Short-term mechanical ventilation of air-conditioned residential buildings: case study and general design framework

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ABSTRACT

Many studies reported that there were insufficient ventilation and excessive CO_2 concentration in air-conditioned residential buildings, but few solutions were provided. This study first investigated the performance of three possible ventilation strategies of air-conditioned residential buildings, including overnight natural ventilation, short-term natural ventilation, and short-term mechanical ventilation. On-site measurements were conducted in a typical occupied residential bedroom in Hong Kong in summer, where a number of environmental parameters including especially the CO_2 concentration were monitored both inside and outside the room. Ventilation rates were calculated based on the time series of CO_2 concentration. The results confirm that ventilation is 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.

This study second developed a general design framework of short-term mechanical ventilation strategy. This framework can determine appropriate design parameters, including ventilation period, ventilation frequency, and start concentration of ventilation, based on various combinations of indoor CO_2 generation rate, net room volume, infiltration rate, and mechanical ventilation rate. A whole sleeping period of 8 h was divided into many repeated single V-shape ventilation periods; each single ventilation period is comprised of a short-term mechanical ventilation period and a follow-up CO_2 build-up period. The single V-shape ventilation process was particularly investigated based on a criterion that the average indoor CO_2 concentration is less than but close to 1000 ppm. A high efficient ventilation strategy, namely requiring a minimum total mechanical ventilation period, is a short single ventilation period and a high ventilation frequency. Although this study focused on air-conditioned residential buildings, the basic concepts and design framework should also be applicable for heated residential buildings.

KEYWORDS

Ventilation, Room air conditioner, residential buildings, on-site measurements, design framework

1 INTRODUCTION

Room air conditioners, particularly the window-type and split-type air conditioners, are widely used in residential buildings in hot and humid regions to provide a thermally comfortable indoor environment. The period of using air-conditioners in a year and the duration in a night are becoming increasingly long, even over 6 months and 8 hours, respectively, in many homes in hot and humid regions like Hong Kong (Lin and Deng, 2006). However, one deficiency of such room air conditioners is the provision of no or very little outdoor air. Many on-site measurements (e.g., Ai et al., 2016) revealed that ventilation rates in air-conditioned residential buildings are much less than the minimum requirement, namely 7.5 l/s/p, stipulated by ventilation standards (ASHRAE Standard 62.1, 2013). In connection with insufficient ventilation, excessive CO_2 concentrations (usually > 1000 ppm) in air-conditioned residential buildings were often reported (Beko et al., 2010). A strong relationship between insufficient ventilation and negative health effects has been widely reported (Seppanen et al., 1999).

In this study, on-site measurements were performed in a typical bedroom of a residential building in Hong Kong and three types of ventilation strategies for air-conditioned residential buildings were evaluated, which include overnight natural ventilation, short-term mechanical ventilation and long-term mechanical ventilation. Then, a general design framework of short-term mechanical ventilation was developed to determine the appropriate design parameters, including ventilation period, ventilation frequency and start CO_2 concentration of ventilation, based on various combinations of indoor CO_2 generation rate, net room volume, infiltration rate, and mechanical ventilation rate.

2 ON-SITE MEASUREMNETS

2.1 Measurement methods

The on-site measurements were conducted in Hong Kong in summer, when the outdoor air temperature was mainly between 27 and 32 °C. An air-conditioned bedroom located on the 11th floor of a 12-storey building was selected. The room was occupied with two adults. The room and window configurations are presented in Figure 1. A room of such dimensions is typical in densely populated urban areas like Hong Kong. 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.

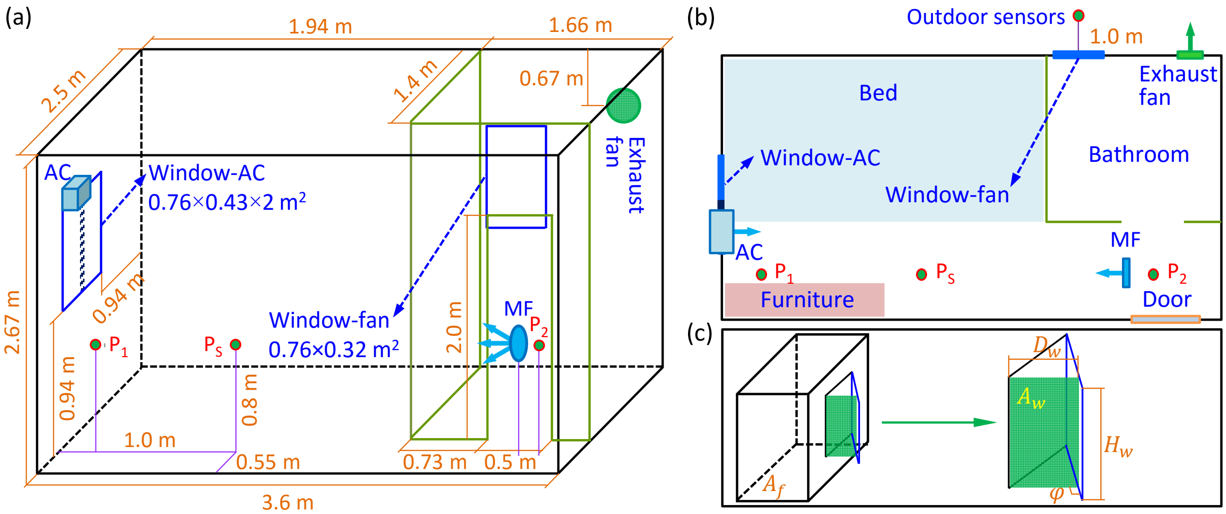

Figure 1: Measurement site: (a) room configuration, (b) top view of indoor layout and (c) schematic view of window configuration; AC is the air conditioner, MF the mixing fan, P_S, P_1 and P_2 the location of indoor sensors.

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). 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. Measurements were conducted at a frequency of 0.2 Hz.

Based on the occupants' schedule, the overnight measurements were conducted from 23:00 p.m. to 7:00 a.m. in nighttime. The measured cases are listed in Table 2, where the 'Open-

5cm' and 'Open-10cm' indicate the D_w (in Figure 1 (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 'Ps'.

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%

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 1 (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%

A measurement of short-term ventilation lasted for no more than 20 minutes. 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.

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%

Tracer gas technique including using human exhaled CO_2 was widely used to determine indoor ventilation rates (Beko et al., 2010; Laussmann and Helm, 2011; Ai et al., 2015; Ai and Mak, 2013; 2014a; 2016a). The CO_2 generation rate per person varies with age, activity and diet (ASHRAE Handbook, 2013; ASHRAE Standard 62.1, 2013).

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

Substituting an empirical equation of human body surface area ($A_D = 0.202H^{0.725}W^{0.425}$, DuBois and DuBois, 1916), the Equation (1) can be modified into the following form:

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

Based on the principle of mass conservation, the calculation of ventilation rates in a well-mixed single zone using tracer gas method (Ai and Mak, 2014b) 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. Discretization of this differential equation onto a discrete temporal grid with a time interval of Δt leads to a theoretical evolution of indoor CO2 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:

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

2.2 Results and analyses: three ventilation strategies

Figure 2 presents the box plots of ACH values and ventilation rates calculated using the CO2 concentration data measured between 1:00 a.m. and 7:00 a.m. The ventilation rates for Cases O-1 and O-2 are larger than but still comparable to those reported in (Lin and Deng, 2003). The minimum ventilation rate for sleeping condition is plotted on Figure 2 (b). 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). 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 (indoor air temperature is not presented).

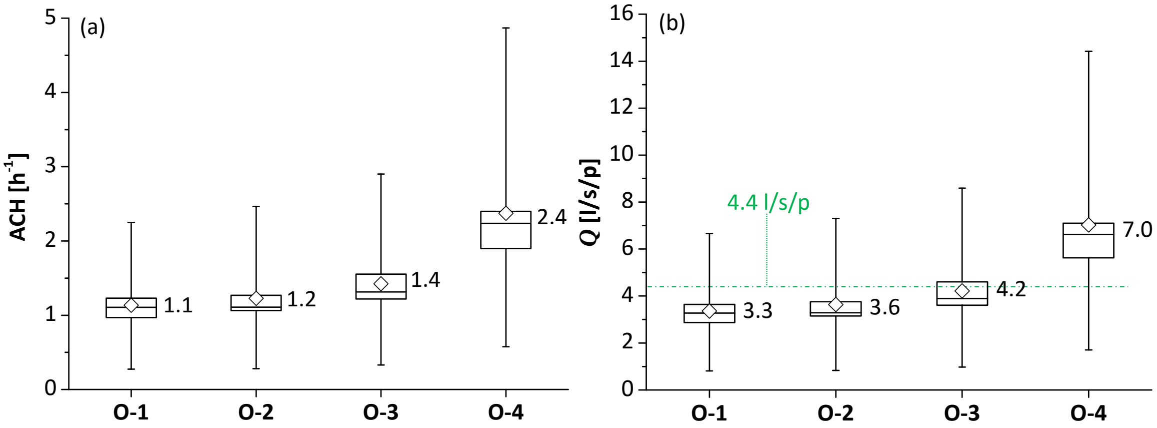

Figure 2: Box plots of average ACH values (a) and ventilation rates (b) during the periods from 1:00 a.m. to 7:00 a.m., where the mean values are presented near the boxes and the recommended ventilation rate for sleeping

condition is also plotted; the box 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.

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 switched off under an average I/O air temperature difference of 5 °C. It is the average ACH of the overnight Case O-1, namely 1.1 h^{-1}; Normalized air change rate is defined as: $ACH^* = ACH/(ACH)_0$.

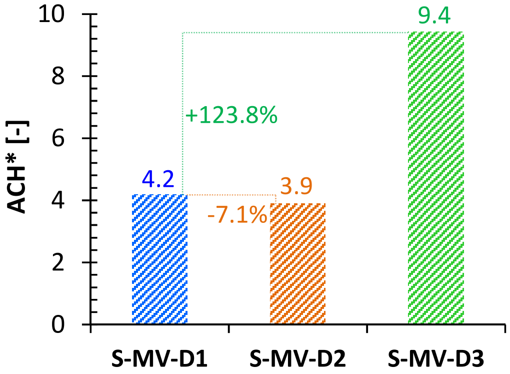

Figure 3: Bargraph of the normalized mean ACH for the short-term mechanical ventilation, where the percentage changes in mean ACH* value compared to Case D1 are also presented for easy comparison.

The normalized mean ACH values for the three cases are presented in Figure 3. 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. Despite of this discount in ventilation rate, the mechanical ventilation strategy should still be an appropriate candidate for ventilation of air-conditioned buildings.

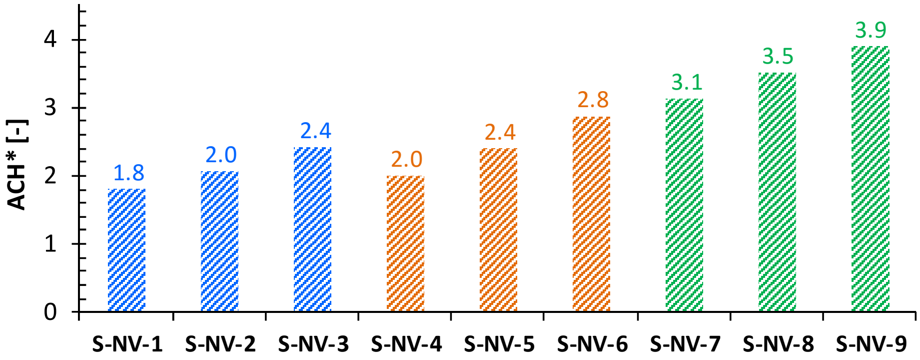

Figure 4: Normalized ACH values for short-term natural ventilation under the same conditions.

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 4). 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.

2.3 Results and analyses: comparison of 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 5). Compared to the natural ventilation strategy, the mechanical ventilation strategy takes a 41% of time to complete one full replacement of indoor air (namely, $\mathrm{ACH} \cdot \Delta t_v = 1$) 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. Considering the instability of natural ventilation, the short-term mechanical ventilation strategy is recommended, even though the mechanical ventilation uses additional energy.

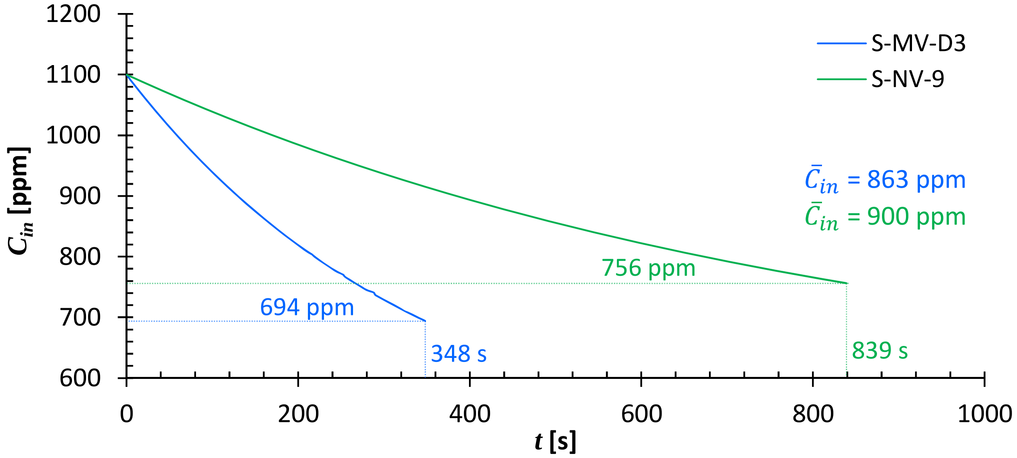

Figure 5: Indoor CO_2 concentration decay from an initial concentration of 1100 ppm during the two types of ventilation for one full replacement of the indoor air, namely a normalized ventilation period of $\mathrm{ACH} \cdot \Delta t_v = 1$; the average indoor CO_2 concentrations ($\bar{C}_{in}$) during the ventilation periods are also provided.

3 DESIGN FRAMEWORK

3.1 Mass conservation and concentration evolution

The elevation of indoor CO_2 concentration is contributed mainly by the emission of indoor occupant(s). An accurate prediction of the CO_2 generation rate of occupants and then the evolution of indoor CO_2 concentration over time is thus the basic prerequisite of a reliable ventilation design.

Transforming the Equation (4) and applying the formula of air change per hour (ACH), $\mathrm{ACH} = Q/V$, one can obtain the following equation:

$$C_{in,i+\Delta t} = \frac{G_r}{V} \cdot \Delta t - \mathrm{ACH} \cdot \Delta t \cdot (C_{in,i} - C_{out}) + C_{in,i} \qquad (6)$$

Provided that the C_{out} is known, the parameters influencing the indoor CO_2 concentration are only G_r/V and ACH. Here, the G_r/V is useful to indicate the indoor CO_2 generation rate per unit volume. Note that ACH represents infiltration rate, $(\mathrm{ACH})_0$, when all windows are closed and the mechanical ventilation system switched off; it represents the air change rate produced by the mechanical ventilation system when mechanical ventilation system is in operation. The Equation (6) is very important, which is the basis of the ventilation design of air-conditioned residential buildings.

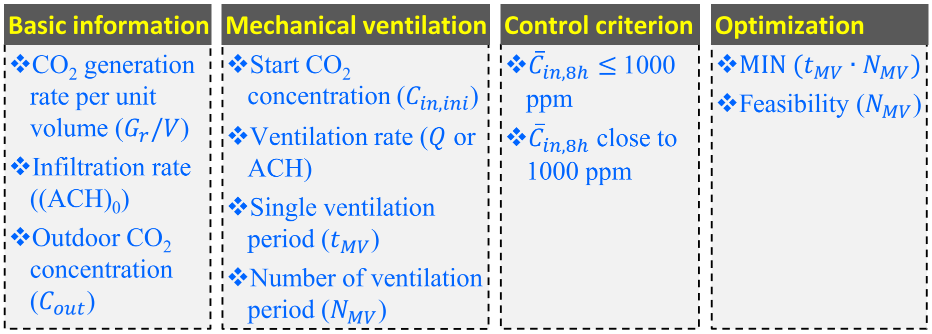

Figure 6: A summary of the basic design and control parameters for ventilation design of air-conditioned residential buildings.

3.2 Design framework and procedures

Based on the evolutions of indoor CO₂ concentration predicted using Equation (6), the ventilation need for a specific case can be determined and then the ventilation design can be conducted. Note that the present study considers only the sleeping condition. However, the general design method proposed in this study is still applicable to non-sleeping conditions, except that the metabolic rate (M) and thus the CO₂ generation rate (G_r) need to be redetermined. It was reported that the CO₂ generation rate of human beings during sleeping condition is lower than non-sleeping conditions (Lin and Deng, 2003).

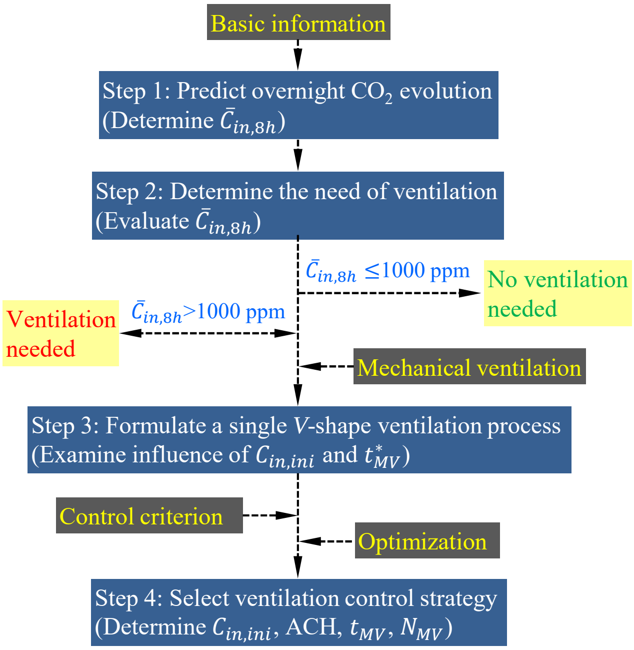

Figure 7: Basic framework for ventilation design of air-conditioned residential buildings.

Figure 6 presents the basic design and control parameters for ventilation design of air-conditioned residential buildings, while Figure 7 presents the framework for ventilation design (Ai and Mak, 2016b). Based on Figure 6 and Figure 7, the detailed design procedures are described as follows:

i. Collect the basic information of the target bedroom and predict the overnight evolution of indoor CO_2 concentration using Equation (6) under the condition without additional ventilation. The infiltration rate may be obtained through on-site measurements, numerical prediction or empirical estimation. As a result, the average indoor CO_2 concentration during a whole sleeping period of 8 hours ($\overline{C}_{in,8h}$) can be determined.

ii. Compare this calculated $\overline{C}_{in,8h}$ with the threshold recommended by the aforementioned IAQ standard, namely 1000 ppm. If $\overline{C}_{in,8h} \le 1000$ ppm, no ventilation is needed and then ventilation design stops. Such conditions occur when G_r / V is relatively small and $(ACH)_0$ is relatively large. If $\overline{C}_{in,8h} > 1000$ ppm, additional ventilation is needed to maintain an acceptable IAQ and then mechanical ventilation design starts.

iii. Formulate a single *V*-shape ventilation process, which is comprised of a short-term mechanical ventilation process and a follow-up CO_2 build-up process. A whole sleeping period of 8 hours consists of many such repeated single *V*-shape ventilation processes. A single *V*-shape ventilation process should meet the control criterion that the average CO_2 concentration during the ventilation period is less than but close to 1000 ppm. In this step, the influence of $C_{in,ini}$ and the normalized mechanical ventilation period t^*_{MV} $(= \text{ACH} \cdot t_{MV})$ is examined.

iv. Select the ventilation control strategy, namely select an appropriate single *V*-shape ventilation process. The selection should take into account two main aspects: energy saving ($\text{MIN}(t_{MV} \cdot N_{MV})$) and the feasibility of mechanical ventilation system (appropriate N_{MV}).

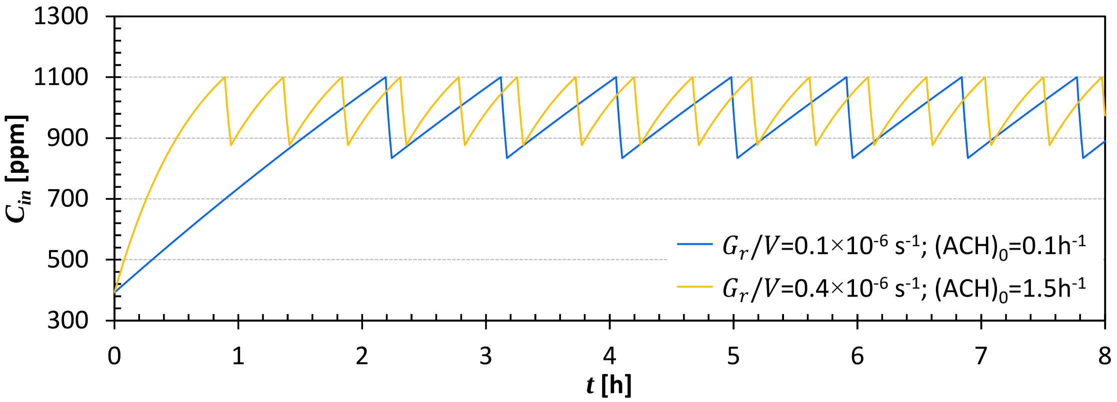

Figure 8: Two examples of the evolution of indoor CO_2 concentration over time during a sleeping period of 8 hours, when $t^*_{MV} = 0.5$.

3.3 Examples of controlled overnight indoor CO2 concentration

Figure 8 presents two examples of the evolution of indoor CO_2 concentration over time during a whole sleeping period of 8 hours, when ventilation control is performed. Two reasons lead to the phenomenon that a larger number of single ventilation period is required in a room with a greater G_r / V. First, a greater G_r / V shortens significantly the period of CO_2 build-up from outdoor concentration or end concentration of a ventilation period to the activation threshold 1100 ppm. Second, a same normalized mechanical ventilation period, e.g., here $t^*_{MV} = 0.5$, can lower the indoor CO_2 concentration to a smaller value in the case with a smaller G_r/V, which in turn helps to extend the time period taken to reach the next activation threshold.

4 CONCLUSIONS

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. Considering also its controllable advantage, the short-term mechanical ventilation strategy is recommended for ventilation of air-conditioned residential buildings. A general design framework and detailed design guidelines on short-term mechanical ventilation of air-conditioned residential buildings were then developed. A high efficient ventilation strategy is a short single ventilation period and a high ventilation frequency. In general, several to dozens of several-minute mechanical ventilation periods are needed to maintain an average indoor CO_2 concentration being less than 1000 ppm during a normal sleeping period of 8 hours.

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