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Economical control of indoor air quality in underground metro station using an iterative dynamic programming-based ventilation system

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Abstract

A set-point of ventilation control system plays an important role for efficient ventilation inside metro stations, since it affects level of indoor air pollutants and ventilation energy consumption concurrently. In this study, to maintain indoor air quality (IAQ) at a comfortable range with a lower ventilation energy consumption, the optimal set-points of the ventilation control system were determined. The concentration of air pollutants inside the station shows a periodic diurnal variation in accordance with the number of passengers and subway frequency. To consider the diurnal variation of IAQ, an iterative dynamic programming (IDP) that searches for a piecewise control policy by separating whole system duration into several stages was applied. The optimal set-points of the ventilation control system in underground D-subway station, Korea were determined at every 3, 2, and 1 h, respectively. Then, according to the set-point changes, the ventilation controller was adjusted to an appropriate ventilation fan speed, correlating to the amount of outdoor PM_{10} that flows into the station. The results showed that the ventilation control system with the IDP-based optimal set-points has a better economical ventilation performance than manual ventilation system, with a 4.6% decrease in energy consumption, maintaining a comfortable IAQ level inside the station.

Keywords

Ventilation control system, Iterative dynamic programming (IDP), Set-point optimization, Indoor air quality, Ventilation energy, Underground metro station

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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.[1,2] Notwithstanding these advantages, there has been a growing concern over indoor air quality (IAQ) in subway systems, since most subway systems are underground in a confined space where indoor air pollutants cannot be easily discharged by natural ventilation.[3,4] Furthermore, due to abrasive force acting on rails and wheel breaking, various types of air pollutants

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such as particulate matters (PMs) are generated internally.[5,6] These indoor air pollutants are trapped and accumulated in the confined space of underground subway systems and could pose a long-term health risk to passengers and subway working staff.[4,7] Therefore, to ensure acceptable good health for passengers and subway workers, recent research in underground subway systems has considered a development of ventilation control systems that maintain IAQ at a comfortable and healthy range.[8–10]

Another important consideration for underground subway systems is a saving of ventilation energy consumption, since the energy for maintaining air comfortable for passengers and workers in the subway system would constitute 14–35% of the total energy consumption.[11,12] In accordance with recommendation of Intergovernmental Panel on Climate Change[13] on the reductions in energy demand in the building sector, the saving of ventilation energy has become a major challenge for building spaces including the underground subway system. Therefore, an attempt to develop an energy-effective ventilation control system that keeps the comfortable IAQ while concurrently saving ventilation energy is vital and timely.

A set-point of ventilation control system, which is the IAQ level the ventilation control system should aim to maintain, plays an important role for efficient ventilation in underground subway systems, since it affects the level of indoor air pollutants and ventilation energy consumption concurrently.[8] The U.S. Environmental Protection Agency[14] has set a threshold limit for moderate level of PMs at $100\,\mu g/m^3$ in indoor air in metro station. Suppose the ventilation set-point for PMs is set at $60\,\mu g/m^3$ for the underground subway systems, then such operation would lead to an increase in ventilation energy consumption, since increased power is required to supply more fresh air into the subway system for diluting polluted air-containing PMs.[7] On the other hand, suppose the ventilation set-point for PMs is set at $130\,\mu g/m^3$, this would thus reduce ventilation energy. However, the IAQ would be deteriorated due to the reduced entry of fresh air into the subway system. Therefore, the set-point of ventilation control system for keeping comfortable IAQ is in direct conflict with that for reducing energy consumption.[8] So, in order to manage the trade-off between these conflicting objectives, optimal set-points are needed to keep the IAQ in the metro station at a comfortable level while simultaneously saving energy.

Recently, several studies on ventilation control of indoor air pollutants in underground subway systems have been reported.[8,15,16] Liu et al.[8] have developed a model predictive control-based ventilation system in the subway station. They also have applied a multi-objective optimization algorithm to determine optimal set-points for the ventilation system which could concurrently improve the IAQ and maintain ventilation energy efficiency. Moreno et al.[15] have investigated variations of subway platform air quality depending on ventilation condition, station design and subway train frequency. Perna et al.[16] have measured air flow rate inside the subway station. Then, using information derived from the air flow rate measurements, they have dynamically controlled mechanical ventilation systems installed in the subway station. These researchers have assumed that the polluted indoor air could be replaced with clean outdoor air by increasing the ventilation rate. In fact, if the outdoor air is contaminated due to aeolian transportation of dust particles or yellow dust, these could flow into the underground subway systems through ventilation systems and could increase the concentrations of air pollutants inside the subway systems.[17,18] Therefore, a new approach that considers the outdoor air quality of the inlet air for diluting indoor air pollutants is necessary. Hence, this article proposes a ventilation control system that could adjust the ventilation rate by taking into account of changes in the outdoor air quality.

The concentration of air pollutants inside the underground subway systems shows a periodic diurnal variation depending on the changes in the number of passengers and subway frequency.[19,20] Several researches have reported that the inaccurate ventilation strategy, which does not consider the diurnal variation in IAQ, could cause the unnecessary energy consumption and air discomfort in the underground subway systems.[20,21] Therefore, in order to balance the ventilation energy saving and comfortable IAQ maintenance in underground subway systems, the set-point of the ventilation control system would need to be reset in accordance with the diurnal variation in IAQ.[22,23] Hence, this study investigates the development of an appropriate ventilation control strategy that would determine the optimal set-points required for considering the diurnal variation in IAQ. For this purpose, an iterative dynamic programming (IDP)-based IAQ ventilation system, which searches for the optimal control action of ventilation system by separating the whole control duration into several segments in time periods, has been proposed by this paper.[24,25]

Theory on IDP

The concentration of air pollutants inside the underground subway station can vary in periodic diurnal pattern in accordance with the number of passengers and subway frequency (as shown in Figure 1).[19,20] In this study, an IDP[24,25] was used to determine the optimal

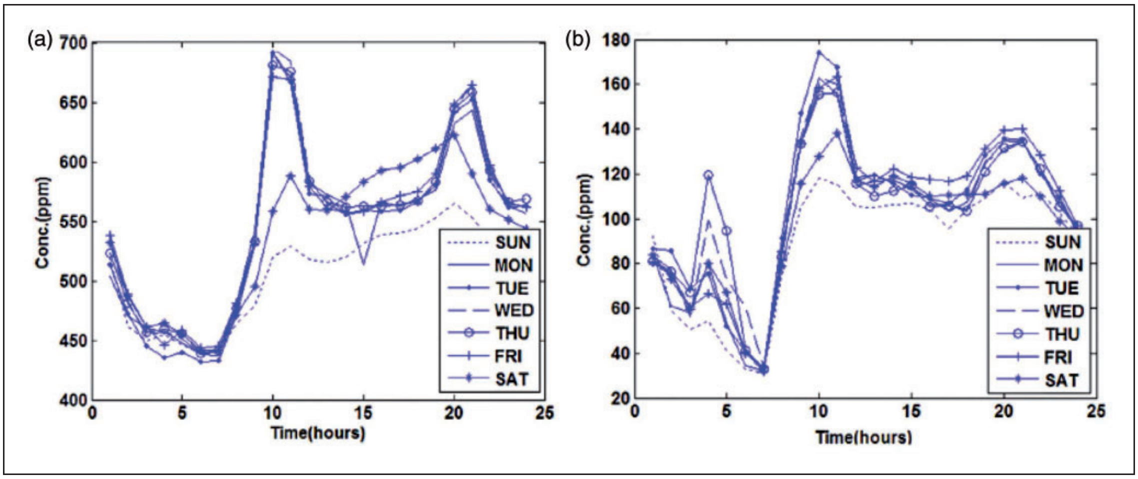

Figure 1. Diurnal variation of indoor air pollutants in underground metro station: (a) CO_2 and (b) particulate matter (PM_{10}).

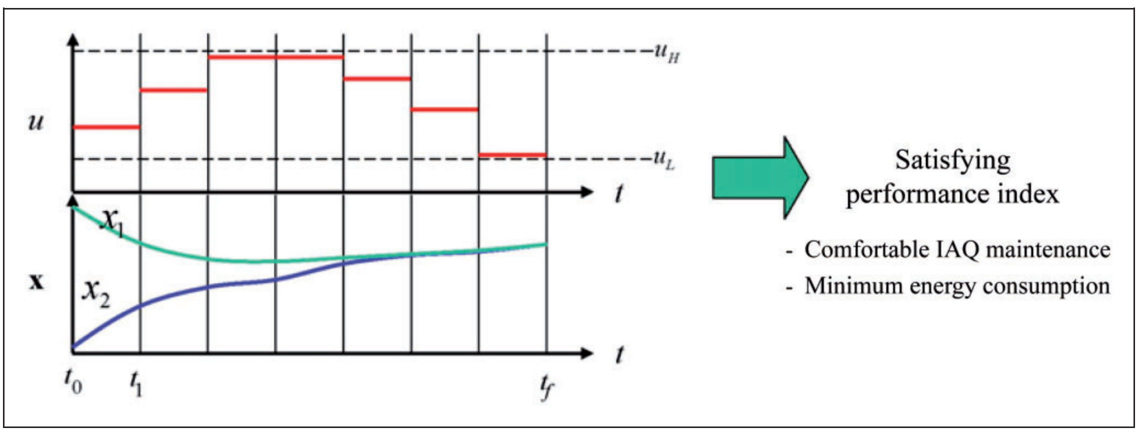

Figure 2. Basic scheme of iterative dynamic programming (IDP) algorithm (revised from Kim et al.[25]).

set-points of the ventilation control system at every time intervals when the IAQ periodic pattern varies. The implementation allows the IDP to search for the optimal set-point for ventilation control during a one-day period which is separated into several time segments of equal intervals.[24,25]

Using the IDP algorithm, a piecewise constant control action of the ventilation system can be established during the various time segments. The operation of IDP is as shown in Figure 2, where **x** is the state vector and **u** is the control vector bounded by upper (u_H) and lower (u_L) limits.[24] The procedure for determining the optimal control action based on IDP is as follows:

1. Separate the whole system duration [0, t_f] into P segments, each of time duration $L = t_f/P$.
2. Choose the number of allowable states grid (N) and control action (M). Choose an initial control action ($u(0)$) and changing size of the control action (namely region size (r)). Then, calculate allowable control actions (u) using equation (1) that are applied to IDP algorithm as follows

$$u = u(0) + [(\text{median value of } m - m) \times r] \quad (m = 1, \cdots, M) \tag{1}$$

For instance, the number of allowable control action (M) is 5, the initial control action [$u(0)$] is 50 and the region size of control action (r) is 5. Then, the allowable control actions (u) to be applied to IDP are calculated by equation (2)

$$u = 50 + [(3 - m) \times 5] \quad m = 1, \cdots, 5 \tag{2}$$

3. Construct grid points for the state vector (namely **x**-grid points) at each time segment, applying the initial control action.

4. At the last time segment P, corresponding to the time interval $t_f - L \leq t < t_f$, apply each of the allowable control actions (u) to each **x**-grid point. Evaluate the performance index of the control system obtained using each allowable control value, and then choose the particular control value that minimizes the performance index.
5. At the $p-1$ time segment, corresponding to the time interval $t_f - 2L \leq t < t_f - L$, apply each of the allowable control actions (u) to each **x**-grid point. To continue integration to the last segment P, take the control policy from Step 4 that corresponds to the **x**-grid point which is *closest* to the state $\mathbf{x}(t_f - L)$ in Step 5. Evaluate the performance index of the control system, and then choose the particular control value that could minimize the performance index from $t_f - 2L$ to t_f.
6. Repeat the procedure with time segments $P-2$, $P-3, \ldots, 1$ (of which the time interval is $0 \leq t < L$). Choose the control value that could minimize the performance index at each stage.
7. Reduce the region size of the control action (r) by a reduction factor (γ), as represented by equation (3)

$$r^{(j+1)} = \gamma r^{(j)} \tag{3}$$

where j is the number of iterations.

8. Select the optimal control action given at Step 6, and then go to Step 3.

For more details of the IDP procedure, refer to Luus.[24]

Performance index for determining the optimal set-points of ventilation control system

In this study, to search for the optimal set-points required for the ventilation control system to maintain the IAQ at a comfortable range with a lower ventilation energy consumption, the performance index used by the IDP is proposed. Figure 3(a) shows the ventilation energy consumption and average concentration of particulate matters (PM_{10}) at the underground subway station measured at different set-point values of the ventilation control system. Since the presence of PM_{10} represents a more potential risk to human health than that of other air pollutants, the PM_{10} is considered as an indicator of air pollution inside the underground subway station.[26] While the position of points could vary somewhat from one experiment to the next due to time-varying disturbances, the trade-off between the ventilation energy and IAQ can be clearly seen in Figure 3(a). More power for the ventilation system is needed to supply more fresh air into the subway station for diluting and removing the polluted indoor air, and this would lead to an increase in energy consumption.[7] Therefore, both the energy consumption needed for ventilation and PM_{10} concentration in the subway station should be incorporated into the performance index to allow a trade-off between the two conflicting requirements to establish the optimum ventilation performance.

Figure 3(b) shows the areas of the ventilation energy consumption (A_E) and PM_{10} concentration (A_{PM10}) in the subway station with two different ventilation set-point values. Note that the areas are integrals of the respective variables over a specified time interval, and the parts highlighted in colour and diagonal lines in Figure 3(b) show the examples for how to calculate the area over the specified time interval. For the specified time interval, A_E is proportional to the energy consumption, thus, a smaller area A_E means less energy consumption for the ventilation required. In terms of the PM_{10} concentration, a smaller area A_{PM10} means a lower average PM_{10} concentration in the station air, that is therefore a more comfortable IAQ condition. To satisfy both the objectives of energy savings and comfortable IAQ for the ventilation setting, the performance index (J) of the IDP algorithm is selected as a weighted combination of the A_E and A_{PM10}.[25] The performance index (J) is determined by equation (4)

$$\begin{aligned} J &= \sum_{k=0}^{N} (QA_E + RA_{PM10}) \\ &= \sum_{k=0}^{N} (Q \cdot \text{energy}(k) \cdot L + R \cdot \text{PM}_{10}(k) \cdot L) \end{aligned} \tag{4}$$

where Q and R are weight factors on the ventilation energy and PM_{10} concentration in the subway station, respectively; N is the number of IDP segments and L is the time duration of the IDP segment.

At each time segment, the IDP algorithm would determine the set-point that would give the minimum value of performance index, and this would be the optimal set-point for the ventilation control system at the corresponding time segment.[24] Furthermore, by applying the weight factors (Q and R) on the ventilation energy and station PM_{10} concentration, the proposed performance index would take into account the trade-off between the ventilation energy consumption and IAQ.[25] For instance, by increasing the value of Q relative to R, the set-point of the ventilation control system would focus more on the energy saving for the ventilation required rather than achieving the comfortable PM_{10}, and vice versa.

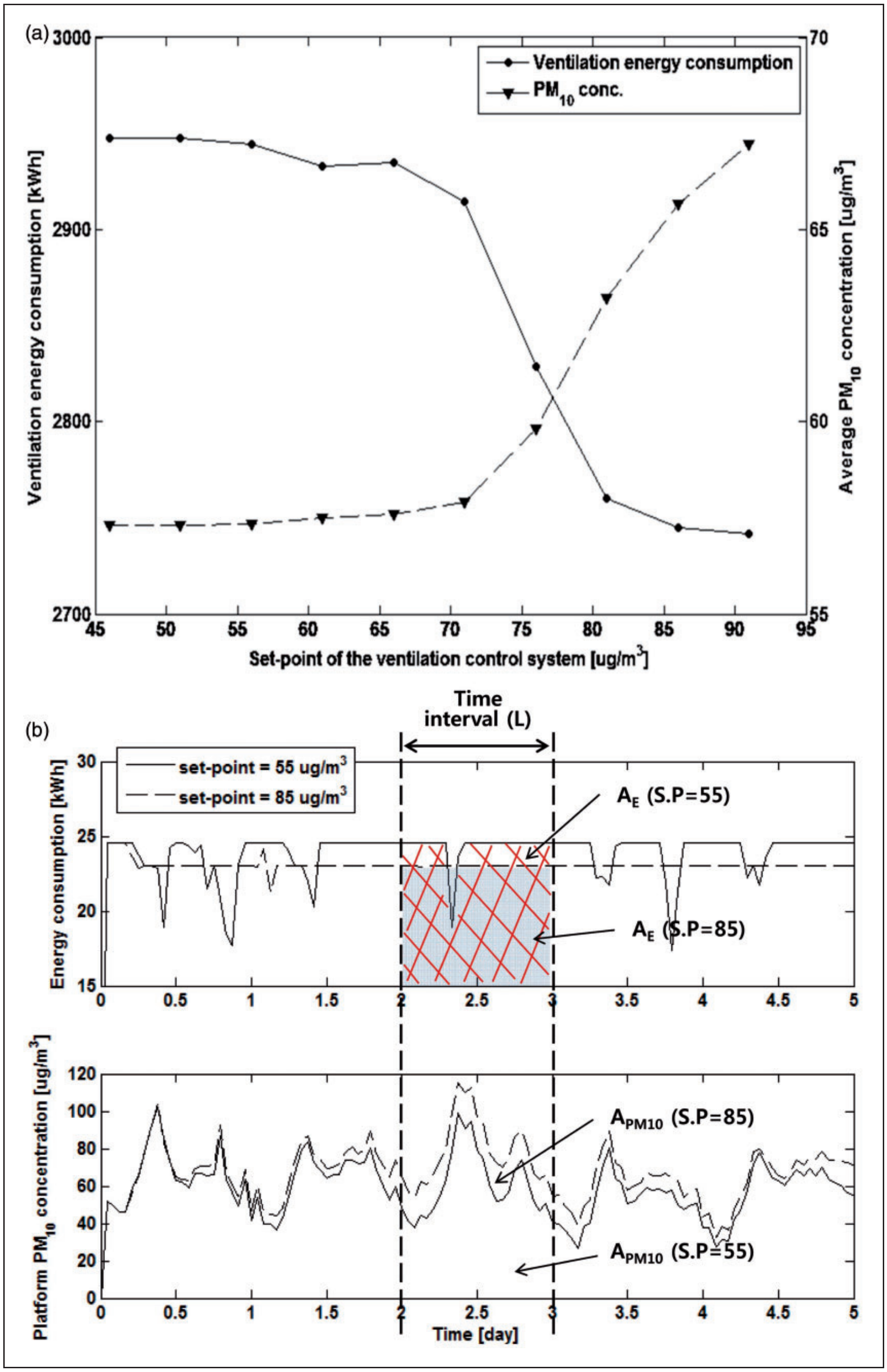

Figure 3. Influence of set-point changes on the ventilation energy and PM_{10} concentration in the underground subway station: (a) Measured variations according to changes in the set-point, (b) areas of the ventilation energy consumption (A_E) and station PM_{10} concentration (A_{PM10}) at two different set-point values.

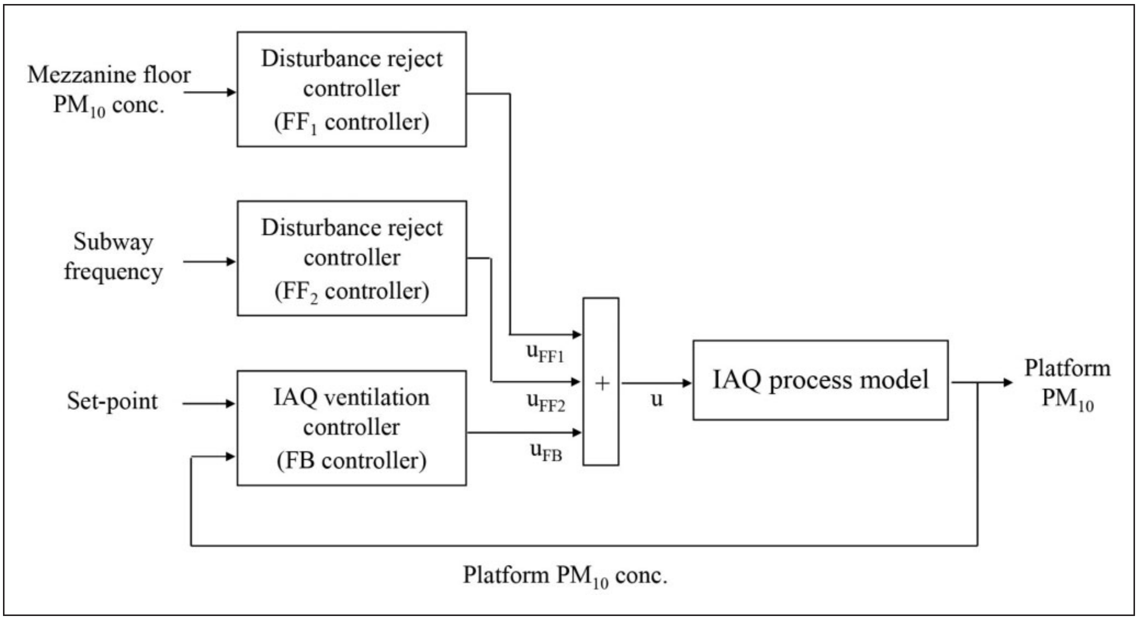

Figure 4. Block diagram of the IAQ ventilation control system developed to keep the comfortable PM_{10} level with lower ventilation energy consumption.

Material and methods

IAQ ventilation control system

Figure 4 shows a block diagram of the IAQ ventilation control system developed by the present study. The controlled variable used for the ventilation control system is the PM_{10} concentration in the station platform. In the actual ventilation control system, the physical manipulated variable is the ventilation fan speed, namely Revolutions Per Minute (RPM).[8,10] However, to consider the outdoor air quality used for ventilating the indoor environment of the subway station, there is a need to formulate the ventilation control design in terms of the amount of PM_{10} that is introduced from the outdoors to the station through the ventilation system. Therefore, the amount of PM_{10} being fed into the station through the ventilation system would be considered a surrogate manipulated variable (denoted by u in Figure 4), which is calculated by equation (5), as

$$PM_{10}\ \text{amount} = \left(Q\frac{\text{RPM}}{\text{RPM}_{\max}}\right)n(1-\alpha) \quad (PM_{10}\ \text{conc. in outdoor air}) \tag{5}$$

where Q is the capacity of the ventilation system ($m^3{}_{\text{outdoor air}}$/hour), $\text{RPM}_{\max}$ is the maximum fan speed of the ventilation system, n is the number of ventilation systems installed in the subway station and α is a filter efficiency.

The use of the PM_{10} amount in equation (5) as the surrogate manipulated variable would allow real-time determination of the RPM based on real-time measurement of the time-varying outdoor PM_{10} concentration. One of disturbance variables of the ventilation control system is the PM_{10} concentration in the mezzanine floor, which connects the station entrance and platform. Passengers' movement could cause the air-containing PM_{10} to flow from the mezzanine floor into the station platform which thus affects the platform PM_{10} concentration.[20] The other disturbance variable is the frequency of subway trains, since the motion of subway trains would drive the air-containing PM_{10} in the tunnel towards the station platform by a piston effect.[15,27]

The IAQ ventilation control system consists of two control strategies, which are feedback (FB) and feedforward (FF) control. The FB control generates a control action when the controlled variable deviates from the ventilation set-point. The FB-based ventilation control system is designed to reduce any difference that could occur between the set-point air quality level and the measured station PM_{10} concentration (i.e. control error).[28,29] The FF control generates the control action before the disturbances could upset the process. Thus, the FF-based ventilation control system is designed to suppress the effects of the disturbances on the station PM_{10} concentration.[28,29] For background on the FB and FF control, refer to Bequette[28] and Seborg et al.[29]

The proposed method

A proposed framework to determine the optimal set-points for the ventilation control system using the IDP method is shown in Figure 5. First, the ventilation control system consisting of FB and FF control was developed to maintain the IAQ at a comfortable range with a lower energy consumption (as shown in Figure 4). Then, the IDP algorithm was applied to search for the optimal set-points of the developed ventilation control system. Since the PM_{10} concentration inside the underground subway station shows a periodic diurnal variation, the period for ventilation using the applied IDP algorithm was set for one day (i.e. 24 h). The algorithm was carried out with four different IDP time-segments scenarios, which are four-segments, eight-segments, twelve-segments and twenty-four-segments scenarios. In each of the IDP time-segment scenarios, the optimal value of each set-point was determined at every 6, 3, 2 and 1 h intervals, respectively. In general operation of the ventilation system, a frequent change in operating conditions of the ventilation system (e.g. inverter frequency, ventilation fan speed) is not suggested, since it would lead to frequent breakdown and maintenance of the ventilation system. Accordingly, in the present study, the minimum time interval of the IDP-based ventilation control system for resetting the optimal set-point is set at 1 h.

Performances of the ventilation control system were evaluated using two indices: the average PM_{10}

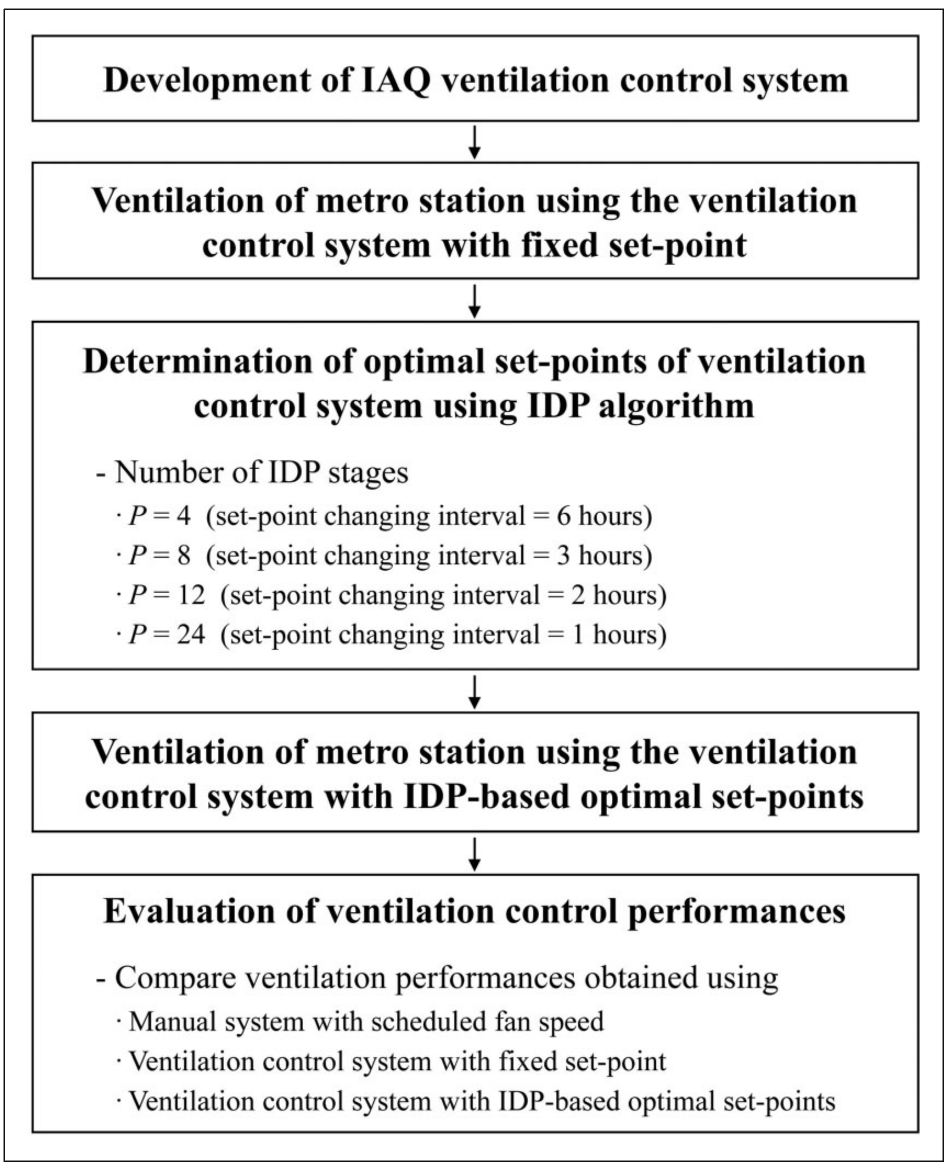

Figure 5. The framework for determination of optimal IAQ set-points for the ventilation control system using the IDP algorithm.

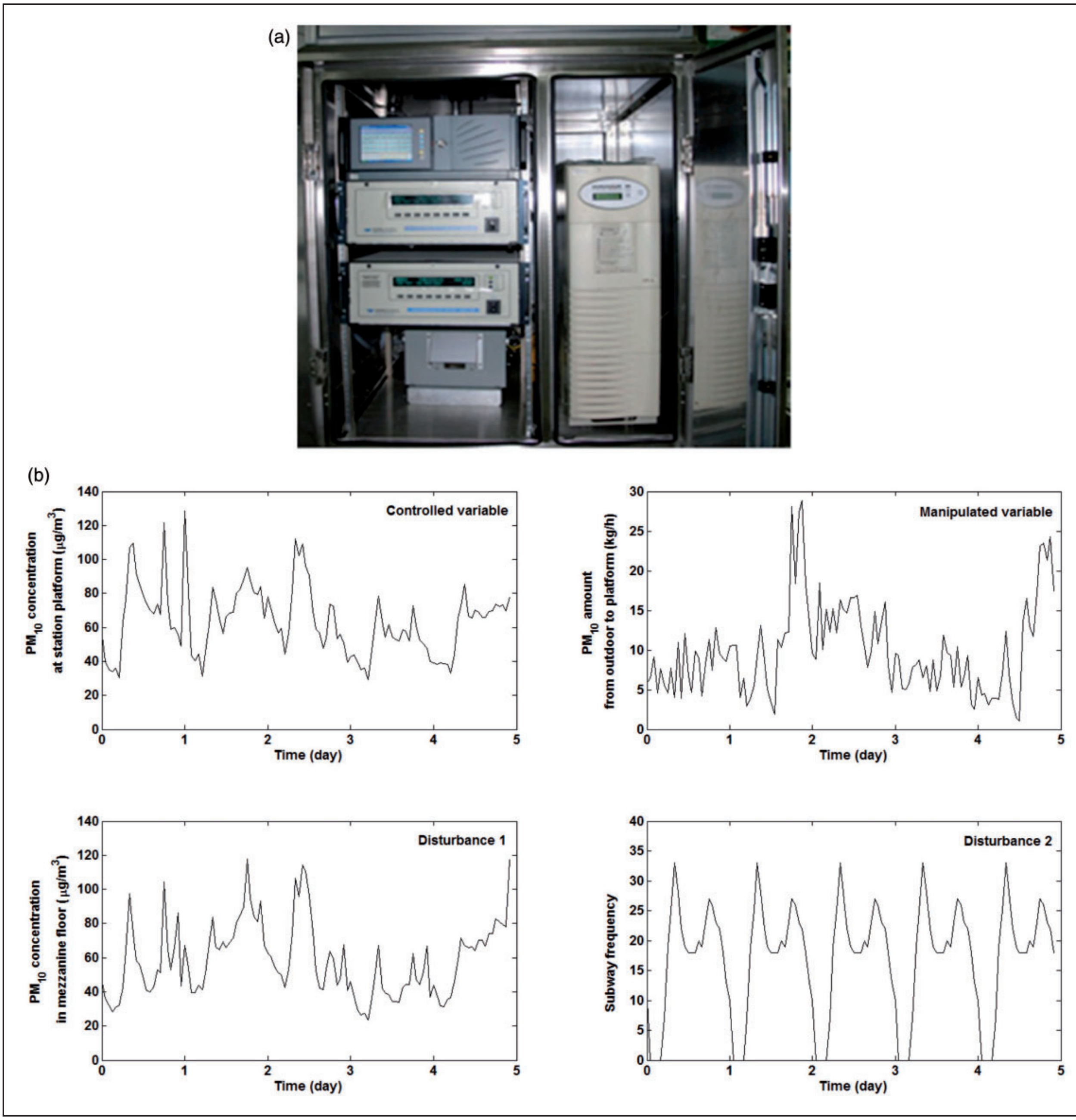

Figure 6. (a) Tele-monitoring system (TMS) in D-subway station, and (b) variations of the controlled variable (PM_{10} concentration at station platform), manipulated variable (PM_{10} amount from outdoors to station) and disturbances (PM_{10} concentration in mezzanine floor, subway frequency).

concentration in the subway station and the energy consumption for the ventilation system. The energy consumption was estimated using a third-order polynomial as represented by equation (6) proposed by Liu et al.[8]

$$\text{Energy consumption} = 0.0007\text{RPM}^3 - 0.046\text{RPM}^2 + 2.01\text{RPM} + 8.8 \quad (6)$$

where RPM is the fan speed of the ventilation control system. In order to confirm the robustness of the proposed ventilation control system, the ventilation performances obtained using three ventilation systems were compared: (1) manual ventilation system operated with the scheduled fan speed, (2) ventilation control system operated with the fixed IAQ set-point and (3) ventilation control system operated with the IDP-based optimal IAQ set-point.

Underground subway station in Seoul metro system

This study was carried out at an underground D-subway station on line number 3 in Seoul Metro, Korea. A real-time tele-monitoring system (TMS) was fixed at the centre of D-subway station, to monitor concentrations of seven air pollutants (NO, NO_2, NO_X, PM_{10}, $PM_{2.5}$, CO, CO_2) with fixed measurement intervals. Concentration of PM_{10} was measured using a β-ray attenuation principle (SPM-613D) with the corresponding size distribution filters.[2] For more details of the air pollutant analysers installed in TMS system, refer to Kim et al.[2]

The variables (PM_{10} concentration in station platform (controlled variable), PM_{10} amount introduced from outdoors to station (manipulated variable), PM_{10} concentration in mezzanine floor and subway frequency (disturbance variables)) collected from 21 November 2011 to 25 November 2011 were used in the present study. Diurnal variations of the controlled, manipulated and disturbance variables collected during the above period are shown in Figure 6(b). In general, two types of IAQ ventilation system were installed in the underground subway stations. These are air supply ventilation system and air exhaust ventilation system. This article focuses on the air supply ventilation controller that ventilates the polluted indoor air in the metro station by drawing in outdoor air. Properties of the air supply ventilation system (e.g. ventilation fan speed, ventilation capacity) installed in the D-station are shown in Table 1.

Table 1. Properties of the air supply ventilation system installed in underground D-subway station.

Property	Symbol in equation (4)	Value
Ventilation capacity ($m^3{}_{outdoor\ air}/h$)	Q	1000
Minimum ventilation fan speed (Hz)	–	0
Maximum ventilation fan speed (Hz)	RPM_{max}	60
Number of ventilation system	N	2
Filter efficiency	A	0.8

Result and discussion

The IAQ set-point of the ventilation control system could affect both the PM_{10} concentration and the energy consumption for ventilation in underground subway station. Therefore, the diurnal variation of the optimal ventilation set-points should be balanced to maintain a comfortable PM_{10} concentration but with an energy saving using the IDP technique. Specifications of the applied IDP algorithm were: an initial set-point of 84, a changing size of set-point (r) of 5, a number of iterations of 5 and a set-point reduction factor (γ) of 0.8.

Table 2 summarizes the control performances obtained using the manual ventilation system and the proposed ventilation control systems. For each day period, the scheduled fan speed of manual ventilation system was set 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 the outdoor air.

Comparing to the manual ventilation system, the ventilation controllers (including the fixed and IDP-based controllers) were specifically controlled based on the outdoor air quality and thus would consume less ventilation energy. The reason is illustrated by Figure 7 which shows the variations in the amount of PM_{10} in the air being drawn in from outdoors to the subway station by the ventilation fan speed, once the ventilation control system was turned

Table 2. Performance evaluation of the manual and proposed ventilation control systems in terms of average station PM_{10} concentration and ventilation energy consumption.

Ventilation configurations		Average station PM_{10} conc. ($\mu g/m^3$)	Ventilation energy consumption (kW h)
Manual ventilation system		67.16	571
Ventilation control system	Fixed set-point (set-point = 70 $\mu g/m^3$)	68.65	556
	Four-segment IDP-based set-point	67.93	549
	Eight-segment IDP-based set-point	67.94	546
	Twelve-segment IDP-based set-point	67.86	546
	Twenty-four-segment IDP-based set-point	67.80	545

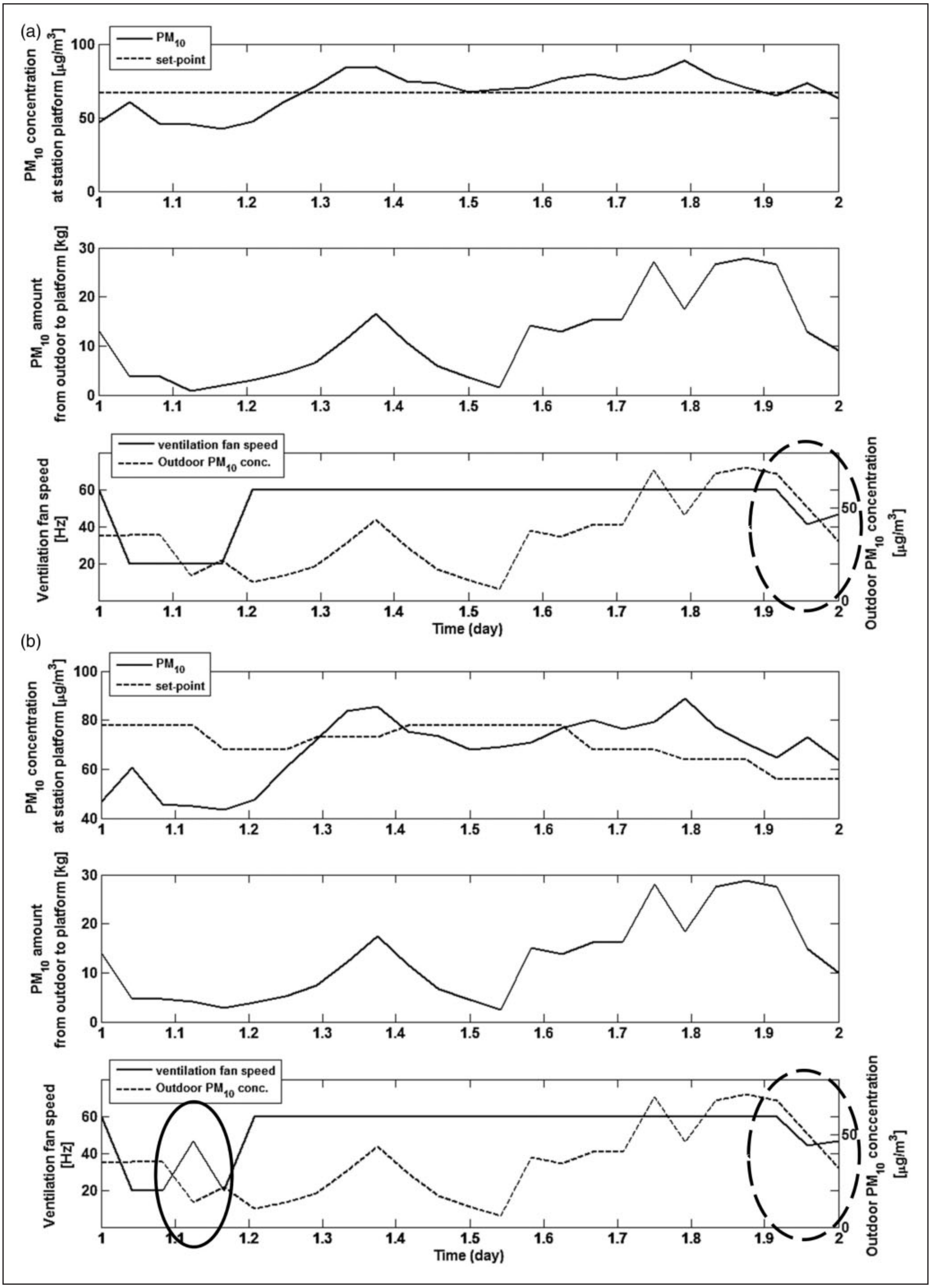

Figure 7. Station PM_{10} concentration (upper plot), amount of PM_{10} being flowed in from the outdoors (middle plot) and ventilation fan speed (lower plot) obtained using the ventilation control system with (a) fixed set-point and (b) eight-segment IDP-based optimal set-points.

Table 3. Diurnal variation of the optimal set-points of the ventilation control system obtained using four different IDP-segment scenarios.

[μg/m^3]	Time																							
	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
With 6-hour interval (i.e., 4-stage)	74						74						70						60					
With 3-hour interval (i.e., 8-stage)	78			68			73			78			78			73			64			56		
With 2-hour interval (i.e., 12-stage)	74		69		54		54		64		79		74		69		64		69		54		74	
With 1-hour interval (i.e., 24-stage)	76	72	67	68	68	59	58	68	58	75	70	78	78	65	64	64	66	66	56	46	51	64	78	70

on, applying the fixed set-point or the eight-segment IDP-based optimal set-points.

The use of fixed set-point ventilation control system means that the ventilation was set at one IAQ target value for the whole ventilation period; while, the use of IDP-based set-point ventilation system means that the value of set-point for the required IAQ could be varied at every time segments during the ventilation period adjusted by the iteration process. Comparing to the manual system operated with the scheduled ventilation fan speed, the ventilation controllers would increase the ventilation fan speed when the outdoor PM_{10} concentration was low and indoor concentration was high (shown in the solid circle in Figure 7(b)) leading to an inflow of fresh outdoor air into the station to improve the IAQ. The ventilation controllers would slow down the ventilation rate once the outdoor PM_{10} concentration was in high concentration, much higher than the indoor concentration (shown in the dotted circle in Figure 7), thus reducing the inflow of air containing a very small amount of outdoor PM_{10} into the station. Overall, the proposed ventilation control system would regulate the ventilation fan speed within 20–60 Hz depending on the outdoor air quality. Consequently, the energy consumption for ventilation in the D-subway station would be reduced.

Once the IDP-based optimal set-points are applied, the energy consumption for the ventilation system is conserved compared to the ventilation control system with the fixed set-point (70 μg/m^3) for IAQ control. The reduced energy usage is associated with the reset of set-points considering the diurnal variation in PM_{10} concentration in the D-station. The diurnal optimal set-points obtained using the IDP algorithm is shown in Table 3. The set-point at the eight-segment, twelve-segment and twenty-four-segment scenarios reveals a similar tendency: (1) low set-point values during the rush hours (6 a.m.–9 a.m. and 6 p.m.–9 p.m.), (2) low set-point values during dawn hours (4 a.m.–6 a.m.) and (3) high set-point values during other hours. During the morning and evening rush hours, the IDP-based set-points were set at a lower PM_{10} concentration value than the fixed set-point. At rush hours, the PM_{10} concentration in the metro station would increase in accordance with the increase in the number of passengers and subway train frequency.[20,27] Therefore, the IDP algorithm would search for the set-points to maintain a comfortable IAQ rather than saving energy for the ventilation system. Accordingly, lower set-point values would be allocated to the ventilation control system during the rush hours, leading to an increase in the ventilation rate. During the dawn hours, the IDP-based set-points would be lower than the fixed set-point. This result can be explained due to the operation of watering carts. The operation of watering carts provides cleaning of the underground tunnels and rails during dawn, could emit pollutants from the fuel consumption and scatter deposited PM in the air of the underground subway station.[19] As a result, a higher PM_{10} concentration in the subway station was found, and thus, lower set-point values were obtained using the IDP algorithm for reducing the station PM_{10} concentration. During other hours (excluding the rush hours and dawn hours), the IDP-based set-points would be kept at similar or higher value than the fixed set-point. A moderate PM_{10} concentration would be found in the station during this timeslot, since the factors which increase the PM_{10} concentration (e.g. passengers' movement, watering carts) would be greatly reduced as compared to the rush hours and dawn hours. Therefore, the IDP algorithm would have a higher emphasis on energy saving rather than on achieving a comfortable PM_{10} concentration, leading to high set-point values. The ventilation control system would therefore slow down the ventilation rate and reduce energy consumption. In the scenario at twenty-four-segment, the set-points during time duration 13–18 h were kept at lower value than those during time duration 9–13 h. This result can be explained due to the PM_{10} concentration in the mezzanine floor. The mezzanine floor PM_{10} concentration could flow into the platform by passengers' movement and affect the platform PM_{10} level.[20] The PM_{10} concentration in the mezzanine floor during time duration 13–18 h is higher than that during time duration 9–13 h, where the mezzanine floor PM_{10} concentration during the time 9–13 and 13–18 h was 67 and 89 $\mu g/m^3$, respectively. It means that the platform PM_{10} level during the time duration 13–18 h has a possibility to be more contaminated due to the inflow of more amount of mezzanine floor PM_{10}. As a result, to suppress the effect of mezzanine floor PM_{10} on the platform PM_{10} concentration, lower set-point values would be allocated to the ventilation control system during the time duration 13–18 h as compared to the time duration 9–13 h. In the scenario at four-segment, the set-point interval was too long to capture the diurnal variation in PM_{10} concentration.

In summary, comparing to the fixed set-point ventilation system, the IDP-based ventilation controllers could flexibly reset the set-points and ventilation fan speed with a due consideration of the diurnal variation in PM_{10} concentration inside the station. When the eight-segment, 12-segment and 24-segment scenarios are applied, the average ventilation fan speed was reduced from 54 to 52.5, 52.9 and 52.5 Hz, respectively, leading to a reduction of ventilation energy consumption from 556 to 546, 546 and 545 kWh, respectively. On average the energy consumption of the IDP-based ventilation system was reduced by 4.6% and 2.0% as compared to the manual system and fixed set-point system, respectively. The ventilation control results (including the variations in the station PM_{10} concentration, amount of PM_{10} being flown in from outdoors and ventilation fan speed) obtained using the three IDP time-segment scenarios are provided in Figures S1 to S3 of the Supplementary material (available at: http://ibe.sagepub.com/)

The energy saving due to the use of the IDP-based ventilation system can be calculated by using equation (7)

$$\text{Energy saving cost} = (\text{saved amount of the ventilation energy}) \times 80 \quad (7)$$

where 80 is the energy charge for multiple-use facilities (Korean Won/kW h) imposed by Korea Electric Power Corporation. Comparing to the manual system installed at the D-station, the IDP-based ventilation system would save 26 k Wh/day of energy for the ventilation of the metro station. Therefore, based on the present exchange rate of 1 US\$ = 1095 ₩ (Korean), 57 US\$/month (i.e. 684 US\$/year) of the energy cost for ventilation can be conserved in the D-station. If the proposed IDP-based ventilation control system is applied to all stations in Seoul Metro, Korea where there are 113 stations, a saving of 6441 US\$/month in energy cost (i.e. 77,292 US\$/year) could be achieved. Furthermore, the application of the proposed ventilation system into the stations is possible by simply modifying computer software of the existing ventilation system without implementing additional equipment. Therefore, the IDP-based ventilation control system also has the economic benefit with regard to the installation and replacement costs.

In terms of the IAQ, the IDP-based ventilation controllers would achieve almost the same average PM_{10} concentration in the subway station as with the manual system (shown in Table 2). The IDP-based systems would regulate the ventilation fan speed depending on the outdoor as well as indoor PM_{10} concentration at subway station. The system thus consequentially adjusts the amount of PM_{10} that enters from outdoors into the station. The result of this study has illustrated the feasibility of the IDP-based ventilation system to reduce energy consumption by maintaining an acceptable IAQ according to the Korean regulation that is comparable to that produced by the manual system. The IDP-based optimal set-points would outperform the manual system, which is operated irrespective of the outdoor PM_{10} concentration and the diurnal variation in PM_{10} concentration in the subway station, with a reduction in the running cost of the ventilation control system.

Conclusions

To maintain an acceptable concentration of PM_{10} inside an underground subway station and to reduce energy consumption, an IDP algorithm was used to determine the optimal set-points for an IAQ ventilation control system for controlling healthy IAQ at subway stations in Seoul. The main contribution of this study is the consideration of IAQ diurnal variation due to the changes in the number of passengers and subway train frequency at the subway station. The results of this study have illustrated the feasibility of the proposed IDP controlled ventilation system. An energy saving of 4.6% and 2.0% is possible as compared to the use of manual system and fixed set-point system, while the PM_{10} concentration in a metro station is increased by 1% as compared to the manual system. If the proposed ventilation controller is applied to Seoul Metro stations, 77,292 US\$/year of the energy cost can be saved. Therefore, we can conclude that the IAQ ventilation control system to be operated with the IDP-based optimal set-points can produce robust ventilation performance to maintain the required comfortable IAQ level and to reduce energy consumption in metro stations. However, this study has limitation that the parameters that might affect the PM_{10} concentration in the subway station (e.g. wind flow, platform screen door) are not considered. For further study, a discussion about how the proposed ventilation control system could adjust the other parameters' effect on the subway station IAQ will be carried out.

Authors' contribution

All authors contributed equally in the preparation of this manuscript.

Declaration of conflicting interests

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