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Ventilation of air-conditioned residential buildings: A case study in Hong Kong

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Abstract: More and more studies reported that there were insufficient ventilation and excessive CO_2 concentration in air-conditioned residential buildings, but few solutions were provided. This study investigates the overnight evolution of CO_2 concentration in air-conditioned residential buildings and then focuses mainly on the evaluation of three ventilation strategies, including overnight natural ventilation, short-term mechanical ventilation and short-term natural ventilation. On-site measurements were conducted in a typical residential bedroom in Hong Kong in September. The indoor and outdoor CO_2 concentration, air temperature and relative humidity as well as the outdoor wind speed during the measurements were analysed. Ventilation rates were calculated based on the time series of CO_2 concentration. This study confirms that additional ventilation is usually needed in air-conditioned residential buildings. Overnight natural ventilation with even a small opening is associated with excessive energy consumption and deteriorated indoor thermal environment. Short-term natural ventilation strategies are inefficient and uncontrollable. Compared to the best short-term natural ventilation strategy, a reasonably designed short-term mechanical ventilation strategy requires only a 41% of ventilation period to complete one full replacement of indoor air and to reach a lower indoor CO_2 concentration. Nighttime case studies and a theoretical analysis suggest that a few several-minute mechanical ventilation periods could potentially maintain an acceptable indoor air quality for a normal sleeping period of 8 hours.

Keywords: Ventilation, room air conditioner, residential buildings, carbon dioxide (CO_2), on-site measurements

Nomenclature

Symbols

ACH	air change per hour, [h^{-1}]
ACH*	normalized air change rate, [-]
$(\mathrm{ACH})_0$	reference infiltration rate, [h^{-1}]
A_D	body surface area, [m^2]
A_f	net floor area, [m^2]
Ar	Archimedes number, [-]
A_w	the largest possible area of indoor/outdoor flow exchange, [m^2]
C_{in}	indoor CO_2 concentration, [ppm]
C_{in}^*	normalized CO_2 concentration, [-]
$\overline{C}_{in}$	average indoor CO_2 concentration during a ventilation period, [ppm]
$C_{in,i}$	concentration at the moment i, [ppm]

$C_{in,ini}$	initial indoor CO_2 concentration at the beginning of ventilation, [ppm]
$C_{in,i+\Delta t}$	concentration at the moment $i+\Delta t$, [ppm]
C_{out}	outdoor CO_2 concentration, [ppm]
D_w	vertical distance of the window frame away from the open window, [m]
e	correction factor for Chinese people, [-]
g	gravitational acceleration, [m/s^2]
G_r	human generation rate of CO_2, [m^3/s]
H	human height, [m]
H_w	window height, [m]
i	a particular moment of time, [s]
M	metabolic rate, [W/m^2]
Q	ventilation rate, [m^3/s]
Q_{CO_2}	volumetric rate of CO_2 generation, [ml/s]
Q_{O_2}	volumetric rate of oxygen consumption, [ml/s]
RQ	respiratory quotient (the molar ratio of exhaled Q_{CO_2} to inhaled Q_{O_2}; 0.83 for light or sedentary activities of an average adult), [-]
t	time, [s]
t^*	normalized time, [-]
T_{in}^*	normalized indoor air temperature, [-]
$T_{in}(t)$	indoor air temperature at the time t, [°C]
$T_{in,ini}$	indoor air temperature at the beginning of ventilation, [°C]
T_{out}	outdoor air temperature, [°C]
U_B	mean outdoor wind speed at the building height in the free stream, [m/s]
U_o	outdoor wind speed, [m/s]
V	volume of the room, [m^3]
W	human mass, [Kg]
β	thermal expansion coefficient, [1/°C]
Δt	time interval, [s]
Δt_v	ventilation period, [s]
ΔT	indoor and outdoor air temperature difference, [°C]
φ	perpendicular angle, 90^o

1. Introduction

Air conditioner is almost indispensable in residential buildings in hot and humid regions to provide a thermally comfortable indoor environment [1-5]. Among others, the window-type and split-type air conditioners are the most popular room air conditioners [1, 5]. A questionnaire survey [1] on the use status of air-conditioners in residential buildings in Hong Kong reveals that most people leave their air conditioners on overnight, while the period of using air-conditioners in a year has been becoming increasingly long, even over 6 months in some homes. Given that people spend more than 50% of their time in homes [6], ventilation to maintain an acceptable indoor air quality (IAQ) in air-conditioned residential buildings is thus of great importance.

One deficiency of room air conditioners is the provision of no or very little outdoor air. Many on-site measurements [3, 5, 7-9] show that ventilation rates in most air-conditioned residential buildings were largely less than the minimum requirement, namely 7.5 l/s/p, recommended by ventilation standards [10], even if there was only one occupant indoors. Accompanying with low ventilation rates, excessive CO_2 concentrations (> 1000 ppm) in air-conditioned residential buildings were often reported [1-5, 8]. Switching on the ventilation damper of window-type air conditioners could lower the indoor CO_2 concentration by approximately 100-200 ppm [2-3], but few occupants were aware of the existence or the function of such a damper [1]. Indoor CO_2 concentration was commonly used as a surrogate of the indoor concentration of human generated bioeffluents and thus as an indicator of the indoor ventilation levels [3-4, 11-17]. ASHRAE Standard 62-1989 [18] suggested that the indoor CO_2 concentration levels should be less than 1000 ppm, which is nearly equivalent to a ventilation rate of 7.5 l/s/p. Such a level of ventilation rate is generally sufficient to control human body odor that approximately 80% of unadapted persons find the odor acceptable [19-23]. More recent (since 1999) series of ASHRAE Standards 62 (e.g., [10, 24]) recommended that the same level of body odor acceptability can be achieved when the indoor and outdoor (I/O) CO_2 concentration difference is less than 700 ppm.

Many evidences show that insufficient ventilation and excessive CO_2 concentration are strongly associated with the increased IAQ complaints and the prevalence of illnesses and sick building syndrome (SBS) symptoms in office buildings [14, 25-31]. For residential buildings, the review by Sundell et al. [31] indicated that ventilation rates above 0.5 h^{-1} are associated with a reduced risk of allergic manifestations among children in a Nordic climate. Wong and Huang [2] reported that the low ventilation rates and high CO_2 concentrations are the basic reasons for that occupants who use air conditioners during sleeping periods exhibit more SBS syndromes than when they use natural ventilation. In addition, insufficient ventilation in bedrooms is also responsible for a poor sleep quality and a reduced next-day performance [5, 32].

The possible ventilation strategies in air-conditioned residential buildings are open window, open door, switching on ventilation damper for window-type air conditioners, and mechanical ventilation using exhaust fan [1, 4], even though most people do not apply any of them in practice [1]. Sekhar [4] reported that operation of a bathroom exhaust fan lowers very quickly the indoor CO_2 concentration from 2000-3000 ppm to 1000 ppm in a residential apartment with a floor area of nearly 20 m^2. Apart from mechanical ventilation, it is believed that opening window(s) to make an air-conditioned room naturally ventilated can also maintain a fairly good indoor IAQ. However, issues of energy loss, thermal comfort and noise ingress do not allow overnight mechanical ventilation or overnight natural ventilation with large openings in air-conditioned residential buildings. Recently, Perino and Heiselberg [33] and Heiselberg and Perino [34] investigated the ventilation of buildings in a very cold wintertime through window airing. They found that the optimum application of window airing is a relatively short opening period and a relatively high opening frequency. Different from the situation in cold regions, the I/O air temperature difference in air-conditioned residential buildings in hot and humid regions is mostly less than 10 ℃, with cold indoor and hot outdoor.

It is imperative to explore feasible ventilation strategies that can maintain an acceptable IAQ while consuming minimum energy and causing a minimum influence on indoor thermal environment. In such a regard, this study investigated three types of ventilation strategies: (a) overnight natural ventilation with a narrow window opening, (b) short-term mechanical ventilation with an exhaust fan and (c) short-term natural ventilation with large window opening(s). These ventilation strategies were evaluated through on-site measurements in a typical bedroom in a high-rise residential building in Hong Kong. This study is intended to provide basic information and implications for ventilation design of air-conditioned residential buildings.

2. Materials and methods

2.1 Measurement site and instrumentation

The on-site measurements were conducted in Hong Kong in September 2015, when the outdoor air temperature was mainly between 27 and 32 ℃. An air-conditioned bedroom located on the 11th floor of a 12-storey building was selected. The room was occupied with two adults. The building locations, its surroundings and the apartment location in the building are presented in Figure 1. The room and window configurations are presented in Figure 2. Note that for the ‘Window-AC’, only the half below the air conditioner was openable. After excluding indoor furniture, partitions, and some protrusive pillars on walls, the estimated net floor area and net volume of this room were 8.6 m^2 and 21.3 m^3, respectively. A room of such dimensions is typical in densely populated urban areas like Hong Kong [3, 7]. There was a bathroom connected to the bedroom through an opening with 0.5 m × 2.0 m in area. The exhaust fan in the bathroom provided a nominal flow rate of 520 m^3/h. During all measurements, the door of this bedroom was always closed.

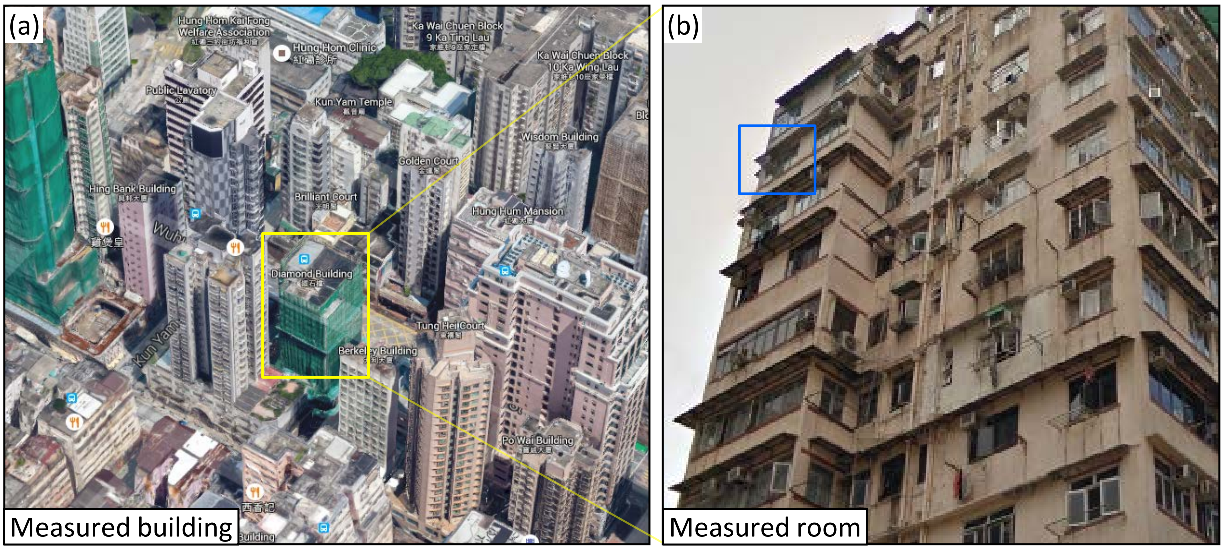


Figure 1 Measurement site: (a) building location and its surroundings and (b) apartment location in the building (modified from Google Maps©).

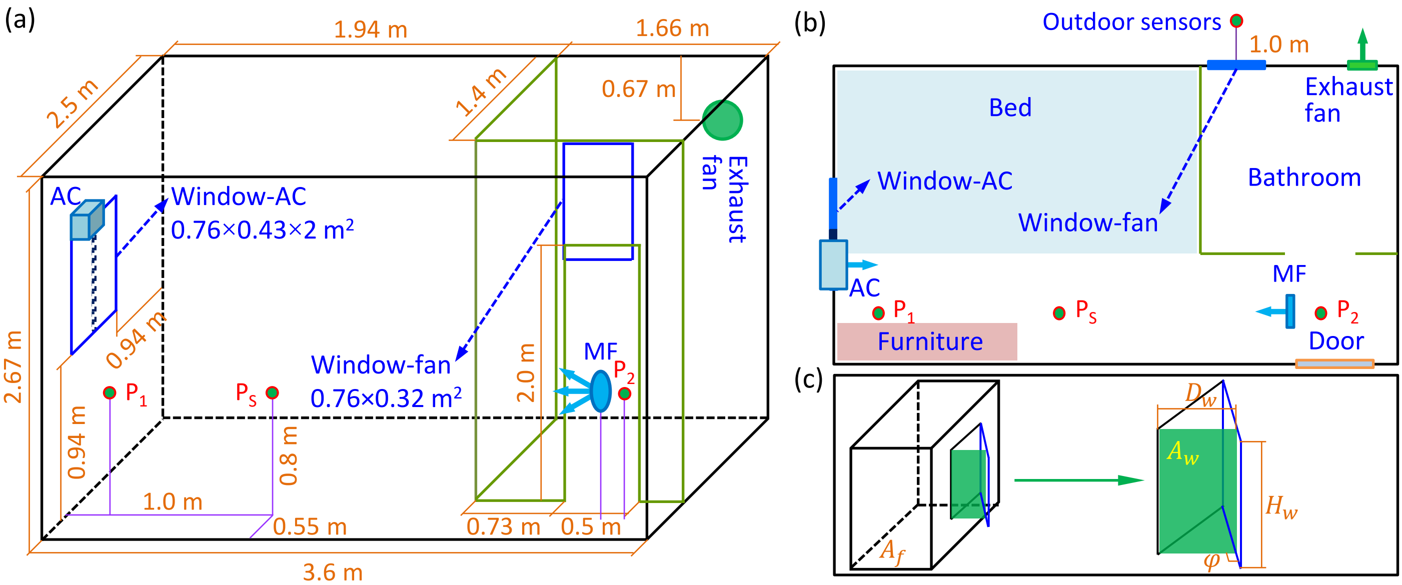


Figure 2 Measurement site: (a) room configuration, (b) top view of indoor layout and (c) schematic view of window configuration; AC is the air conditioner, MF the mixing fan, P_S, P_1 and P_2 the location of indoor sensors.

Parameters monitored during the measurements were indoor and outdoor CO_2 concentration, air temperature and relative humidity. The outdoor wind speed data during the on-site measurements was retrieved from the nearby King's Park Observatory (within 1500 m away from the measured building). All equipment was calibrated regularly according to the suggestions of manufacturers, which was further calibrated against known values before measurements. The known values refer to the outdoor CO_2 concentration, air temperature and relative humidity recorded in the King's Park Observatory. The measured parameters, equipment, and their uncertainties and ranges are listed in Table 1. In addition, the two occupants were the CO_2 generators during all measurements. Their generation rates were calculated based on the method described in Section 2.4. When air change per hour (ACH) would be calculated, a mixing fan was used to enhance the mixing of the human generated CO_2 and the indoor air, which was located in 'MF' in Figure 2 (a) and (b). Measurements were conducted at a frequency of 0.2 Hz.

Table 1 Summary of the parameters measured and the equipment used.

Parameters	Equipment	Uncertainty and range
CO_2	Telaire 7001 CO_2 monitor (Telaire, Goleta, CA, USA)	±50 ppm or ±5% of reading in a range of 0 to 2500 ppm
Temperature and relative humidity	HOBO data loggers (Onset Computer Corporation, Bourne, MA, USA)	±0.21 ℃ in a range of -20 ℃ to + 50 ℃; ±2.5% in a range of 10% to 90%, a maximum of 3.5% in a range of 0% to 100%

2.2 Overnight measurements

Based on the occupants' schedule, the overnight measurements were conducted from 23:00 p.m. to 7:00 a.m. in nighttime. The objectives of overnight measurements are (a) to examine the build-up of CO_2 concentration in the bedroom during nighttime sleeping periods and (b) to evaluate the performance of overnight natural ventilation strategies. The measured cases are listed in Table 2, where the 'Open-5cm' and 'Open-10cm' indicate the D_w (in Figure 2 (c)) equal to 5 cm and 10 cm, respectively. Each case was conducted at least for two nights. Sensors for indoor CO_2 concentration, air temperature and relative humidity were placed near the bed at the height of 0.8 m above the floor, which was around the location 'P_S' (in Figure 2 (a) and (b)). Uniformity tests of CO_2 distribution during these overnight measurements were performed with additional CO_2 sensors placed at the locations 'P_1' and 'P_2' (in Figure 2 (a) and (b)).

Table 2 Cases for overnight measurements; 'O' in the 'Case' column represents 'overnight', 'AC damper' ventilation damper of the air conditioner; the 'WFR' is defined as the ratio of A_w to A_f (in Figure 2 (c)).

Case	AC damper	Exhaust fan	Window-AC	Window-fan	WFR
O-1	Off	Off	Closed	Closed	0%
O-2	On	Off	Closed	Closed	0%
O-3	On	Off	Closed	Open-5cm	0.44%
O-4	On	Off	Closed	Open-10cm	0.88%

2.3 Short-term ventilation

A measurement of short-term ventilation lasted for no more than 20 minutes. The objectives of short-term measurements are (a) to examine the evolution of indoor CO_2, air temperature and relative humidity during and after short-term ventilation and (b) to evaluate the performance of various short-term ventilation strategies. Two scenarios were investigated for short-term ventilation, namely short-term mechanical ventilation through an exhaust fan and short-term natural ventilation through open window(s). Cases for the two scenarios are presented in Tables 3 and 4, respectively. Measurements of short-term ventilation were conducted in daytime, except that one case for mechanical ventilation (S-MV-N) was in nighttime to examine the real-life ventilation effect of short-term mechanical ventilation during nighttime sleeping periods. Measurements in daytime were performed according to the following procedures:

(i) switch on the air conditioner (ventilation damper on) for a sufficiently long period with all windows closed and the exhaust fan off to reach a quasi-steady-state indoor condition, namely with relatively stable air temperature and relative humidity. Note that CO_2 concentration may not be in a steady-state condition due to the continuous release by the two occupants;

(ii) switch on the mixing fan for several minutes to ensure an uniform CO_2 concentration within the room and then switch off the mixing fan. The initial CO_2 concentration at this moment was around 1100 ppm;

(iii) switch on the exhaust fan and/or open the window(s) quickly according to the predefined cases (as shown in Tables 3 and 4);

(iv) switch off the exhaust fan and/or close the window(s) quickly after a certain period of time. Such a period was around 5 to 10 minutes for mechanical ventilation and around 10 to 20 minutes for natural ventilation;

(v) switch on the mixing fan immediately to mix the indoor air and CO_2 to obtain a final CO_2 concentration. This final CO_2 concentration and the initial CO_2 concentration recorded in the step (ii) were used to calculate the average ACH value during the ventilation period.

For each case, at least three measurements were conducted repeatedly, in order to increase the validity of the measured results and to facilitate cross comparisons of different cases under similar environmental conditions, namely similar I/O air temperature difference and outdoor wind speed.

Short-term measurements in nighttime were similar with these in daytime, except that (a) the initial CO_2 concentration as described in above step (ii) was not necessarily around 1100 ppm and (b) no mixing fan was used to mix the indoor air and CO_2 before and after ventilation. For all short-term cases, the locations of both indoor and outdoor sensors were the same with those in Section 2.2.

Table 3 Cases for short-term mechanical ventilation through the exhaust fan; 'S', 'MV', 'D' and 'N' in the 'Case' column represent 'short-term', 'mechanical ventilation', 'daytime' and 'nighttime', respectively.

Case	Exhaust fan	Window-AC	Window-fan	WFR
S-MV-D1	On	Closed	Closed	0%
S-MV-D2	On	Closed	Open-10cm	0.88%
S-MV-D3	On	Open-10cm	Closed	0.88%
S-MV-N	On	Open-10cm	Closed	0.88%

Table 4 Cases for short-term natural ventilation through open window(s); 'S' and 'NV' in the 'Case' column represent 'short-term' and 'natural ventilation', respectively.

Case	Exhaust fan	Window-AC	Window-fan	WFR
S-NV-1	Off	Closed	Open-10cm	0.88%
S-NV-2	Off	Closed	Open-20cm	1.76%
S-NV-3	Off	Closed	Open-30cm	2.64%
S-NV-4	Off	Open-10cm	Closed	0.88%
S-NV-5	Off	Open-20cm	Closed	1.76%
S-NV-6	Off	Open-30cm	Closed	2.64%
S-NV-7	Off	Open-10	Open-10cm	1.76%
S-NV-8	Off	Open-20	Open-20cm	3.52%
S-NV-9	Off	Open-30	Open-30cm	5.28%

2.4 Calculation of ACH

Tracer gas method was commonly used to measure ventilation rates in buildings [35-40]. Among others, more and more studies used human exhaled CO_2 as a tracer gas to determine indoor ventilation rates [3, 8-9, 36, 41-43]. The CO_2 generation rate per person varies with age, activity and diet [10, 44]. The empirical equation for metabolic rate given in ASHRAE Handbook [44] was widely used to estimate CO_2 generation rate of human beings [42, 45-46].

$$M = \frac{21(0.23RQ + 0.77)Q_{O_2}}{A_D} \quad (1)$$

Qi et al. [46] questioned the accuracy of this empirical equation for Chinese people and then conducted chamber experiments to test CO_2 generation of Chinese people at light and sedentary activities. They found that the empirical model overestimates CO_2 generation rate of Chinese people and proposed correction factors – 0.75 and 0.85 – for Chinese females and males, respectively. Substituting an empirical equation of human body surface area ($A_D = 0.202H^{0.725}W^{0.425}$, [47]), the Equation (1) can be modified into the following form:

$$Q_{CO_2} = e \cdot \frac{0.202RQ \cdot M \cdot H^{0.725} \cdot W^{0.425}}{21(0.23RQ + 0.77)} \quad (2)$$

With the door closed, the bedroom described in the present study can be treated as a single zone [42-43]. Based on the principle of mass conservation, the calculation of ventilation rates in a well-mixed single zone using tracer gas method can be achieved through the following equation:

$$V\frac{dC_{in}}{dt} = Q\left(C_{out} - C_{in}\right) + G_r \tag{3}$$

Note that the G_r is the total generation rate of the two occupants, which were 7.2 × 10^{-6} m^3/s and 4.2 × 10^{-6} m^3/s for daytime sedentary and nighttime sleeping conditions, respectively. Discretization of this differential equation onto a discrete temporal grid with a time interval of Δt leads to a theoretical evolution of indoor CO_2 concentration over time, where the concentration ($C_{in,i+\Delta t}$) at the moment $i+\Delta t$ has the following correlation with the concentration ($C_{in,i}$) at its previous moment i:

$$C_{in,i+\Delta t} = \frac{\Delta t}{V}[G_r - Q(C_{in,i} - C_{out})] + C_{in,i} \tag{4}$$

Based on the Equation (4), the ACH ($\mathrm{ACH} = Q/V$) of the room during the time interval of Δt can be expressed as:

$$\mathrm{ACH} = \frac{G_r \Delta t - V(C_{in,i+\Delta t} - C_{in,i})}{V(C_{in,i} - C_{out})\Delta t} \tag{5}$$

3. Results and analyses

3.1 Overnight measurements

For all overnight measurements, the uniformity of indoor CO_2 concentration distribution was tested. Figure 3 presents the uniformity test for Case O-2. The overall trend of the evolution of CO_2 concentration at the three measured locations was generally the same. The CO_2 concentrations measured at the location 'P_S' were, on average, less than 6 ppm than the mean values of the three, indicating that the measurements at the location 'P_S' could represent acceptably the indoor average CO_2 concentration. The uniformity condition for Case O-1 was very close to this for Case O-2, while those for Cases O-3 and O-4 were slightly worse. For the latter two cases, the deviations of the CO_2 concentrations at 'P_S' from the average values of the three locations were, on average, less than 20 ppm and 50 ppm, respectively. Such deviations were even smaller after around 1:00 a.m. when occupants fell to sleep. An uncertainty analysis (see Section 4.1) shows that this nonuniform level of CO_2 distribution propagates less than 8% of uncertainty to ACH calculations. The achievement of this level of uniformity can be attributed to two reasons: (a) the relatively stable CO_2 generation rate during sleeping periods and (b) the strong mixing effect of the flow circulation created by the air conditioner.

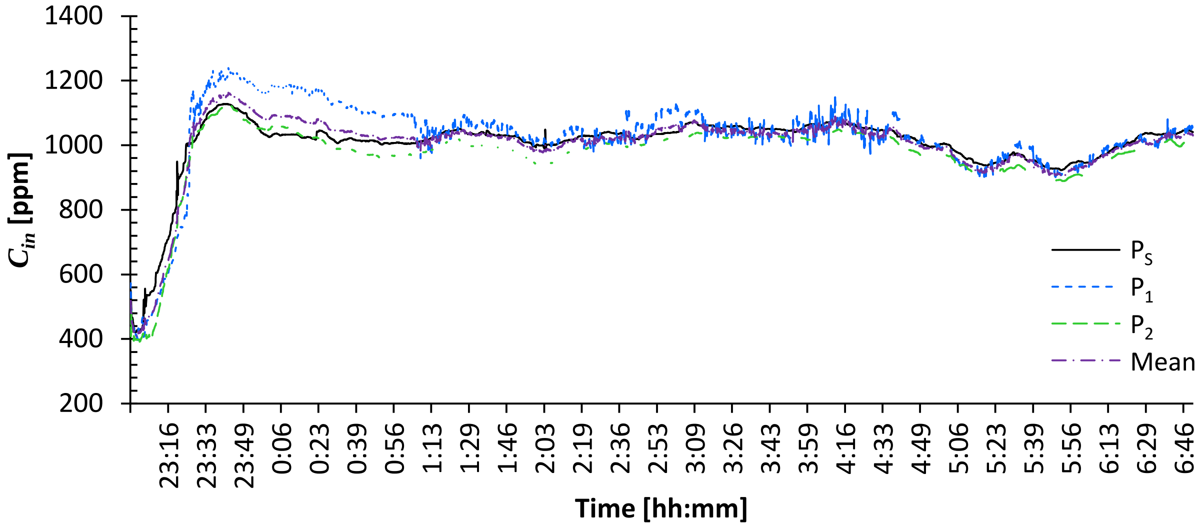
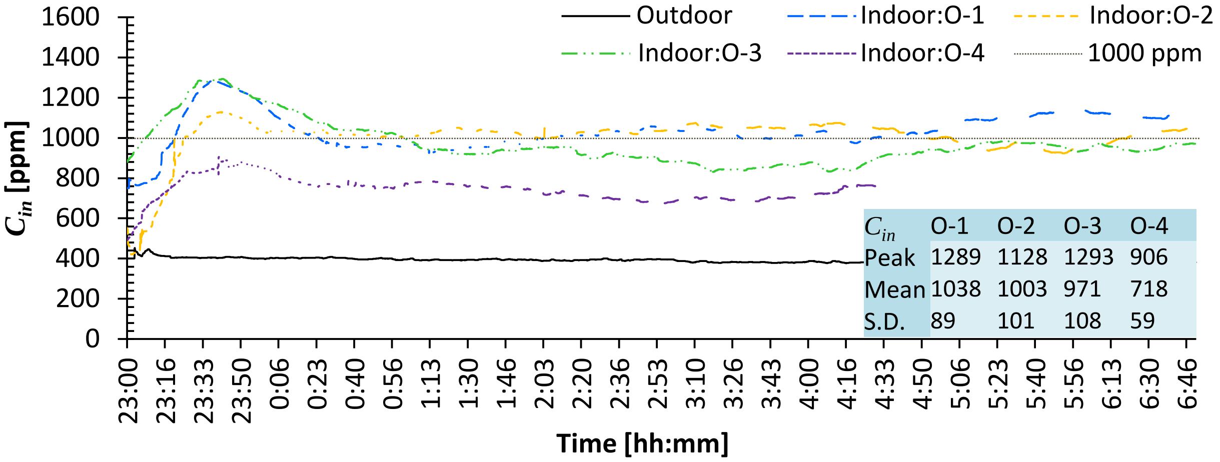
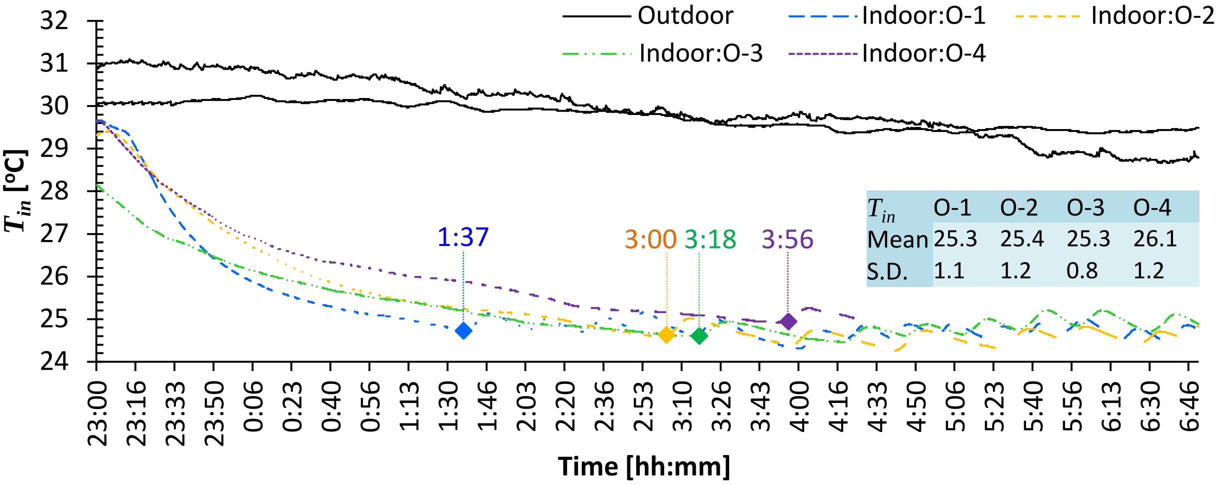


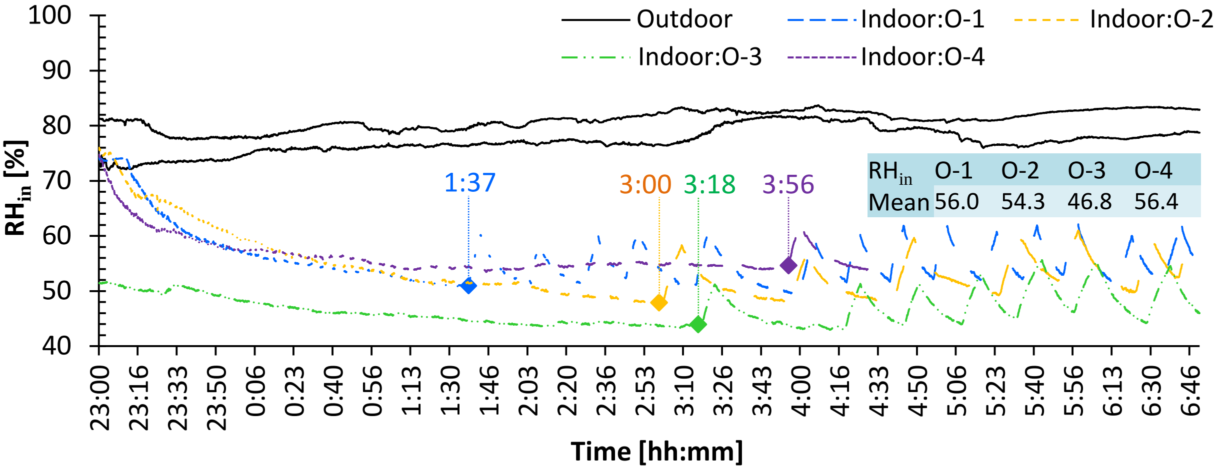
Figure 3 Uniformity test of indoor CO_2 concentration distribution for Case O-2.



(a) CO_2 concentration



(b) air temperature



(c) relative humidity

Figure 4 Overnight evolution of (a) CO_2 concentration, (b) air temperature and (c) relative humidity; for air temperature and relative humidity, only two cases' outdoor data are plotted, where data of other cases falls almost in between the two curves; the times when the first stops of air conditioner occur are marked on (b) and (c); the tables summarize the statistical values, where S.D. denotes standard deviation.

Figure 4 presents the overnight evolution of indoor CO_2 concentration, air temperature and relative humidity. Note that the Case O-4 stopped at 4:30 a.m., because the occupants felt too hot and humid to fall to sleep again after awaking. During the measurements, the outdoor CO_2 concentration was relatively stable and the average value was 392 ppm, which is very close to the 397 ppm retrieved from the King's Park Observatory as well as to that obtained in a previous measurement in Hong Kong [48]. The outdoor air temperature and relative humidity among these measurements were very close, with the average deviations being less than 1 ℃ and 5%, respectively, indicating the negligible influence of outdoor air temperature and relative humidity on the comparison of these cases. The outdoor wind speeds for the four cases are presented in Figure 5; they were very close among Cases O-2, O-3, and O-4. For Case O-1, with all windows closed, the outdoor wind speed was not the main influencing factor of the infiltration rate [43].

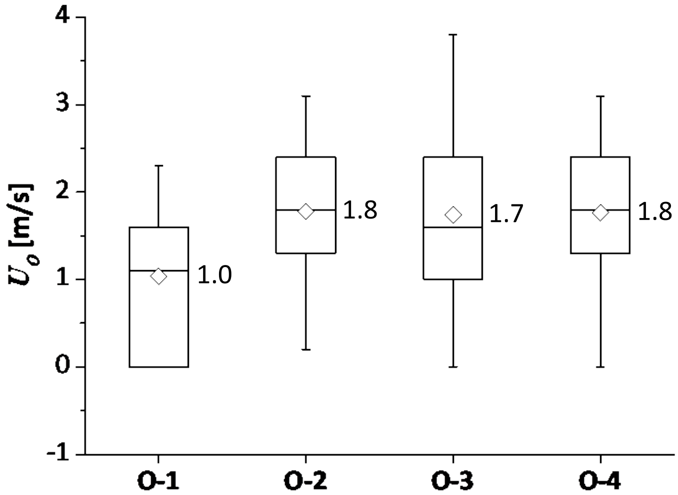


Figure 5 Box plots of outdoor wind speeds (U_o) during the overnight measurements from 23:00 p.m. to 7:00 a.m., where the mean values are presented near the boxes; the box edges represent the 25th and 75th percentiles, the whiskers for the 5th and 95th percentiles, the lines in the boxes for median values, and the symbols (◊) for mean values.

Figure 4 shows that the indoor CO_2 concentration increases at the beginning of sleep and decreases to reach a relatively stable level. Such CO_2 evolutions are determined by the combined effect of the indoor CO_2 generation rate, the infiltration rate and the net room volume. Comparison of different cases leads to the following three remarks.

First, with all windows closed and the ventilation damper switched off, the indoor CO_2 concentration frequently exceeds 1000 ppm during nighttime, indicating a need of ventilation. This situation is slightly improved when the ventilation damper is switched on (O-2).

Second, leaving a small window opening (5 cm, O-3) overnight lowers the mean CO_2 concentration to an acceptable level. A relatively larger window opening (10 cm, O-4) helps to decrease significantly the mean CO_2 concentration, but the energy consumption of the air conditioner and the indoor thermal environment are important issues.

Third, the indoor average air temperature is very close among the Cases O-1, O-2 and O-3. However, the time to reach the first stop of air conditioner varies largely among these cases. Particularly, switching on the ventilation damper delays the first stop of air conditioner for nearly 1.4 h and decreases obviously its stop frequency. The first stop time, together with the stop frequency, indicates obviously the energy performance of a ventilation strategy.

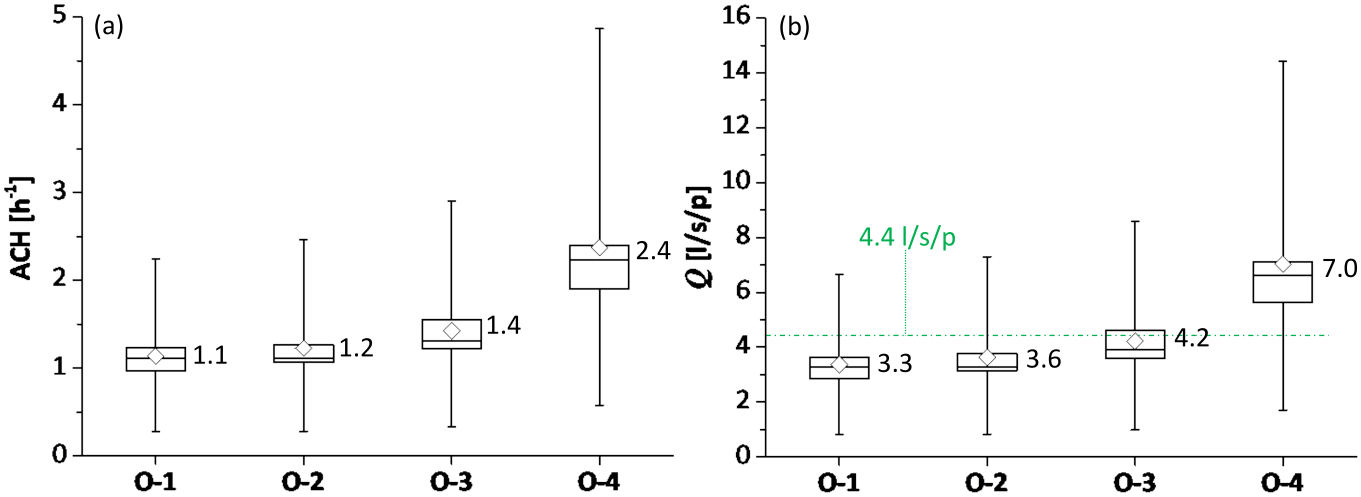


Figure 6 Box plots of average ACH values (a) and ventilation rates (b) during the periods from 1:00 a.m. to 7:00 a.m., where the mean values are presented near the boxes and the recommended ventilation rate for sleeping condition is also plotted; the box plots can be read according to the explanations given in the caption of Figure 5.

Figure 6 presents the box plots of ACH values and ventilation rates calculated using the CO_2 concentration data measured between 1:00 a.m. and 7:00 a.m., when the sleeping conditions were relatively stable and the CO_2 distributions were more uniform (see Figure 3). The ventilation rates for Cases O-1 and O-2 are larger than but still comparable to those reported in [3]. The minimum ventilation rate for sleeping condition is plotted on Figure 6 (b), which is determined based on a linear correction (using the relationship of metabolic rate) from the threshold ventilation rate recommended for sedentary condition [3, 10], namely 4.4 l/s/p = 7.5 l/s/p × (0.7 Met ÷ 1.2 Met). It can be seen that, compared to Case O-2, the ventilation rate for Case O-3 is increased by 16.7% and is close to the recommended value, while it is nearly doubled under a greater opening area (Case O-4), again, at the expense of deteriorated indoor thermal environment.

Overall, the overnight natural ventilation strategies with a small opening can maintain an acceptable IAQ, however, at the expense of excessive energy consumption and a high risk of deteriorated indoor thermal environment.

3.2 Short-term mechanical ventilation

In order to generalize the later analyses of short-term ventilation, the following parameters are defined.

Reference infiltration rate, $(\mathrm{ACH})_0$, is defined as the average infiltration rate of the measured room with the windows closed and the exhaust fan and ventilation damper switched off under an average I/O air temperature difference of 5 ℃. It is the average ACH of the overnight Case O-1 (see Section 3.1), namely 1.1 h^{-1};

Normalized air change rate is defined as:

$$\mathrm{ACH}^* = \frac{\mathrm{ACH}}{(\mathrm{ACH})_0} \tag{6}$$

Normalized time is defined as:

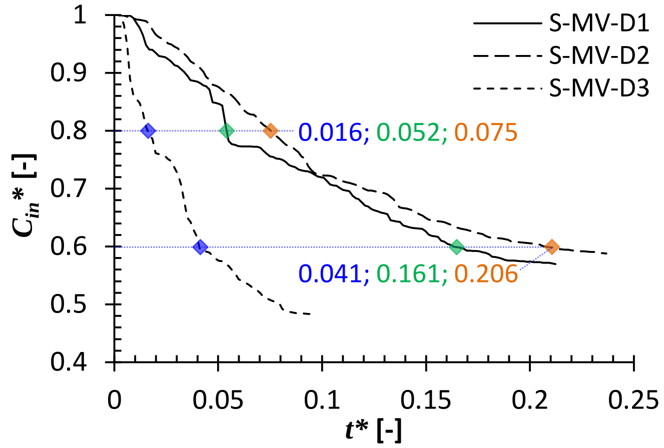
$$t^* = \frac{t \cdot (\mathrm{ACH})_0}{3600} \tag{7}$$

Normalized CO_2 concentration is defined as:

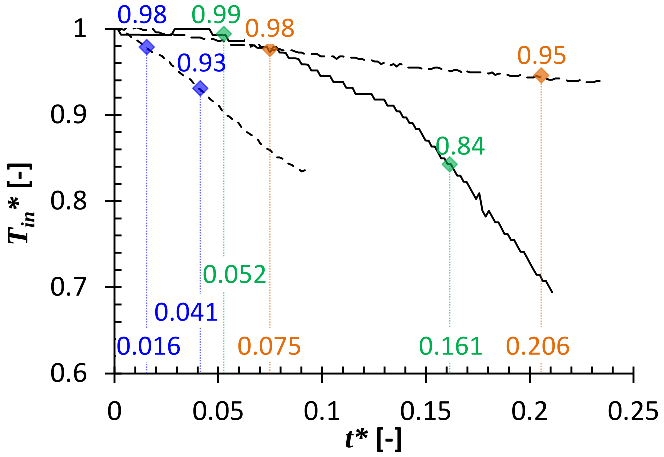
$$C_{in}^* = \frac{C_{in}}{C_{in,ini}} \tag{8}$$

Normalized indoor air temperature is defined as:

$$T_{in}^{*}=\frac{T_{out}-T_{in}(t)}{T_{out}-T_{in,ini}} \tag{9}$$



(a) normalized indoor CO_2 concentration



(b) normalized indoor air temperature

Figure 7 Evolution of normalized indoor CO_2 concentration (a) and normalized indoor air temperature (b) during short-term mechanical ventilation, where the normalized times to reach $C_{in}^{*}=0.8$ and 0.6 are marked on (a) and the normalized indoor air temperatures being achieved at those times are marked on (b).

Figure 7 presents the evolution of normalized indoor CO_2 concentration and air temperature during the short-term mechanical ventilation. From this figure, four observations can be made.

First, in general, the indoor CO_2 concentration decreases fast at the beginning of ventilation. Such a decrease becomes slow gradually over time, as the I/O concentration difference decreases over time during ventilation.

Second, the Case S-MV-D3 (called D3 later) has the best ventilation efficiency in terms of the decreasing rate of CO_2 concentration, while the Case S-MV-D2 (called D2 later) is even worse than the Case S-MV-D1 (called D1 later). Considering that the exhaust fan produces a constant ventilation rate, the essential difference among the three cases is the indoor airflow distribution. For Cases D1 and D2, serious short circuits of inflows occurs, namely, a large portion of outdoor airflows entering the room from the door and window cracks (D1) or from the nearby open window (D2) flows out quickly through the exhaust fan, which does not contribute effective ventilation to diluting the indoor CO_2. On contrary, for Case D3, the outdoor airflows entering from the window on another facade of the room can flow through the whole room before exhaust, which improve substantially the ventilation efficiency. Such a significant difference in ventilation efficiency caused by the location of intake opening implies the importance of a reasonable ventilation design.

Third, the times taken to achieve $C_{in}^* = 0.8$ and 0.6 for the Case D3 are nearly 20%-30% of those for Case D1 (see Figure 7 (a)). This means that Case D3 can achieve a target indoor CO_2 concentration within a shorter ventilation period. As the ventilation efficiency decreases over time, a ventilation strategy allowing a shorter ventilation time is a better choice.

Fourth, for all three cases, the indoor air temperature increases only slightly after the short mechanical ventilation (see Figure 7 (b)). Assuming an I/O air temperature difference equal to 10 ℃, $T_{in}^* = 0.8$ means the indoor air temperature increasing by 2 ℃. A short-term elevation of indoor air temperature in such a level would not influence indoor thermal comfort.

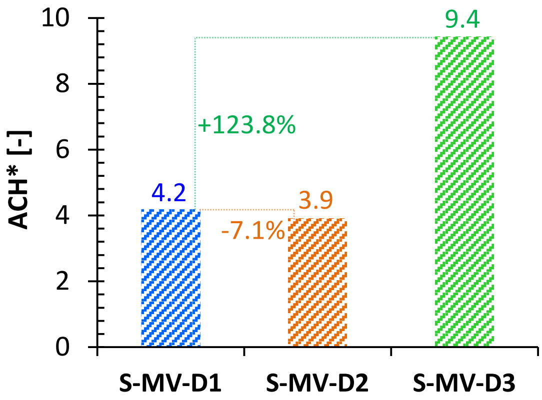


Figure 8 Bargraph of the normalized mean ACH for the short-term mechanical ventilation, where the percentage changes in mean ACH* value compared to Case D1 are also presented for easy comparison.

The normalized mean ACH values for the three cases are presented in Figure 8. Note that these mean ACH values were calculated based on the uniform CO_2 concentrations recorded at the beginning and at the end of ventilation (see Section 2.3). It is important to examine the influence of concentration uniformity on the calculated ACH value, given that using nonuniform CO_2 concentrations to calculate ACH value is a common mistake in practice. Under a nonuniform condition, the ACH* calculated based on the measurements at the location 'P_S' are 6.8, 6.6 and 18.4 for the three cases, respectively, which are larger considerably than those calculated from uniform CO_2 concentrations. However, it is evident that, under a specific indoor airflow distribution, the ACH* value calculated using nonuniform CO_2 concentrations is highly dependent on the location of CO_2 sensors. Overestimation occurs when the CO_2 sensor is located within the well ventilated regions like near the intake, whereas underestimation occurs when the CO_2 sensor is located within regions with inadequate ventilation. Another important finding is that the effective ACH value obtained even in Case D3 is less than the nominal ACH value $24.4h^{-1}$ (the ratio of the nominal ventilation rate of the exhaust fan to the net volume of the room). This phenomenon should be attributed to the short circuit of inflows from the cracks of the door and the windows near the exhaust fan. In addition, some inflows even from the open Window-AC do not necessarily produce effective ventilation, as airflows move always along a route with the smallest resistance. Despite of this discount in ventilation rate, the mechanical ventilation strategy should still be an appropriate candidate for ventilation of air-conditioned buildings.

3.3 Short-term natural ventilation

Figure 9 presents the evolution of normalized indoor CO_2 concentration during short-term natural ventilation. The curves presented in Figure 9 were selected from a large number of measurements to make the I/O air temperature difference and outdoor wind speed as close as possible to reduce their influences on the comparison of these cases. Comparison of these cases leads to the following three observations.

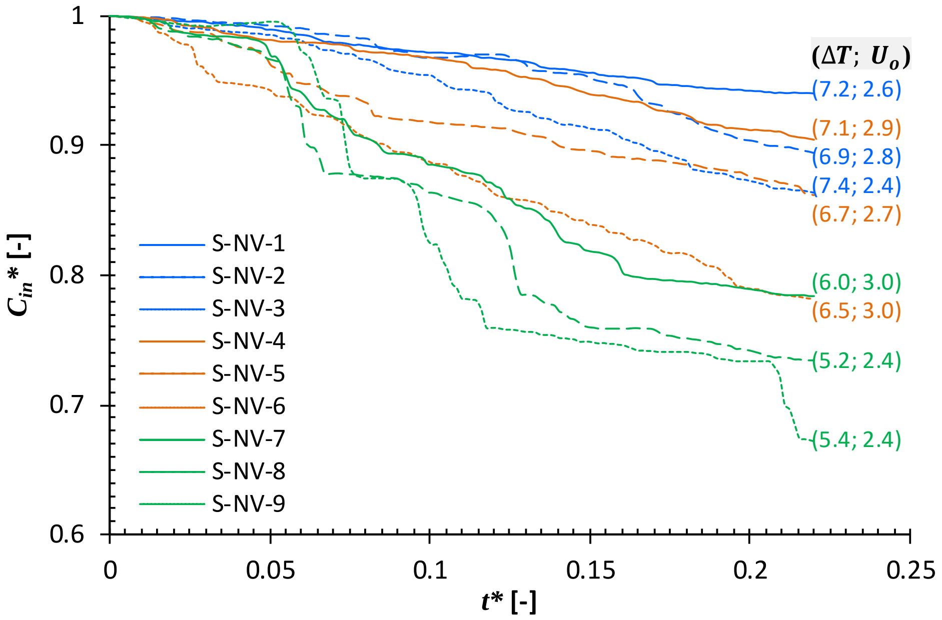


Figure 9 Evolution of normalized indoor CO_2 concentration during short-term natural ventilation, where the average I/O air temperature difference ΔT and average outdoor wind speed U_o during the measurements are also presented in the brackets.

First, the opening characteristics (location and area) are the dominant factors to differentiate the general development trend of CO_2 concentration among these cases. Particularly, for a same opening area, opening the window near the region of interest (Cases S-NV-4, 5, 6) would be more effective to decrease CO_2 concentration in that region.

Second, cases with better ventilation performance, namely Cases S-NV-8 and S-NV-9, involve some sudden decreases in CO_2 concentration. This phenomenon is caused basically by the instability of the driving force of natural ventilation due to particularly the constantly changing outdoor wind environment.

Third, according to Archimedes number ($Ar = \beta \Delta T g H_w / U_B^2$), the driving force produced by the I/O air temperature difference ranging around 5-8 ℃ is nearly equivalent to that produced by a wind speed ranging around 0.3-0.5 m/s. As outdoor wind speeds were mostly greater than 0.3-0.5 m/s, the short-term natural ventilation in air-conditioned residential buildings was dominated by wind effect, rather than buoyancy effect. This is also supported by our observation during measurements; namely an outdoor CO_2 sensor located near the upper part of a window detected rising CO_2 concentration immediately after opening the window for ventilation. However, the influence of wind condition (namely, both wind direction and wind speed) on the room ACH and in turn the CO_2 decay is very complex (see references like [37-38, 49-51]), which is not the interest of the present study.

Note that the variation of indoor air temperature and relative humidity during short-term natural ventilation was very small, being less than 1 ℃ and 10%, respectively, meaning a negligible influence on indoor thermal environment.

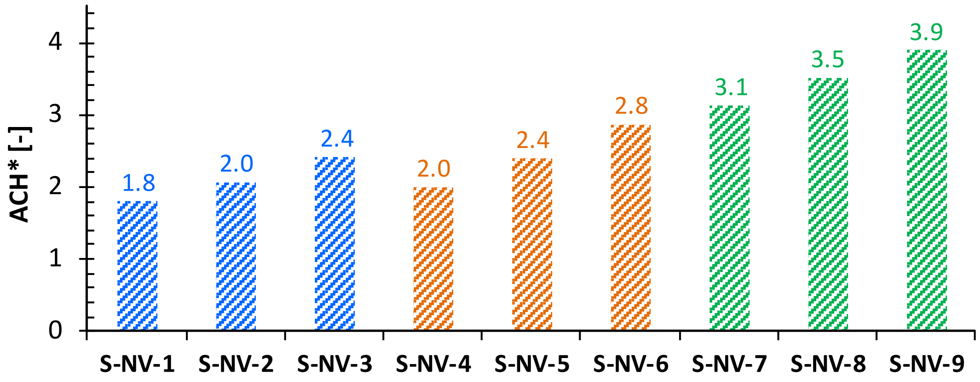


Figure 10 Normalized ACH values for short-term natural ventilation under the same conditions (namely ΔT and U_o) as presented in Figure 9.

Based on the initial and final uniform indoor CO_2 concentration, the normalized ACH values for the short-term natural ventilation are calculated (see Figure 10). As analysed in Section 3.2, a ventilation strategy producing a higher ACH value is better in terms of ventilation efficiency. Therefore, apart from mechanical ventilation strategy (S-MV-D3), the most excellent natural cross ventilation strategy (S-NV-9) may be an alternative candidate for ventilation of air-conditioned buildings. Further discussions are provided in Section 3.4.

3.4 Comparison of natural and mechanical ventilation strategies

This section compares the best natural ventilation strategy (S-NV-9) and the reasonably designed mechanical ventilation strategy (S-MV-D3), so as to make recommendations for ventilation design of air-conditioned residential buildings. Based on the measured room, the decays of indoor CO_2 concentration from an initial level of 1100 ppm, when applying the two ventilation strategies, were predicted using Equation (4) (see Figure 11). Compared to the natural ventilation strategy, the mechanical ventilation strategy takes a 41% of time to complete one full replacement of indoor air (namely, $\text{ACH} \cdot \Delta t_v = 1$) and to reach a 92% of indoor concentration. Moreover, the average indoor CO_2 concentration during the mechanical ventilation process is lower, by 4%, than that during the natural ventilation process.

Owing to lower ventilation efficiency, the natural ventilation strategy requires a larger amount of air exchange ($\text{ACH} \cdot \Delta t_v$) to achieve a target indoor CO_2 concentration, which would cause more cooling energy losses and a higher risk of noise penetration. In addition, owing to an inconstant ACH, the natural ventilation strategy is not reliable for ventilation control. Overall, even though the mechanical ventilation uses additional electrical energy, the short-term mechanical ventilation strategy is recommended for ventilation of air-conditioned residential buildings.

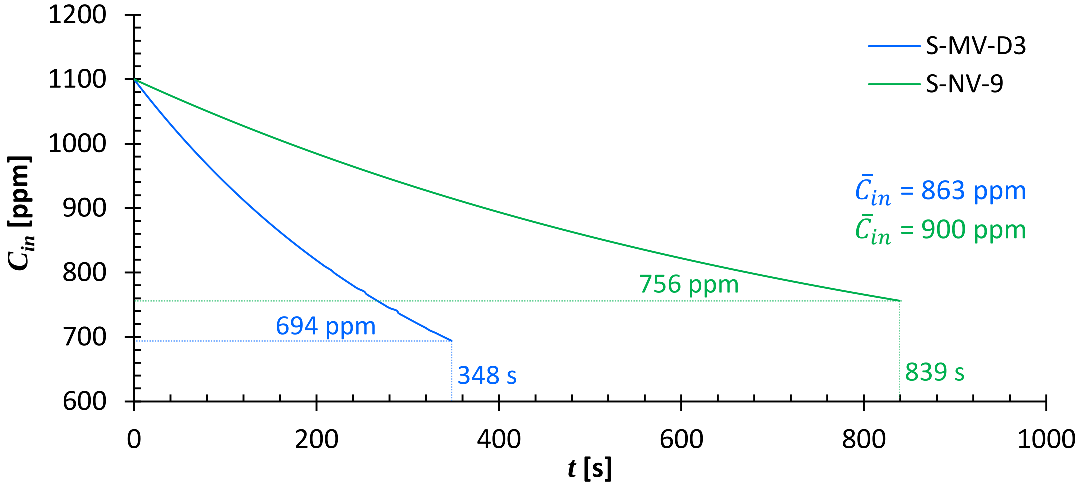


Figure 11 Indoor CO_2 concentration decay from an initial concentration of 1100 ppm during the two types of ventilation for one full replacement of the indoor air, namely a normalized ventilation period of $ACH \cdot \Delta t_v = 1$; the average indoor CO_2 concentrations ($\overline{C}_{in}$) during the ventilation periods are also provided.

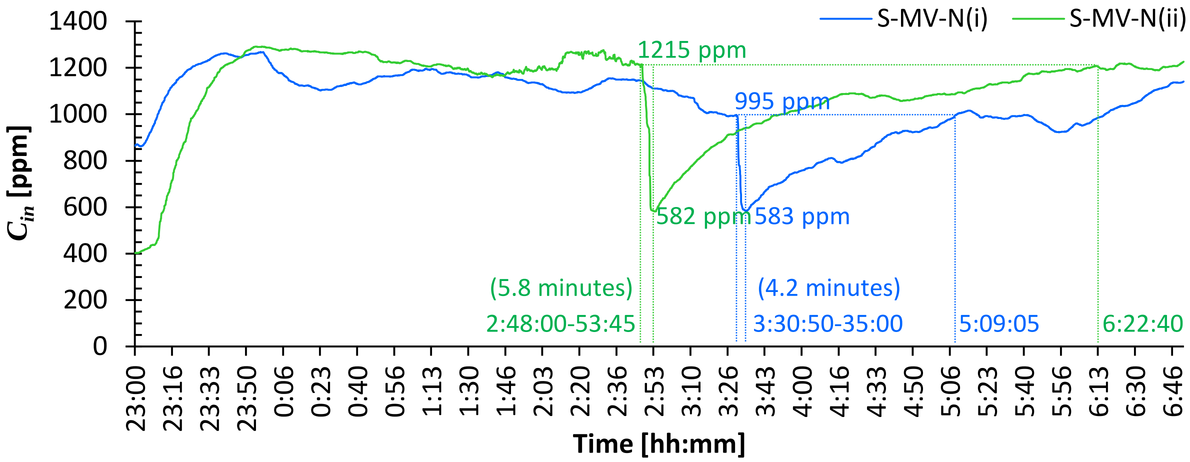
3.5 Specific nighttime cases

Specific case studies of short-term mechanical ventilation applied during nighttime sleeping periods were conducted to demonstrate its ventilation performance, which is the Case S-MV-N described in Section 2.3. Figure 12 shows the evolution of indoor CO_2 concentration, air temperature and relative humidity before, during and after the occurrence of short-term mechanical ventilation. From this figure, three important remarks can be made.

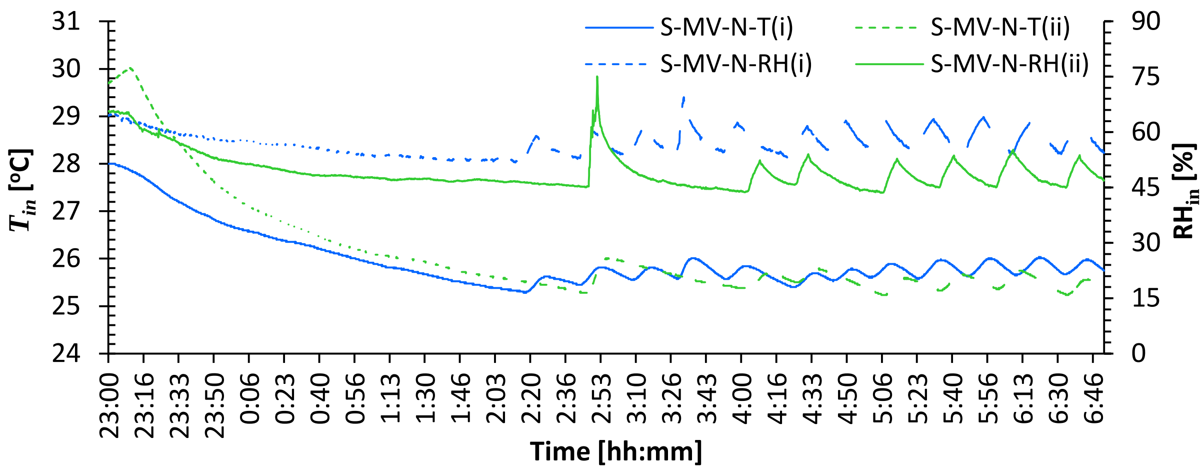
First, short-term mechanical ventilation for several minutes is very effective to lower the indoor CO_2 concentration. A ventilation period of 4.2 minutes decreases the CO_2 concentration to 59% of its original concentration, while this is 47% for a ventilation period of 5.8 minutes, where the decreasing rates are nearly 99 ppm/min and 110 ppm/min, respectively. The percentage decrease of CO_2 concentration is certainly influenced by (a) the CO_2 concentration at the beginning of ventilation, (b) the ventilation period and (c) the ACH value during the ventilation period.

Second, the CO_2 build-up rate after the short-term ventilation periods is, on average, 262 ppm/h during the first 1.5 hour. As a result, the times taken for the indoor CO_2 concentration to reach the initial values before ventilation are 1.6 h and 3.5 h, respectively.

Third, the indoor thermal environment, namely the air temperature and relative humidity, are almost not influenced by the presence of short-term ventilation, although the time to reach the next stop of air conditioner is extended.



(a) CO_2 concentration



(b) air temperature and relative humidity

Figure 12 Evolution of indoor CO_2 concentration, air temperature and relative humidity when there was one short-term mechanical ventilation period in nighttime; (i) and (ii) differentiate two cases conducted in two different nights.

Based on the above case studies and the best short-term mechanical ventilation (Case S-MV-D3), a whole-night evolution of CO_2 concentration was theoretically predicted using Equation (4). The results are presented in Figure 13, where additional two cases with $(\mathrm{ACH})_0$ = 0.8 h^{-1} and 0.3 h^{-1} are also predicted for comparison. For the present case with a relatively large infiltration rate ($(\mathrm{ACH})_0$ = 1.1 h^{-1}), even one ventilation period can stop the indoor CO_2 concentration returning 1100 ppm again, leading to a fairly low overnight average CO_2 concentration $\overline{C}_{in}$, namely, 887 ppm. Together with the nighttime case studies, these theoretical predictions suggest that a few several-minute mechanical ventilation periods can cover a whole nighttime sleeping period. However, further studies should be conducted to optimize the ventilation period and the initial and final CO_2 concentrations of ventilation, based on various combinations of G_r / V and $(\mathrm{ACH})_0$.

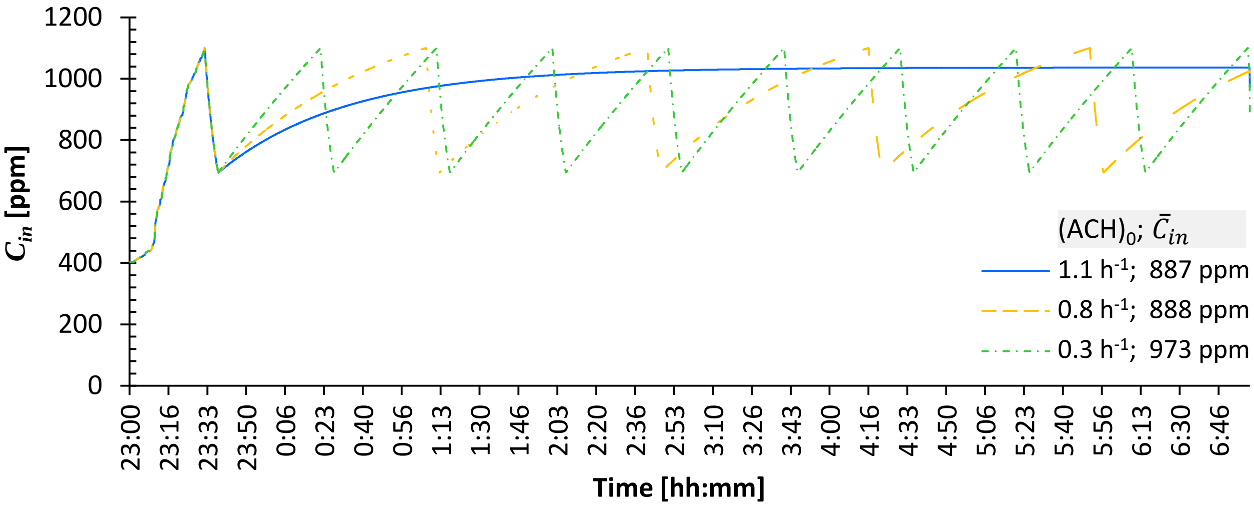


Figure 13 Theoretical prediction of the evolution of indoor CO_2 concentration within an 8-h nighttime sleeping period, where the short-term mechanical ventilation (S-MV-D3) starts once C_{in} reaches 1100 ppm and each ventilation lasts for $\mathrm{ACH} \cdot \Delta t_v = 1$.

4. Discussion

4.1 Uncertainty analyses

Apart from the uncertainties of the equipment (see Table 1), there are three main uncertainty sources in the estimation of ventilation rates and in turn in the prediction of the evolution of indoor CO_2 concentration: (a) estimation of CO_2 generation rate by the occupants (G_r), (b) estimation of the net indoor volume (V), and (c) the uniformity of the indoor CO_2 concentration. For on-site measurements, the uniformity problem occurs most probably at the end of a ventilation measurement, namely the measurement of $C_{in,i+\Delta t}$. Based on Equation (5), the uncertainty in determining ACH value can be evaluated quantitatively according to the well-known statistical theory of uncertainty propagation.

$$(\mathrm{ACH})_u = \left|\frac{\partial(\mathrm{ACH})}{\partial G_r}\right|(G_r)_u + \left|\frac{\partial(\mathrm{ACH})}{\partial V}\right|(V)_u + \left|\frac{\partial(\mathrm{ACH})}{\partial C_{in,i+\Delta t}}\right|(C_{in,i+\Delta t})_u \tag{10}$$

where the subscripts 'u' denote uncertainty.

First, in the estimation of CO_2 generation rate G_r, the metabolic rate M of a person is dependent on its body surface area, age and activity [10, 44, 52]. However, the data provided by ASHRAE Handbook [44] is based on an adult with $A_D = 1.8\ \mathrm{m}^2$. The correction factor e for Chinese people proposed in [46] was obtained based on university students (on average 21 years old), whereas the occupants in the present study were 29 years old. It was reported that the basal metabolic rate declines with age by 5%-10% from 20 to 40 years old [53-54]. In addition, a mixture of activities, namely sitting and short-term walking, of the occupants was presented during the measurements. For the best short-term mechanical ventilation (Case S-MV-D3), assuming $C_{in,i} - C_{out}$ =700 ppm, a 5% uncertainty in G_r would propagate a 0.8% uncertainty to ACH.

Second, the net room volume V is another source of uncertainty. The on-site measurements were conducted in a real residential room, where the common indoor goods like bed, furniture and sundries as well as occupants were presented. Although the volumes of all indoor goods and occupants were estimated rigorously in this study, the deviation of the estimated volume from the real volume should still exist. Under a similar condition assumed in the above first point, a 5% uncertainty in V would propagate a 0.8% uncertainty to ACH.

Third, the non-perfect mixing of CO_2 with the indoor air could result in overestimation or underestimation of ACH. As described in Section 3.1, the uncertainty of CO_2 concentration was less than 50 ppm. Under a similar condition assumed in the above first point, considering a time period Δt = 348 s ($\mathrm{ACH} \cdot \Delta t = 1$), a 50 ppm uncertainty in $C_{in,i+\Delta t}$ would propagate a 7.3% uncertainty to ACH.

In summary, the overall uncertainty of ACH propagated from uncertainties of the above three factors is less than 9.0%, of which the contribution of the uncertainties in G_r and V is negligible. However, the nonuniform distribution of CO_2 is well appreciable. This uncertainty analysis, together with the analysis in Section 3.2, highlights the importance of ensuring acceptable uniformity of the spatial distribution of tracer gas.

4.2 Limitations

The general limitations of on-site measurements exist inevitably in the present study, namely based on specific measurement site(s) under a certain local meteorological condition. Although Hong Kong has a very long air-conditioning period, its outdoor air temperature in the hottest months is mostly between 26 and 32 ℃ [55], which means that the I/O air temperature difference of air-conditioned residential buildings ranges mostly from 4 ℃ to 8 ℃. The findings of this study are applicable to climatic regions with these levels of outdoor air temperature and I/O air temperature difference. However, in other climatic regions where the outdoor air temperature approaches and even exceeds 40 ℃, the characteristics of I/O flow exchange and the evolution of indoor environmental parameters during ventilation need further investigations.

The measured residential room is typical in densely populated Hong Kong in terms of its floor area and number of occupant. However, in other less densely populated cities, the floor area per occupant could be much larger, namely a smaller G_r / V. In addition, the infiltration rate $(\mathrm{ACH})_0$ of the present measured room is relatively large. A recent study [43] shows that the infiltration rate of a residential room depends on its floor area, construction year, and location of floor. Therefore, based on the present study, the indoor CO_2 build-up and the optimization of short-term mechanical ventilation, as a function of G_r / V and $(\mathrm{ACH})_0$, need further investigations.

The influence of outdoor wind speed and wind direction on the ventilation strategies was not fully evaluated throughout the present measurements. Although the outdoor wind speed in a range of 1-3 m/s recorded during the present measurements showed a very limited influence on the short-term mechanical ventilation, the influence of wind speed should still be evaluated for climatic regions with a frequent occurrence of high wind speeds. In addition, this case study focused on a bedroom located on the 11th floor of a 12-storey building. The wind condition around rooms located on lower floors should be different. It is necessary to examine the influence of wind condition due to floor difference in future studies.

5. Conclusions

In order to explore the ventilation of air-conditioned residential buildings, a case study in a bedroom of a high-rise residential building in Hong Kong was conducted. A series of on-site measurements were performed to investigate the overnight indoor CO_2 build-up and to evaluate various ventilation strategies.

Excessive CO_2 concentration and insufficient ventilation rate are found, confirming that additional ventilation is usually needed in air-conditioned residential buildings. Overnight natural ventilation strategies through an open window can maintain an acceptable IAQ, however, at the expense of deteriorated indoor thermal environment and excessive energy consumption. Short-term natural ventilation strategies are inefficient and uncontrollable. Compared to the best short-term natural ventilation strategy, a reasonably designed short-term mechanical ventilation strategy requires only a 41% of ventilation period to complete one full replacement of indoor air and to reach a lower indoor CO_2 concentration. Nighttime case studies, together with a theoretical analysis, suggest that a few several-minute mechanical ventilation periods can potentially maintain an acceptable IAQ for a normal sleeping period of 8 hours. Considering also its controllable advantage, the short-term mechanical ventilation strategy is recommended for ventilation of air-conditioned residential buildings.

The optimization of short-term mechanical ventilation strategy, in terms of initial and final concentrations of ventilation, each ventilation period and ventilation frequency, as a function of indoor CO_2 generation rate, mechanical ventilation rate, infiltration rate and net room volume requires further investigations.

Acknowledgement

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