proposed a model based on theoretical analysis and focused on the energy model of the VAC system for underground subway stations. The energy model consists of the model for the cooling load and the energy efficient ratio. In this model, basic station information and environmental parameters should be tested and inputted. Then with the help of simple simulation tools, Subway Thermal Environment Simulation Software (STESS), the energy consumption of the station can be fast estimated by the model proposed in this paper. This model can be applied to determine the energy-saving potential of changing operation pattern and adopting energy-saving technologies, which gives guidance to the energy-saving retrofit of the station.

1 Introduction

1.1 Background

Nowadays, with the rapid economic development, more and more cities are equipped with the subway system to improve urban infrastructure. It has been pointed out that by the end of 2014, more than 20 cities have constructed the subway system in China [1]. According to statistics, annual electricity consumption ranges from 131 to 144 kWh/m² in underground non-transfer stations in China [2], among which the energy consumption of the station accounts for about 42% of the total energy consumption of the urban rail transit system in Beijing [3]. Similarly, for subway with the same level of operating mileage, the energy consumption conditions are similar to that of Beijing [4]. According to Annual Report of Urban Rail Transit (2014), the energy consumption composition of the underground subway station is shown in Fig. 1[1]. The VAC system accounts for 54-71% of the total energy consumption, followed by the lighting system (21-27%). The vertical transport system takes up approximately 14-21%, while the proportion of the drainage system and other devices are relatively small (9-12% and 2-5%, respectively).

By the large expansion of the subway scale in many cities, the amount of energy consumed by subway stations has drawn a large amount of attention, considering that the subway energy conservation project is of great significance in reducing the cost of the subway operators and the energy supply burden of the

Fig. 1. Statistical data on energy consumption

1.2 Literature review

districts or even the country.

In order to calculate the energy consumption, many researchers have established the energy models for subway stations. Traditionally, the energy consumption is modelled by the computer-based simulation tools, including DOE-2, Energy Plus, BLAST, etc. Former researchers have put forward the framework of energy use model for underground subway stations, considering building construction, ventilation, occupant behaviour, and environmental conditions [5]. Li has evaluated the indoor thermal conditions and their influencing factors on a train station building via Computational Fluid Dynamics (CFD) software [6]. Generally, simulation method could describe the detail information for each case studied. However, the process is extremely time-

Drainage Other devices Vertical system 2-5% 14-21% Lighting system 21-27% VAC

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consuming and resource-intensive, making it not suitable to be applied widely in actual engineering projects.

Also, numerous studies have focused on the regression analysis for different types of buildings such as five-star hotels, railway passenger stations, large commercial complexes, etc[7-9]. The advantages of the regression model lie in two aspects. One is that the calculation process is simple and fast. Another is that it serves as the benchmark and assessment standard for current buildings. Nevertheless, regression model cannot comprehensively analyse the energy-saving potential, in that the principles concerning the operation are not considered.

Thus, in this study, theoretical energy consumption model for the VAC system of the subway station is proposed. The input parameters are characterized by simplicity and accessibility for engineering application. The suitability and accuracy of the model has been validated via field tests and simulation. The model proposed in this paper serves as an effective tool to guide the overall energy-saving projects of subway stations in that it reveals the operation principle of each part and the results can be fast obtained.

2 Energy model for VAC system

The energy model for the VAC system is related to the cooling load, the energy efficiency ratio (EER) and the operation mode:

$$W_{\rm VAC} = Q_{\rm VAC} \cdot EER \cdot \tau_{\rm VAC} \tag{1}$$

Where W, Q and τ are the energy consumption (kWh), cooling load(kW) and operating time (h) respectively; the subscript VAC represents parameters related to the ventilation and air conditioning system.

2.1 Cooling load model

Subway stations are commonly located underground. Thus, the heat gain is considered as the cooling load in this model. According to the character of heat gain, the cooling load of the VAC system is composed of the following parts.

2.1.1 Heat dissipation of the passengers

The $Q_{\text{passenger}}$ is determined to the number of passengers and the time they spent in the station, which can be calculated by the following equations.

$$Q_{\text{passenger}} = q_{\text{p}} \cdot (N_{\text{hall}} + N_{\text{platform}})$$
(2)

$$N_{\text{hall}} = (A_{\text{in}} \cdot a_1 + A_{\text{out}} \cdot b_1)/60 \tag{3}$$

$$N_{\text{platform}} = (A_{\text{in}} \cdot a_2 + A_{\text{out}} \cdot b_2)/60 \tag{4}$$

Where N is the equivalent passenger number, person; q_p is the heat dissipation of a standard adult man, kW; A_{in} and A_{out} are the number of passengers getting in and out of the station, respectively, person/h; the subscript *hall* and *platform* represent parameters related to the hall and the platform respectively; a_{1,a_2} and b_{1,b_2} are coefficients related to the time spent in the station, min.



Fig. 2. Cooling load model for $Q_{\text{passenger}}$

2.1.2 Heat gain from the unorganized air infiltration

There are two passageways for the unorganized air infiltrating into the station: the entrance and the PSD. The $Q_{\text{infiltration}}$ could be calculated by equation (5).

$$Q_{\text{infiltration}} = \rho \cdot (G_1 \cdot \Delta h_1 + G_2 \cdot \Delta h_2)/3600$$
(5)

Where ρ is the air density, kg/m³; G_1 and G_2 are the infiltration volume through the entrance and the PSD respectively, m³/h; Δh_1 is the enthalpy difference between the indoor and outdoor air, kJ/kg; and Δh_2 is the enthalpy difference between the indoor and tunnel air, kJ/kg.

In this model, the first step is to obtain the air infiltration volume. The Subway Thermal Environment Simulation Software (STESS) is applied to simulate the dynamic air infiltration volume[10].



Fig. 3. Part of the STESS model



Fig. 4. Cooling load model for $Q_{\text{infiltration}}$

The input parameters of this part and its sources have been listed in **Fig. 4.** By carrying out the ventilation simulation module of STESS and the calculation of the proposed model, the heat gain of the unorganized air infiltration through the entrance and the PSD can be obtained.

2.1.3 Heat gain from the envelope

The envelop of the underground subway station consists of the wall and the PSD.Considering that the heat storage ability of the PSD could be ignored, the Q_{PSD} can be simplive calculated by equation (6).

$$Q_{\rm PSD} = K_{\rm PSD} \cdot F_{\rm PSD} \cdot (t_{\rm tunnel} - t_{\rm in}) \tag{6}$$

Where K is the heat transfer coefficient, $kW/m^2 \cdot K$; F is the area, m^2 ; t is the air temperature; the subscripts PSD, tunnel and in represent parameters related to PSD, tunnel and indoor respectively.

As for the Q_{enve} , we have compared 3 calculation methods, including steady-state method, threedimensional simulation via CFD software and a simplified unsteady-state method, to determine the suitable and efficient one for underground subway stations. The result is discussed in **Section 3.1**.

2.1.4 Heat gain from the mechanical fresh air

The $Q_{\text{mech air}}$ can be calculated by the following equation.

$$Q_{\text{mech}_air} = \rho \cdot G_{\text{mech}_air} \cdot \Delta h_1 / 3600 \tag{7}$$

Where the subscript *mech_air* represents parameters associated with the mechanical qir supply.

The demanding fresh air volume is determined by the number of passengers according to the standard for indoor air quality. The mechanical air volume should be determined by the difference between the demanding amount and the unorganized infiltration amount.



Fig. 5. Cooling load model for $Q_{\text{mech air}}$

2.1.5 Heat dissipation of the station devices

The devices in the station include the lighting equipment, vertical transport system and other devices. Based on theoretical analysis, there are several parameters that are related to the heat dissipation of these devices, including the lighting power density, the passenger flow, the raising height and operation mod of the vertical transport, etc. Taking these into consideration, the detailed models for different types of devices are established.



Fig. 6. Cooling load model for Q_{device}

2.2 Energy Efficient Ratio Model

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EER = 1 / (1/EER_{rLV} + 1/WTF_{chwLV} + 1/EER_{tLV}) (8)
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Where the subscripts rLV and tLV of EER represent the refrigerator and the end equipment respectively; WTF_{chwLV} is the water transfer factor of the chilled water.

3 Discussion

3.1 Calculation model for heat transfer through the wall

The CFD simulation has been done using PHOENICS and the studied model is shown in **Fig. 7**. The results reveal that the one-dimensional steady-state simplified method can be applied in deep-buried buildings (-10m below the ground). And for shallow buried buildings, steady-state method doesn't fit well whereas the relative error between the simplified unsteady-state method and the detailed CFD simulation is within 5%.



Fig. 7. CFD model for the calculation of heat transfer through the wall

Therefore, in this study, different methods are applied in the calculation of the envelope heat transfer of the platform and station hall floors. The station platform is usually 15m below the ground surface, with the constant soil temperature. Thus, the heat transfer of the platform wall is suggested to be calculated by the steadystate method. On the other hand, the depth of the hall is approximately 5-10m, where the influence of the annual temperature fluctuations cannot be neglected. Therefore, the simplified unsteady-state method is expected to be applied in the calculation of heat transfer of the hall wall.

3.2 Validation of the model

The accuracy and suitability of the proposed model has been validated using the annual overall statistics collected in a station located in China. In this process, field tests have been carried. The results of STESS simulation are given in **Table 1**.

Table 1.	Result	of the	STESS	simulation
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Train Departure Density (h ⁻¹)	$G_1(\times 10^3 m^3/h)$	$G_2(\times 10^3 m^3/h)$
7	28.3	34.0
8	38.9	40.2
9	30.9	38.0
10	30.6	43.1
11	28.5	46.5
12	24.8	47.3

Results show that cooling load model is applicable for the prediction of the hourly (or daily) cooling load, with the relative deviation below 16% (or 10%) and that of the energy consumption model is below 13%.



Fig. 8. Validation of the model for hourly cooling load

Daily Cooling Load of the VAC System



Fig. 9. Validation of the model for the daily cooling load



 $\label{eq:Fig.10.Validation of the energy model for the VAC system$

3.3 Application of the model

The most distinct advantage of this model lies in that the calculation process is fast and effective, using only several parameters that is easy to obtain in the actual operation of the station. And it can be applied to determine the energy-saving potentials of the operation management and energy-saving technologies.

For instance, in the studied station, the unorganized air infiltration volume is no less than $62.3 \times 10^3 \text{m}^3/\text{h}$ and the mechanical fresh air supply is $74.6 \times 10^3 \text{m}^3/\text{h}$, which is much more than the designed $13.0 \times 10^3 \text{m}^3/\text{h}$ (12.6m³/person/h) If the mechanical fresh air supply was abandoned, there would be 58% energy savings of the VAC system for a cooling season.

Besides, there are other energy-saving approaches that can be further analysed using the model proposed in this paper. Moreover, the application is suitable for other subway stations.

4 Conclusion

In this paper, the fast and effective energy calculation model for the VAC system of underground subway stations has been established and validated The model can be used to determine the energy-saving potential of changing operation pattern and adopting energy-saving technologies, which gives guidance to the energy-saving retrofit of the station. In future, further studies will concentrate on the extensive research on the database of the parameters in this model to give the guideline of VAC energy consumption for subway stations. And more energy-saving measurements will be studied to instruct energy-saving projects of subway stations.

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