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Influence of mechanical ventilation system on indoor carbon dioxide and particulate matter concentration

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\textbf{ABSTRACT}

Common ventilation strategies may fail to maintain indoor air quality when atmosphere is heavily polluted by particulate matter. This paper evaluates the performances of common constant air volume (CAV) system and variable air volume (VAV) system when carbon dioxide and particles are significantly present in outdoor environment. Major system parameters including filter efficiency, occupancy number, ventilation air rate, and outdoor particle concentration are thoroughly examined. Firstly, a full-scale chamber experiment is performed to investigate the dynamics of CO\textsubscript{2} and airborne particles under steady and non-steady scenarios. The result is further validated with a previously-developed state-space model. Secondly, an exhaustive case study is conducted using an established mathematical model. In order to reduce CO\textsubscript{2} concentration, both CAV and CO\textsubscript{2}-based demand-controlled VAV may cause an undesirable increase in particle concentration when outdoor air is heavily polluted by particles. This dilemma requires further studies on the optimization of ventilation schemes.

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1. Introduction

Particulate matter (PM) is documented as a significant threat to global health [1]. For the past few decades the concern has been steered towards ambient air quality. After the outbreak of severe acute respiratory syndrome (SARS) and various avian influenza worldwide, there has been a speedy rush in studying the building-related factors which are linked to the risk in airborne transmitted pathogens and indoor air quality (IAQ). The increasing concern over IAQ has highlighted the need for ventilation strategies suitable to control pollutant concentrations in indoor environments of buildings. One major challenge is the control of indoor particulate matter (PM) concentration, which is governed by a complex set of engineering factors and physical processes [2,3]. Indoor particles can be generated from either indoor or outdoor sources. Indoor particles may arise from sources such as office printers, occupant activity, combustion related activities such as stove cooking [4], and resuspension of deposited particles as a result of walking [5]. For residential buildings outdoor particles can enter buildings through penetration building cracks or window frames [6] whereas for commercial buildings, particles entry pathways are mainly through mechanical ventilation systems [7–10]. In fact, the increase of indoor fine particles concentration is mainly affected by outdoor traffic condition particularly in urban district [11–13].

Currently, several investigations have emphasised the removal of pollutants (including PM) emitted from indoor environments rather than the control of PM from outdoor air. For instance, researchers have identified the major indoor sources of PM contributing to elevated airborne particles level, as reviewed elsewhere [3]. Theoretical work has also been drawn to carry analysis of ventilation strategies for indoor dynamical particle sources [14] and dilution of PM coming from indoor or outdoor sources [15–17]. Even the current ASHRAE 62.1, “Ventilation for Acceptable Indoor Air Quality”, suggests that the ventilation rate is determined by the number of people and the floor size of building [18]. Therefore ventilation requirement for floor area deals with the contaminants emitting from indoor environments.

Air conditioning of ventilation air requires significant amount of energy. This has been an important energy conservation consideration for air conditioning engineers for past decades [19,20]. Demand-controlled ventilation (DCV), which provides way in the control of fresh air rate with both IAQ and energy efficiency is taken into account [21]. The most common method is CO\textsubscript{2}-based DCV, which is particularly valuable in densely occupied environments.
such as offices, lecture theatre, and public buildings [22]. Based on the new standard ASHRAE 62.1, researchers have designed new implementation strategies of CO2-based DCV under this new standard [23–25]. It should be clear that fresh air supply will be increased with the number of occupancy in an indoor environment, and highly polluted atmosphere can make the low efficiency filters, which are widely used nowadays due to economical consideration, deemed insufficient for maintaining acceptable IAQ.

Thus particle-polluted atmosphere may elevate the level of difficulty for designing effective ventilation system when particles from outdoor atmosphere environment and other pollutants must be simultaneously controlled. This scenario as mentioned above requires the engineering optimization of fresh air flow rate as well as energy efficiency in order to tackle pollutants from indoor sources and outdoor atmosphere. Although some studies have been performed to determine the relationship between indoor and outdoor PM concentrations [13,26,27], limited information has been known on the determination of ventilation rate under significant influence of outdoor particles.

Although the standard 62.1 requires that particle filters or air cleaning devices shall be provided to clean the outdoor air if the particle concentration is exceeded the national standard, due to the budget concern, it sometimes to be ignored in practice. In general, the standard ASHRAE 62.1 is applicable for developed countries such as USA, where atmosphere quality is good, but it may be unsuitable for developing countries such as China, where atmosphere quality is poor due to serious pollution by intense industrial development.

The purpose of this paper is to elucidate the influence of particle-contaminated atmosphere on IAQ and the performance of common ventilation systems, including CAV and CO2-based demand-controlled VAV causes an undesirable increase in indoor particle concentrations. This intricate relationship between CO2 and particle concentrations will pose a serious challenge in the development of effective ventilation system for particle populated outdoor environment.

2. Experimental set-up and measurement

The experiment was conducted in a 2.25 m × 2.3 m × 2.25 m air-conditioned environmental chamber. The chamber represents a typical office room with a variable refrigerant volume (VRV) air-conditioning system. A CO2 tank with a regulator was used to generate solid testing particles recently developed by our group is applied to analyse the trend in the experimental findings. Afterwards, we performed an exhaustive case study using a new mathematical model. Both the experimental and the theoretical results support that the dilution of CO2 with either CAV or CO2-based demand-controlled VAV causes an undesirable increase in indoor particle concentrations. This intricate relationship between CO2 and particle concentrations will pose a serious challenge in the development of effective ventilation system for particle populated outdoor environment.

2.1. Full-scale environmental chamber setup

In the experiments, the supply air grille is located at the ceiling. The exhaust air duct is also located there to prevent the occurrence of the air lock phenomenon in the chamber. A 24-jet nebulizer (BGI) was connected to the fresh air duct, whereby polydisperse particles were generated to model different ambient pollutant levels. An optical particle counter (983, Fluke) was used to record particle concentration in five specific particle size bins ranging from 0.3 to 9.99 μm, i.e., 0.3–0.49 μm, 0.5–0.99 μm, 1.0–1.99 μm, 2.0–4.99 μm, 5.0–9.99 μm. All other particles larger than 10.0 μm were also recorded in a separate bin. The unit recorded was in number per litre. The system parameters in this study were carefully chosen in order to best match the practical values. Two different ventilation rates were applied. A normal ventilation rate for a two-person office is 20 L/s, while 30 L/s was used for achieving a higher air quality. The choice of particle concentration is based on the principle of mass conservation are described by the following differential equations

\[
\frac{dc_i}{dt} = (P_i k_R - k_m - k_d) c_i + P_i k_0 c_{Io},
\]

(1a)

and

\[
\frac{dc_{CO2}}{dt} = (k_R - k_m) c_{CO2} + k_0 c_{CO2,0} + C_{CO2}.
\]

(1b)

together with
\[ k_R = \frac{Q_R}{V}, \quad k_m = \frac{Q_m}{V}, \quad k_o = \frac{Q_o}{V}, \quad C_{CO_2} = \frac{S_{CO_2}}{V}. \]  

(2)

where \( C_i \) is the concentration \( C \) of particle with size \( i \); \( C_{io} \) is the outdoor particles concentration; \( P_i \) denotes the filter efficiency in the fan coil unit. The emission source of \( CO_2 \) may operate at a rate of \( S \) in the chamber. The outdoor fresh air flow rate is denoted as \( Q_o \); \( V \) denotes the room volume; \( C_{CO_2} \) denotes the generation of \( CO_2 \) inside the chamber. \( Q_m \) and \( Q_R \) are the flow rates of the mechanical supply air and return air, respectively. The first-order loss-rate coefficients \( k_{di} \) represents particle loss due to the deposition mechanism. Based on a previous review paper by the author and the nature of the current study, a fixed value of 0.1 h\(^{-1}\) for \( k_d \) is deemed to be reasonable and adopted herein [29]. Infiltration for commercial buildings is generally very small compared to the supply air flow [30] and hence it is assumed to be zero. It should be emphasized that infiltration rates and deposition are not sensitive parameters in this study as the removal rate by ventilation is at substantially higher than those values for practical scenarios.

The set of mass balance equations including Eqs. (1) and (2) are validated by many theoretical and experimental studies as an important tool for addressing IAQ problems [31,32]. The following Eq. (3) introduces a state vector \( C_i \) and an input vector \( u \), based on the state-space concept [17,33].

\[
C_i(t) = \begin{pmatrix}
C_1(t) \\
\vdots \\
C_{CO_2}(t)
\end{pmatrix}, \quad u(t) = \begin{pmatrix}
C_{1o}(t) \\
\vdots \\
C_{CO_2,o}(t)
\end{pmatrix}
\]

(3)

The state vector \( C_i \) denotes the states of the indoor pollutant concentrations; input vector \( u \) represents the influence factors from both indoors and outdoors. Based on Eq. (3), Eq. (1) can be rewritten in a first-order vector-matrix form, i.e. the state equation, as follows.

\[
\frac{dC_i(t)}{dt} = AC_i(t) + Bu(t).
\]

(4)

Here, matrices \( A \) and \( B \) are called the system matrix and the input matrix, respectively. If we introduce \( a = k_m + k_{di} \) and \( b_i = P_i k_o \), the matrices \( A \) and \( B \) will be read as
ory provides an explicit solution, as given by Ref. [34]. For a time-independent system, the state-space theory provides an explicit solution, as given by Ref. [34].

\[
P_k = A \begin{pmatrix} p_k & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & p_k \end{pmatrix}
\]

\[
B = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \end{pmatrix}
\]

For CAV systems, the parameter matrices \( A \) and \( B \) are independent of time. For a time-independent system, the state-space theory provides an explicit solution, as given by Ref. [34].

\[
C(t) = \Phi(t)C_0 + \int_{t_0}^{t} \Phi(t - \tau)Bu(\tau)d\tau, \quad t \geq 0
\]

Thus the analytical solution to Eq. (4), subject to an initial condition, \( C(t_0) = C_0 \), where

\[
(t) = e^{At} = I + At + \frac{1}{2!}A^2t^2 + \cdots = \sum_{n=0}^{\infty} \frac{1}{n!}A^n t^n
\]

is the state-transition matrix.

The state-space model as shown in Eq. (4) is just a vector-matrix form of the dynamics equations Eq. (1), which is derived from the principle of mass conservation. Therefore these equations are valid for any concentration unit for particles and CO2. In these equations, variables \( C, C_0, C_{CO2}, \) and \( C_{CO2} \) depend on the particle concentration units, i.e. mass concentration, number concentration or ppm. However, the other parameters including \( p_k, k_m, k_o, k_r, \) and \( k, \) are independent of concentration, and thus their values will not vary when different concentration units are used.

4. Comparison of the experimental data and modelling prediction

The experiments for CAV were carried out for two ventilation rates, i.e., 20 L/s and 30 L/s. Figs. 2 and 3 compare the experimental data with the model predictions for these CAV cases, showing the agreement between the measured and modelled CO2 and PM concentrations at both fresh air flow rates.

The CO2-based DCV strategy concept was adopted in the experiment of VAV case. In this strategy, the fresh air supply volume is under control based on the occupancy number. In the experiment, the fresh air supply decreases from 30 L/s to 20 L/s after 40 min and is completed at 80 min to mimic a reduction of number of occupants, i.e. from three to two. The experimental data and model prediction are compared in Fig. 4. The results show that the amount of outdoor fresh air decreases when the particle concentration decreases simultaneously. The experimental data for particle of 0.3–0.49 μm in size matches the simulated result relatively well, particularly at the earlier time point compared to that for particle of 1.0–1.39 μm in size. There are various factors or uncertainties which can affect the trend in the experimental results. Given these uncertainties and the complexity of the experiments, the concentration discrepancies as shown in Figs. 2 to 4 are within a rational and acceptable range of magnitude. Thus it would be sensible to confirm that the state-space model can provide a viable approach for modelling the temporal trend of indoor PM and CO2 concentrations.

5. Case study

In this section, the validated state-space model is used to investigate the relationship between concentrations of indoor particles and CO2 in CAV and VAV ventilation systems. The simulation parameters for the two schemes are listed in Table 1. For all simulations carried herein, the total air exchange rate is maintained at 5 h⁻¹, regardless of the ventilation scheme. Regarding the VAV setting, the number of occupants is designed to vary according to a typical office working hours. In these simulations, it is assumed that the indoor temperature and humidity are well controlled by the air-conditioning system.

The study considers three major parameters. They are fresh air flow rate per person L/s/p, filter efficiency \( F_r \), outdoor air particle concentration \( C_{IO} \). The constant parameters are an outdoor concentration of CO2 at 400 ppm and initial indoor air particle concentration is set at 0 μg/m³ and indoor concentration of CO2 is set at 400 ppm.

The ventilation air flow rate per person selected for simulation purpose are 8.5 L/s/p, 12.75 L/s/p and 17 L/s/p. The minimum value of 8.5 L/s is selected based on practical experience. The filter efficiency is assumed to be 40%, 60% or 80%, representing a normal
The selected concentrations of fine suspended particle (PM$_{2.5}$) in outdoor environment are 50 mg/m$^3$, 100 mg/m$^3$ and 200 mg/m$^3$, which resemble well with real and severe outdoor environmental conditions in Hong Kong [35]. Thus total nine cases for each ventilation scheme are computed. The schedule of fresh air flow rate is listed in Table 2.

In this study, the first key parameter which will be closely followed is the PM$_{2.5}$ level. World Health Organization (WHO) 2005 [36] requires that PM$_{2.5}$ mass concentration does not exceed 25 µg/m$^3$ and 10 µg/m$^3$ for 24-h mean and annual mean, respectively. This PM$_{2.5}$ was approximated by particle size 1.0–1.99 µm. The second key parameter is indoor CO$_2$ concentration which is compared against the requirement of an IAQ voluntary scheme of Hong Kong Environmental Protection Department (HKEPD) [37]. This scheme requires concentration below 800 ppm or less and 800 ppm–1000 ppm as the excellent class and good class, respectively.

6. Discussion

The simulation results of CO$_2$ concentrations for CAV cases with outdoor air particle concentrations of 200 µg/m$^3$ is shown in Fig. 5.
whereas results for 50 and 100 μg/m³ are shown in Supplementary Material. The summarized results are shown on Tables 3–5. First of all, it should be noted that the CO₂ concentration under three different particle concentrations is at the same level under the same fresh air flow rate because the efficiency of mechanical filter does not affect the CO₂ concentration. The trend in the tables have also shown that high fresh air will trigger the room CO₂ concentration to attain the steady state faster while lower ventilation rate delays CO₂ concentration to reach steady state. As anticipated, the CO₂ concentration is found to be inversely proportional to the ventilation rate, i.e. the higher the fresh air flow rate, the lower the CO₂ concentration level was resulted. It is also found that the CO₂ concentration level varies with the number of occupants’ accommodation.

The assigned lowest fresh air flow rate 8.5 L/s/p is very common in practice as it is the default requirement of outdoor fresh air per person recommended from ASHRAE Standard 62.1 [18]. Inferring from Tables 3–5, for CAV cases under this ventilation rate, the maximum CO₂ concentration level is around 1000 ppm while the 12 h average is 855 ppm. The other two ventilation rates 12.75 L/s/p and 17 L/s/p give the average CO₂ concentration level of around 710 ppm and 635 ppm respectively. By inferring from the results, fresh air flow rate of 8.5 L/s/p would result in good class while the other two fresh air rates would fall into excellent class based on the HKEPD requirement. However, it should be noted that there will not have energy saving even during less people accommodated period under CAV fresh air supply.

For CAV cases, the particle concentrations of indoor air increases to steady level fairly fast within 1 h. Afterwards, these particle concentrations are maintained at the same level during the rest of the operation period. It is found that filtration efficiency significantly influences PM concentration. For instance, under outdoor air particle concentration of 50 μg/m³ and fresh air flow rate of 8.5 L/s/p, filters with 40%, 60% and 80% filtration efficiency gives the mean PM1.0–1.99 values of 11.4 μg/m³, 6.0 μg/m³ and 2.5 μg/m³ in 12 h, respectively. These results as mentioned above are all considered to be low. Nevertheless, when the filter efficiency is low, outdoor condition is adverse and fresh air flow rate is high, the indoor PM level cannot be ignored. Inferring from Tables 3–5, when outdoor concentration is 100 μg/m³, two cases exceed the WHO guideline which occurs at the 40% filter efficiency and the highest ventilation rate. The trend as mentioned above suggests that high fresh air flow rate does not always give better IAQ. When the outdoor condition is worsened with PM concentrations of 200 μg/m³, five out of six results of two lowest filter efficiency cases exceed the guideline considerably. One may considers lowering the fresh air flow rate under this adverse condition, leading to an increase of CO₂ level but in only marginal level. Another possible measure is to install filter with efficiency >80%. This will increase the air-conditioning running cost whenever the system is operating. In fact if the outdoor PM level is very high, in order to lower exposure, indoor cleaning devices, such as those install air filtration systems, can be an option. In fact this measure has been becoming more popular aiming at providing enhanced filtration during adverse ambient conditions [38].

For the VAV cases, the results for particle concentrations of 200 μg/m³ is shown in Fig. 6 whereas the results for 50 and 100 μg/m³ are shown in Supplementary Material. Under a fixed ventilation rate, the maximum CO₂ concentration is the same as that of the CAV case. The average concentration is calculated in Tables 3–5. Good

| Time (h) | Occupancy schedule | Total outdoor air flow rate L/s a,b |
|----------|--------------------|----------------------------------|
|          |                    | CAV | VAV |
| 9:00–12:00 | 5                  | 42.5 | 63.75 | 85 | 42.5 | 63.75 | 85 |
| 12:00–14:00 | 2                  | 42.5 | 63.75 | 85 | 17.0 | 25.50 | 34 |
| 14:00–18:00 | 5                  | 42.5 | 63.75 | 85 | 42.5 | 63.75 | 85 |
| 18:00–21:00 | 3                  | 42.5 | 63.75 | 85 | 25.5 | 38.25 | 51 |

We assume that the outdoor CO₂ concentration is 400 ppm and initial indoor air particle concentration is 0 μg/m³. All outdoor air flow rates in column (I), (II) and (III) are applied for each case separately.

a The period of time-dependent particle source is 12 h. Only the values within 12 h are listed in this table. The simulation time is 12 h.

b The values of outdoor fresh air flow rate per person.

![Fig. 5. Relationship between concentrations of particles and CO₂ indoor for CAV case at outdoor air particles concentration 200 μg/m³.](image-url)
class can still be obtained under 8.5 L/s/p and excellent class can be obtained when 12.75 L/s or 17 L/s fresh air flow rates are provided. However, slight difference can be observed and the trend is that VAV scheme would result in higher CO2 concentration. Besides, the temporal variation between CAV and VAV is obvious. Under the VAV scheme, the CO2 concentration is kept constant during the operation periods. This is because the fresh air is varied based on the number of people accommodated in the office space. The total fresh air is designed to dilute the exact CO2 which is generated by each occupant. Therefore, the ventilation system seems like a CO2-based DCV operation. In this case energy saving can be achieved during less accommodation period. On the other hand, the particle concentration level varies due to variation of the total supply of fresh air. Less fresh air causes less particle concentration indoors. The calculated mean as shown in Tables 3–5 shows that the particle concentrations mean values for CAV cases are consistently higher than those of VAV cases approximately 16%–24%. Besides, more fresh air supplied, the more energy is being consumed. By comparing between CAV and VAV cases, the energy impact in CAV case is quite obvious. It is because under the CAV the total ventilation air is kept at constant regardless of the number of people. However, the energy supply for cooling and dehumidifying the hot and humid outdoor air is fixed. On the other hand, under the VAV case energy consumption is based on CO2-based DCV. Thus the energy demand is varied over operation period. It would result in less total energy consumption than that of the CAV case. Although it is not the scope of the present work, the energy consumption can be calculated by the ventilation air rate and its temperature different between outdoor and indoor temperature in terms of enthalpy.

There are a few limitations of this study. Due to the instrument constraint and no outdoor particle size—resolved concentration provided by the local environmental agent, it is not possible to model PM2.5 without the prior knowledge of the outdoor PM size distribution. In this work only one particle size bin is selected, it cannot represent the exact PM concentration regulated by WHO, it is believed the choice is acceptable.

### 7. Conclusion

The ventilation factors affecting indoor CO2 and particle levels for CAV and CO2-based demand-controlled VAV systems remain to be elucidated. In this study, a state-space model was first validated by in-house experiments under both steady and unsteady ventilation rates. Good agreement between the experimental measurement and model prediction with respect to particle and CO2 concentrations were found. Twenty-seven case scenarios studies were conducted from both CAV and VAV cases to explore the relationship among filter efficiency, ventilation rate, outdoor PM level and modes of ventilation. Normal ventilation rate of 8.5 L/s/p can lead to CO2 concentration lower than 1000 ppm at CAV fresh air supply. Notwithstanding, the other two highest ventilation air flow rates results in even lower CO2 concentration, however, it does not always give better IAQ if ambient PM level is severe. The results support the existence of an interaction between PM and CO2 concentrations. It is shown that high efficiency filter plays a key role in the management of indoor PM concentration. In tackling those adverse ambient conditions, filter with efficiency >80% to be implemented is suggested. The result also shows that 16–24% less particle concentrations mean values were found in VAV cases than those in CAV cases. Our results also show that CAV and VAV systems, under low ACH situations, can meet the requirements of the particle and CO2 concentrations of WHO 2005 [36] and HKEPD [37] standards. This study confirms that a dilemma to be further studied may occur in heavily polluted cities: dilution of indoor CO2.

### Table 3

Results of maximum and mean values of PM1.0–1.0μg/m3 and CO2 concentration at outdoor air particles of 50 μg/m.

| Filter efficiency Pi (%) | Outdoor fresh air flow rate (L/s) | Maximum/mean PM1.0–1.0μg/m3 | Maximum/mean CO2 (μg/m3) |
|------------------------|-------------------------------|-------------------------------|-------------------------------|
|                        | CAV I | II | III | VAV I | II | III | CAV I | II | III | VAV I | II | III |
| 40                     | 60    | 80 | 8.5 | 11.9/11.4 | 6.2/6.0 | 2.5/2.5 | 11.9/9.5 | 6.2/4.9 | 2.5/2.0 | 1007/855 | 1007/956 |
| 40                     | 60    | 80 | 12.75 | 15.9/15.3 | 8.7/8.4 | 3.7/3.6 | 15.9/13.0 | 8.7/7.0 | 3.7/2.9 | 807/710 | 807/782 |
| 40                     | 60    | 80 | 17 | 19.2/18.5 | 11.0/10.6 | 4.8/4.7 | 19.2/15.9 | 11.0/8.8 | 4.8/3.8 | 706/635 | 706/690 |

### Table 4

Results of maximum and mean values of PM1.0–1.0μg/m3 and CO2 concentration at outdoor air particles of 100 μg/m.

| Filter efficiency Pi (%) | Outdoor fresh air flow rate (L/s) | Maximum/mean PM1.0–1.0μg/m3 | Maximum/mean CO2 (μg/m3) |
|------------------------|-------------------------------|-------------------------------|-------------------------------|
|                        | CAV I | II | III | VAV I | II | III | CAV I | II | III | VAV I | II | III |
| 40                     | 60    | 80 | 8.5 | 23.8/22.8 | 12.4/11.9 | 5.1/4.9 | 23.8/19.1 | 12.4/9.8 | 5.1/4.0 | 1007/855 | 1007/956 |
| 40                     | 60    | 80 | 12.75 | 31.9/30.6 | 17.5/16.9 | 7.4/7.2 | 31.9/26.0 | 17.5/14.0 | 7.4/5.8 | 807/710 | 807/782 |
| 40                     | 60    | 80 | 17 | 38.4/37.0 | 22.0/21.3 | 9.6/9.3 | 38.4/31.7 | 22.0/17.7 | 9.6/7.6 | 706/635 | 706/690 |

### Table 5

Results of maximum and mean values of PM1.0–1.0μg/m3 and CO2 concentration at outdoor air particles of 200 μg/m.

| Filter efficiency Pi (%) | Outdoor fresh air flow rate (L/s) | Maximum/mean PM1.0–1.0μg/m3 | Maximum/mean CO2 (μg/m3) |
|------------------------|-------------------------------|-------------------------------|-------------------------------|
|                        | CAV I | II | III | VAV I | II | III | CAV I | II | III | VAV I | II | III |
| 40                     | 60    | 80 | 8.5 | 47.6/45.6 | 24.7/23.8 | 10.1/9.8 | 47.6/38.1 | 24.7/19.5 | 10.1/7.9 | 1007/855 | 1007/956 |
| 40                     | 60    | 80 | 12.75 | 63.8/61.3 | 35.0/33.7 | 14.8/14.3 | 63.8/51.9 | 34.9/27.8 | 14.8/11.7 | 807/710 | 807/782 |
| 40                     | 60    | 80 | 17 | 76.9/74.1 | 44.0/42.5 | 19.3/18.7 | 76.9/63.4 | 44.0/35.4 | 19.3/15.2 | 706/635 | 706/690 |
concentration by introducing outdoor air probably import other pollutants outdoors, such as particles.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2014.03.004.

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