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NUMERICAL EVALUATION OF ENERGY CONSUMPTION AND INDOOR ENVIRONMENT IN SUBWAY ISLAND PLATFORM WITH DCV SYSTEM

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ABSTRACT

This paper established a demand control ventilation (DCV) strategy for subway platform. Firstly, steady-state CFD simulation was carried out to predict the space CO_2 distribution in the platform. Secondly, both CO_2 control point and base ventilation rate were determined. Then authors developed a DCV dynamic model by control processing simulation. The simulation results show that using this ventilation strategy can achieve an acceptable indoor air quality. Additionally, comparing with the conventional CAV system and VAV system, this strategy can save about 30.16% and 8.21% of the annual energy consumption, respectively.

INTRODUCTION

CO_2-based demand controlled ventilation (DCV) is a method to modulate outside air ventilation based on real-time occupancy. Fig. 1 is the control diagram of a typical DCV system. When properly applied, it can reduce unnecessary over-ventilation and then offer significant energy savings over traditional fixed ventilation approaches (e.g. Wachenfeldt et al., 2007). The best potential applications for DCV are indoor spaces with high occupancy density and highly variable occupancy, e.g., conference rooms or educational buildings. However, limited previous researches can be found for the application of this kind of ventilation strategy in subway stations, where shows obvious variability of passenger flow (Jiang et al., 2008). The aim of this study is to develop the model of DCV system for subway platform and evaluate the energy saving by numerical simulation.

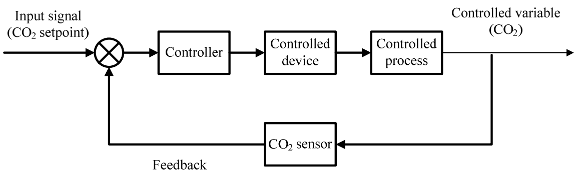

Figure 1 Control diagram for DCV system

MODEL SUBWAY PLATFORM

This study selected an existent subway island platform in Guangzhou. The platform screen door (PSD) system has safety doors along the platform close to the track. The dimension of this station is 120m(L)×10m(W)×4.8m(H). There are 76 supply air inlets installed on the two sides of the ceiling, and 37 exhaust outlets installed on the ceiling close to PSD. The layout of the platform is shown in Fig. 1. The runtime of this subway is from 5:00 to 24:00.

CFD SIMULATION

CO_2 sensors are typically mounted in the return or exhaust air duct for DCV system. Therefore the duct-mounted readings should be modified if there is a diverse occupancy density in the space (Schell et al., 1998). In this study, CFD simulation was carried out to study the CO_2 distribution in the platform, and then find the relation between CO_2 concentration of exhaust airstream and the mean CO_2 level in the platform.

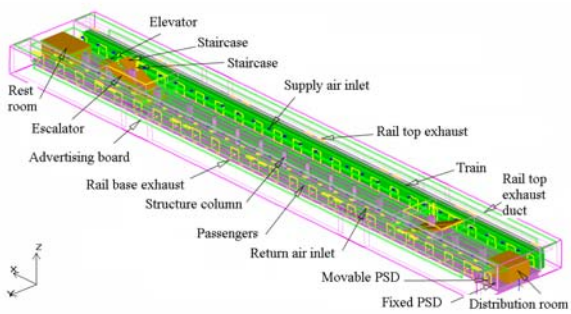

Figure 2 Three-dimensional model of subway island platform

Simulation conditions

Authors used commercial CFD software and standard k-ε turbulent model for simulation. The main simulation conditions are listed below.

Because the real platform is too complex to simulate by CFD, some simplifications have to be taken:

(1) Consider the enclosure of platform as thermal-isolated surfaces.

(2) Assume the generation of lighting load is evenly on the ceiling.

(3) Simplify the crowd of passengers as a solide cube.

(4) Conduct only steady-state simulation when the PSDs are closed. Additionally, neglect both PSD infiltration and exfiltration.

(5) Neglect the air exchange through exits.

Table 1
CFD simulation conditions

Comments	**Values**
Lighting and equipment load	Lighting density 20W/m^2; each elevator 7kW; each escalator 15kW; advertisement lamp-boxes 15kW; PSDs 30kW
Passenger load and CO_2 emission rate	1200 passengers at rush time; total heat gain 181.43W/p; sensible heat gain 46.52W/p; CO_2 generation rate 45g/(h•p)
Inlets	Design airflow rate 920m^3/h; air temperature 19^{o}C; air CO_2 concentration 700ppm
Outlets	Based on mass balance
Wall	Standard log-law

Simulation results

Fig. 3 shows the distribution of CO_2 concentration at the height of 1.65m above the platform. It shows that CO_2 is not well-mixed, ranging from 800 to 1500ppm for most of the passenger area, with an average value of about 1000ppm. The reason is mainly due to the unperfected ventilation design. This study used the CO_2 concentration in the exhaust duct plus 300ppm to ensure most of the passenger area is adequately ventilated.

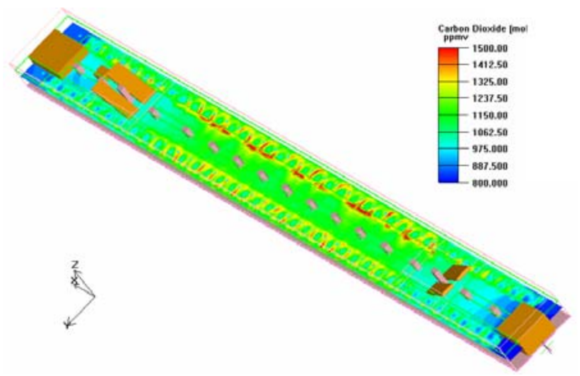

Figure 3 CO_2 concentration distribution at the height of 1.65m above the platform

DETERMINATION OF BASE VENTILATION RATE AND CO_2 CONTROL POINT

A DCV system must maintain a minimum ventilation airflow rate to control non-occupant-related contaminants, which are emitted from furnishings, equipments or other materials within the space. This base ventilation rate generally ranges from 10% to 50% of the design ventilation rate (Schell et al., 1998). For subway station, these contaminants include PM_{10}, CO, VOCs, radon and so on (Kwon S. et al., 2008), and radon can be identified as the dominant non-occupant-related contaminant. However, because of the piston effect produced by moving trains, radon concentration can be considered below the acceptable level, and the base ventilation is not necessary for this case.

The CO_2 control point was determined as 1100ppm, which was 700ppm above the outdoor CO_2 level.

DEVELOPMENT OF PLATFORM DCV MODEL

This study developed the model of DCV system for PSD platform. During operating periods, after receiving the signals sent from temperature and CO_2 sensors installed in the exhaust ducts, the PID controllers control the fan speed to provide the desired outdoor airflow rate and supply airflow rate, and then control damper positions of chilled water to maintain supply air temperature set point.

CO_2 control sub-model

The CO_2 governing equation is presented based on mass balance of CO_2 in the platform space. Indoor CO_2 was assumed to be completely mixed:

$$m_{CO2}(t) - m_{CO2}(t_0) = \int_{t_0}^{t} M_0 X(\tau)\, d\tau + \rho_{CO2}\int_{t_0}^{t}[Y_0 - Y(\tau)]Z(\tau)d\tau + \rho_{CO2}\int_{t_0}^{t}[Y_1 Z_1(\tau) - X(\tau)Z_2(\tau)]\, d\tau \quad (1)$$

where $m_{CO2}(t)$ is the mass of indoor CO_2 at time t (kg). $X(\tau)$, $Y(\tau)$, $Z(\tau)$, $Z_1(\tau)$ and $Z_2(\tau)$ are the time-dependent occupancy number, CO_2 concentration at the platform (ppm) and outdoor airflow rate, infiltration and exfiltration through PSDs (m^3/h), respectively. They are all time-dependant functions. M_0 is the CO_2 emission rate, =0.045 kg/h. ρ_{CO2} is the CO_2 density (kg/m^3). Y_0 and Y_1 are outdoor and subway tunnel CO_2 concentration, which are 400 and 600ppm, respectively (Zhu et al., 2006).

Based on the before-mentioned equation, the CO_2 control sub-model for PSD platform was developed, as shown in Fig. 4.

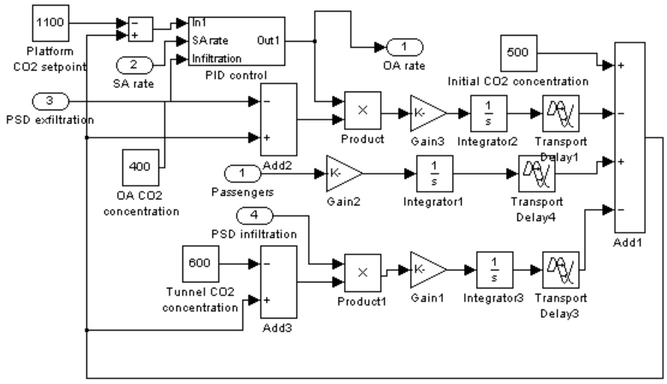

Figure 4 CO_2 control sub-model

Temperature control sub-model

In this study, the platform temperature is calculated based on sensible heat balance. Some assumptions were taken as:

(1) Neglect the heat storage of interior objects.

(2) The platform temperature distribution is even.

$$T_N(t)-T_N(t_0)=\int_{t_0}^{t}\left\{\begin{array}{c} q_sX(\tau)+q_1(\tau)+q_e\\ +\rho Z_0(\tau)c_p[T_s(\tau)-T_N(\tau)]\\ +\rho c_p[T_w(\tau)Z_1(\tau)-T_N(\tau)Z_2(\tau)]\end{array}\right\}d\tau\Big/Mc_p \quad (2)$$

where $T_N(t)$ is the platform temperature at time t (°C), $q_l(\tau)$ is the lighting load (W). The lighting factor is given as a waveform function. q_e is the heat released from equipments such as escalators, elevators and advertising board (W). $Z_0(\tau)$ is the supply air flow rate (m^3/h). T_s is the supply air temperature, =19°C. $T_w(\tau)$ is the mean air temperature in the tunnel (°C). M is the mass of air in the platform space (kg).

Based on the before-mentioned equation, the temperature control sub-model for the PSD platform is shown in Fig. 5.

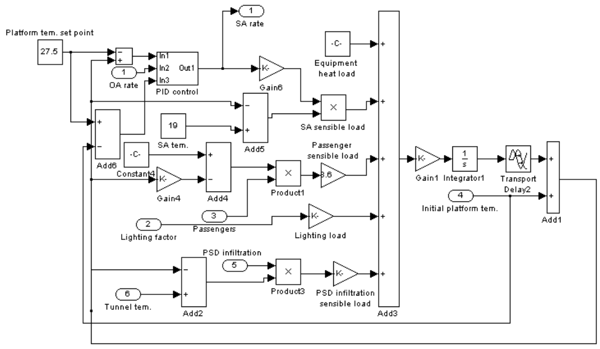

Figure 5 Temperature control sub-model

DCV system control model

As mentioned before, the DCV system controls the platform CO_2 concentration by outdoor airflow rate, and controls the platform temperature by supply airflow rate. Both CO_2 and temperature control guarantee that the minimum outdoor airflow rate should be larger than 10% of supply airflow rate. The diagram of the developed DCV control model for PSD platform is shown in Fig. 6.

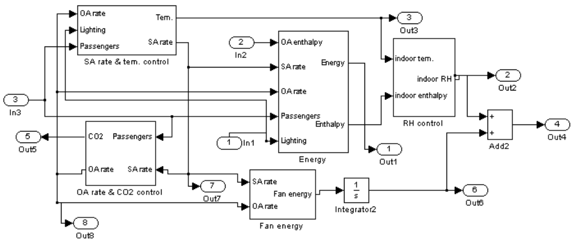

Figure 6 The DCV system control model

For the case of subway station, compared with occupancy heat load, heat gain through the exterior envelope from both radiation and conduction can always be neglected, and cooling is necessary over the whole year. However, when the outdoor enthalpy is relatively low (<47kJ/kg in this study), the operation of air-side economizer is taken into account.

DYNAMIC SIMULATION ON DCV SYSTEM PERFORMANCE

Calculation conditions

The CFD calculation conditions as shown in Table 1 are also used in this simulation. Additionally, the annual weather data in Guangzhou is shown in Fig. 7. The rating volume flow rate of the supply fan was assumed as 73559 m^3/h, with total pressure of 1870Pa and power of 49.67KW. The rating volume flow rate of return fan was assumed as 47420m^3/h, with total pressure of 1580Pa and power of 27.86KW. When the economizer is run on, the return fan will be turned off. The variation of passengers, infiltration and exfiltration rate through PSDs are shown in Fig. 8. In this study, the infiltration and exfiltration rate through PSDs were considered as a function of departure frequency of trains.

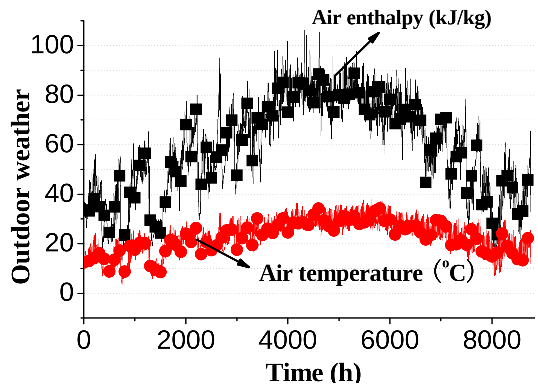

Figure 7 Weather data of Guangzhou city

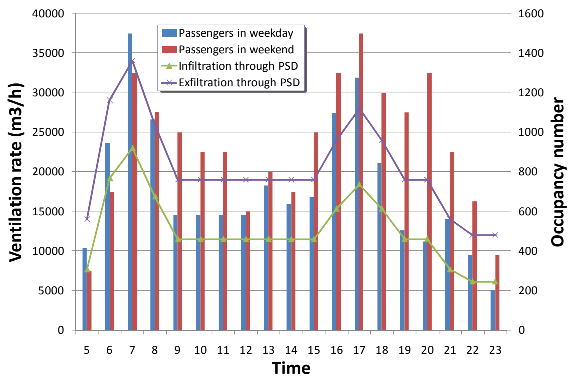

Figure 8 Variation of passengers, infiltration and exfiltration rate through PSDs

In order to estimate the potential energy savings using DCV system, this study also developed the models for conventional CAV system and VAV system for comparison. The CAV system uses the design ventilation rate during all the operating time, and the VAV system only uses temperature control strategy, with no CO_2 control.

Variation of CO_2 concentration and temperature during a typical summer day

The variation of outdoor airflow rate and CO_2 concentration during a typical summer day is shown in Fig. 9. For most of the time, the platform CO_2 level is below 1100ppm when DCV system is applied. The outdoor airflow rate is a strong function of the number of passengers. When there are few passengers in the platform, the outdoor airflow rate is much less than the design value of 34000m^3/h, which means the outdoor air cooling load can be significantly reduced.

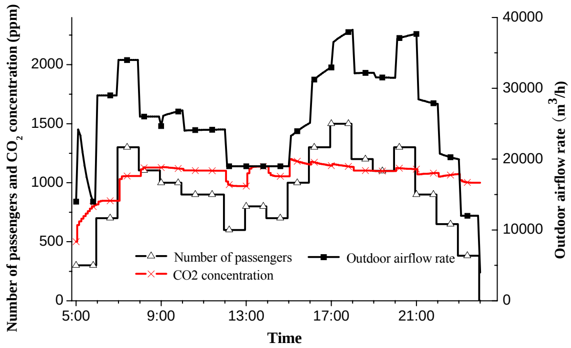

Figure 9 The variation of number of passengers, CO_2 concentration and outdoor airflow rate

The variation of temperature and supply airflow rate is shown in Figure 10. In fact, the platform air temperature is strongly dependent on departure frequency of trains. However, the results show that the developed DCV system can maintain the temperature in a range from 27.0°C to 28.0°C.

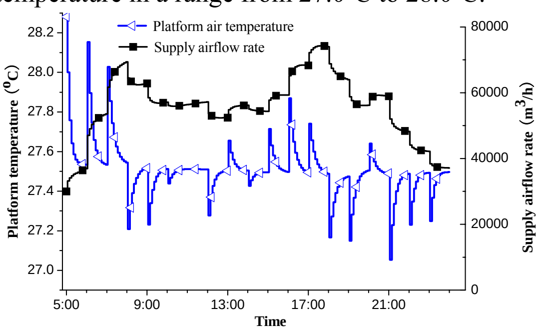

Figure 10 The variation of temperature and supply airflow rate

Prediction of annual energy savings

The annual energy consumptions for the three different systems are summarized in Table 2. For the case of DCV system, the fan electricity consumption is about 10% of the annual energy consumption. Compared with conventional CAV system and VAV system, DCV system can reduce energy consumption by 30.16% and 8.21%, respectively. The results indicate that DCV system can have a better performance than other systems in terms of energy savings.

Table 2

Annual energy consumptions for the different systems

	Fan (10^9kJ)	Cooling (10^9kJ)	Total (10^9kJ)
DCV system	0.56	5.50	6.06
CAV system	1.19	7.48	8.67
VAV system	0.45	6.15	6.60

CONCLUSIONS

In this study, a dynamic model for estimating the performance of DCV system in subway PSD platform was developed. Both CO_2 control and temperature control were implemented by PID controller. The results show that an acceptable level of platform temperature and CO_2 concentration can be obtained by this system. Additionally, comparing the conventional CAV system and VAV system, about 30.16% and 8.21% of the annual energy consumption can be saved, respectively. That indicates that this kind of ventilation strategy can achieve significant potential of energy savings in subway station.

Although the before-mentioned evaluation of DCV system for subway platform seems reasonable, this methodology would be applied to real subway platform and the model developed in this study should be verified with field testing.

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REFERENCES

Wachenfeldt, B.J., Mysen, M., Schild P.G. 2007. Air flow rates and energy saving potential in schools with demand-controlled displacement ventilation, Energy and Buildings, 39: 1073-1079.

Jiang, C.S., Deng, Y.F., Hu, C., Ding, H., Chow, H.K. 2008. Crowding in platform staircases of a subway station in China during rush hours, Safety Science (in press)

Schell, M.B., Turner, S.C., Shim, R.O. 1998. Application of CO2-based demand controlled ventilation using ASHRAE Standard 62: Optimizing energy use and ventilation, ASHRAE Tractions, 104(2): 1213-1225.

Kwon, S., Chao, Y., Park, D., Park, E. 2008. Study on the indoor air quality of Seoul metropolitan subway during the rush hour, Indoor and Built Environment, 17: 361-369, 2008.

Zhu, P., Zhu, Y. 2006. Study on fresh air of passenger carriage in underground railway, HV&AC, 36(3): 75-77, 2006 (in Chinese)