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Short-term mechanical ventilation of air-conditioned residential buildings: A general design framework and guidelines

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Abstract: Ventilation is needed in air-conditioned residential buildings, particularly the bedrooms in nighttime sleeping periods, to maintain an acceptable indoor air quality. Our previous on-site measurements evaluating various ventilation strategies suggest that short-term mechanical ventilation is overall the most appropriate ventilation strategy for air-conditioned residential buildings. However, there is still no a general design framework of short-term mechanical ventilation strategy, which 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. This study for the first time develops such a design framework and then provides the detailed design guidelines. A whole sleeping period of 8 hours is 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 is 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. The outcomes of this study are presented in the form of figures and tables, with most parameters normalized, which are useful to assist a rapid ventilation design.

Keywords: Ventilation, room air conditioner, residential buildings, design framework, CO_2

Nomenclature

Symbols

ACH	air change per hour, [h^{-1}]
$(ACH)_0$	infiltration rate, [h^{-1}]
A_D	body surface area, [m^2]
C_{in}	indoor CO_2 concentration, [ppm]
$C_{in,i}$	indoor CO_2 concentration at the moment i, [ppm]
$C_{in,i+\Delta t}$	indoor CO_2 concentration at the moment $i+\Delta t$, [ppm]
$C_{in,ini}$	initial or start indoor CO_2 concentration, [ppm]
$C_{in,end}$	end indoor CO_2 concentration, [ppm]
C_{out}	outdoor CO_2 concentration, [ppm]
$\overline{C}_{in,8h}$	average indoor CO_2 concentration during a sleeping period of 8 hours, [ppm]
$\overline{C}_{in,t_d^*}$	average indoor CO_2 concentration during a single ventilation period, [ppm]

e	correction factor for Chinese people, [-]
G_r	human generation rate of CO_2, [m^3/s]
G_r/V	CO_2 generation rate per unit volume, [s^{-1}]
H	human height, [m]
M	metabolic rate, [W/m^2]
N_{MV}	number of single ventilation period, [-]
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, [-]
t	time, [h]
t_d	period of a single *V*-shape ventilation process, [h]
t_d^*	normalized period of a single *V*-shape ventilation process, [-]
t_{MV}^*	normalized mechanical ventilation period, [-]
t_{MV}	mechanical ventilation period, [-]
$t_{MV,8h}^*$	normalized total period of mechanical ventilation during a sleeping period of 8 hours, [-]
Δt	time interval, [s]
V	volume of the room, [m^3]
W	human mass, [Kg]

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 [1-5]. 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 these regions like Hong Kong [1]. However, one deficiency of such room air conditioners is the provision of no or very little outdoor air. Many on-site measurements [3, 5-9] 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 [10]. In connection with insufficient ventilation, excessive CO_2 concentrations (usually > 1000 ppm) in air-conditioned residential buildings were often reported [2-5, 7].

A strong relationship between insufficient ventilation and negative health effects has been widely observed in office buildings [5, 11-18]. Particularly, Seppanen et al. [15] reported that the increased indoor air quality (IAQ) issues and health symptoms are statistically significantly related to a ventilation rate below 10 l/s/p, while increasing ventilation rate up to 20-30 l/s/p can effectively remedy these health symptoms [17-18]. In residential buildings, a risk of allergic manifestations among children in a Nordic climate was reduced when ventilation rates exceed 0.5 h^{-1} [18]. A recent study [19] reported that an improved bedroom air quality was associated with an improved sleep quality and then a better next-day performance in terms of less sleepy, easy concentration and improved logical thinking. Moreover, some evidences [2, 13-14] show that sick building syndromes (SBS) are more likely to occur in air-conditioned residential buildings than in naturally and mechanically ventilated buildings, which is basically due to insufficient ventilation (usually indicated by excessive CO_2 concentration levels) in air-conditioned buildings.

CO_2 at ordinary concentrations occurred in typical built environments is generally not regarded as a harmful pollutant. There is no physiological evidence that CO_2 has any metabolic influence at a concentration below 8500 ppm. The time-averaged safety thresholds for long-term (40 hours a week) and short-term (15 minutes) exposure are 5000 ppm and 30000 ppm, respectively [20]. However, high CO_2 concentrations provide an indication of inadequate ventilation rate to dilute or remove other possible harmful indoor pollutants. Therefore, indoor CO_2 concentration is commonly used as a surrogate of indoor concentration of human generated bioeffluents and an indicator of the indoor ventilation levels [3, 4, 15, 21-27]. ASHRAE Standard 62-1989 [28] recommends that the indoor CO_2 concentration levels should be less than 1000 ppm, which is nearly equivalent to an outdoor air ventilation rate of 7.5 l/s/p. More recent series of ASHRAE Standards 62, e.g., [10, 29], recommend an indoor-outdoor CO_2 concentration difference being less than 700 ppm.

Our previous on-site measurements [9] evaluated three types of ventilation strategies for air-conditioned residential buildings, suggesting that the short-term (several minutes) mechanical ventilation is the most appropriate ventilation strategy. However, on-site measurements were conducted in a specific measurement site under a certain type of local meteorological condition. Particularly, a specific measurement site is associated with specific CO_2 generation rate, net room volume, infiltration rate and mechanical ventilation rate, which could be very different in different buildings and in different climatic regions. Therefore, a general design framework is strongly needed 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. As a further work of the on-site measurements, this study develops such a general design framework, and then provides the detailed design guidelines, on short-term mechanical ventilation of air-conditioned residential buildings. The on-site measurements and findings are briefly described in Section 2. The design basis, framework, and procedures are presented in Section 3. The important aspects of the design framework are investigated and detailed design guidelines are presented in Section 4. Discussion is made in Section 5. Section 6 summarizes this paper.

2. On-site evaluation of ventilation strategies

The on-site measurements [9] were conducted by the authors in an air-conditioned residential bedroom in Hong Kong in September 2015, when the outdoor temperature ranged from 27 °C and 32 °C. During the measurements, the room (8.6 m^2 in net floor area) was occupied with two adults. Two windows were located on different facades of the room, which were 0.33 m^2 and 0.24 m^2 in area, respectively. An exhaust fan mounted on the upper part of a facade provided a nominal flow rate of 520 m^3/h. The on-site measurements evaluated 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). The indoor and outdoor CO_2 concentration, 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.

When no ventilation was provided, excessive CO_2 concentration and insufficient ventilation rate are found, indicating that additional ventilation is usually needed in air-conditioned residential buildings. Overnight natural ventilation maintains an acceptable indoor CO_2 level at the expense of excessive energy consumption and degraded 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. The influence of short-term mechanical ventilation on the indoor thermal environment is negligible. Overall, the short-term mechanical ventilation strategy is recommended for ventilation of air-conditioned residential buildings.

3. Design basis, framework and procedures

3.1 Mass conservation and concentration evolution

Indoor CO_2 concentration is the core parameter throughout the ventilation design, which is used to determine the ventilation need and predict the required ventilation period and frequency. 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.

The CO_2 generation rate per person varies with age, activity and diet [10, 30]. The empirical equation for metabolic rate given in ASHRAE Handbook [30] was widely used to estimate CO_2 generation rate of human beings [31-33].

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

where M is the metabolic rate, RQ the 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), Q_{O_2} the volumetric rate of oxygen consumption, and A_D the body surface area. Based on chamber experiments, Qi et al. [33] proposed correction factors, namely 0.75 and 0.85, for Chinese females and males, respectively. Substituting an empirical equation of human body surface area ($A_D = 0.202H^{0.725}W^{0.425}$, [34]), the Equation (1) can be transformed into the following form:

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

where Q_{CO_2} is the volumetric rate of CO_2 generation, e the correction factor for Chinese people, H human height and W human mass.

A normal bedroom with closed door (as shown in Figure 1) considered in the present study can be treated as a single zone [31, 35-37], where the indoor CO_2 concentration is governed by the indoor CO_2 generation rate, outdoor CO_2 concentration, ventilation rate and net room volume. Based on the principle of mass conservation, the average CO_2 concentration in a well-mixed single zone can be expressed through the following equation:

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

where V is the volume of the room, C_{in} the indoor CO_2 concentration, C_{out} the outdoor CO_2 concentration, t the time, Q the ventilation rate, G_r the human generation rate of CO_2. Note that G_r is the total generation rate of all occupants, which is different from Q_{CO_2} for a single occupant. 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:

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

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

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

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 (5) is very important, which is the basis of the ventilation design of air-conditioned residential buildings.

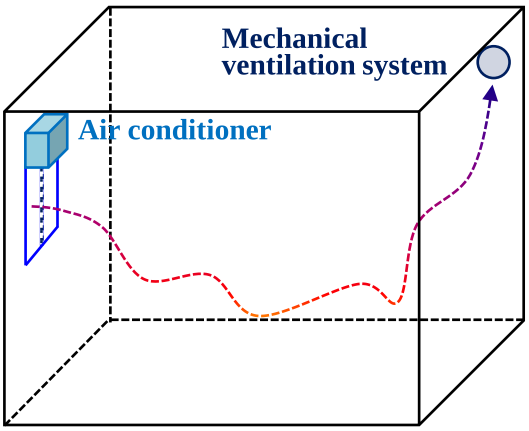


Figure 1 A general bedroom with an air conditioner, a window, and a mechanical ventilation system (simply an exhaust fan).

Basic information	Mechanical ventilation	Control criterion	Optimization
❖CO_2 generation rate per unit volume (G_r/V) ❖Infiltration rate ($(\mathrm{ACH})_0$) ❖Outdoor CO_2 concentration (C_{out})	❖Start CO_2 concentration ($C_{in,ini}$) ❖Ventilation rate (Q or ACH) ❖Single ventilation period (t_{MV}) ❖Number of ventilation period (N_{MV})	❖$\bar{C}_{in,8h} \leq 1000$ ppm ❖$\bar{C}_{in,8h}$ close to 1000 ppm	❖MIN ($t_{MV} \cdot N_{MV}$) ❖Feasibility (N_{MV})

Figure 2 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 CO_2 concentration predicted using Equation (5), 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 CO_2 generation rate (G_r) need to be redetermined. It was reported that the CO_2 generation rate of human beings during sleeping condition is lower than non-sleeping conditions [3, 30].

Figure 2 presents the basic design and control parameters for ventilation design of air-conditioned residential buildings, while Figure 3 presents the framework for ventilation design. Based on Figure 2 and Figure 3, 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 (5) 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 [28], namely 1000 ppm. If $\overline{C}_{in,8h} \leq 1000$ 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. Note that the ASHRAE Standard 62-1989 [28] '*indoor CO_2 concentration levels should be less than 1000 ppm*' is taken as an example in this study to elaborate the design framework. If one intends to adopt a new control criterion in terms of indoor CO_2 concentration level, it will be convenient to change the control criterion of the design framework.

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}^* ($= \mathrm{ACH} \cdot t_{MV}$) 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 (MIN($t_{MV} \cdot N_{MV}$)) and the feasibility of mechanical ventilation system (appropriate N_{MV}).

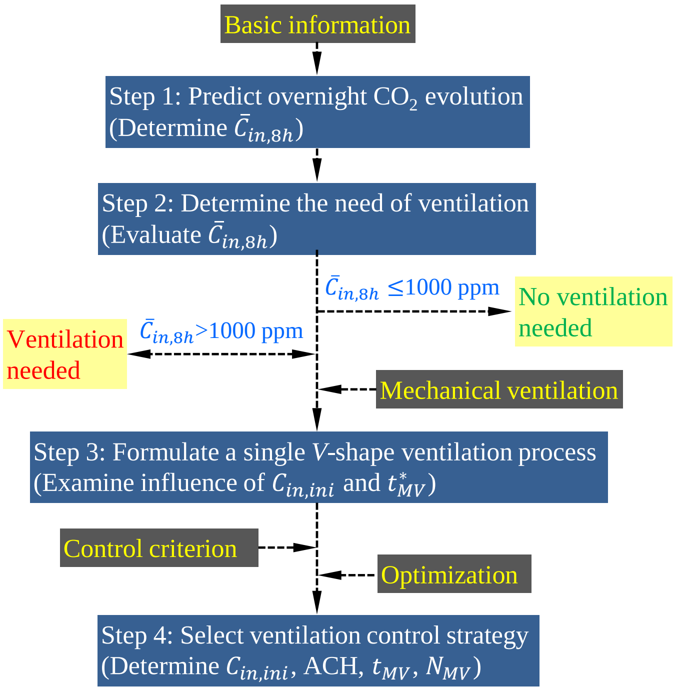


Figure 3 Basic framework for ventilation design of air-conditioned residential buildings.

4. Ventilation design

This section investigates in detail the important aspects of the general design framework developed in Section 3. Based on a wide range of G_r/V and $(ACH)_0$ values that commonly occur in practice, the figures and tables generated in this section can be used directly to assist a rapid ventilation design. The objective of this section is thus to provide detailed design guidelines on short-term mechanical ventilation of air-conditioned residential buildings.

4.1 Overnight CO_2 build-up

This section investigates the indoor CO_2 build-up over time during a normal sleeping period of 8 hours, when there is no additional ventilation. The objective of this section is to provide a general view on the indoor CO_2 evolution over time and to determine the overnight average CO_2 concentration, under various combinations of G_r/V and $(ACH)_0$. Table 1 provides examples of the bedroom dimensions corresponding to typical G_r/V values. Given that the G_r/V values being less than 0.1 × 10^{-6} s^{-1} and larger than 0.4 × 10^{-6} s^{-1} should be extremely rare in practice, this paper considers only G_r/V values ranging from 0.1 to 0.4 × 10^{-6} s^{-1}. CO_2 evolutions are predicted based on the assumption that occupants fall to sleep immediately after going to bedroom. This assumption would underestimate the CO_2 concentration at the beginning of sleep, given that the occupants do not fall to sleep immediately. However, this assumption would not affect the results and analyses in later sections.

Table 1 Examples of net floor areas (m^2) corresponding to various G_r/V values under two conditions: (a) a Chinese male (1.75 m in height and 65 Kg in weight) sleeps in a bedroom with 2.7 m in floor height and (b) a Chinese couple (male: 1.75 m in height and 65 Kg in weight, female: 1.6 m in height and 55 Kg in weight) sleep in a bedroom with 2.7 m in floor height.

G_r/V [×10^{-6} s^{-1}]	0.05	0.1	0.2	0.3	0.4	0.45
A male	18.8	9.4	4.7	3.1	2.4	2.1
A couple	33.3	16.7	8.3	5.6	4.2	3.7

Figure 4 presents the evolutions of indoor CO_2 concentration over time and the overnight average CO_2 concentrations as a function of G_r/V and $(ACH)_0$. Note that, throughout this study, the outdoor CO_2 concentration, C_{out}, is assumed to be 392 ppm, which is the overnight average concentration during our on-site measurements in Hong Kong [9]. The influence of the outdoor CO_2 concentration on the design parameters is evaluated and described in Section 5. In general, the indoor CO_2 concentration is strongly dependent on both G_r/V and $(ACH)_0$. A lower G_r/V helps to extend the time to reach 1000 ppm. For a specific G_r/V, there is a threshold infiltration rate $(ACH)_0$, above which the overnight average CO_2 concentration would not exceed 1000 ppm, indicating that no additional ventilation is needed. This threshold $(ACH)_0$ value increases evidently with the increase of G_r/V. Note that the previous measurements [9] for the case with no additional ventilation are generally in agreement with the predictions in Figure 4.

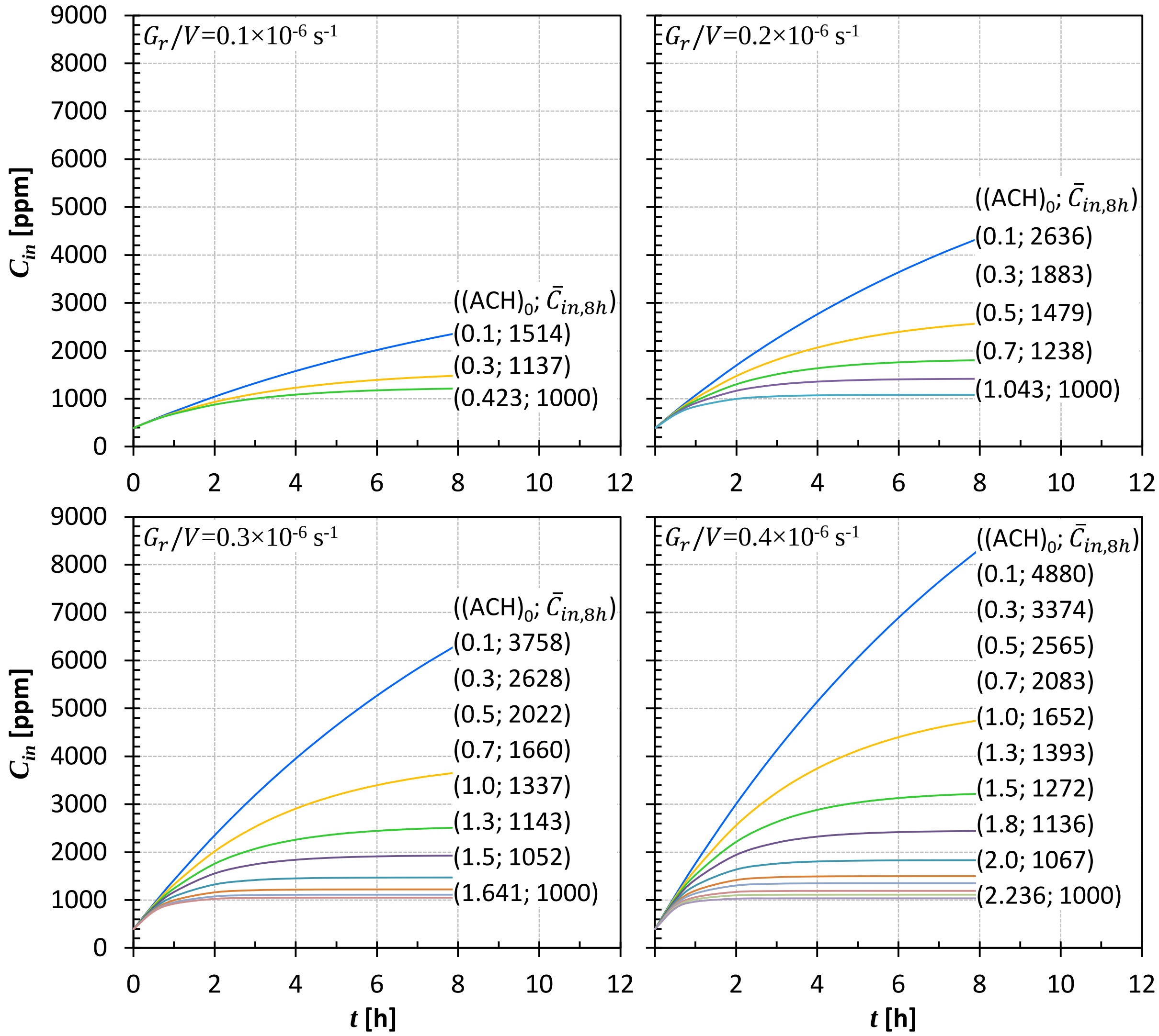


Figure 4 Build-up of indoor CO_2 concentration over a period of 8 hours as a function of G_r/V and $(ACH)_0$ when the initial indoor concentration is equal to the outdoor concentration, namely $C_{in,ini}$ = 392 ppm.

4.2 Ventilation need

The ventilation need can be determined by comparing the overnight average indoor CO_2 concentration ($\overline{C}_{in,8h}$) to the control target, namely 1000 ppm. $\overline{C}_{in,8h}$ being less than or equal to 1000 ppm indicates that no additional ventilation is needed. On contrary, ventilation is necessary to maintain an acceptable IAQ.

Within the first hour of sleep (see Figure 4), the indoor CO_2 concentration increases from the outdoor concentration to a certain value. The average CO_2 concentration during the first hour for most scenarios is less than 1000 ppm, although the CO_2 concentration at t = 1 h exceeds 1000 ppm under relatively high G_r/V values. In addition, the sleeping condition during the first hour is not stable [9], as a bedroom could be occupied before the occupants go to bed and occupants could not fall to sleep immediately after going to bed. Therefore, the determination of the ventilation need is based on the average CO_2 concentration of the latter 7 hours, namely from t = 1 h to 8 h, starting from several typical initial CO_2 concentrations, namely 1100, 1300, 1500, and 2000 ppm. Note that, excluding the first hour data, these 7-hour average CO_2 concentrations would overestimate the 8-

hour average concentrations for low G_r/V (≤ 0.2 × 10^{-6} s^{-1}) scenarios, where the indoor CO_2 concentrations at t = 1 h do not reach these assumed initial concentrations (see Figure 4). Such an overestimation would suggest a higher infiltration rate $(ACH)_0$, leading to a better IAQ.

Figure 5 presents the relationship between G_r/V and $(ACH)_0$, when the overnight average indoor CO_2 concentrations ($\overline{C}_{in,8h}$) are equal to 900, 1000 and 1100 ppm. The line $\overline{C}_{in,8h}$ = 1000 ppm indicates the threshold of ventilation, while other two lines are plotted for reference. In this figure, if a point determined by a certain pair of G_r/V and $(ACH)_0$ is located above the line $\overline{C}_{in,8h}$ = 1000 ppm, the overnight average CO_2 concentration is less than 1000 ppm and thus no additional ventilation is needed. On contrary, a point located below the line means a need for ventilation. In general, these charts help to determine rapidly whether additional ventilation is needed for a specific case.

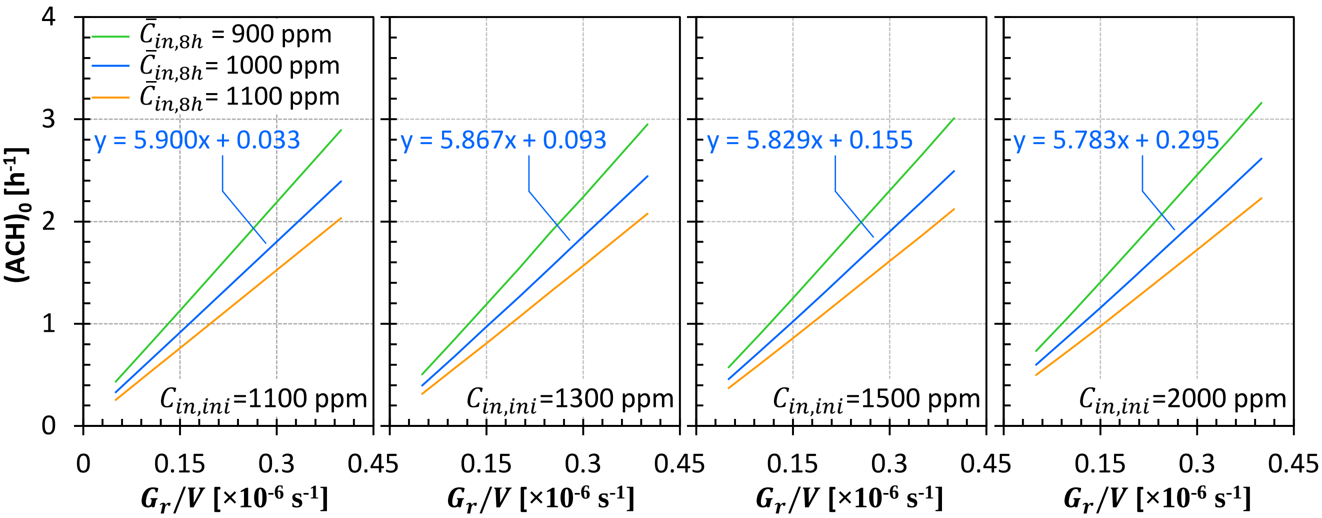


Figure 5 Overnight (last 7 hours) average indoor CO_2 concentration as a function of G_r/V and $(ACH)_0$.

4.3 A single *V*-shape ventilation process

Figure 6 presents an example of the evolution of indoor CO_2 concentration during a short-term mechanical ventilation period and its follow-up CO_2 build-up until reaching the start concentration of the next ventilation. An overnight sleeping period is comprised of many such repeated *V*-shape ventilation and CO_2 build-up processes. An investigation of ventilation in an overnight sleeping period can be simplified to the investigation of a single *V*-shape process, which is defined as a single *V*-shape ventilation process. Obviously, optimization of a single *V*-shape ventilation process means the optimization of the overnight ventilation. Here the normalized period for the short-term mechanical ventilation is defined as:

$$t_{MV}^* = \mathrm{ACH} \cdot t_{MV} \tag{6}$$

where the t_{MV} is the period of short-term mechanical ventilation. The normalized ventilation period t_{MV}^* indicates the degree of ventilation. For instance, t_{MV}^* = 1 means a full replacement of indoor air, regardless of the ACH provided by the mechanical ventilation system and the period of mechanical ventilation t_{MV}. In this study, t_{MV}^* values ranging from 0.5 to 1.0 are investigated. Similarly, the normalized period for a single *V*-shape ventilation process is defined as:

$$t_d^* = \mathrm{ACH} \cdot t_d \tag{7}$$

where the t_d is the period of a single *V*-shape ventilation process. The t_d^* is an important parameter, which determines the ventilation frequency and in turn the number of single ventilation period required for a whole sleeping period. The average indoor CO_2 concentration during a single ventilation period is expressed as $\overline{C}_{in,t_d^*}$.

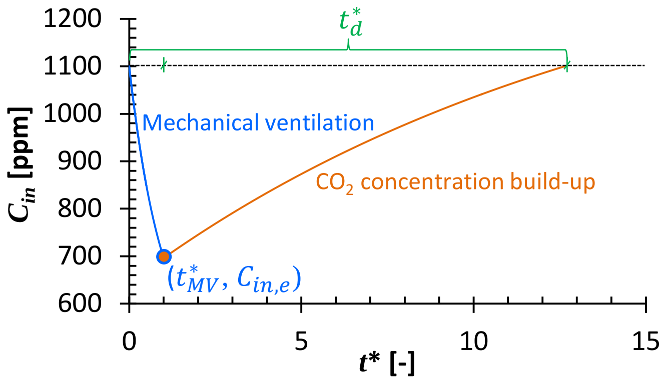


Figure 6 A whole process of a short-term mechanical ventilation and a follow-up CO_2 build-up until reaching start concentration of ventilation when $C_{in,ini}$ = 1100 ppm, $t_{MV}^* = 1$, $(ACH)_0$ = 0.7 h^{-1} and the indoor CO_2 generation rate G_r / V = 0.2 × 10^{-6} s^{-1}, where $C_{in,e}$ is the end CO_2 concentration of ventilation.

4.4 Ventilation control criterion

The criterion of appropriate ventilation is defined in this study as that the average CO_2 concentration during a single *V*-shape ventilation process ($\overline{C}_{in,t_d^*}$) is less than, but close to, 1000 ppm. $\overline{C}_{in,t_d^*}$ being less than 1000 ppm is a must, while $\overline{C}_{in,t_d^*}$ being close to 1000 ppm means saving electrical energy of the mechanical ventilation system.

To facilitate the explanation of the ventilation control criterion and the occurrence of other possible special situations, Figure 7 presents the single *V*-shape ventilation processes for a specific case under t_{MV}^* = 0.5 and t_{MV}^* = 1.0. It can be seen that, compared to a short normalized ventilation period (t_{MV}^* = 0.5), a relatively long normalized ventilation period (t_{MV}^* = 1.0) results in a lower indoor CO_2 concentration at the end of mechanical ventilation, which extends the single ventilation period (t_d^*) and decreases the average CO_2 concentration during the ventilation period ($\overline{C}_{in,t_d^*}$). This figure also shows two special situations, marked in red. The first one is that the $\overline{C}_{in,t_d^*}$ is larger than 1000 ppm when $(ACH)_0$ exceeds 0.9 h^{-1} under t_{MV}^* = 0.5. The second one is that the C_{in} would never increase to 1100 ppm again after one mechanical ventilation period when $(ACH)_0$ exceeds 1.0 h^{-1} under t_{MV}^* = 1.0. Here the $\overline{C}_{in,t_d^*}$ happens to be 1000 ppm. A similar concentration curve (namely never reaching 1100 ppm again) could correspond to $\overline{C}_{in,t_d^*}$ being larger than 1000 ppm, as found in some other cases. Regardless of aforementioned situations, the appropriateness of a ventilation scenario is determined by the ventilation control criterion defined at the beginning of this section.

It is important to find that the ventilation efficiency of a short normalized ventilation period (t_{MV}^* = 0.5) is higher than a long normalized ventilation period (t_{MV}^* = 1.0) in terms of the decreasing rate of CO_2 concentration. The indoor CO_2 concentration decreases by 252 ppm after a normalized ventilation period of t^*_{MV} = 0.5; this is only 152 ppm after a, further, same normalized ventilation period. This reduced efficiency in lowering CO_2 concentration over time can be attributed to a reduced indoor-outdoor CO_2 concentration difference along with ventilation. In addition, Figure 7 shows that $\overline{C}_{in,t^*_d}$ values during a shorter ventilation period are closer to 1000 ppm than those during a longer ventilation period, suggesting that a shorter ventilation period is more energy-efficient. However, a shorter single ventilation period means a higher ventilation frequency, which should also be a factor to consider in the selection of an appropriate single ventilation period. This is further explained in Section 4.7.

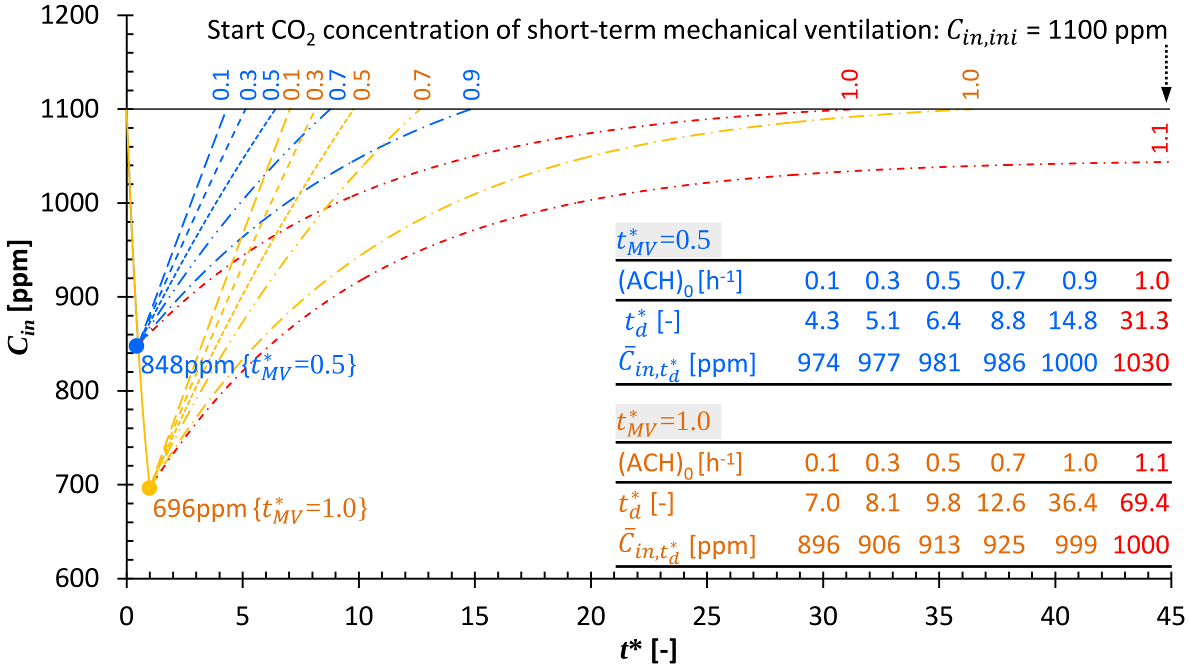
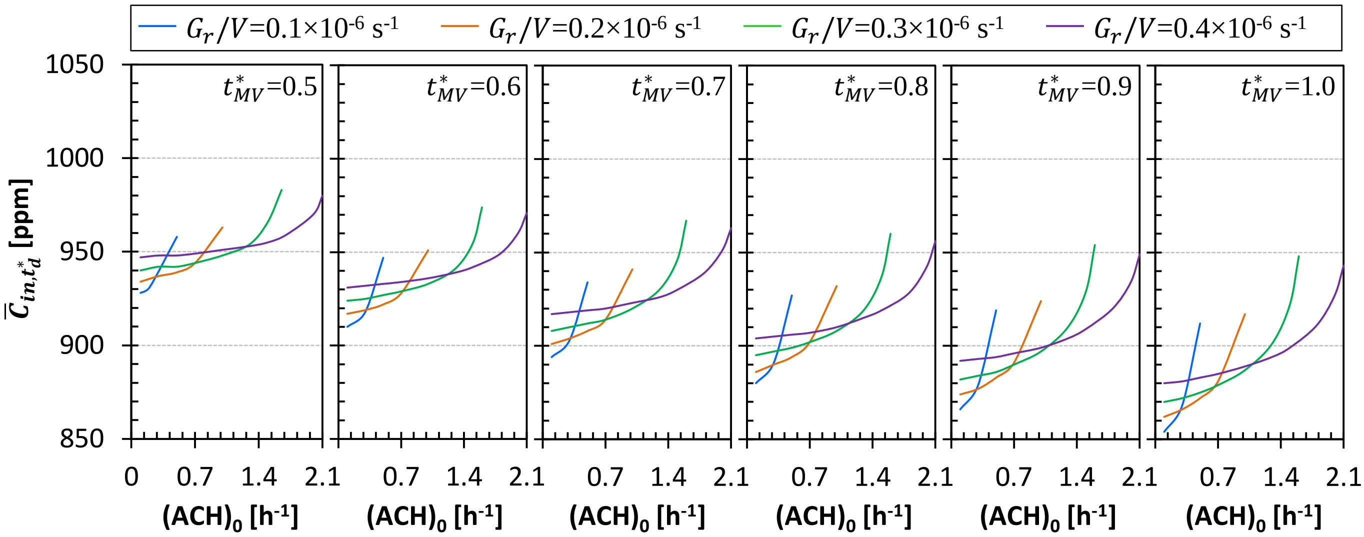


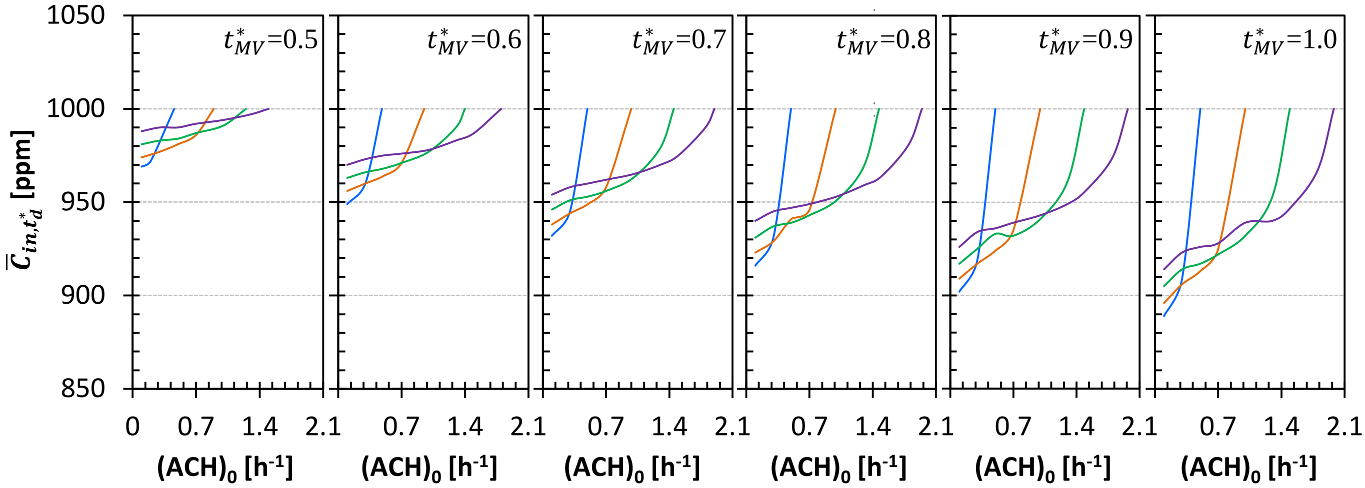
Figure 7 Single *V*-shape ventilation processes when the indoor CO_2 generation rate G_r / V = 0.2 × 10^{-6} s^{-1}; the two table summarize the t^*_d and the $\overline{C}_{in,t^*_d}$ of these processes, respectively.

4.5 Start CO_2 concentration of ventilation

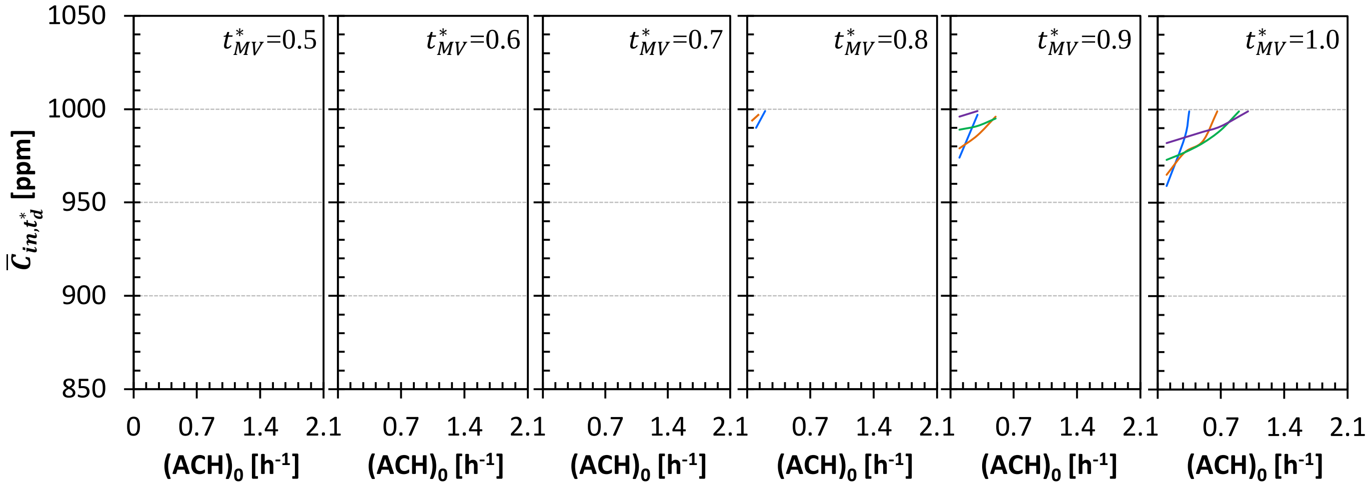
The start indoor CO_2 concentration that activates the short-term mechanical ventilation is an important parameter to determine. A higher start CO_2 concentration provides a better ventilation efficiency, which, however, extends the single ventilation period and thus influences the $\overline{C}_{in,t^*_d}$ value. Based on the ventilation control criterion, this section explores an appropriate start CO_2 concentration ($C_{in,ini}$) for ventilation. Figure 8 presents the $\overline{C}_{in,t^*_d}$ values for three $C_{in,ini}$ values, as a function of $(ACH)_0$ and t^*_{MV}. Note that cases leading to the situation of $\overline{C}_{in,t^*_d}$ > 1000 ppm are excluded. According to the ventilation control criterion defined in Section 4.4, the scenario of $C_{in,ini}$ = 1100 ppm has the overall best performance, as the resultant $C_{in,ini}$ values are closer to 1000 ppm. The scenarios of $C_{in,ini}$ = 1050 and 1200 ppm show some advantages in relatively shallow (t^*_{MV} = 0.5) and deep (t^*_{MV} = 1.0) ventilation, respectively, which can be complements for $C_{in,ini}$ = 1100 ppm. The scenario of $C_{in,ini}$ = 1100 ppm is selected in the later sections to conduct further optimizations of the ventilation strategy.



(a) $C_{in,ini}$ = 1050 ppm



(b) $C_{in,ini}$ = 1100 ppm



(c) $C_{in,ini}$ = 1200 ppm

Figure 8 Average indoor CO_2 concentration during a single *V*-shape ventilation process ($\overline{C}_{in,t_d^*}$) as a function of indoor infiltration rate ($(ACH)_0$) and normalized time period of mechanical ventilation (t_{MV}^*): (a) $C_{in,ini}$ = 1050 ppm, (b) $C_{in,ini}$ = 1100 ppm and (c) $C_{in,ini}$ = 1200 ppm.

Based on $C_{in,ini}$ = 1100 ppm, the indoor CO_2 concentrations at the end of mechanical ventilation ($C_{in,end}$) as a function of mechanical ventilation period (t_{MV}^*) and indoor CO_2 generation rate per unit volume (G_r/V) can be determined (see Figure 9). On average, the short normalized ventilation period (t_{MV}^* = 0.5) decreases the indoor CO_2 concentration from 1100 ppm to approximately 850 ppm, while the long normalized ventilation period (t_{MV}^* = 1.0) decreases it further to 700 ppm.

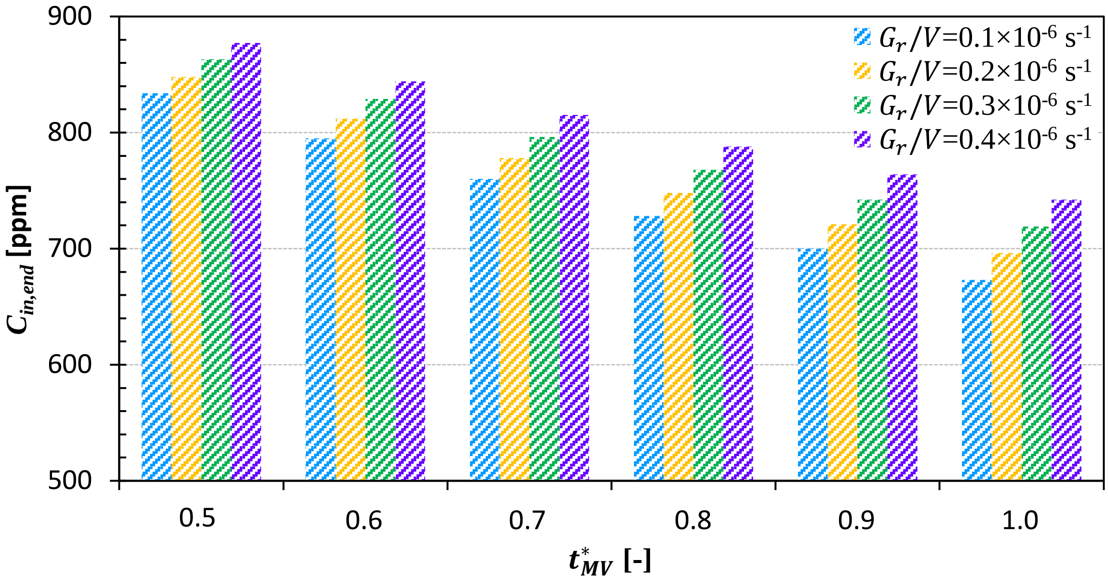


Figure 9 Indoor CO_2 concentration at the end of short-term mechanical ventilation as a function of ventilation period (t_{MV}^*) and indoor CO_2 generation rate (G_r/V).

4.6 Single ventilation period

Based on the ventilation control criterion stated in Section 4.4 and the $C_{in,ini}$ value equal to 1100 ppm suggested in Section 4.5, this section calculates and summarizes the normalized single ventilation period (t_d^*) under various normalized mechanical ventilation periods (t_{MV}^*) as a function of G_r/V and $(ACH)_0$. Note that the single ventilation period corresponds to the ventilation period of a single *V*-shape ventilation process. Figure 10 presents the results, where the areas above the dashed lines represent $\overline{C}_{in,t_d^*}$ exceeding 1000 ppm. The charts in Figure 10 allow a quick identification of single ventilation period based on known G_r/V and $(ACH)_0$. For those G_r/V values that do not appear on the charts, the interpolation method can be used to determine the t_d^* values. The results presented in Figure 10 are very important, which are the basis of further development of ventilation control strategies.

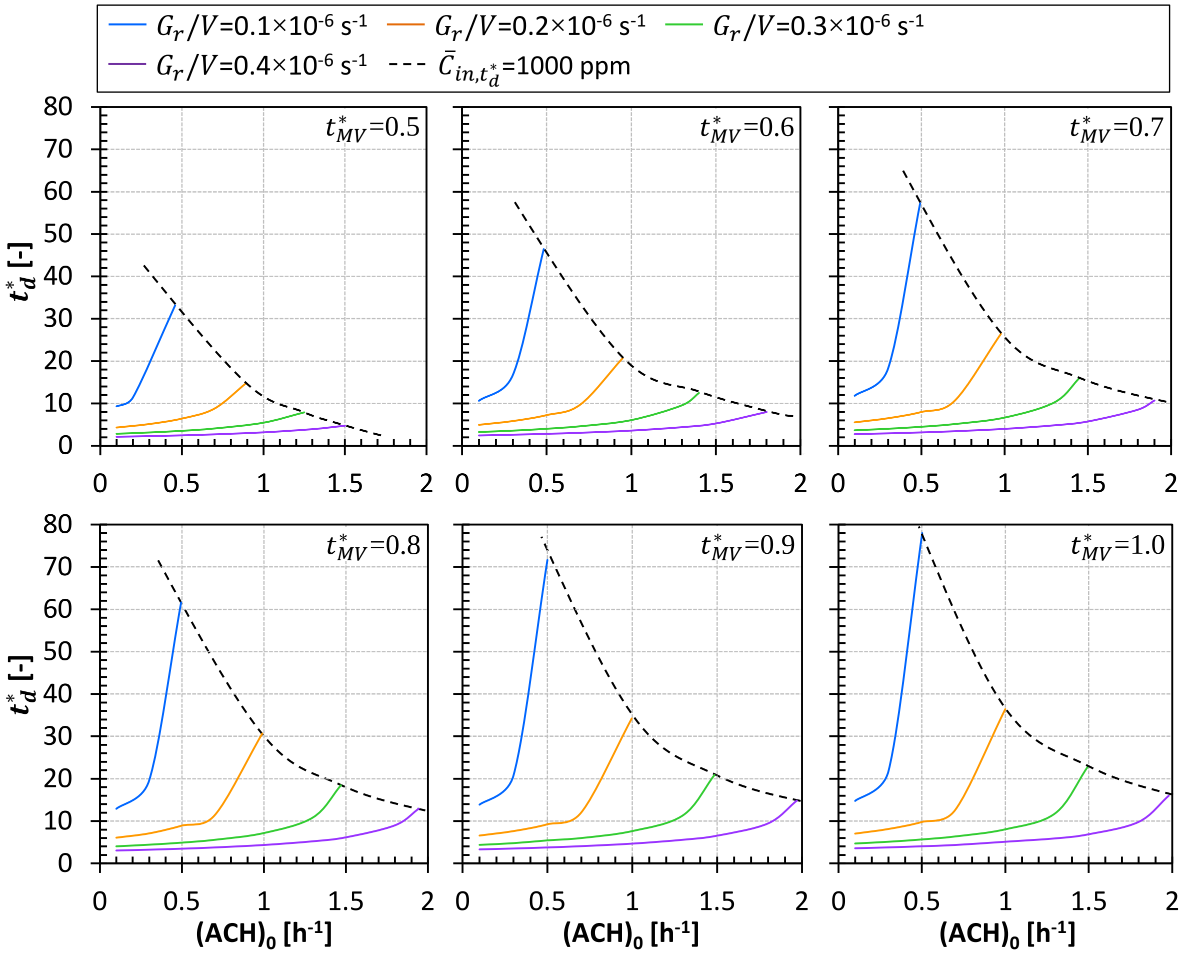


Figure 10 Normalized single ventilation period (t_d^*) as a function of indoor CO_2 generation rate (G_r/V) and infiltration rate ((ACH)$_0$), when $C_{in,ini}$ = 1100 ppm.

4.7 Ventilation frequency and total ventilation period

Based on the normalized single ventilation period (t_d^*), the required number of single ventilation period during a sleeping period of 7 hours (plus the first 1 hour equal to a whole period of 8 hours, as explained in Section 4.2) can be determined by:

$$N_{MV} = \frac{7 \cdot \mathrm{ACH}}{t_d^*} \tag{8}$$

Then, the normalized total period of mechanical ventilation during a whole sleeping period of 8 hours can be obtained by:

$$t_{MV,8h}^* = t_{MV}^* \cdot N_{MV} \tag{9}$$

N_{MV} and $t_{MV,8h}^*$ are two important parameters of a ventilation strategy, which indicate directly two important aspects of a ventilation strategy, namely ventilation frequency and energy need. Table 2 summarizes N_{MV} values for various conditions and Table 3 summarizes $t_{MV,8h}^*$ values. It can be seen that several to dozens of short-term mechanical ventilation periods are required to maintain an average indoor CO_2 concentration being less than 1000 ppm during a normal sleeping period of 8 hours. In particular, N_{MV} decreases with the increase of t_{MV}^*, whereas $t_{MV,8h}^*$ increases with the increase of t_{MV}^*. This is an important finding. For specific G_r/V and (ACH)$_0$, a shorter normalized mechanical ventilation period (t^*_{MV}) means a larger number of single ventilation period (N_{MV}) required, but it also means a shorter normalized total period of mechanical ventilation ($t^*_{MV,8h}$) required. This again indicates that a shorter normalized ventilation period holds higher ventilation efficiency in terms of lowering CO_2 concentration.

Considering that a mechanical ventilation system provides an ACH value of 10 h^{-1}, the highest $t^*_{MV,8h}$ (equal to 20) corresponds to a total mechanical ventilation period of 2 hours. The $t^*_{MV,8h}$ = 20 is a result of G_r/V = 0.4 × 10^{-6} s^{-1} and $(ACH)_0$ = 0.1, which is equivalent approximately to the situation that one Chinese male (1.75 m in height and 65 Kg in weight) sleeps in a bedroom with a net floor area of 2.4 m^2 or two in 4.7 m^2 (see Table 1). Moreover, all door and windows are closed, and the room has a very excellent envelope air tightness, namely $(ACH)_0$ = 0.1. This situation should be relatively rare in practice. If increasing the ACH to 20 h^{-1}, the median $t^*_{MV,8h}$ value (equal to 10.2) of all $t^*_{MV,8h}$ values listed in Table 3 corresponds to a total mechanical ventilation period of 0.51 hours, which is 6.4% of a sleeping period of 8 hours.

The selection of an appropriate ventilation strategy should consider both ventilation efficiency and feasibility of mechanical ventilation control. A ventilation strategy with a shorter ventilation period (t^*_{MV}) holds higher ventilation efficiency at the expense of more frequent mechanical ventilation, namely more frequent start and stop of ventilation system. This study does not suggest the selection of ventilation strategy, which can be accomplished by ventilation designers based on practical conditions. If the ventilation efficiency is the primary consideration, the highest N_{MV} should be selected. If the highly frequent start and stop of ventilation system cause problems, a compromised N_{MV} should be selected.

Table 2 The number of single short-term mechanical ventilation period (N_{MV}) required to maintain an average indoor CO_2 concentration ($\overline{C}_{in,8h}$) being less than 1000 ppm during a normal sleeping period of 8 hours as a function of G_r/V, $(ACH)_0$ and t^*_{MV}.

G_r/V [× 10^{-6} s^{-1}]	$(ACH)_0$	$t^*_{MV}=0.5$	$t^*_{MV}=0.6$	$t^*_{MV}=0.7$	$t^*_{MV}=0.8$	$t^*_{MV}=0.9$	$t^*_{MV}=1.0$
0.1	0.1	8	7	6	6	5	5
	0.3	5	5	4	4	4	4
0.2	0.1	17	15	13	12	11	10
	0.3	14	12	11	10	10	9
	0.5	11	10	9	8	8	8
	0.7	8	8	7	7	6	6
0.3	0.1	25	22	20	18	16	15
	0.3	23	20	18	16	15	14
	0.5	20	18	16	15	13	13
	0.7	18	16	14	13	12	11
	1.0	13	12	11	10	10	9
0.4	0.1	33	29	26	23	22	20
	0.3	31	27	24	22	20	19
	0.5	29	25	23	21	19	18
	0.7	26	23	21	19	18	17
	1.0	22	20	18	17	15	14

	1.3	18	16	15	14	13	12
	1.5	15	14	13	12	11	11

Table 3 The normalized total period of mechanical ventilation ($t^*_{MV,8h}$) required to maintain an average indoor CO_2 concentration being less than 1000 ppm throughout a normal sleeping period of 8 hours as a function of G_r/V, $(ACH)_0$ and t^*_{MV}.

G_r/V [× 10^{-6} s^{-1}]	$(ACH)_0$	$t^*_{MV}=0.5$	$t^*_{MV}=0.6$	$t^*_{MV}=0.7$	$t^*_{MV}=0.8$	$t^*_{MV}=0.9$	$t^*_{MV}=1.0$
0.1	0.1	4.0	4.2	4.2	4.8	4.5	5.0
	0.3	2.5	3.0	2.8	3.2	3.6	4.0
0.2	0.1	8.5	9.0	9.1	9.6	9.9	10.0
	0.3	7.0	7.2	7.7	8.0	9.0	9.0
	0.5	5.5	6.0	6.3	6.4	7.2	8.0
	0.7	4.0	4.8	4.9	5.6	5.4	6.0
0.3	0.1	12.5	13.2	14.0	14.4	14.4	15.0
	0.3	11.5	12.0	12.6	12.8	13.5	14.0
	0.5	10.0	10.8	11.2	12.0	11.7	13.0
	0.7	9.0	9.6	9.8	10.4	10.8	11.0
	1.0	6.5	7.2	7.7	8.0	9.0	9.0
0.4	0.1	16.5	17.4	18.2	18.4	19.8	20.0
	0.3	15.5	16.2	16.8	17.6	18.0	19.0
	0.5	14.5	15.0	16.1	16.8	17.1	18.0
	0.7	13.0	13.8	14.7	15.2	16.2	17.0
	1.0	11.0	12.0	12.6	13.6	13.5	14.0
	1.3	9.0	9.6	10.5	11.2	11.7	12.0
	1.5	7.5	8.4	9.1	9.6	9.9	11.0

4.8 Examples of controlled overnight indoor CO_2 concentration

Figure 11 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.

These examples are also used to verify the accuracy of the ventilation frequency presented in Section 4.7. Note that, in Section 4.7, the ventilation frequency is calculated based on the last 7 hours of a whole sleeping period of 8 hours (see also Section 4.2). The examples given in this section provide the evolution of indoor CO_2 concentration in a whole sleeping period of 8 hours with a start level equal to the outdoor concentration. The numbers of mechanical ventilation period required to cover the 8-hours period given in Figure 11 are 7 and 15 for the two specific cases, which correspond respectively to 8 and 15 in Table 2. This comparison shows that the 7-hour method used in this paper slightly overestimates the ventilation frequency for cases with relatively low G_r/V values, while it is accurate for cases with high G_r/V values. Overall, the 7-hour method and the resultant predictions are reasonably accurate, and the design method and the results presented in this paper can be used for ventilation design.

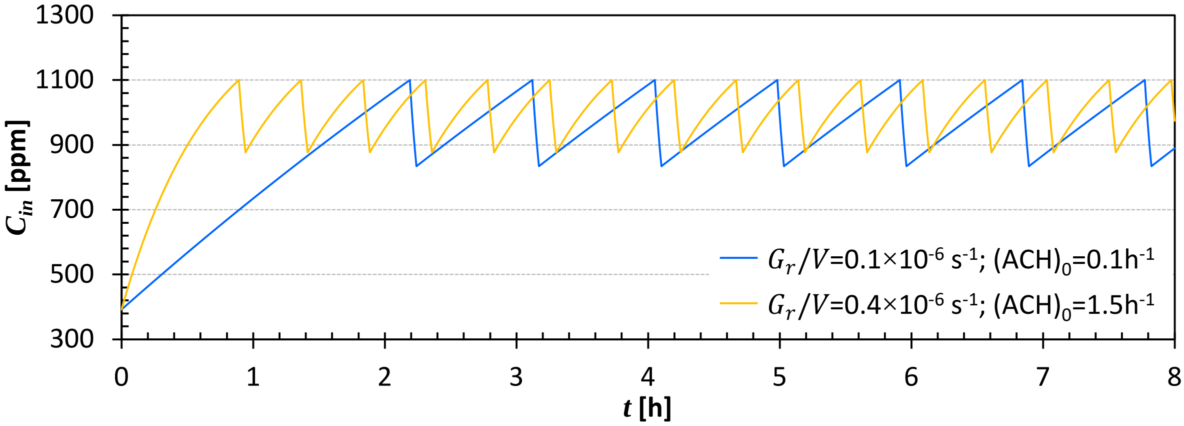


Figure 11 Two examples of the evolution of indoor CO_2 concentration over time during a sleeping period of 8 hours, when t^*_{MV} = 0.5.

5. Discussion

Throughout the ventilation design presented in this paper, the outdoor CO_2 concentration is specified as 392 ppm, which is the measured overnight average concentration during our previous on-site measurements conducted in Hong Kong. The outdoor CO_2 concentration in urban areas normally varies from 350 to 400 ppm, being relatively high in areas with dense industrial and traffic exhausts. Taking the scenario of G_r/V = 0.3 × 10^{-6} s^{-1} and t^*_{MV} = 0.5 as an example, the influence of outdoor CO_2 concentration on the resultant design parameters is evaluated and the results are presented in Table 4. Values of three important design parameters, namely t^*_d, $\overline{C}_{in,t^*_d}$ and N_{MV}, calculated from C_{out} = 370 ppm and 410 ppm are compared to those obtained using C_{out} = 392 ppm. An increase of C_{out} by 40 ppm would result in an increase of N_{MV} by 1 (for low $(ACH)_0$ values) or 2 (for high $(ACH)_0$ values). Basically, the influence of C_{out} in such a range on ventilation design is small, but should still be taken into account.

Table 4 Influence of outdoor CO_2 concentration (C_{out}) on the design parameters, when G_r/V = 0.3 × 10^{-6} s^{-1} and t^*_{MV} = 0.5.

$(ACH)_0$	t^*_d			$\overline{C}_{in,t^*_d}$			N_{MV}		
	C_{out} = 370 ppm	C_{out} = 392 ppm	C_{out} = 410 ppm	C_{out} = 370 ppm	C_{out} = 392 ppm	C_{out} = 410 ppm	C_{out} = 370 ppm	C_{out} = 392 ppm	C_{out} = 410 ppm
0.1	2.9	2.8	2.8	976	981	984	24	25	25
0.3	3.3	3.2	3.1	978	983	987	22	22	23
0.5	3.7	3.5	3.4	980	984	988	19	20	20
0.7	4.3	4.1	3.9	982	987	990	16	17	18
1.0	5.8	5.5	5.2	988	991	994	12	13	14

This study does not consider any outdoor climatic parameters, such as temperature and relative humidity. The ventilation design described here is conducted under a presumption that the indoor-outdoor flow exchange during a short-term mechanical ventilation period has a negligible influence on the indoor thermal environment of an air-conditioned bedroom. This is true for cities where the indoor-outdoor temperature difference is less than 10 °C during air-conditioning seasons, which was proved in our previous on-site measurements in Hong Kong. However, for cities in other climatic regions where the indoor-outdoor temperature difference is much higher than 10 °C, the influence of short-term mechanical ventilation on indoor thermal environment needs further investigation.

Ventilation rates (or ACH values) of mechanical ventilation system in this paper refers to the effective ventilation rates. Owing to short circuits of inflow, the effective ventilation rates are not necessarily equal to the nominal ventilation rates produced by the mechanical ventilation system. This suggests that the indoor air should be reasonably distributed so that the outdoor flows entering a room can go through the room, or at least those important areas, before exhaust. As discussed by Ai et al. [9], inflow openings should be far away from outflow openings to avoid the occurrence of unnecessary flow short circuits, as such short circuits would significantly lower the ventilation efficiency. This implies that the performance of mechanical ventilation system would influence the success of the short-term mechanical ventilation of air-conditioned residential buildings, which thus should be paid sufficient attention.

6. Summary

This paper develops a general design framework and provides the detailed design guidelines on short-term mechanical ventilation of air-conditioned residential buildings. The important aspects of the framework are investigated in detail and findings are presented in figures and tables, which are useful for a rapid ventilation design. Ventilation need of a wide range of conditions with various combinations of indoor CO_2 generation rates per unit volume and infiltration rates is determined. The ventilation control criterion used in this study is that the overnight average indoor CO_2 concentration is less than but close to 1000 ppm. It will be convenient to change this criterion if one intends to have another ventilation target. The influence of the start CO_2 concentration of short-term mechanical ventilation is examined and 1100 ppm is, overall, the most appropriate start value. The single *V*-shape ventilation process, which is comprised of the short-term mechanical ventilation and the follow-up CO_2 build-up, is particularly investigated in terms of the single ventilation period and the average CO_2 concentration during this period. Eventually, the required number of single ventilation period and the total period of mechanical ventilation during an 8-hour sleeping period are obtained. 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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