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Indoor air quality control for improving passenger health in subway platforms using an outdoor air quality dependent ventilation system

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ABSTRACT

Indoor air quality (IAQ) ventilation systems are widely used to control air pollutants in subway platforms. When outdoor air is heavily contaminated by particulate matters (PMs), it enters the subway platform through the ventilation system, resulting in the deterioration of platform IAQ and adverse effects on passenger health. In this study, a new IAQ ventilation system that takes into account the outdoor air quality used for ventilating platform is proposed to control the platform PM_{10} concentration. For this, the amount of PM_{10} that flows from the outdoors into the subway platform is considered a manipulated variable of the proposed ventilation system. The influence of the platform PM_{10} on passengers' health risk is evaluated using a comprehensive indoor air-quality index (CIAI). The CIAI level of platform PM_{10} is compared using the manual and proposed ventilation systems, where the manual system operates at fixed ventilation inverter frequency without regard to the outdoor air quality. Experimental results from an underground subway platform showed that the proposed ventilation system can improve the platform PM_{10} level, leading to the passengers' exposure to the reduced PM_{10} concentration (i.e., health risk reduction), and reduce the ventilation energy compared to the manual system by adjusting the ventilation inverter frequency and inflow of outdoor PM_{10} into the subway platform depending on the outdoor air quality.

1. Introduction

Millions of people in metropolitan areas depend on the convenience of subway systems for transportation, which have been described as the "lifeline of urban development" by reducing traffic congestion above ground and providing environment-friendly transit [1–3]. Notwithstanding these advantages, there has been a growing concern over indoor air quality (IAQ) in subway systems, since people spend a considerable amount of time in the subway systems daily [4,5]. Most subway systems are underground in a confined space where air pollutants are generated internally as well as enter from the outside atmosphere. Furthermore, due to heavy use and overcrowding, various types of hazardous pollutants which present a health risk to passengers and subway working staff are accumulated in subway systems [3,6]. Therefore, to ensure passengers and subway workers good health, ventilation systems are necessary for controlling hazardous air pollutants in the subway systems.

Recently, several studies on ventilation of indoor air pollutants in different building spaces have been reported [7–12]. Chao and Hu [8] have established a dual-mode demand control ventilation strategy that maintains the occupant-related and non-occupant-related indoor air pollutants at acceptable levels. Kolokotsa et al. [9] have proposed a bilinear model-based ventilation system to achieve the optimum indoor environmental conditions while minimizing energy cost. Liu et al. [10] have developed a model predictive control (MPC) based ventilation system in the subway station. They also have applied a multi-objective optimization algorithm to determine optimal set-points of the ventilation system which concurrently improve the IAQ and ventilation energy efficiency. Lim et al. [12] have proposed a new ventilation index, Net Escape Velocity (NEV), which directly provides information in behavior of the contaminants to the ventilation system. These researchers have assumed that the polluted indoor air is replaced with clean outdoor air by increasing the ventilation rate. In fact, if the outdoor air is strongly contaminated due to aeolian

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transportation of dust particles or yellow dust, its entry into the building spaces through the ventilation systems increases the air pollutants inside the building spaces [13,14]. This article proposes a new approach that considers the outdoor air quality used for diluting indoor air pollutants. The development of ventilation control system, which takes the changes of outdoor air quality into account, is the central theme of the present study.

The ventilation under contaminated outdoor air conditions can increase the potential that the passengers in the subway systems will be exposed to health risk. Suppose the concentration of particulate matters (PMs) in the outdoor air is higher than usual (for example on megacities where the PMs concentration is far above the recommendations due to yellow dust etc., see Refs. [15,16]). If the ventilation system is operated with the identical ventilation rate to the usual, then a larger amount of PMs enters the subway system through the ventilation under such contaminated outdoor air conditions [14,17]. The PMs with aerodynamic diameters less than 10 μm (PM_{10}) and 2.5 μm ($PM_{2.5}$) deposit to trachea-bronchial compartment of the human respiratory system, and then, cause respiratory illnesses such as bronchial asthma, rhinitis and chronic bronchitis [18,19]. As such, the ventilation with contaminated outdoor air has a large influence on the passengers' health risk. Therefore, to protect the passengers' health inside the subway systems, it is necessary to evaluate the influence of IAQ that is ventilated with the contaminated outdoor air. Another theme of this study is the evaluation of the influence of the ventilated IAQ on the passengers' health risk depending on the consideration of outdoor air quality.

In the first part of this study, the ventilation control system is developed to keep the PM_{10} concentration in the subway system at a comfortable and healthy range. To take the changes of outdoor air quality into account, the amount of PM_{10} that is introduced from the outdoors to the subway system is used for developing the ventilation control system. Feedback and feed-forward ventilation control strategies are proposed to compensate for dynamic variations of the PM_{10} concentration in the subway systems and effects of disturbances on the subway system's PM_{10} concentration, respectively (for background on feedback and feed-forward control, see Bequette [20] and Seborg et al. [21]).

This article uses a comprehensive indoor air-quality index (CIAI) to evaluate the influence of the ventilated IAQ on the passengers' health risk inside the subway system. The CIAI describes ambient air quality based on the health risk of the air pollutants [18]. The variations of PM_{10} level in the subway system are evaluated using the ventilation control system with and without the consideration of outdoor air quality, respectively. Then, the influence of PM_{10} level on the passengers' health risk is investigated using the CIAI. These methods are applied to an underground subway station at Seoul Metro, South Korea.

2. Comprehensive indoor air-quality index (CIAI)

A comprehensive indoor air-quality index (CIAI), of which the aim is to help the public understand the condition of current indoor air and the associated health effects, determines the health risk of indoor air pollutants using six levels of concern (good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous) [18,22]. The CIAI value of each indoor air pollutant is represented as:

$$\mathrm{CIAI} = \frac{I_{HI} - I_{LO}}{BP_{HI} - BP_{LO}}(C_P - BP_{LO}) + I_{LO} \tag{1}$$

where C_P is the current concentration of air pollutants (μg/m^3); BP_{LO} and BP_{HI} are the concentration breakpoints of each health concern level (μg/m^3); and I_{LO} and I_{HI} are the index breakpoints of each health concern level [18]. Specifications of the CIAI are shown in Table 1.

3. Description of the IAQ ventilation control system

Fig. 1 shows a schematic diagram of the IAQ ventilation control system in a subway platform. The ventilation control system generates control signals to ventilation inverter frequency to control the air pollutants inside the platform, where the inverter is an electronic device that regulates revolution speed of ventilation fan motor. Then, depending on the controlled inverter frequency, outdoor air with the massive PMs filtered out is distributed to the platform to dilute the polluted indoor air [23].

In this study, a controlled variable taken for the ventilation control system is the PM_{10} concentration at the subway platform. A manipulated variable is the amount of PM_{10} (mg/h) introduced from the outdoors to the platform through the ventilation system, which is calculated as:

$$PM_{10}\,\mathrm{amount} = \left(Q\frac{\mathrm{Hz}}{\mathrm{Hz}_{max}}\right) n(1-\alpha) PM_{10}\,\mathrm{conc.\,in\,out\,door\,air}/10^3 \tag{2}$$

where Q is the air volume of the ventilation system ($\mathrm{m}^3_{\mathrm{outdoor\ air}}$/h); Hz is the inverter frequency of the ventilation system; Hz_{max} is the maximum inverter frequency of the ventilation system; n is the number of ventilation systems installed in the subway platform; α is an average filter efficiency; and PM_{10} conc. in outdoor air is the outdoors PM_{10} concentration (μg/m^3). In Eq. (2), the filter efficiency α dependent on the filters' efficiencies could be an important factor, since it affects both of the IAQ and filtration cost in the subway platform. Table 2 compares the filtration cost of PM_{10} filters with

Table 1
Comprehensive indoor air quality index (CIAI) suggested by the U.S. Environmental Protection Agency.

Level of health concern	Good		Moderate		Unhealthy for sensitive groups		Unhealthy		Very unhealthy		Hazardous	
CIAI	0-50		51-100		101-150		151-250		251-350		351-500	
ILO	0		51		101		151		251		351	
IHI	50		100		150		250		350		500	
Conc. level	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}	BP_{LO}	BP_{HI}
NO_2 (ppm)	0	0.03	0.031	0.05	0.051	0.15	0.151	0.25	0.251	0.5	0.501	2
CO (ppm)	0	5	5.01	10	10.01	20	20.01	30	30.01	40	40.01	50
CO_2 (ppm)	0	500	501	1000	1001	1500	1501	2000	2001	3000	3001	5000
PM_{10} (ppm)	0	50	51	150	151	250	251	350	351	450	451	600
PM2.5 (ppm)	0	15	16	40	41	140	141	250	251	350	351	500

Note: I_{LO} is the index breakpoint corresponding to BP_{LO}, I_{HI} is the index breakpoint corresponding to BP_{LO}, and BP_{LO} and BP_{HI} are the concentration breakpoints of each health level.

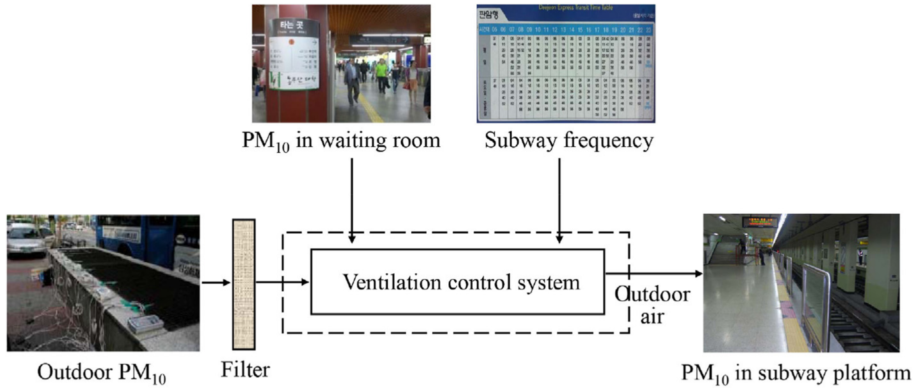

Fig. 1. Schematic diagram of indoor air quality (IAQ) ventilation control system installed in a platform of subway station.

Table 2
Comparison of filtration performances obtained using single-layer and double-layer PM$_{10}$ filter installed in Seoul Metro, Korea.

		Fabric panel filter (single-layer filter)	Fabric panel + electret pleated filter (double-layer filter)
Filter efficiency (%)		69	80
Average platform PM$_{10}$ conc. (μg/m^3)		38	22
Filtration cost	Installation cost (₩/time)	76,000	354,000
	Replacement cost (₩/time)	56,000	674,000
	Waste filter disposal cost (₩/time)	138,000	746,000
	Replacement times (time/year)	24	6
	Total filtration cost (₩/year)	6,480,000	10,644,000

different filter efficiency including filter installation, replacement and waste filter disposal costs, where each PM$_{10}$ filters were installed in Seoul Metro, Korea. Once fabric panel filter and electret pleated filter (namely, double-layer filter) are installed, 10% of the filtration efficiency increases compared to single-layer fabric panel filter (the average concentration of the platform PM$_{10}$ with the single and double-layer filters is 38 and 22 μg/m^3, respectively). In fact, the platform PM$_{10}$ filtered using both of the single and double-layer filters belongs to 'good' level of health concern. However, compared to the single-layer filter, the filtration cost of the double-layer filter increases by 65% (the annual filtration cost of the single and double-layer filters is 6,476,000 and 10,693,000 Korean Won (₩), respectively). This means that the double-layer filter cannot be considered better filter than the single-layer filter, since it increases 65% of the filtration cost, while the platform PM$_{10}$ concentration using this filter and single-layer filter results in the same level of health level. Accordingly, it could be inferred that the ventilation system with higher efficiency filter does not assure better ventilation performance with respect to the IAQ and operation cost. In this regard, the ventilation control system that uses the existing ventilation system with the conventional filter and also manipulates the amount of PM$_{10}$ from the outdoors to the platform could be a reasonable equipment considering the IAQ and ventilation cost in the subway platform. Therefore, the amount of PM$_{10}$ fed into the platform is estimated using Eq. (2), and then, employed as the manipulated variable.

One of disturbances of the ventilation control system is the PM$_{10}$ concentration in the waiting room, since it flows into the platform by passengers' movement and affects the platform PM$_{10}$ level [24]. The other disturbance is a subway frequency, since the subway moving pushes the PM$_{10}$ in tunnel toward the platform (i.e., piston effect) [5].

4. Materials and methods

4.1. The proposed method

A proposed framework that develops the IAQ ventilation control system that considers the outdoor air quality and estimates its influence on the passengers' health risk is shown in Fig. 2. The

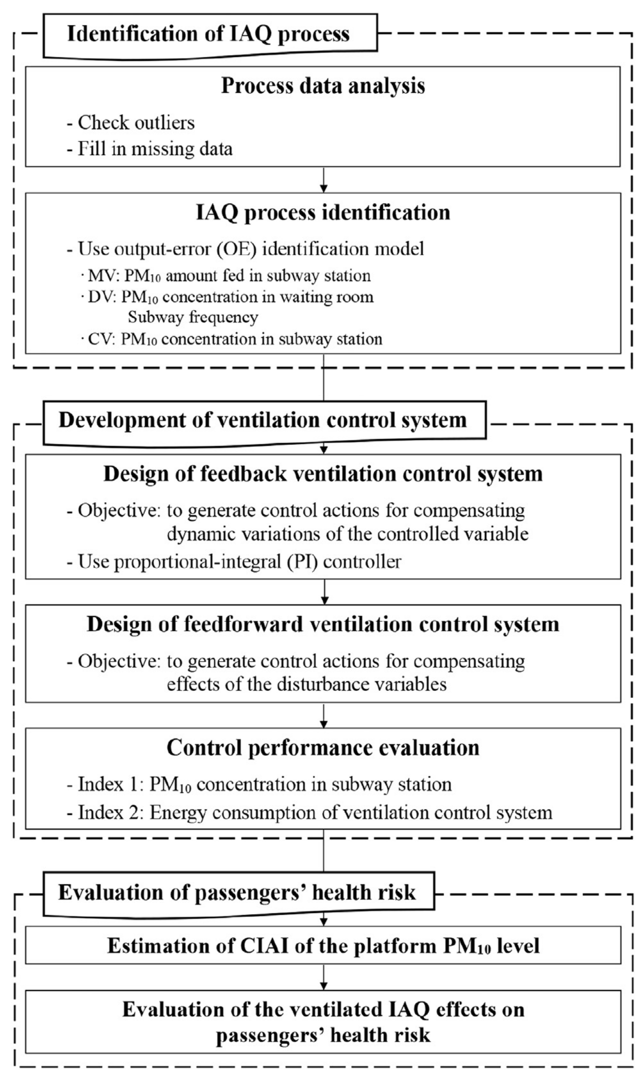

Fig. 2. Framework for development of the IAQ ventilation control system and evaluation of the ventilated IAQ effect on passenger health risk in the subway station.

implementation of the proposed method consists of three parts: (1) identification of the IAQ process in the subway platform, (2) development of the IAQ ventilation control system, and (3) evaluation of the effects of the ventilated IAQ on passenger health risk.

4.1.1. Identification of the IAQ process in the subway platform

To control the PM_{10} concentration inside the subway platform, an identification of dynamics of the platform PM_{10} concentration plays an important role. Therefore, a development of the dynamic models that describe the variations in platform PM_{10} concentration (i.e., process identification) is carried out first. Due to the high complexity required to model the dynamics of PMs in a subway platform using first-principles, this study uses the prediction-error minimization (PEM) method that derives empirical dynamic models from experimental data [21,25].

A first-order plus time-delay (FOPTD) process model identified using the PEM method is represented as:

$$G(s) = \frac{y(s)}{u(s)} = \frac{K}{1+\tau s}\exp(-\theta s) \tag{3}$$

where u is the input variable; y is the output variable; K is the process gain; τ is the time constant; and θ is the time delay [21]. It is well known that the PM_{10} concentration at the subway platform is affected by the subway frequency and PM_{10} concentrations in the outdoor air and waiting room [5,24]. Therefore, the input variables taken for the PM_{10} process identification are the subway frequency, the PM_{10} amount introduced from the outdoors to the subway platform (calculated using Eq. (2)), and the waiting room PM_{10} concentration. Then, using each input variable, three FOPTD process models that capture the dynamics of the platform PM_{10} concentration are identified.

4.1.2. Development of the IAQ ventilation control system

To keep the PM_{10} concentration inside the subway platform at a comfortable and healthy range, the IAQ ventilation control system consisting of feedback and feed-forward control strategies is developed. The feedback control generates a control action when the controlled variable deviates from a set point [20,21]. To reduce a difference between the set point and the measured platform PM_{10} value (i.e., control error), the feedback based ventilation control system is designed first. The manipulated and controlled variables of the feedback control system are the PM_{10} amount introduced from the outdoors to the subway platform and platform PM_{10} concentration, respectively. In this study, a proportional-integral (PI) controller is used, which generates the control action as being proportional to a weighted sum of the control error and its integral. The transfer function of the PI controller is

$$G_{FB}(s) = \frac{u(s)}{e(s)} = k_c\left(1+\frac{1}{\tau_i s}\right) \tag{4}$$

where $G_{FB}(s)$ is the PI controller transfer function; $u(s)$ is the control action; $e(s)$ is the control error; k_c is the proportional control parameter; and τ_i is the integral control parameter [21]. To tune the control parameters, an integral of the time-weighted absolute error (ITAE) tuning rule is applied:

$$\begin{aligned} k_c &= \frac{0.859}{K}(\theta/\tau)^{-0.977} \\ \tau_i &= \frac{\tau}{0.674(\theta/\tau)^{-0.680}} \end{aligned} \tag{5}$$

where K, τ, and θ are the process gain, time constant, and time delay of the process model obtained using the manipulated variable during the identification period [21]. The identification period is nothing but the term of dataset used for identifying the system.

The feed-forward based ventilation control system is designed for rejecting the effects of the disturbances (subway frequency and waiting room PM_{10} concentration) on the platform PM_{10} concentration. The feed-forward control system makes control moves before the disturbances upset the process, and is designed by

$$G_{FF}(s) = \frac{u(s)}{d(s)} = -\frac{G_d(s)}{G_p(s)} \tag{6}$$

where $G_{FF}(s)$ is the feed-forward controller transfer function; $u(s)$ is the control action; $d(s)$ is the disturbance signal; and $G_p(s)$ and $G_d(s)$ are the process models for the manipulated and disturbance variables, respectively [20].

Performances of the IAQ ventilation control system are evaluated using two indices: (1) average PM_{10} concentration at the subway platform and (2) ventilation energy consumption. The PM_{10} inside a subway platform relates to increased respiratory and cardiovascular diseases of the passengers [6]. Thus, a good ventilation control system should maintain low platform PM_{10} concentration; accordingly, the average platform PM_{10} value is considered the first performance index. The energy consumption of the ventilation control system is taken as the second performance index, since powered equipment (e.g., fans and blowers) installed in the ventilation system is responsible for significant energy consumption [3]. The ventilation energy consumption (kWh) is estimated using a third-order polynomial proposed by Liu et al. [10]:

$$\begin{aligned} \text{Energy consumption} = {} & 0.0007\ \text{Hz}^3 - 0.046\ \text{Hz}^2 + 2.01\ \text{Hz} \\ & + 8.8 \end{aligned} \tag{7}$$

where Hz is the inverter frequency of the IAQ ventilation control system.

4.1.3. Evaluation of the passenger health risk

The influence of ventilated platform PM_{10} on the passengers' health risk is evaluated using the CIAI. In order to investigate the effect of IAQ ventilation that takes the outdoor air quality into account, the platform PM_{10} values that are ventilated using the manual control system (i.e., without the consideration of outdoor air quality) and the proposed control system (i.e., with the consideration of outdoor air quality) are estimated, respectively. Then, to assess the passengers' health risk under two different control conditions, the CIAI values of the ventilated platform PM_{10} are compared.

4.2. Subway station in Seoul metro system

This study is carried out in underground D-subway station on line number 3 at the Seoul Metro, Korea. IAQ data (including NO, NO_2, CO, CO_2, PM_{10}, $PM_{2.5}$, temperature and humidity) is collected from a real-time tele-monitoring system (TMS) installed in the D-station. TMS system is located at the center of the waiting room and platform respectively, to collect the IAQ data which represents the IAQ dynamics in each place, while not to interrupt passengers' movement. The position of the TMS system in waiting room and platform is shown in Fig. 3. Diurnal variations of the controlled, manipulated and disturbance variables in the D-station are shown in Fig. 4(a)–(d). Properties of the manual ventilation system (e.g., ventilation inverter frequency, ventilation capacity) installed in the D-station are shown in Fig. 4(e) and Table 3. In general operation of the ventilation system, it has been suggested that the minimum volume of air is supplied to the

(a)

(b)

Fig. 3. Real-time tele-monitoring system (TMS) installed in (a) waiting room and (b) platform of underground D-subway station.

platform, even if the platform IAQ level satisfies good level of health concern. Accordingly, the minimum value of the inverter frequency of manual ventilation system is set at 20 Hz. For each day, the scheduled inverter frequency of manual ventilation system is 45 Hz from 12 a.m. to 5 p.m., 60 Hz from 5 p.m. to 9 p.m. (i.e., rush hours) and 40 Hz from 9 p.m. to 12 a.m. The number of passengers has been identified as one of the major factors of the IAQ variation in the platform [4]. According to the number of passengers, a time zone from 5 p.m. to 9 p.m. is considered as rush hours, since the number of passengers in this timeslot is almost twice that in other times (namely, non-rush hour). In the D-subway station, the number of passengers in rush hour and non-rush hour is 1762 and 960, respectively [26]. During the rush hours, to increase the ventilation performance inside the platform, the inverter frequency of manual ventilation system is set at its maximum value, that is, 60 Hz. On the other hand, at the non-rush hours, the inverter frequency is set at 40–45 Hz.

To know the influence of the variations in outdoor air quality on the control actions of the proposed ventilation control system, the data with the following two scenarios are compared: (1) moderate outdoor PM_{10} data and (2) deteriorated outdoor PM_{10} data. The moderate outdoor data was collected from November 21st, 2011 to November 25th, 2011. The average value of outdoor PM_{10} is 31 $\mu g/m^3$, and all outdoor PM_{10} samples belong to 'moderate' level of health concern suggested by Ministry of Environment of South Korea. The deteriorated outdoor data was collected from March 26th, 2014 to March 30th, 2014 when the yellow sand storm occurred. The average outdoor PM_{10} value is 73 $\mu g/m^3$, and 17 samples exceed a threshold for 'unhealthy for sensitive group' level (which is 120 $\mu g/m^3$). The variations of outdoor PM_{10} concentration in the moderate and deteriorated outdoor air conditions are shown in Fig. 5.

5. Results and discussion

5.1. Identification of IAQ process in the subway platform

Using the PEM method, three FOPTD process models that describe the dynamics of PM_{10} concentration in the subway platform are identified. The process model from the manipulated variable (PM_{10} amount introduced from the outdoors to platform) to the controlled variable (platform PM_{10} concentration) is

$$G_p(s) = \frac{0.22658}{1 + 0.0641s}\exp(-0.44796s) \tag{8}$$

where the process gain, which explains how much the controlled variable changes in response to the variation of manipulated variable, is positive ($K = 0.22658$). This implies the PM_{10} that enters the platform from the outdoors increases the PM_{10} concentration inside the subway platform [14]. The disturbance models identified from the waiting room PM_{10} variable and subway frequency variable, respectively, are

$$G_{d1}(s) = \frac{0.62838}{1 + 0.04726s} \tag{9}$$

$$G_{d2}(s) = \frac{0.41117}{1 + 0.0465s}\exp(-0.90s) \tag{10}$$

The process gains in both disturbance models are positive, which is in accordance with the fact that the PM_{10} movements from the waiting room and tunnel by the passengers' movement and subway piston effect increase the PM_{10} level inside the platform [27].

Fig. 6 shows the measured and fitted concentrations of the platform PM_{10} using the three FOPTD process models. The FOPTD process models have a 46% fit with the measured platform PM_{10} data, where the fit between the measurement (y) and identified model output ($\hat{y}$) is calculated as [28]:

$$\text{Fit} = \left(1 - \frac{\|y - \hat{y}\|}{\|y - \text{mean}(y)\|}\right)100\% \tag{11}$$

This result means that the identified IAQ process models explain 46% of the total variance in the platform PM_{10} concentration. It could be caused by the fact that the IAQ process models do not interpret all factors contributing to the platform PM_{10} concentration. The preceding researches on identification of major sources of the platform PM_{10} have reported that Fe-containing particles, secondary aerosols-containing particles and soil-derived particles are the major components of the platform PM_{10} [27,29,30]. The Fe-containing particles, accounting for 44–48% of the platform PM_{10}, are mainly generated from friction process at rail-wheel-brake interface and mechanical wear of wheels and rails, that is, tunnel

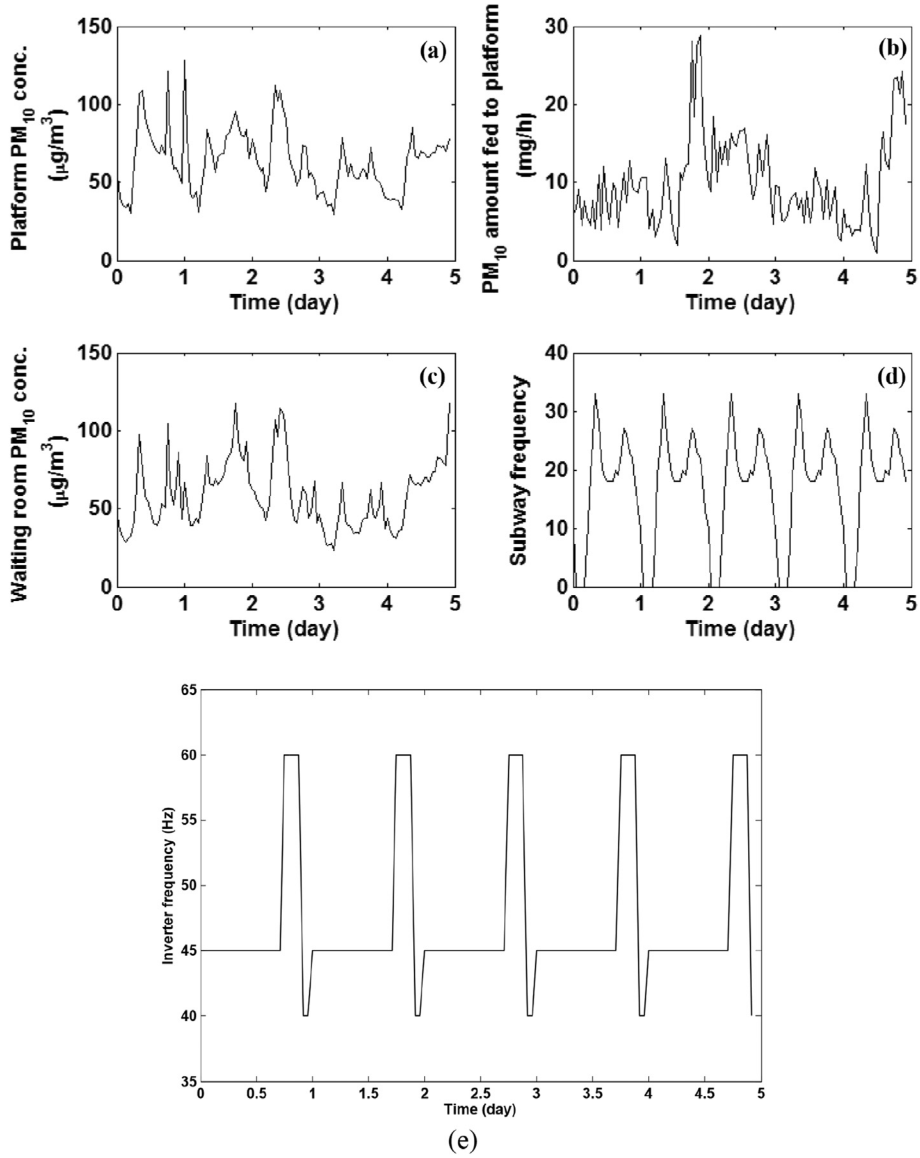

Fig. 4. Variations of IAQ measurements from an underground D-subway station: (a) PM_{10} concentration at the platform (controlled variable); (b) PM_{10} amount introduced from the outdoors to the platform (manipulated variable); (c) PM_{10} concentration in the waiting room (disturbance variable); (d) subway frequency (disturbance variable); (e) inverter frequency of the ventilation system.

Table 3
Properties of the IAQ ventilation system installed in an underground D-subway station.

Property	Symbol in Eq. (2)	Value
Ventilation capacity ($m^3{}_{outdoor\ air}$/hour)	Q	1000
Minimum inverter frequency (Hz)	–	20
Maximum inverter frequency (Hz)	Hz_{max}	60
Number of ventilation system	n	2
Filter efficiency	α	0.8

and railroad-derived particles. The secondary aerosols-containing particles, which derive from the oxidation of primary gases in atmosphere (e.g., sulfur and nitrogen oxide) to salts (e.g., $(NH_4)_2SO_4$, NH_4NO_3), contributes to 30% of the platform PM_{10}. The secondary aerosols are abundantly encountered in outdoor air (the abundances of the secondary aerosols in outdoor air and tunnel was 51% and 5.1%, respectively) [27]. It means that the particles introduced from the outdoors are the second source of the platform PM_{10}. The soil-derived particles contributing 26% of the platform PM_{10} are transported to the platform by the passengers' clothes and shoes [27,29,30]. It has been well known that the inflow of Fe-containing particles from the tunnel to platform can be reduced by installing platform screen doors (PSD), since the PSD separates the platform region from the tunnel. Nonetheless, the Fe-containing particles are identified the major source of the platform PM_{10} in company with the outdoor secondary aerosols-containing particles [27,30]. In the present study, there is a limitation that the on-site measurement about outdoor PM_{10} concentration is only considered for developing the IAQ process models. The identification of the platform IAQ process is challenged by the apparent large amount of unmeasured platform PM_{10} sources such as the mechanical wear of railroad, the brake on subway vehicles, and the flow rate of air that accompanies passengers as they enter or leave the platform. Therefore, to further improve the explanation of IAQ process identification, additional information about the unmeasured platform PM_{10} sources would be needed.

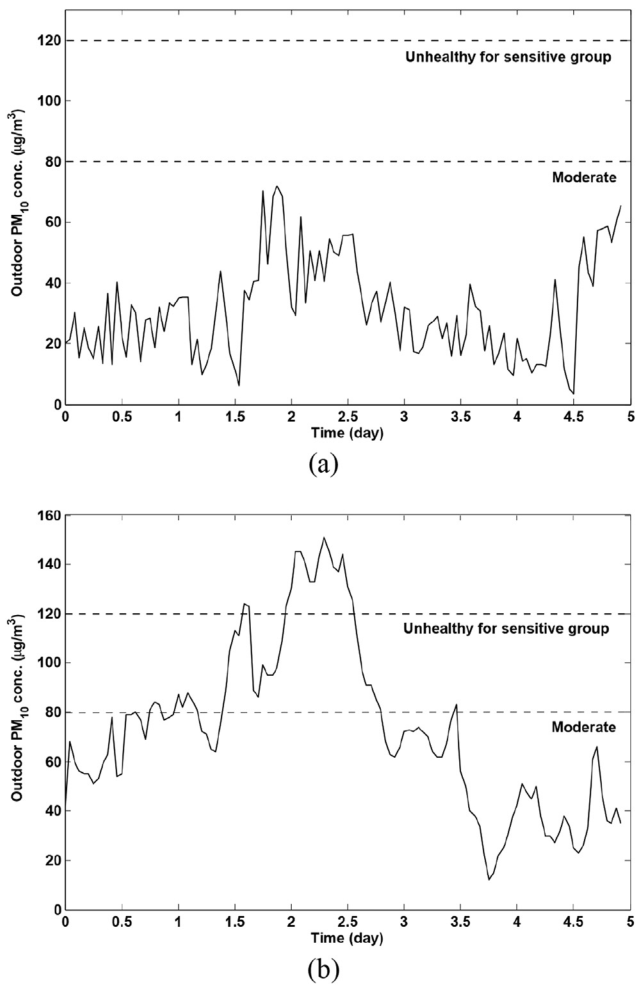

Fig. 5. Variations of outdoor PM_{10} concentration in (a) moderate outdoor PM_{10} data and (b) deteriorated outdoor PM_{10} data.

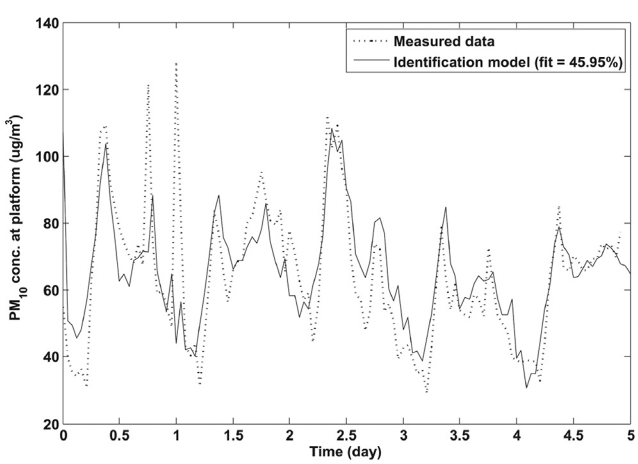

Fig. 6. Simulation result of platform PM_{10} concentration obtained using IAQ process identification models.

5.2. IAQ ventilation control under the moderate outdoor PM_{10} condition

The block diagram of the IAQ ventilation control system that generates the control action taking the outdoor air quality into account is depicted in Fig. 7, where the objective of the FB feedback controller is to reduce the control error; and the objectives of the FF_1 and FF_2 feed-forward controllers are to suppress the effects of variations in the waiting room PM_{10} concentration and subway frequency, respectively. To tune the parameters of the FB controller, the ITAE tuning rule is applied: the proportional (k_c) and integral control parameters (τ_i) are equal to 0.567 and 0.357.

The manipulated variable of the IAQ ventilation control system is the amount of outdoor PM_{10} that is flowed into the platform. In fact, the physical modulated variable of the ventilation system for regulating the inflow of outdoor PM_{10} is the ventilation inverter frequency (Hz). In this section, to show the variation of manipulated variable according to PM_{10} outdoors and the variation in physical operation of ventilation control system according to the manipulated variable changes, the ventilation inverter frequency (Hz) is calculated using the following equation revised from Eq. (2):

$$Hz = PM_{10}\,\mathrm{amount}\cdot \mathrm{Hz_{max}}\cdot 10^3 / Qn(1-\alpha)PM_{10}\,\mathrm{conc.in outdoor air} \tag{12}$$

where PM_{10} amount is the manipulated variable (mg/h); Hz_{max} is the maximum inverter frequency of the ventilation system; Q is the air volume of the ventilation system(m^3/h); n is the number of ventilation systems installed in the subway platform; and α is an average filter efficiency (shown in Table 3).

In this study, four configurations of the IAQ ventilation control system are implemented: (1) FB controller alone, (2) combination of FB and FF_1 controllers, (3) combination of FB and FF_2 controllers, and (4) combination of FB, FF_1, and FF_2 controllers. The combined feedback of the PID controller and two feed-forward controllers in Fig. 7 is utilized to simultaneously control the platform PM_{10} concentration as well as suppress the disturbance effects of the subway train schedule and waiting room PM_{10} concentration. The performance of each control configuration is compared with that of the manual ventilation system, which is operated with the scheduled ventilation inverter frequency without regard to the outdoor air quality. Table 4 summarizes the control performances obtained using the four ventilation control configurations, where the performance indices are the average concentration of platform PM_{10} and ventilation energy consumption. Since the PM_{10} inside the platform presents the health risk both for passengers and subway workers, a good control strategy from the platform PM_{10} point of view should have low concentration of platform PM_{10}. Compared to the manual ventilation system, all proposed control configurations have lower platform PM_{10} values. The reason is explained by Fig. 8, which shows the variations of PM_{10} amount flowed from the outdoors to the platform and the ventilation inverter frequency once the manual ventilation system and FB controller are applied. For the manual system, the inverter frequency is kept at 45 Hz from 12 a.m. to 5 p.m., 60 Hz from 5 p.m. to 9 p.m., and 40 Hz from 9 p.m. to 12 a.m. without regard to the PM_{10} concentration in outdoor air. On the other hand, the FB controller slows down the inverter frequency once the outdoor PM_{10} is in high concentration (shown in the solid circle in Fig. 8(b)), which results in the inflow of a lower amount of outdoor PM_{10} into the platform. The FB controller picks up the inverter frequency when the outdoor PM_{10} is in low concentration (shown in the dotted circle in Fig. 8(b)), which leads to the inflow of fresh outdoor air into the platform for diluting the deteriorated IAQ. Compared to the manual ventilation system, the FB controller decreases the amount of PM_{10} that enters from the outdoors to platform, where the average amount of outdoor PM_{10} flowed through the manual system and FB controller is 9.96 and 7.07 mg/h, respectively. About 29% of the outdoor PM_{10} is less

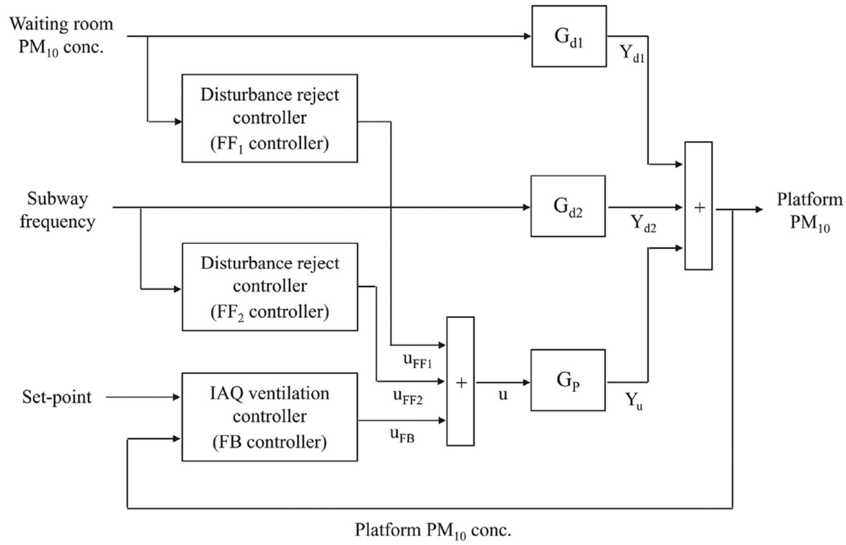

Fig. 7. Block diagram of the IAQ ventilation control system proposed to keep the platform PM_{10} level at a healthy range.

Table 4
Performance evaluation of four ventilation control configurations in terms of average platform PM_{10} concentration and ventilation energy consumption under moderate outdoor PM_{10} condition.

Control configuration	Average platform PM_{10} conc. ($\mu g/m^3$)	Ventilation energy consumption (kWh)
Manual ventilation system	65.51	1827
FB controller	61.16	1670
FB + FF_1 controller	60.59	1563
FB + FF_2 controller	60.45	1448
FB + FF_1 + FF_2 controller	60.36	1444

flowed in the platform using the FB controller, where the inflow reduction percentage of outdoor PM_{10} is calculated as:

$$\text{Inflow reduction} = \left(\frac{PM_{10}\ \text{amount}_{\text{manual system}} - PM_{10}\ \text{amount}_{\text{proposed system}}}{PM_{10}\ \text{amount}_{\text{manual system}}}\right)100\% \tag{13}$$

where PM_{10} amount$_{\text{manual system}}$ and PM_{10} amount$_{\text{proposed system}}$ are the amount of outdoor PM_{10} (mg/h) flowed through the manual system and proposed ventilation system, respectively. Consequently, the platform PM_{10} level of the FB controller is kept at a more moderate range. Note that, if the FB controller reduces the inverter frequency to even lower level once the outdoor PM_{10} is in high concentration, it would lead to the inflow of less amount of outdoor PM_{10}. However, it concurrently reduces the inflow of outdoor air into the platform for diluting the deteriorated IAQ. In the present study, to assure the supply of the minimum volume of outdoor air to the platform, the minimum inverter frequency of the ventilation control system is set at 20 Hz.

Once the FF controllers are applied in concert with the FB controller, the PM_{10} concentration inside the platform is slightly improved compared to the single implementation of FB controller. The combined FB and FF_1 controller, which rejects the influence of waiting room PM_{10} on the platform IAQ, slows the ventilation inverter frequency once the waiting room PM_{10} is in high concentration (shown in Fig. 9(a)). This control action reduces the amount of PM_{10} that is introduced from the outdoors to platform. Since the PM_{10} in the waiting room moves into the platform by passenger movement or natural ventilation, the inflow of less outdoor PM_{10} can compensate for the increase of platform PM_{10} caused by the PM_{10} movement from waiting room [24]. Therefore, the combined FB and FF_1 controller that manipulates the inflow of outdoor PM_{10} depending on the waiting room PM_{10} concentration shows improved platform PM_{10} level compared to the single implementation of FB controller.

The combined FB and FF_2 controller, which has the aim of reducing the influence of subway frequency on the platform IAQ, reduces the ventilation inverter frequency when a large number of subway trains pass the platform (shown in Fig. 9(b)). On the other hand, the FB controller alone has peaks of the ventilation inverter frequency despite the large number of subway trains passing. In general, it is well known that a subway train passing through the platform increases the platform PM_{10} concentration by the piston effect (push of the PM_{10} from tunnel to station) or mechanical wear of subway rails [5,31]. This fact indicates that the combined FB and FF_2 controller, which reduces the inflow of outdoor PM_{10} by decreasing ventilation inverter frequency, takes corrective control actions before the subway passing through the platform deteriorates the platform IAQ.

The IAQ ventilation system operated with powered equipments (such as fan and blower) is the major energy-consuming system of buildings [1]. Thus, in this study, the ventilation control configuration that consumes a small amount of energy is considered a good control strategy. In Table 4, all proposed control configurations have better performance with respect to ventilation energy saving than the manual ventilation system. The reason is explained by Figs. 7 and 8 which display the variations of ventilation inverter frequency once the proposed controllers are applied. Compared to the manual system of which the ventilation inverter frequency is in the

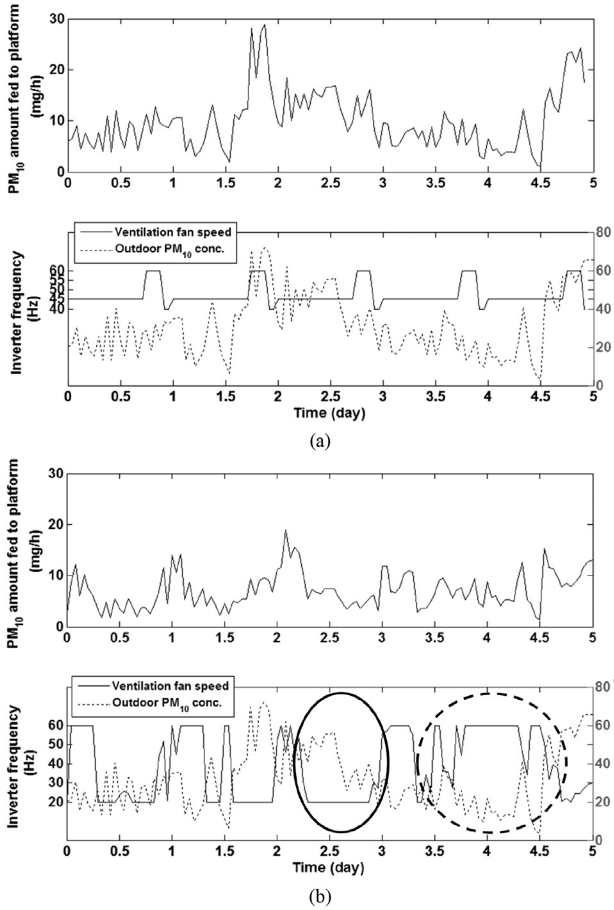

Fig. 8. Amount of PM_{10} flowed into the platform from the outdoors (upper plot) and ventilation inverter frequency (lower plot) obtained using the (a) manual ventilation system and (b) FB controller.

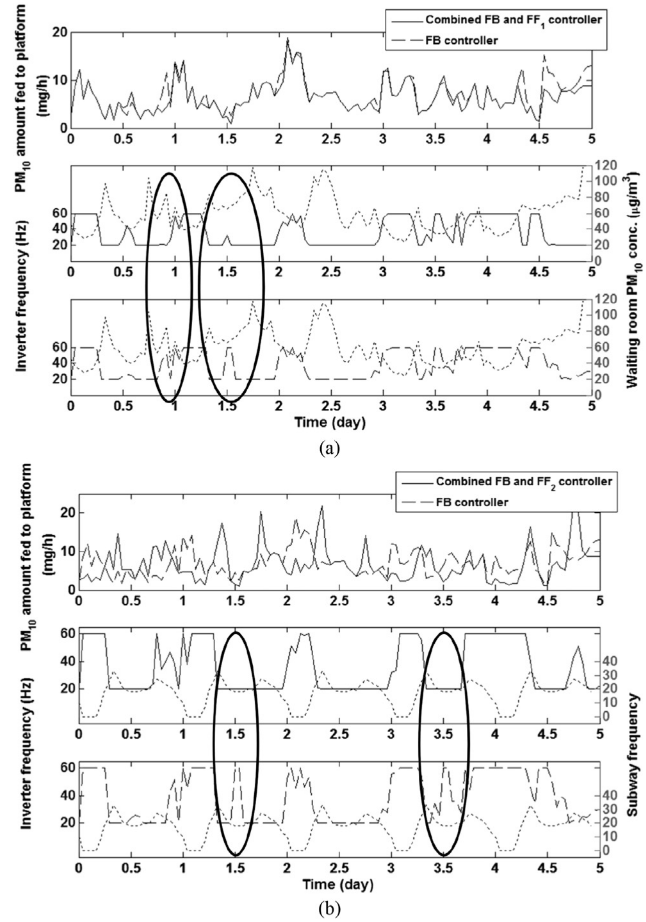

Fig. 9. Amount of PM_{10} flowed into the platform from the outdoors and ventilation inverter frequency obtained using the (a) combined FB and FF_1 controller and (b) combined FB and FF_2 controller.

range of 40–60 Hz, the proposed controllers regulate the ventilation inverter frequency within 20–60 Hz depending on the outdoor air quality, waiting room PM_{10} concentration, and subway frequency. On average the inverter frequency of the proposed IAQ ventilation controllers is slower than that of the manual ventilation system. The combined FB, FF_1, and FF_2 controller that has the best energy saving performance decreases the average ventilation inverter frequency from 47 to 33 Hz, resulting in a significant reduction of the ventilation energy consumption from 1827 to 1444 kWh. This result highlights that the ventilation energy in the D-station can be saved using the proposed ventilation controllers.

In this study, the IAQ ventilation control systems are shown to be able to improve the platform PM_{10} level as well as conserve the ventilation energy consumption. This improved operation is obtained by the proposed control systems flexibly adjusting the ventilation inverter frequency and inflow of outdoor PM_{10} into the platform depending on the PM_{10} concentration of the outdoor air. The IAQ ventilation control systems outperform the manual system operated at the fixed ventilation inverter frequency irrespective of the outdoor PM_{10} concentration.

5.3. IAQ ventilation control under deteriorated outdoor PM_{10} condition (yellow sand storm)

Once the outdoor air used to dilute the platform air pollutants is contaminated, it can increase the level of air pollutants inside the platform, and then, have adverse effects on passenger health. To evaluate the influence of IAQ ventilation control that takes the outdoor air quality into account on the ventilation efficiency and passenger health, the amount of outdoor PM_{10} flowed in the platform and the PM_{10} concentration at the platform are tested using the deteriorated outdoor air data from a yellow sand storm. Fig. 10(a) shows the variations in the inflow of outdoor PM_{10}, concentration of platform PM_{10} and CIAI level of platform PM_{10} once the manual ventilation system is applied. Under the deteriorated outdoor air condition, the outdoor PM_{10} between 1.3 and 3 days are in high concentration due to a yellow sand storm (shown in Fig. 5(b)). The manual operation results in the inflow of a large amount of PM_{10} from the outdoors to the platform and the waiting room. After 1.3 days, the concentration and CIAI level of platform PM_{10} start to increase. We can see that the CIAI values of platform PM_{10} belong to 'unhealthy for sensitive groups' level of health concern from 2.3 to 2.5 days. Senior citizens or children exposed to this level can be adversely affected by the toxicity of PM_{10}. This result implies that the ventilation of platform IAQ with fixed ventilation inverter frequency regardless of the outdoor air quality adversely affects passenger comfort as well as health.

Fig. 10(b) presents the inflow of outdoor PM_{10} and CIAI values on the platform PM_{10} once the proposed ventilation controller is applied. The combined FB and FF_1 controller, which displayed the best performance among the four control configurations, is shown. The performance of each ventilation control configuration is summarized in Table 5. Compared to the manual ventilation system, the combined FB and FF_1 controller noticeably decreases the amount of

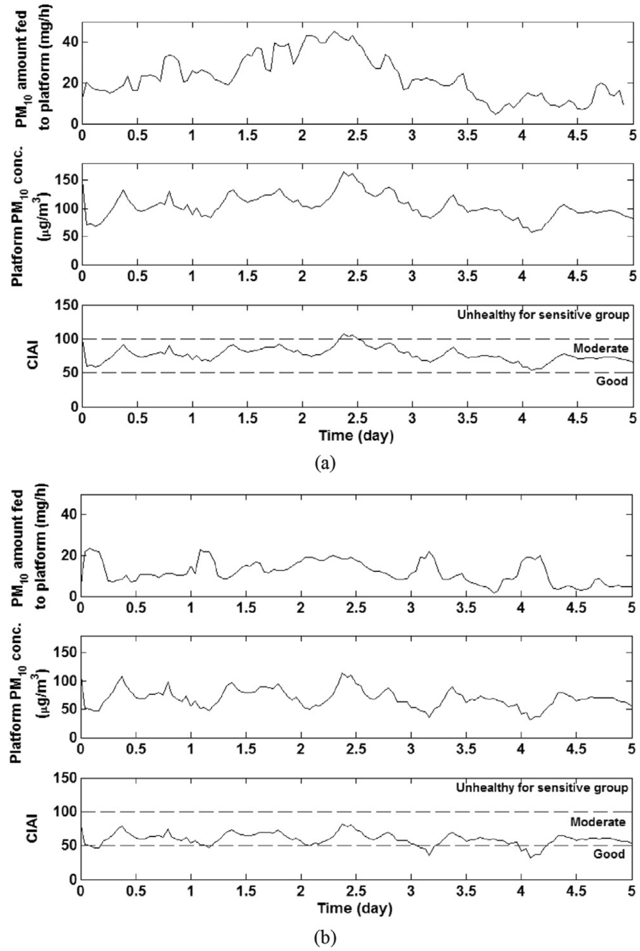

Fig. 10. Amount of outdoor PM_{10} flowed into the platform, PM_{10} concentration in the platform and CIAI level of platform PM_{10} under the deteriorated outdoor PM_{10} condition: (a) manual ventilation system and (b) combined FB and FF_1 controller.

outdoor PM_{10} that enters the platform between 1.3 and 3 days (the average amount of outdoor PM_{10} flowed through the manual system and combined FB and FF_1 controller is 33 and 15 mg/h, respectively). Note that the FF_1 controller is designed to suppress the disturbance effect of the variations of waiting room PM_{10} concentration due to the deteriorated outdoor PM_{10} condition from the yellow sand storm. As a result, the inflow of outdoor PM_{10} on these days reveals a similar tendency to that on another day when the outdoor PM_{10} is in moderate concentration. The proposed ventilation controller takes the correct control action for maintaining healthy PM_{10} level inside the platform, even though the platform IAQ has a possibility to be contaminated due to the inflow of deteriorated outdoor air. With the controlled operation, the CIAI level of the platform PM_{10} is improved from ‘unhealthy for sensitive groups’ (under the manual system) to ‘moderate’ (under the proposed controller), where the IAQ is acceptable. This result demonstrates that the IAQ ventilation control system that generates the control actions while taking outdoor air quality into account provides significantly improved air quality inside the platform. Accordingly, the passengers and subway workers could be exposed to the reduced PM_{10} concentration, resulting in the public health promotion.

If the inverter frequency of ventilation control system is kept at low level the entire time under the deteriorated outdoor PM_{10} condition, it would lead to the inflow of less amount of outdoor PM_{10} and higher ventilation energy savings. However, it could not

Table 5
Performance evaluation of four ventilation control configurations in terms of average platform PM_{10} concentration, ventilation energy consumption, and maximum CIAI value of platform PM_{10} under deteriorated outdoor PM_{10} condition.

Control configuration	Average platform PM_{10} conc. (μg/m^3)	Ventilation energy consumption (kWh)	Maximum CIAI of platform PM_{10}
Manual ventilation system	84.32	1827	107.45 (unhealthy for sensitive groups)
FB controller	68.96	1203	81.93 (moderate)
FB + FF_1 controller	68.65	1121	82.36 (moderate)
FB + FF_2 controller	68.90	1208	82.63 (moderate)
FB + FF_1 + FF_2 controller	68.74	1193	81.95 (moderate)

assure the inflow of sufficient outdoor air into the platform for diluting the deteriorated IAQ. In the present study, even if the outdoor PM_{10} is in high concentration, the inverter frequency of the ventilation control system is flexibly regulated within 20–60 Hz depending on the changes in PM_{10} outdoors. In case of the exceedingly contaminated outdoor PM_{10} condition, if the inverter frequency is kept at low level the entire time, an air exhaust ventilation system that ventilates the polluted indoor air by circulating indoor air with the pollutants filtered out would become a complementary IAQ controlling method [32].

6. Conclusion

To keep the PM_{10} concentration inside subway platforms at a healthy range, an IAQ ventilation control system consisting of one feedback and two feed-forward control strategies was investigated. The main contribution of this study is to investigate the effect of outdoor air quality diluting the platform air pollutants on the indoor air quality in a subway station. Moreover, the influence of ventilated IAQ on the passenger and subway worker's health was evaluated using a comprehensive indoor air-quality index. The results of this study showed that the proposed control system can improve the platform PM_{10} level and conserves the ventilation energy consumption, compared to the manual ventilation system which operates at the fixed ventilation inverter frequency without regard to the outdoor air quality. Furthermore, once the outdoor air is contaminated, the health level of platform PM_{10} by a proposed ventilation controller can be improved from ‘unhealthy for sensitive groups’ to ‘moderate’ level by manipulating the inflow of contaminated outdoor air into the platform. Therefore, we can conclude that the IAQ ventilation control system taking the outdoor air quality into account results in robust ventilation performances which save energy consumption, enhance the IAQ level, and minimize the health risk in subway platforms. Notwithstanding the advantages of the proposed ventilation control system, this study has limitation that the influences of other outdoor air pollutants (e.g., SO_X and NO_X) on the IAQ ventilation performance and passengers' health has not been analyzed. As an on-going research work, we plan to continue on researching the IAQ ventilation control system that takes into account the PM_{10} as well as other pollutants in the outdoor air.

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