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RESEARCH ARTICLE

OPTIMIZATION OF HVAC SYSTEM FOR HEALTHY INDOOR AIR ENVIRONMENT: REAL OPTIONS OF TIME-VARYING VENTILATION LOADS

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ABSTRACT

The loads of ventilation systems in underground subway stations are time-varying since the subway schedule of rush hour (morning and evening), and ordinary time zone is varied in stations according to time zones. The objective of this study is to develop a real-time energy-efficient ventilation control strategy based on the real option of time-varying ventilation loads for the periodic variations of indoor air quality (IAQ) in a subway station. The experimental results from an underground subway platform showed that the proposed ventilation control method with 6 hours time interval could reduce the ventilation energy by 3%, compared to the ventilation energy with manual control while maintaining a healthy and comfortable IAQ level.

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INTRODUCTION

In underground subway stations, various air pollutants including volatile organic compounds heavy metals, and particulate matters can damage passengers health and cause respiratory symptoms and lung malfunction (Kim *et al*., 2012; Liu *et al*., 2011). Therefore, it is important to maintain a healthy level of indoor air quality (IAQ) for the public health. Mechanical ventilation systems utilizing fans and ducts are used for managing IAQ level through forced air circulation in buildings. However, the energy demand of ventilation systems accounts for 40% of the total energy demand in buildings, therefore, developing an energy efficient ventilation system is a hot issue in building space (Rackes *et al.,* 2014; Ghahramani *et al.,* 2014). The main problem of development of an energy efficient ventilation system is the conflicted relation between the energy demand of ventilation systems and IAQ (Quang *et al.,* 2014; Preglej *et al.,* 2014).

MATERIALS AND METHODS

Data collection of the IAQ ventilation system

The IAQ data are measured at a platform of subway station in Indore, India, from April 20 to 24, 2015. Four measured variables in the ventilation system are particulate matter (PM) with a diameter of less than 10μm at platform (denoted as platform PM10) and at outside (denoted as outside PM10), revolutions per minute of the ventilation fan speed (denoted as RPM), and the subway schedule . The platform PM10 is measured at every three minutes and it shows a diurnal periodic pattern with two peaks at rush hours in a day (Fig.1.) Four measured variables in the ventilation system are particulate matter with a diameter of less than 10μm at platform (denoted as platform PM_{10}) and at outside (denoted as outside PM_{10}), revolutions per minute of the ventilation fan speed (denoted as RPM), and the subway schedule. The platform PM_{10} is measured at every three minutes and it shows a diurnal periodic pattern with two peaks at rush hours in a day (Fig. 2 (a)). The outside PM_{10} (Fig. 2 (b)) measured with sampling time of one hour at outside of the D-subway station does not present a specific diurnal pattern in contrast with other variables. Fig. 2 (c) shows a currently used daily RPM schedule whose values are 50 Hz from 6 p.m. to 9 p.m., and 40 Hz for the other time period of one day. The subway schedule represents the number of passed trains per hour in D-subway station and this value is also predefined like the case of RPM schedule (Fig. 2 (d)).

Development of IAQ control model

In the model based control strategy, the process model is very important because the control performance largely depends on the accuracy of the process model (Liu *et al*., 2013). A black-box model is implemented for developing an IAQ model

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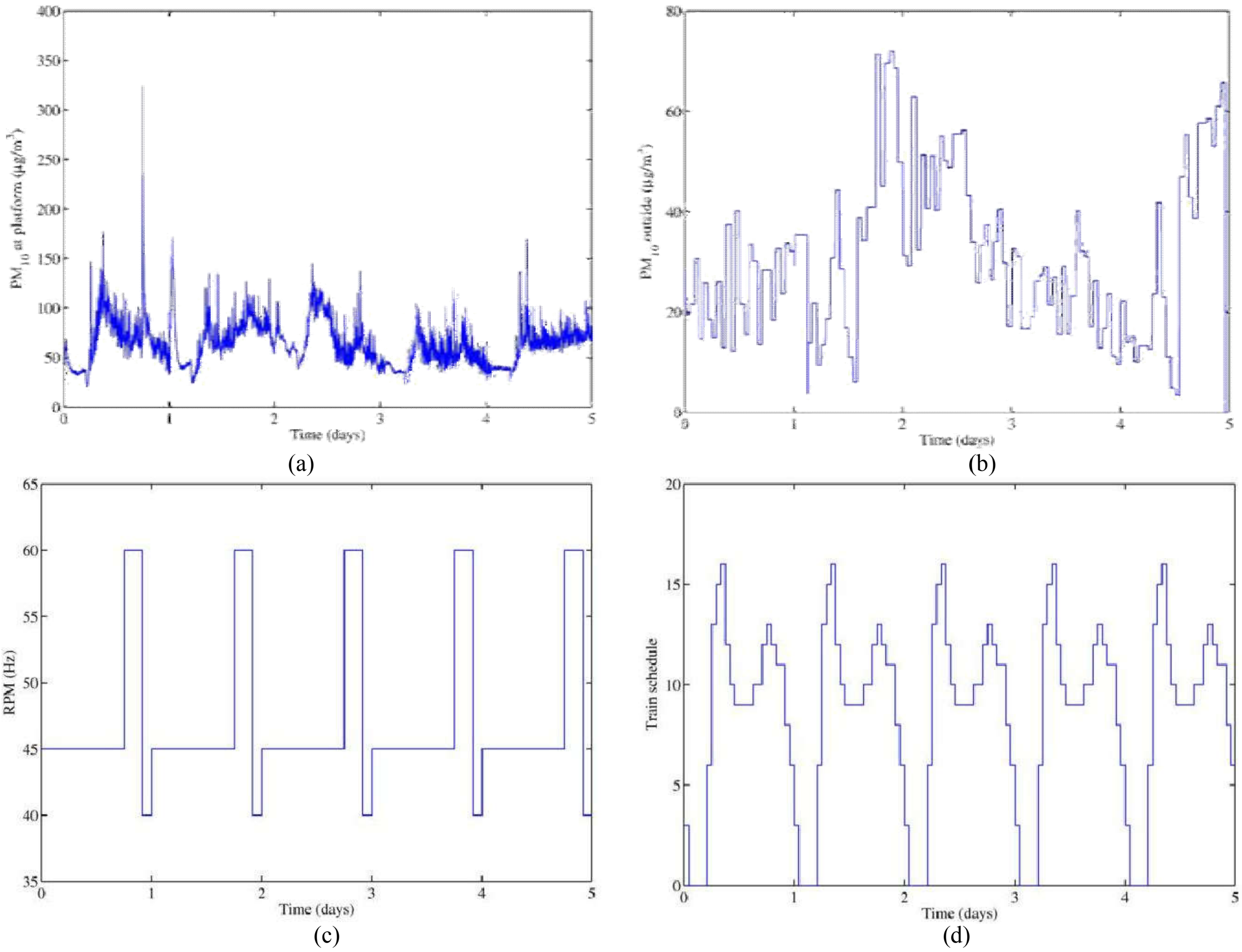
(Afram *et al.,* 2015). Among various black-box models, output error (OE) model called as a multistep-ahead predictor has an advantage that it can predict system output value, which is different from time-series models such as ARX (autoregressive with exogenous input) model, ARMAX (autoregressive moving average with exogenous input) model, and BJ (Box-Jenkins) model. This advantage of the OE model is described in a following equation (Sung *et al.,* 2009):

$$u(t) = u_P(t) + u_I(t) + u_D(t)$$

$$=k_c\ (y_s(\mathrm{t})-\mathrm{y(t)})+\frac{\mathrm{k_c}}{\tau_\mathrm{i}}\int_o^t (y_s(t) - y(t)d\tau + k_c\tau_d\,\frac{d(y_s(t)-y(t))}{dt} \quad \ldots\ldots\ldots\ldots..\ (2)$$

where Δt is the sampling time, $\acute{d}\Delta t$ is the time-delay, n is the model order, $\hat{y}\ (k\,\Delta t\,)$ and $u\ (\ k\ \Delta\ t\ )$ are the predicted process output and the process input at the k^{th} sampling time, respectively, $\acute{B}$ is the bias term, and the coefficients $\acute{a}_\iota$ and $\acute{b}_\iota$ (i=1,2,…,n) are the OE model parameters.



(a) (b)

(c) (d)

Fig. 1. Variations of IAQ and ventilation rate in D-subway station: (a) PM$_{10}$ concentration at platform; (b) PM$_{10}$ concentration at outside; (c) manual ventilation fan speed; and (d) the number of passed subway

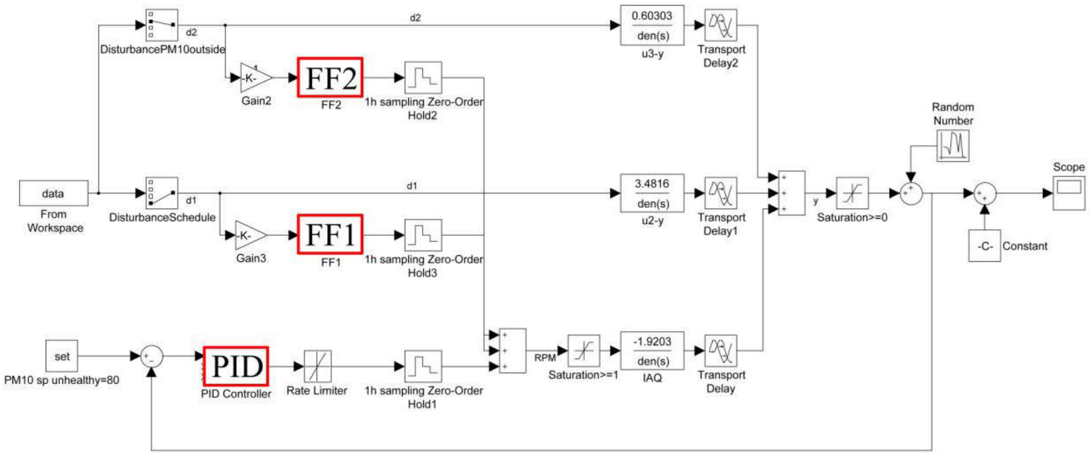


Fig. 2. Control structure of the designed ventilation control system for IAQ.

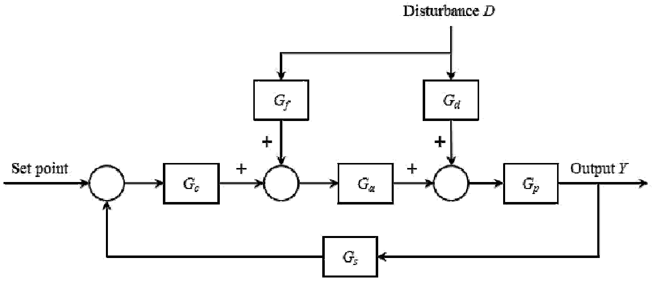


Fig. 3. General feed forward control system [17]

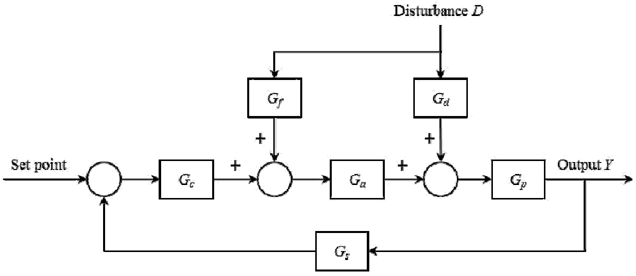


Fig. 4. General feed forward control system [17].

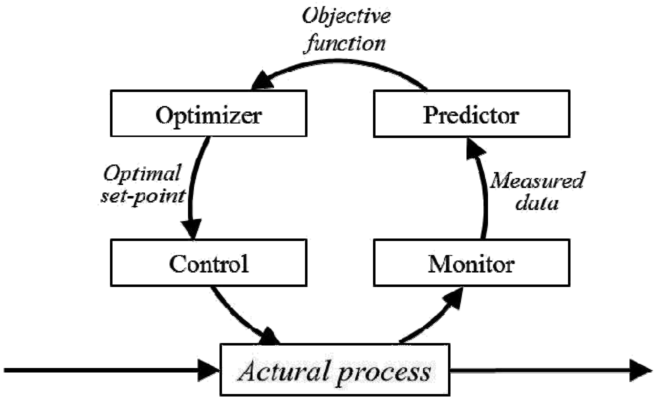


Fig. 5. Concept of real-time control strategy [10]

Table 1. Tuning paramter of PID controller

Controller	Tuning parameters	
	k_c	τ_i
PI	-0.3066	0.0471

Design of ventilation control system for managing IAQ

To manage IAQ in the ventilation system, an integrated control system is applied to the ventilation system by combining one proportional-integral-derivative (PID) controller and two feed-forward controllers (Fig. 2). PID controllers have been widely used in most industrial control systems due to their advantages of simplicity, clear functionality, applicability, easy implementation, and good performance (Sung *et al.*, 2009; Araki. 2002; Ang *et al.*, 2005). PID controllers are composed of three term and the control output is the sum of the three terms as follows (Sung *et al.*, 2009):

$$u(t) = u_P(t) + u_I(t) + u_D(t)$$

$$= k_c\ (y_s(t)\text{-}y(t)) + \frac{k_c}{\tau_i}\int_o^t (y_s(t) - y(t)d\tau + k_c\tau_d\frac{d(y_s(t)-y(t))}{dt} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\ (2)$$

where $u_P(t)$, $u_I(t)$, and $u_D(t)$ are the controller outputs of the proportional, integral, and derivative parts, respectively, $y_s(t)$ is the set-point of the process output, and $y(t)$ is the process output. The constants k_c, τ_i and τ_d in Eq. (2) are the proportional gain, integral time, and derivative time, respectively. Based on the general structure of the feed forward controller shown in Fig. 4, the relationship between feed forward controller and disturbance should be satisfied the following equations (Seborg *et al.,* 2006):

$$DG_fG_p = -DG_d \qquad (3)$$

$$G_f = -\frac{G_d}{G_p} \qquad (4)$$

where, G_c, G_f, G_d, G_a, G_p, and G_s are the transfer function for feedback controller, feed forward controller, disturbance, actuator, process, and sensor, respectively. The ventilation control system has one PID and two feed forward controllers as shown in Fig. 3. The optimal trajectory of PM_{10} concentration at platform can be determined using an real-time control method.

Determination of optimal set-point of real-time ventilation control

In the subway station, IAQ with a diurnal pattern which is real situation of underground subway station is disturbed by the number of passed trains and the outdoor air quality and it should be managed under a healthy level by a ventilation system.

Table 2. Comparison of the average of platform PM_{10} concentration and energy demand with respect to the manual control and real-time set point optimization

Control strategies	Time interval (hr)	Average PM_{10} conc. at platform ($\mu g/m^3$)	Energy demand (kWh/d)
Manual control	-	64.11	1838.78
Real-time control	1	63.68	1795.74
	2	63.96	1791.43
	3	63.88	1792.20
	4	63.43	1799.82
	6	63.78	1786.71
	8	63.75	1787.57
	12	63.44	1798.60
	24	63.85	1798.93

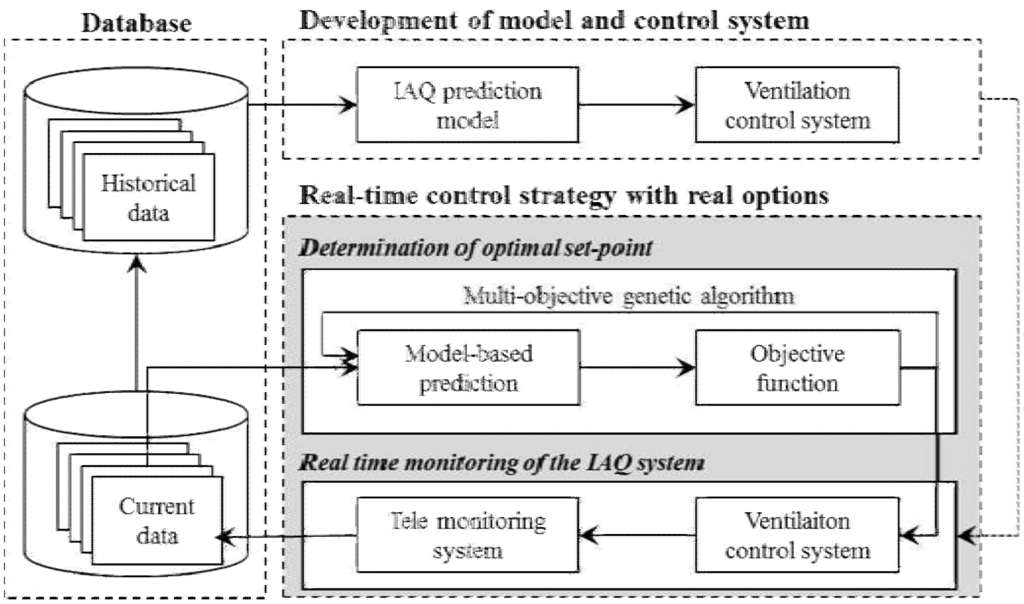
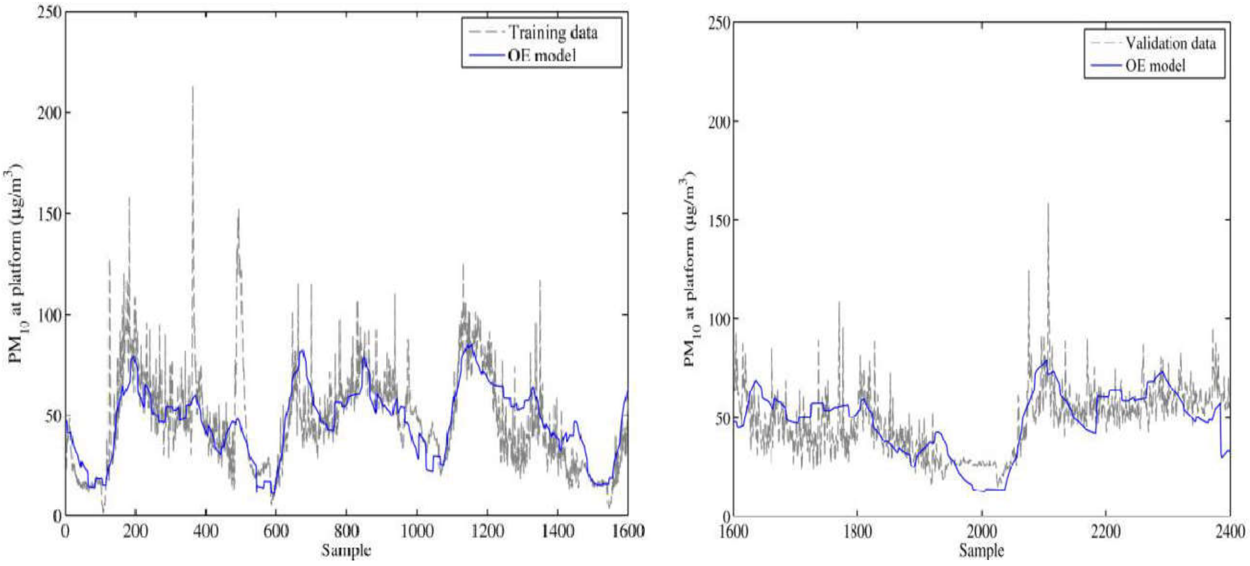


Fig. 6. The schematic diagram of the proposed real-time ventilation control strategy under real options of varying ventilation load



(a) (b)

Fig. 7. Modeling results of the developed IAQ model in (a) training data set and (b) validated data set

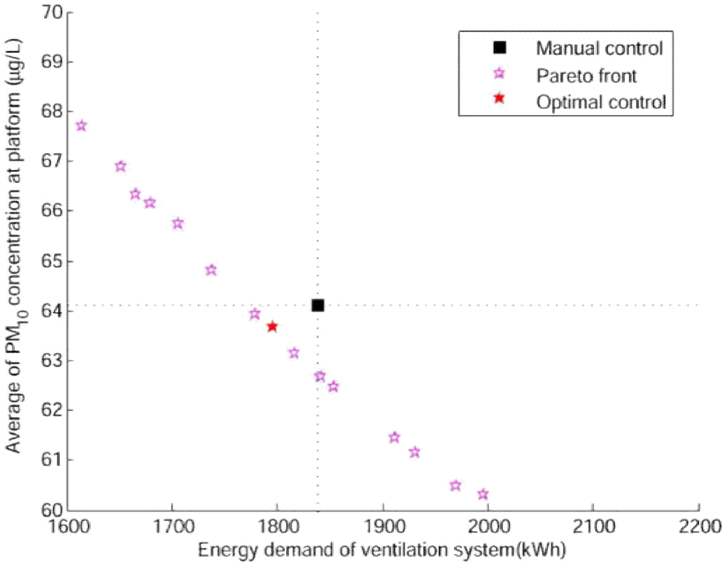


Fig. 8. Pareto set of optimal set-points for real-time ventilation control system obtained by the MOGA with 1 hour time interval

Therefore, the set-point of the ventilation control system needs to be changed against the varying ventilation load, which for maintaining the IAQ under the healthy level. Fig. 5 shows a concept of the real-time control strategy which integrates the concepts of monitoring, prediction, optimization, and control. The real-time control strategy is used to maximize the control efficiency of the target system by instantly responding to a varying system condition caused by a disturbance or other unexpected results (Wang *et al.,* 2011; Pual and Hawkins, 2004). Finally, the obtained optimal set-points are applied to the control system for improving the condition of the actual process. This procedure can be manually and automatically switched depending on situations of a fixed time schedule, abnormal events of the system, and requests from operators (Pual and Hawkins, 2004).

Multi-objective genetic algorithm for set point optimization

Multi-objective optimization (MOO) is a method to simultaneously search for an optimum solution from more than one conflicted objective functions. The obtained optimal solution through the MOO has a set of solutions (i.e., Pareto set). To search for a reasonable Pareto set, various algorithms are developed such as niched pareto genetic algorithm (NPGA), weight-based genetic algorithm (WBGA), random weighted genetic algorithm (RWGA), and non-dominated sorting genetic algorithm (NSGA-II), and the last one is the most widely implemented method (Liu *et al.,* 2013; Lu *et al.,* 2015). The genetic algorithm (GA) based MOO method starts with a population composed with a number of initial solutions called chromosomes. The population is randomly generated and is used to find an optimal solution through the processes of selection, mutation, and crossover. Because of this characteristic of the GA-based optimization method, it shows a good performance for searching optimum solutions in difficult optimization problems such as non-convex, discontinuous, and multi-model solutions spaces (Konak *et al.,* 2006). In this work, NSGA-II is used to determine a set of optimal set-points of real-time control strategy for ventilation systems. To improve the energy efficiency of the ventilation system an the IAQ in the underground subway station, average value of PM_{10} concentrations at platform and energy demand of the ventilation system for a day are used as objective functions of the MOGA. The energy demand of the ventilation system is regressed by a third order polynomial regression model expressed in the as following equation:

$$\textit{Energy demand}\ (\text{kWh}) = 0.0007\,(RPM)^3 - 0.046\,(RPM)^2 + 2.01(RPM)+8.8$$

The proposed method

As shown in Fig. 6, the proposed schematic diagram of the real-time ventilation control strategy considering real options consists of three parts: (1) development of IAQ prediction model (2) control system design, and (3) implementation of the real-time control strategy to the ventilation control system. To evaluate the control performance of the proposed method, the average value of PM_{10} concentration at platform and the energy demand of the ventilation system are used as a performance criterion. The proposed method is compared to the manual control which is used in the D-subway station.

RESULTS AND DISCUSSION

Development of IAQ model and ventilation control strategy

For predicting the IAQ and developing the ventilation control system at D-subway station, an IAQ model is developed by the OE model. Two thirds of the measured data (Fig. 7(a)) are used to determine the model parameters and the rest measured data are used to validate the developed IAQ model (Fig. 7 (b)), finally the developed IAQ model is evaluated by the correlation coefficient (R^2).

The developed IAQ model shows higher accuracy in the training data (38.63%) than the validation data (28.46%). The relatively low prediction accuracy of the developed model is due to the noise of the measured data, however, the model can still capture the dynamic pattern of the IAQ. For implementing the PI controller, the developed IAQ model is converted to the first order plus time delay (FOPTD) model which represents a relation between input and output variables in a more easy form to understand. The OE model is converted to three FOPTD models as follows

$$G_p(s) = \frac{-1.14s}{0.0075s+1}e^{-0.079s} \tag{6}$$

$$G_{d1}(s) = \frac{3.068s}{0.026\,s+1}e^{-0.031s} \tag{7}$$

$$G_{d2}(s) = \frac{0.53s}{0.053s+1} \tag{8}$$

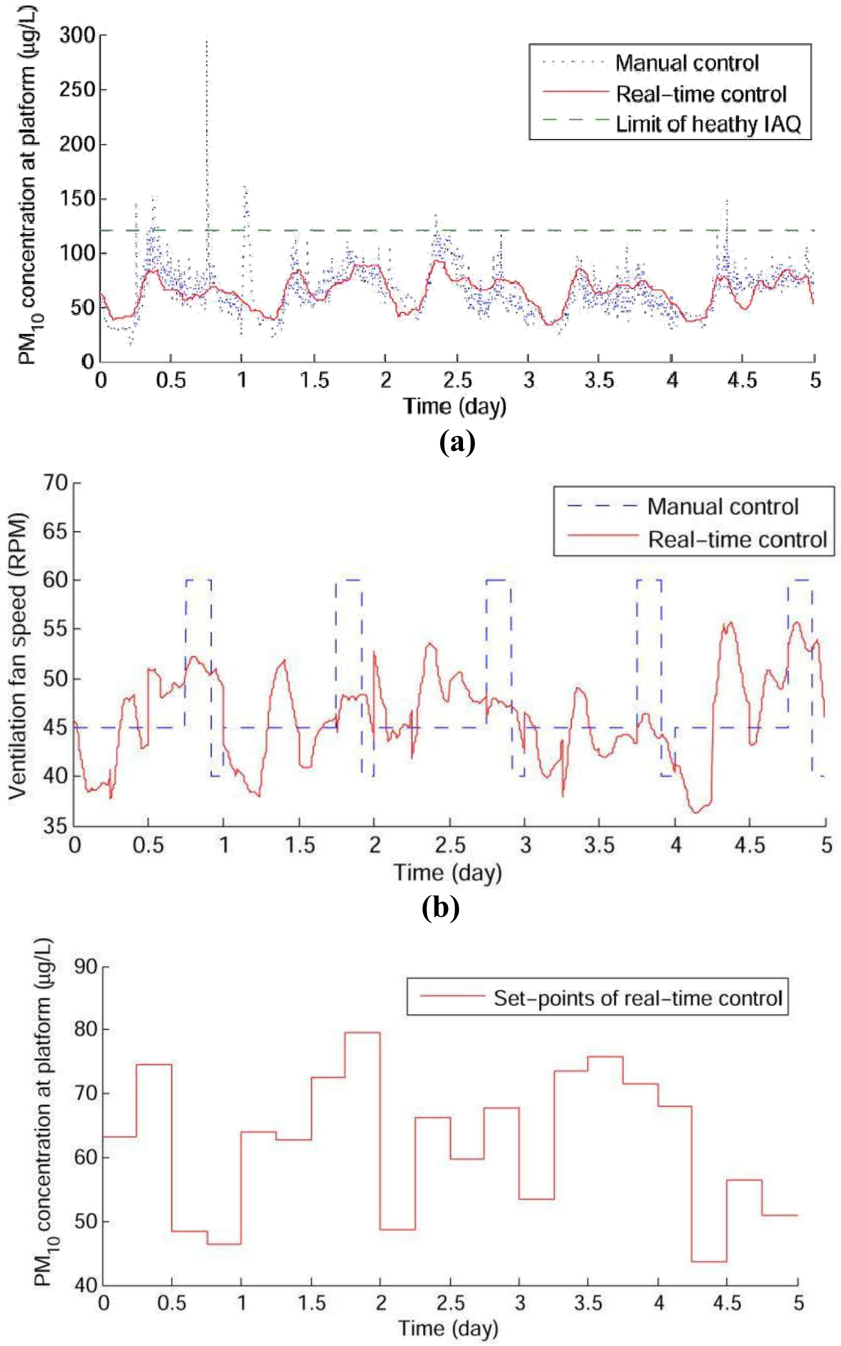
where, $G_p(s)$, $G_{d1}(s)$, and $G_{d2}(s)$ present RPM, subway schedule and outdoor PM_{10} relation with platform PM_{10}, respectively. Based on the FOPTD model, relation between variable are clearly identified. From the sign of three FOPTD models, the positive impacts of the subway schedule and the outdoor PM_{10} on the platform PM_{10} are characterized whereas the RPM give a negative impact based on the sign of the FOPTD model. The feedback controller has a PI structure and the control parameters tuned with the parameter in Table 1. Two feed forward controllers for removing the effect of the subway schedule (G_{FF1}) and the outdoor PM_{10} concentration

(G_{FF2}) are shown in Eqs (9)-(10), respectively:

$$G_{FF1} = \frac{0.023s+3.07}{0.030\,s+1.14} \tag{9}$$

$$G_{FF2} = \frac{0.004\,s+0.53}{0.061s+1.14} \tag{10}$$

The tuned PI controller manipulates RPM to reduce the platform PM_{10} and two feed-forward controllers (FF1 and FF2) cancel out the disturbed effects of the subway schedule and outdoor PM_{10} on the platform PM_{10}, respectively. The real-time ventilation control system is developed by implementing the real-time control strategy on the ventilation control system integrated three controllers.



(a)

(b)

(c)

Fig. 9. Comparison of the ventilation control performance of the manual control and the real-time control strategy with 6 hours time interval (a) PM$_{10}$ concentration at platform, (b) ventilation fan speed, and (c) set point of the real-time ventilation system

Real-time ventilation control system under the varying load

The proposed real-time control strategy is implemented to the ventilation control system for reducing the energy demand of the ventilation system and keeping the PM$_{10}$ concentration at platform under the healthy level of 120 μg/m^3. The set-point of ventilation control system is real-time updated after every eight time intervals, where each set-point is optimized by the MOGA with 50 individuals as a population size and 40 generations. Fig. 8 shows the optimal set-points of the ventilation control system with 1 hour time interval. The result of the real-time control strategy and the current manual control strategy are compared in Error! Reference source not found. Therefore, it is reasonable that the real-time control strategy with a relatively long time intervals shows better performance for updating set-point than that with short time intervals. On the other hand, time intervals with 12 and 24 hours for the real-time control strategy consume more energy than others. The IAQ in the underground subway station is affected by the disturbances of OAQ and subway schedule which continuously change in a short time. Therefore, it is hard to response to the varying ventilation loads using the real-time control strategy with time intervals longer than 4, 6 or 8 hours. Fig. 9 shows the control results of the manual control and the real-time control strategy with the time interval of 6 hours. As shown in Fig. 9 (a), the manually controlled PM$_{10}$ concentration at platform exceeds the limitation of heathy PM$_{10}$ level several times (Fig. 9(a)), the PM$_{10}$ concentration with real-time control is maintained under the heathy level because real-time control updates the set-points of the ventilation control under real time-varying loads (Fig. 9 (c)). Fig. 9 (b) shows the ventilation fan speed of the manual control and the optimal trajectory of ventilation fan speed by the real-time control strategy for the ventilation system. This is a reason that the real-time control strategy reduces the energy demand of the ventilation system without increase of the PM_{10} concentration at platform.

Conclusions

Real-time set point's optimization of ventilation control systems considering real option of time varying loads was implemented to improve IAQ level and minimize energy demand of the ventilation system. Real-time control strategy for the ventilation system is applied to the implemented control system by updating the set-points of the control system. The results of this study showed that the real-time control strategy for manipulating the ventilation system could reduce 3% of the energy with a healthy IAQ level by comparing with the manual control by updating the optimal set-point at every 6 hours.

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REFERENCES

Afram, A. and Janabi-Sharifi, F. 2015. Black-box modeling of residential HVAC system and comparison of gray-box and black-box modeling methods, Energy and Buildings 94, 121-149.

Ang, K.H., Chong, G. and Li, Y. 2005. PID control system analysis, design, and technology, IEEE Trans. Control *Syst. Technol.,* 13, 559-576.

Araki, M. 2002. PID control, Control systems, robotics and automation 2, 1-23.

Ghahramani, A., Jazizadeh, F. and Becerik-Gerber, B. 2014. A knowledge based approach for selecting energy-aware and comfort-driven HVAC temperature set points, Energy and Buildings 85, 536-548.

Kim, M., Sankara Rao, B., Kang, O., Kim, J. and Yoo, C. 2012. Monitoring and prediction of indoor air quality (IAQ) in subway or metro systems using season dependent models, Energy and Buildings 46, 48-55.

Konak, A., Coit, D.W. and Smith, A.E. 2006. Multi-objective optimization using genetic algorithms: A tutorial, Reliab. Eng. Syst. Safe. 91, 992-1007.

Lee, S., Kim, M.J., Pyo, S.H., Kim, J.T. and Yoo, C.K. 2015. Evaluation of an optimal ventilation IAQ control strategy using control performance assessment and energy demand, Energy and Buildings 98, 134-143.

Liu, H. Kim, M. Kang, O. Sankararao, B. Kim, J.T. Kim, J.C. Yoo, C.K. 2011. Sensor validation for monitoring indoor air quality in a subway station, Indoor Built Environ. 21 205-221.

Liu, H., Lee, S., Kim, M., Shi, H., Kim, J.T., Wasewar, K.L. and Yoo, C. 2013. Multi-objective optimization of indoor air quality control and energy consumption minimization in a subway ventilation system, Energy and Buildings 66, 553-561.

Lu, Y., Wang, S., Zhao, Y. and Yan, C. 2015. Renewable energy system optimization of low/zero energy buildings using single-objective and multi-objective optimization methods, Energy and Buildings 89, 61-75.

Preglej, A., Rehrl, J., Schwingshackl, D., Steiner, I., Horn, M. and Škrjanc, I. 2014. Energy-efficient fuzzy model-based multivariable predictive control of a HVAC system, Energy and Buildings 82, 520-533.

Pual, G. and Hawkins, C. 2004. The real-time optimisation of an industrial fermentation process, in: 9th IFAC International Symposium, Narcy, France, 28-31.

Quang, T.N., He, C., Knibbs, L.D., Dear, R. and Morawska, L. 2014. Co-optimisation of indoor environmental quality and energy consumption within urban office buildings, Energy and Buildings 85, 225-234.

Rackes, A. and Waring, M.S. 2014. Using multiobjective optimizations to discover dynamic building ventilation strategies that can improve indoor air quality and reduce energy use, Energy and Buildings 75, 272-280.

Seborg, D., Edgar, T.F. and Mellichamp, D. 2006. Process dynamics & control, John Wiley & Sons.

Sung, S.W., Lee, J. and Lee, I.B. 2009. Process Identification and PID Control, John Wiley & Sons.

Wang, S. Sun, Z. Sun, Y. Zhu, N. 2011. Online optimal ventilation control of building air-conditioning systems, Indoor Built Environ. 20, 129-136.

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