Occupancy-aided ventilation for airborne infection risk control: Continuously or intermittently reduced occupancies?

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Abstract

Ventilation is an important engineering measure to control the airborne infection risk of acute respiratory diseases, e.g., Corona Virus Disease 2019 (COVID-19). Occupancy-aided ventilation methods can effectively improve the airborne infection risk control performance with a sacrifice of decreasing working productivity because of the reduced occupancy. This study evaluates the effectiveness of two occupancy-aided ventilation methods, i.e., the continuously reduced occupancy method and the intermittently reduced occupancy method. The continuously reduced occupancy method is determined by the steady equation of the mass conservation law of the indoor contaminant, and the intermittently reduced occupancy method is determined by a genetic algorithm-based optimization. A two-scenarios-based evaluation framework is developed, i.e., one with targeted airborne infection risk control performance (indicated by the mean rebreathed fraction) and the other with targeted working productivity (indicated by the accumulated occupancy). The results show that the improvement in the airborne infection risk control performance linearly and quadratically increases with the reduction in the working productivity for the continuously reduced occupancy method and the intermittently reduced occupancy method respectively. At a given targeted airborne infection risk control performance, the intermittently reduced occupancy method outperforms the continuously reduced occupancy method by improving the working productivity by up to 92%. At a given targeted working productivity, the intermittently reduced occupancy method outperforms the continuously reduced occupancy method by improving the airborne infection risk control performance by up to 38%.

1   Introduction

Infectious respiratory diseases significantly affect occupants' health and society development (Desai et al. 2021; Guo et al. 2021; Dong et al. 2022). Airborne transmission can be one of the infection routes of respiratory diseases (D'Orazio et al. 2021), e.g., influenza, measles, chickenpox, smallpox, tuberculosis, MERS, SARS, and rhinovirus (Peng et al. 2022). Particularly, more and more evidence supports the airborne transmission route of Corona Virus Disease 2019 (COVID-19) with the detected viruses in exhaled air and in indoor air (Tellier 2022). Li (2021a) classifies the transmission routes of COVID-19 into three types, i.e., droplet-borne transmission, fomite transmission, and airborne transmission.

Airborne transmission can be the predominant transmission route of COVID-19 (Li 2021b), e.g., the outbreak on two buses (Cheng et al. 2022b). Dai and Zhao et al. (2020) estimated the airborne transmissibility of COVID-19 with a quantum generation rate of 14–48 h^{-1}. Cheng et al. (2022c) found the airborne transmissibility of COVID-19 was largely enhanced by Omicron with a quantum generation rate up to 1023 h^{-1}. Studies on the airborne infection risk evaluation models (Sun and Zhai 2020; Zhang and Lin 2021) also highlight the importance of controlling the airborne infection risk of COVID-19.

Ventilation is an effective engineering measure to control the airborne infection risk in indoor environments (Morawska et al. 2021; Vouriot et al. 2021). Except for the

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physical elimination of pathogens, the engineering measure with ventilation is regarded as the most effective method for airborne infection risk control compared with the administrative and personal protective measures (Morawska et al. 2020). Ventilation dilutes indoor contaminated air with clean air (Fan et al. 2022; Gan et al. 2022). Zhang et al. (2022b) found two mechanisms for ventilation to control airborne infection risk. First, dispersing the contaminant reduces the peak contaminant concentration in the indoor air, thereby reducing the local airborne infection risk. Second, removing the contaminant from indoors to outdoors reduces the mean contaminant concentration in the indoor air, thereby reducing the overall airborne infection risk. Since the clean air provided by natural ventilation is significantly affected by the number, size and position of openings, outdoor weather conditions, etc. (Zhang et al. 2022d), mechanical ventilation is generally used to provide desired clean air for robust control of airborne infection risk (Stabile et al. 2021; Zhang et al. 2022c). When the capacity of the mechanical ventilation is sufficiently large, different ventilation strategies could be developed to deliver the desired clean air for airborne infection risk control while reducing the energy consumption of mechanical ventilation, e.g., the occupancy-density based ventilation method (Wang et al. 2021), metabolism based ventilation method (Wang et al. 2022), and equivalent fresh airflow rate based ventilation method (Guo et al. 2022).

However, the flowrate of clean air required for the airborne infection risk control can be generally higher than the capacity of existing ventilation systems since the existing ventilation systems are designed for the non-pandemic condition (Guo et al. 2021; Nardecchia et al. 2022; Zhang et al. 2022e). For the non-pandemic condition, the required clean air from the outdoor is generally around 10 L/s per person (ASHRAE 2010). In contrast, with COVID-19, World Health Organization (WHO 2020) recommends the flowrate of clean air as high as 160 L/s for an airborne precaution room. Dai and Zhao (2020) found that to control the airborne infection risk below 1%, the required flowrate of clean air is 28–97 L/s per infector for 0.25-hour exposure and 333–1111 L/s per infector for 3-hours exposure. Auxiliary countermeasures can be implemented to complement ventilation for airborne infection risk control, generally including mask, air ionization, air filtration, ultraviolet germicidal irradiation, filter coatings, non-thermal plasma, reactive oxygen species, heat inactivation, chemical disinfectants, etc. (Berry et al. 2022). Even with cost-effective auxiliary countermeasures, the required flowrate of clean air can still be higher than the design capacity of existing ventilation systems. For example, Guo et al. (2022) conducted a global optimization on the ventilation rate together with auxiliary countermeasures of masks, air cleaner

and supply air disinfection, and found that the required flowrate of clean air from the outdoor was around 17 L/s, i.e., 70% higher than the general design capacity of 10 L/s.

Occupancy-aided ventilation methods are suggested to control the airborne infection risk when the design capacity of a ventilation system is limited (Agarwal et al. 2021). Reducing the occupancy, on the one hand, reduces the contaminant generation by reducing the number of infectors; and on the other hand, reduces the inhalation of the contaminant by reducing the number of the susceptible, which is equivalent to the increase in the flowrate of clean air (Morawska et al. 2020). There are two occupancy-aided ventilation methods. The first one reduces the number of occupants continuously, e.g., limiting the number of occupants to half of the non-pandemic condition (Peng et al. 2022). The continuously reduced occupancy method is intuitive and has been implemented in practice, e.g., by the epidemic prevention policy of Hong Kong. The second one reduces the number of occupants intermittently, e.g., in an indoor environment that is normally occupied and unoccupied periodically (Melikov et al. 2020). Although reducing the occupancy in an indoor environment effectively reduces the airborne infection risk, it reduces the working productivity in that indoor environment due to the reduced working time. Zhang et al. (2021b) optimized the intermittently reduced occupancy method to make a reasonable trade-off between the reduced airborne infection risk and the reduced working productivity.

However, although the occupancy-aided ventilation based on the intermittently reduced occupancy is recently developed, whether it should be implemented instead of the intuitive one based on the continuously reduced occupancy is unclear. Compared with the continuously reduced occupancy method, the intermittently reduced occupancy method is more complicated due to the periodic control between normal occupancy and reduced occupancy. Only if the effectiveness of the intermittently reduced occupancy method outperforms largely that of the continuously reduced occupancy method, the intermittently reduced occupancy method should be implemented instead of the continuously reduced occupancy method. Otherwise, the continuously reduced occupancy method is more attractive due to its practical convenience. The effectiveness comparison between the two occupancy-aided ventilation methods is unclear (Melikov et al. 2020; Zhang et al. 2021b).

The objective of this study is to evaluate the effectiveness of the two occupancy-aided ventilation methods, i.e., the continuously reduced occupancy method and the intermittently reduced occupancy method. To comprehensively compare the effectiveness of the two occupancy-aided ventilation methods, two scenarios are designed. The first

scenario evaluates the working productivities of the two methods with a targeted airborne infection risk control performance. The second scenario evaluates the airborne infection risk control performances of the two methods with targeted working productivity. The comparison results can contribute to improving the decision-making of airborne infection risk control strategies for healthy buildings with high working productivity. Two occupancy-aided ventilation methods and the two-scenarios-based evaluation framework are explained in Section 2. Results of the two occupancy-aided ventilation methods under the two scenarios are presented in Section 3. Since the targeted airborne infection risk control performance under Scenario 1 and the targeted working productivity under Scenario 2 determine the operations of the two occupancy-aided ventilation methods, the effects of the targeted airborne infection risk control performance and the targeted working productivity on the effectiveness of the two occupancy-aided ventilation methods are discussed in Section 4.

2 Methodology

2.1 Brief introduction into occupancy-aided ventilation methods

As shown in Figure 1, in the non-pandemic condition, the normal occupancy in an indoor environment is at α_1. The design capacity of the ventilation system can cope with this occupant density. However, when in a pandemic condition, the design capacity of the ventilation system cannot cope with the normal occupancy due to the airborne transmission of infectious respiratory diseases. The occupancy-aided ventilation based on continuously reduced occupancy operates at the occupancy reduced to α_2 with the ventilation system running at its maximal capacity. In contrast, the occupancy-aided ventilation based on intermittently reduced occupancy periodically operates at the normal occupancy
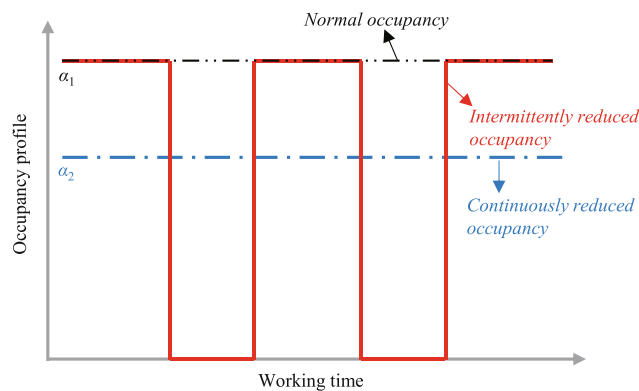
of α_1 and the occupancy of zero, with the ventilation system running at its maximal capacity.

The continuously reduced occupancy method deteriorates the working productivity mainly because of the lowered occupant density. In contrast, the intermittently reduced occupancy method deteriorates the working productivity mainly because of the idle time with the occupancy of zero (Figure 1) (Melikov et al. 2020; Zhang et al. 2021b). On the other hand, the reduced occupancy of both two methods helps to reduce the contaminant concentration in the indoor air (Figure 2). According to the law of conservation of mass for the indoor contaminant concentration (Eq. (1)), the steady indoor contaminant concentration is linearly proportional to the number of occupants (Eq. (2)). The continuously reduced occupancy method reduces the steady indoor contaminant concentration from C_1 of the normal occupancy method to C_2. The indoor contaminant concentration with the intermittently reduced occupancy method varies between C_3 and C_4. Thus, both the continuously reduced occupancy method and the intermittently reduced occupancy method can reduce the mean exposure to the indoor contaminant during the working time with the penalty of the sacrificed working productivity. It should be noted that Eq. (1) is based on the assumption that the indoor air is well mixed, which is reasonably acceptable for the widely used air distribution, i.e., mixing ventilation (Rudnick and Milton 2003; Zhang et al. 2021a; Lu et al. 2022a). For non-uniform air distribution (Tian et al. 2022), the contaminant removal efficiency can be introduced to indicate the non-uniform indoor contaminant distribution (Sun and Zhai 2020), which is not the focus of this study.

$$V\frac{dC_{in}}{dt} = NG - Q(C_{in} - C_{out}) \tag{1}$$
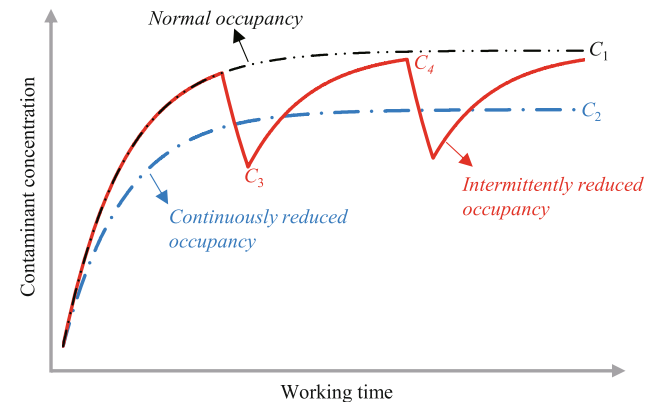
$$C_{in,steady} = \frac{NG}{Q} + C_{out} \tag{2}$$

Fig. 1 Schematic of profiles of normal occupancy, continuously reduced occupancy and intermittently reduced occupancy

Fig. 2 Schematic of indoor contaminant concentrations of normal occupancy, continuously reduced occupancy and intermittently reduced occupancy

where C_{in} and $C_{in,steady}$ are the dynamic and steady contaminant concentrations in the indoor air, respectively; C_{out} is the contaminant concentration in the outdoor air; G is the contaminant generation rate of an occupant (m³/s); N is the number of occupants; Q is the ventilation airflow rate (m³/s); V is the volume of the room (m³).

2.2 Scenarios for effectiveness evaluation of occupancy-aided ventilation methods

For respiratory diseases with high airborne transferability like COVID-19, the design capacity of existing ventilation system could be insufficient for airborne infection risk control (Melikov et al. 2020; Zhang et al. 2021b). Facing such conditions, the occupancy-aided ventilation methods operate the ventilation system at its maximal capacity to fully implement the ventilation capacity for airborne infection risk reduction, and simultaneously use the reduced occupancy to supplementally reduce airborne infection risk (Section 2.1). Since both the two occupancy-aided ventilation methods operate the ventilation system at its maximal capacity, the energy consumptions of the two occupancy-aided ventilation methods are the same. Thus, in the following context, the two occupancy-aided ventilation methods are compared regarding the effects of the reduced occupancy on the airborne infection risk control performance and working productivity, and the energy consumption is not the focus.

Two scenarios are designed to justify the effectiveness of the two occupancy-aided ventilation methods. The first scenario targets airborne infection risk control performance. Under this scenario, achieving the targeted airborne infection risk control performance is the prerequisite, and higher working productivity indicates better effectiveness. The second scenario targets working productivity. Under this scenario, the targeted working productivity is the prerequisite, and the lower airborne infection risk indicates better effectiveness. The widely used airborne infection risk index (Tian et al. 2022), i.e., rebreathed fraction, is adopted. The rebreathed fraction is defined as the proportion of exhaled air in the inhaled air (Li et al. 2022). Since the exhaled air has the risk of containing aerosol pathogens, the smaller the rebreathed fraction, the lower the airborne infection risk (Andrews et al. 2013). The rebreathed fraction can be calculated from the indoor CO_2 concentration (Eq. (3)), and thus is convenient to be implemented in practice. It should be noted that the rebreathed fraction is calculated during the occupancy period. When there are no occupants in the room with the intermittently reduced occupancy method, the rebreathed fraction is zero. The detailed reasoning of Eq. (3) refers to Rudnick and Milton (2003). The working productivity is assessed by the accumulated occupancy (Eq. (4)) (Melikov et al. 2020; Zhang et al. 2021b). Larger

accumulated occupancy indicated higher working productivity.

$$RF = \frac{C_{in} - C_{out}}{C_b} \tag{3}$$

$$AO = \sum T_i N_i \tag{4}$$

where AO is the accumulated occupancy (person·hour); C_b is the exhaled CO_2 concentration (ppm); i is the ith occupied period; N is the number of occupants; RF is the rebreathed fraction; T is the time period (h).

For the continuously reduced occupancy method, the reduced occupancy required to meet the targeted airborne infection risk control performance (i.e., the targeted mean rebreathed fraction) under Scenario 1 and to meet the targeted working productivity under Scenario 2 are explained as follows. According to the mass conservation law (Eq. (1)), the CO_2 concentration in the indoor air is derived to be Eq. (5). By combing Eqs. (3) and (5), Equation (6) shows the mean rebreathed fraction is linearly proportional to the number of occupants. Equation (4) shows that the working productivity is also linearly proportional to the number of occupants. Thus, the targeted airborne infection risk control performance is linearly proportional to the working productivity. For example, when the targeted airborne infection risk control performance under Scenario 1 is a 10% improvement compared with the normal occupancy method, the mean rebreathed fraction over the working time is required to be reduced by 10%. This means that the number of occupants over the working time, i.e., the accumulated occupancy, needs to be reduced by 10%, with the working productivity reduced by 10%. When the targeted working productivity under Scenario 2 is 10% less than the normal occupancy method, the number of occupants over the working time is reduced by 10%. This means that the mean rebreathed fraction can be reduced by 10%, with the airborne infection risk control performance improved by 10%.

$$C_{in} = \frac{NG}{Q}\left(1 - e^{-\frac{Qt}{V}}\right) + C_{out} \tag{5}$$

$$RF = \frac{NG}{QC_b}\left(1 - e^{-\frac{Qt}{V}}\right) \tag{6}$$

For the intermittently reduced occupancy method, the reduced occupancy required to meet the targeted airborne infection risk control performance under Scenario 1 and the targeted working productivity under Scenario 2 are determined by a genetic algorithm-based optimization. The operation of the intermittently reduced occupancy method is controlled by the upper and lower limits of the indoor CO_2 concentration (Zhang et al. 2021b). When the indoor

CO$_2$ concentration evolves to the upper limit, the occupancy is reduced to zero. With the reduced occupancy, the indoor CO$_2$ concentration decreases. When the indoor CO$_2$ concentration decreases to the lower limit, the occupancy is increased to the normal level. The optimization uses the genetic algorithm to search for the optimal upper and lower limits of the indoor CO$_2$ concentration. The objectives are to maximize the working productivity by maximizing the accumulated occupancy under Scenario 1 and maximize the airborne infection risk control performance by minimizing the mean rebreathed fraction under Scenario 2 (Figure 3). The search for the optimal upper and lower limits of the indoor CO$_2$ concentration also needs to satisfy the following constraints. (1) The mean rebreathed fraction should not exceed the predefined value for the targeted airborne infection risk control performance under Scenario 1; and (2) the accumulated occupancy should not be lower than the predefined value for the targeted working productivity under Scenario 2. Moreover, the unit periods of the normal and reduced occupancies should not be too small to avoid impractically frequent coming into and leaving the indoor environment. The upper and lower limits are searched in a reasonable range to avoid unnecessarily large computational load and unreasonable results. The limits should be larger than the outdoor CO$_2$ concentration and lower than the steady indoor CO$_2$ concentration at the normal occupancy (Eq. (2)). Due to the variation in the number of occupants with time, Eq. (1) is converted to Eq. (7) to obtain the

dynamic indoor CO$_2$ concentration iteratively for the calculation of the rebreathed fraction (Zhang et al. 2021b), with the CO$_2$ generation rate per person referring to Eq. (8) (Andrews et al. 2013; Qi et al. 2014). More details about the genetic algorithm refer to Shahraki and Noorossana (2014).

$$C_{in,i+\Delta t} = \frac{\Delta t G_i}{V} - \Delta t Q \left(C_{in,i} - C_{out} \right) + C_{in,i} \tag{7}$$

$$G_{CO_2} = \frac{0.202 \cdot e \cdot RQ \cdot M \cdot H^{0.725} \cdot W^{0.425}}{21 \left(0.23 RQ + 0.77 \right)} \tag{8}$$

where G_{CO_2} is the CO$_2$ generation rate by an occupant (mL/s); e is a correction factor, i.e., 0.85 and 0.75 for Chinese males and females, respectively; H is the height of an occupant (m); M is the metabolic rate (W/m^2); RQ is the molar ratio of the exhaled CO$_2$ to the inhaled O$_2$, i.e., 0.83 for an averaged adult at the sedentary activity; Δt is the calculation time interval (s); W is the mass of the body (kg).

The evaluation framework in this study is based on the mass conservation law. Although the mass conservation law has been widely validated for the indoor contaminant concentration calculation under mixing ventilation (Melikov et al. 2020; Zhang et al. 2021b), this study further validates it based on Reference (Zhang et al. 2022b) as shown in Figure 4. The experimentally validated computational fluid dynamics (CFD) simulation is used as the reference. Compared with the experiment results, the mean absolute errors of the CFD simulation for the predictions of the air
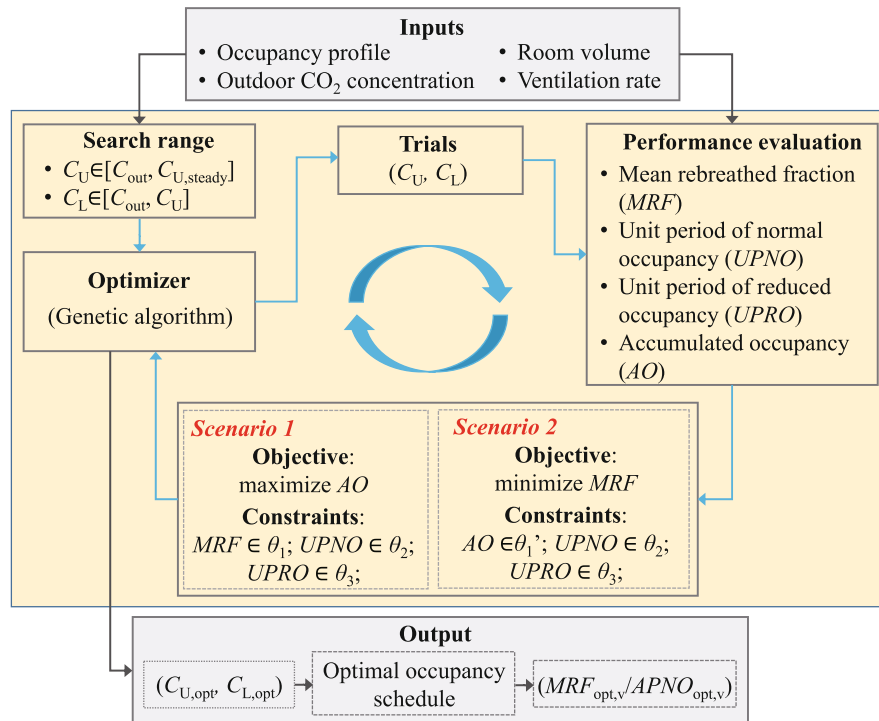

Fig. 3 Optimization of occupancy-aided ventilation based on intermittently reduced occupancy
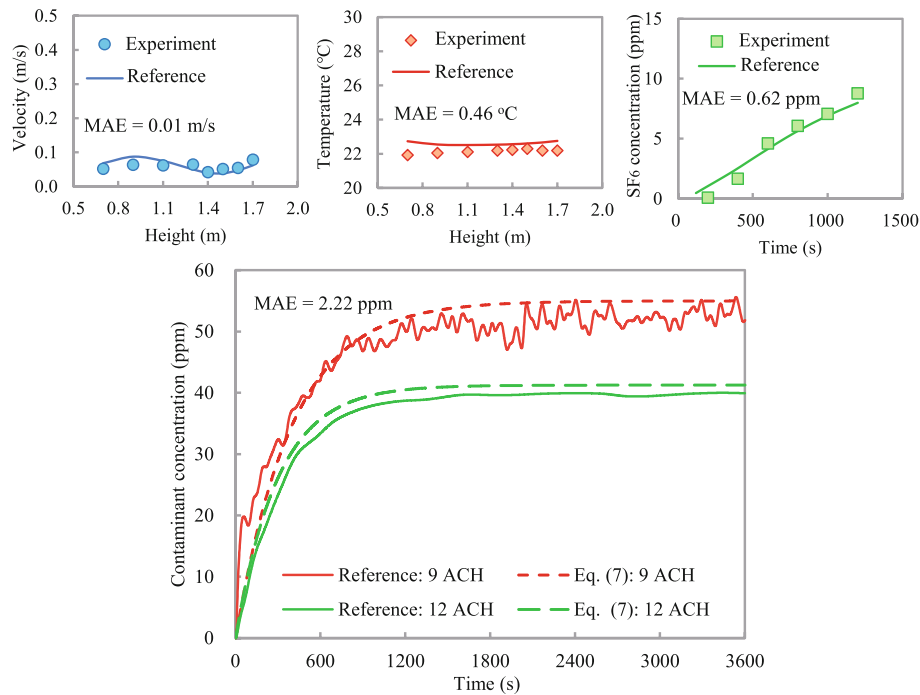
Fig. 4 Validation of mass conservation law (Eq. (7)) for indoor contaminant concentration calculation under mixing ventilation (MAE is the mean absolute error; Reference: Zhang et al. (2022b))

velocity, air temperature and trace gas contaminant (SF_6) are 0.01 m/s, 0.46 °C and 0.62 ppm respectively. Thus, the CFD simulation is credible and can be used as the reference. Figure 4 shows that with the supply airflow rate increasing from 9 ACH to 12 ACH, the indoor air gets mixed more sufficiently with the decreased random variation in the indoor contaminant concentration (Figure 4). Compared with the reference for mixing ventilation under the supply airflow rate of 9 AHC and 12 ACH, the mean absolute error of the indoor contaminant concentration exhaled by the infector predicted by Eq. (7) is 2.22 ppm. Thus, the validation results in this study also support that the mass conservation law can be used for the indoor contaminant concentration calculation under mixing ventilation. More details about the experiment and the reference simulation (i.e., CFD simulation) can be found in Reference (Zhang et al. 2022b).

2.3 Studied cases

Case studies are conducted based on the environmental chamber located at the City University of Hong Kong. The dimensions of the environmental chamber are 8.8 m (length) × 6.1 m (width) × 2.4 m (Zhang et al. 2022a). The environmental chamber can be configured as hospital wards (Zhang et al. 2022b), classrooms (Zhang et al. 2022a), etc. The environmental chamber can be served by mixing ventilation (Cheng and Lin 2015). Thus, the mass

conservation law and the related equations in Section 2 are applicable. There are 25 occupants in the case studies and the working time is 4 hours. Thus, with the normal occupancy method, the accumulated occupancy indicating the benchmark working productivity is 100 person·hour (i.e., 25 × 4). The ventilation is designed to achieve Category II indoor air quality, i.e., the indoor CO_2 concentration is not larger than the value of 800 ppm above the outdoor CO_2 concentration (ISO/TR 17772-2 2018.). The outdoor CO_2 concentration is relatively steady and the value of 400 ppm is used (Zhang et al. 2021b). Thus, the ventilation is designed with a steady indoor CO_2 concentration of 1200 ppm. The design airflow rate corresponding to the steady indoor CO_2 concentration of 1200 ppm is 2.8 ACH (Eq. (2)). The initial indoor CO_2 concentration at the start of the working time is the same as the outdoor CO_2 concentration. For the intermittently reduced occupancy method, the unit period of reduced occupancy is constrained to be larger than 5 min to avoid the frequent change between the normal and reduced occupancies. The unit period of normal occupancy is constrained between 30 min and 90 min to keep a reasonable uninterrupted period for working (Figure 3).

In Section 3, to demonstrate the detailed processes and effectiveness of the two occupancy-aided ventilation methods, a desired airborne infection risk control performance with the mean rebreathed fraction reduction of 20% is tested under Scenario 1 and a desired working productivity with the accumulated occupancy reduction of 20% is tested

under Scenario 2. To further compare the effectiveness of the two occupancy-aided ventilation methods, in Section 4, different desired airborne infection risk control performances with the mean rebreathed fraction reductions of 0%, 20%, 40%, 60%, and 80% are tested under Scenario 1 and different desired working productivities with the accumulated occupancy reductions of 0%, 20%, 40%, 60%, and 80% are tested under Scenario 2.

3 Results

3.1 Scenario 1

To demonstrate the effectiveness of the two occupancy-aided ventilation methods, the first scenario is set as that the airborne infection risk control performance is improved with the mean rebreathed fraction reduced by 20% compared with the benchmark value of the normal occupancy method. As illustrated in Section 2.2 that the reduction in the mean rebreathed fraction of the continuously reduced occupancy method is linearly proportional to the reduction in the accumulated occupancy, thus the number of occupants with the continuously reduced occupancy method is reduced by 20%. Figure 5 shows that the indoor CO_2 concentration of the normal occupancy method increases from 400 ppm to 1200 ppm. The indoor CO_2 concentration of the continuously reduced occupancy method increases from 400 ppm to 1040 ppm. For the intermittently reduced occupancy method, the genetic algorithm optimization determines the upper and lower limits of the indoor CO_2 concentration as 1178 ppm and 918 ppm, respectively. Accordingly, the occupants stay in the indoor environment for 54 min and leave the indoor environment for 9 min periodically until the working time is over. Figure 5 shows the indoor CO_2
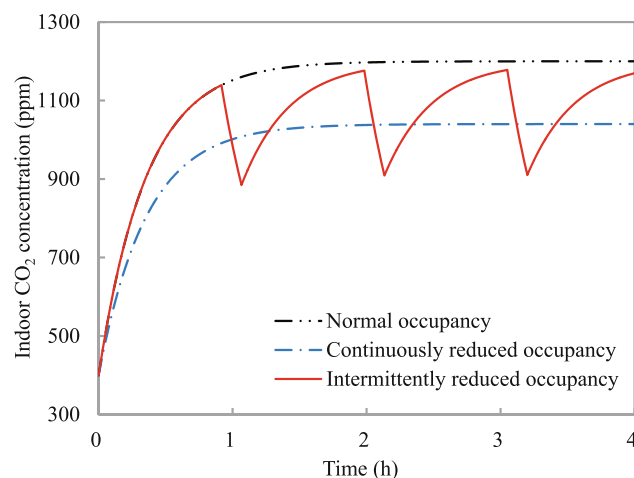
concentration of the intermittently reduced occupancy method is smaller than the steady indoor CO_2 concentration of the normal occupancy method and fluctuates around the steady indoor CO_2 concentration of the continuously reduced occupancy method.

Based on the indoor CO_2 concentration, the mean rebreathed fraction over the working time is obtained (Eq. (6)). The rebreathed fraction of the normal occupancy method increases from 0% to 2.13% with a mean value of 1.94%, and that of the continuously reduced occupancy method increases from 0% to 1.71% with a mean value of 1.55% (Figure 6). Thus, the continuously reduced occupancy method achieves the targeted airborne infection risk control performance by reducing the mean rebreathed fraction by 20% compared with the normal occupancy method. Figure 6 shows that the rebreathed fraction of the intermittently reduced occupancy method during the reduced occupancy period is 0% since the indoor environment is unoccupied. The rebreathed fraction of the intermittently reduced occupancy method varies between 0% and 2.05%, with a mean value of 1.52%. Thus, the intermittently reduced occupancy method also achieves the targeted airborne infection risk control performance.

Figure 7 shows that the accumulated occupancy of the continuously reduced occupancy method linearly increases with the working time at the speed of 20 persons per hour, and finally reaches 80 person·hour. Compared with the benchmark value of the normal occupancy method, the working productivity of the continuously reduced occupancy method is decreased by 20%. The accumulated occupancy of the intermittently reduced occupancy method increases stepwise. When the intermittently reduced occupancy method operates at the normal occupancy, the accumulated
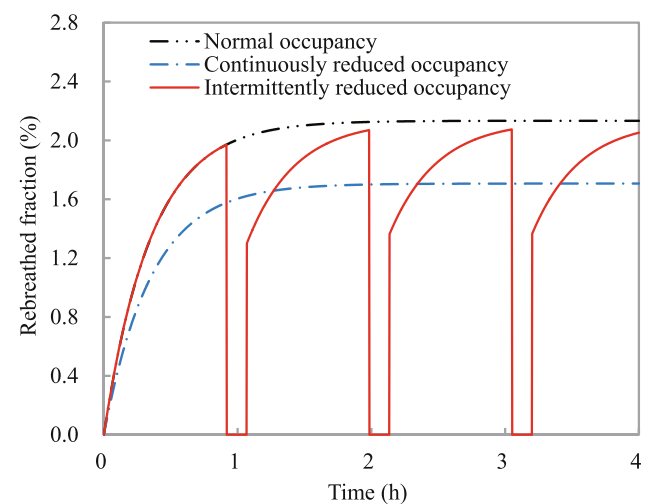

Fig. 5 Indoor CO_2 concentrations of normal occupancy, continuously reduced occupancy and intermittently reduced occupancy: Scenario 1 targeting reduced mean rebreathed fraction of 20%
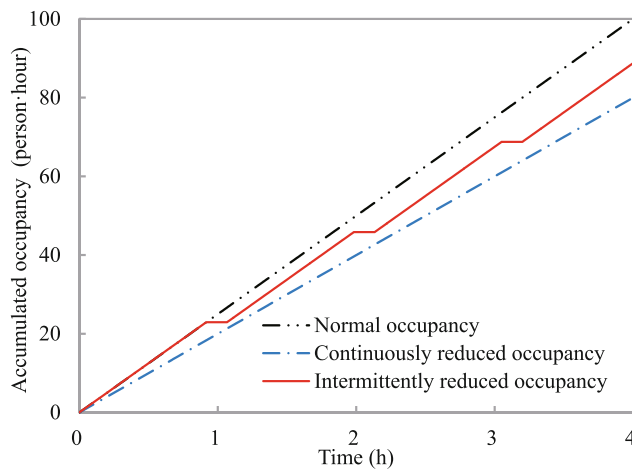

Fig. 6 Rebreathed fractions of normal occupancy, continuously reduced occupancy and intermittently reduced occupancy: Scenario 1 targeting reduced mean rebreathed fraction of 20%

Fig. 7 Accumulated occupancies of normal occupancy, continuously reduced occupancy and intermittently reduced occupancy: Scenario 1 targeting reduced mean rebreathed fraction of 20%

Fig. 8 Indoor CO_2 concentrations of normal occupancy, continuously reduced occupancy and intermittently reduced occupancy: Scenario 2 targeting accumulated occupancy reduced by 20%

occupancy linearly increases with the working time at 25 persons per hour. When the intermittently reduced occupancy method operates at the reduced occupancy, the accumulated occupancy keeps unchanged since the indoor environment is unoccupied. The final accumulated occupancy of the intermittently reduced occupancy method reaches 89 person·hour, which is decreased by 11% compared with the benchmark value of the normal occupancy method. Thus, the intermittently reduced occupancy method outperforms the continuously reduced occupancy method, with the working productivity improved by 11% (from 80 to 89 person·hour).

3.2 Scenario 2

The second scenario is set as that the working productivity is deteriorated by 20% compared with the benchmark value of the normal occupancy method to improve the airborne infection risk control performance. Figure 8 shows that the indoor CO_2 concentration of the normal occupancy method increases from 400 ppm to 1200 ppm. The indoor CO_2 concentration of the continuously reduced occupancy method increases from 400 ppm to 1040 ppm. For the intermittently reduced occupancy method, the genetic algorithm optimization determines the upper and lower limits of the indoor CO_2 concentration as 1137 ppm and 820 ppm respectively. Accordingly, the occupants stay in the indoor environment for 39 min and leave the indoor environment for 12 min periodically until the working time is over. The indoor CO_2 concentration of the intermittently reduced occupancy method is smaller than the steady indoor CO_2 concentration of the normal occupancy method and fluctuates around the steady indoor CO_2 concentration of the continuously reduced occupancy method.
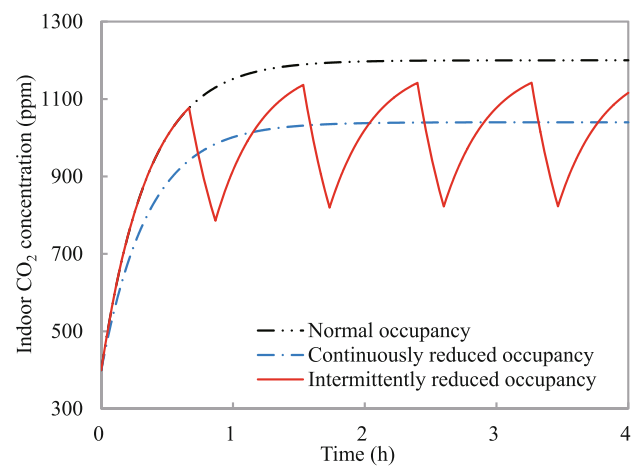
Figure 9 shows that the accumulated occupancy of the continuously reduced occupancy method linearly increases to 80 person·hour and the accumulated occupancy of intermittently reduced occupancy method increases to 80 person·hour in a stepwise manner. Thus, both the two occupancy-aided ventilation methods achieve the targeted working productivity of Scenario 2. According to the indoor CO_2 concentration, the mean rebreathed fraction over the working time is obtained (Eq. (6)). The rebreathed fraction of the continuously reduced occupancy method increases from 0% to 1.71%, with a mean value of 1.55% (Figure 10). The rebreathed fraction of the intermittently reduced occupancy method varies between 0% and 1.91%, with a mean value of 1.24%. Thus, the intermittently reduced occupancy method outperforms the continuously reduced occupancy method regarding the airborne infection risk control performance by reducing the mean rebreathed fraction by 20% (from 1.55% to 1.24%).
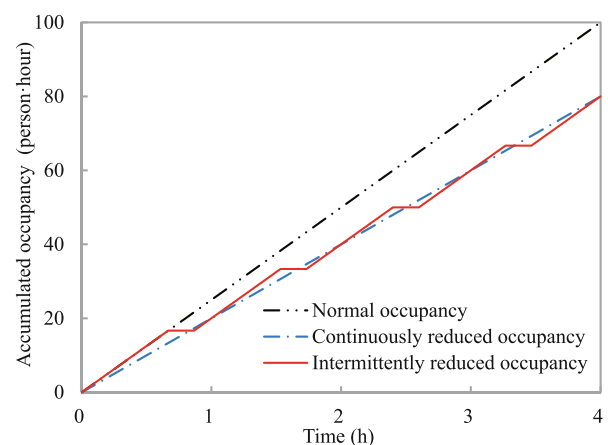

Fig. 9 Accumulated occupancies of normal occupancy, continuously reduced occupancy and intermittently reduced occupancy: Scenario 2 targeting accumulated occupancy reduced by 20%
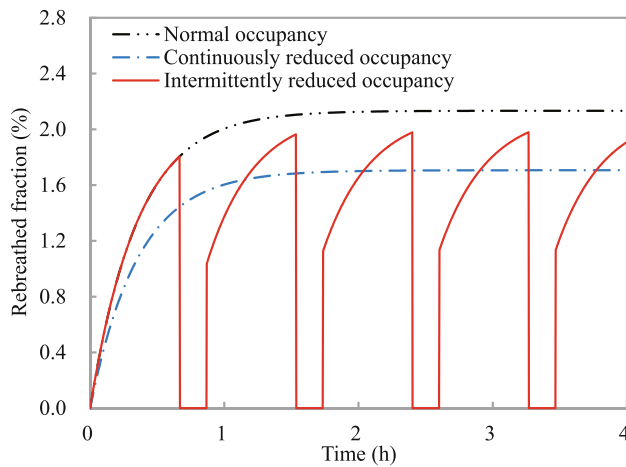
Fig. 10 Rebreathed fractions of normal occupancy, continuously reduced occupancy and intermittently reduced occupancy: Scenario 2 targeting accumulated occupancy reduced by 20%

4 Discussion

The above results show the details of the performance evaluations and comparisons of the continuously reduced occupancy method and the intermittently reduced occupancy method. The results show that under both Scenarios 1 and 2, the intermittently reduced occupancy method outperforms the continuously reduced occupancy method regarding either the working productivity or the airborne infection risk control performance. The above results are based on a fixed value of the targeted airborne infection risk control performance and a fixed value of the targeted working productivity. The targeted airborne infection risk control performance under Scenario 1 and the targeted working productivity under Scenario 2 determine the two occupancy-aided ventilation methods (Section 2.1). Therefore, the effects of the targeted airborne infection risk control performance

and the targeted working productivity are further tested on the effectiveness of the two methods. The variations of the indoor CO_2 concentration and accumulated occupancy with the targeted airborne infection risk control performance (i.e., the reduced mean rebreathed fraction) and the targeted working productivity (i.e., the reduced accumulated occupancy) are presented in Figures 11–14. Based on Figures 11–14, Figure 15 shows that when the targeted mean reduced rebreathed fraction under Scenario 1 increases from 20% to 80%, the accumulated occupancies of the continuously reduced occupancy method and the intermittently reduced occupancy method reduce from 80 person·hour to 20 person·hour and from 89 person·hour to 38 person·hour respectively. Thus, under Scenario 1, the intermittently reduced occupancy method outperforms the continuously reduced occupancy method by 11%–92% regarding working productivity. When the targeted accumulated occupancy increases from 20% to 80%, the mean rebreathed fractions of the continuously reduced occupancy method and the intermittently reduced occupancy method decrease from 1.55% to 0.39% and from 1.24% to 0.26%, respectively. Thus, under Scenario 2, the intermittently reduced occupancy method outperforms the continuously reduced occupancy method by 20%–38% regarding the airborne infection risk control performance. It should be noted that when the targeted reduced mean rebreathed fraction under Scenario 1 is 100% or the targeted reduced accumulated occupancy under Scenario 2 is 100%, it means that the indoor environment is unoccupied with the reduction in the airborne infection risk of 100% and the reduction in the working productivity of 100% where the two occupancy-aided ventilation methods perform the same. When the targeted reduced mean rebreathed fraction under Scenario 1 is zero or the targeted reduced accumulated occupancy
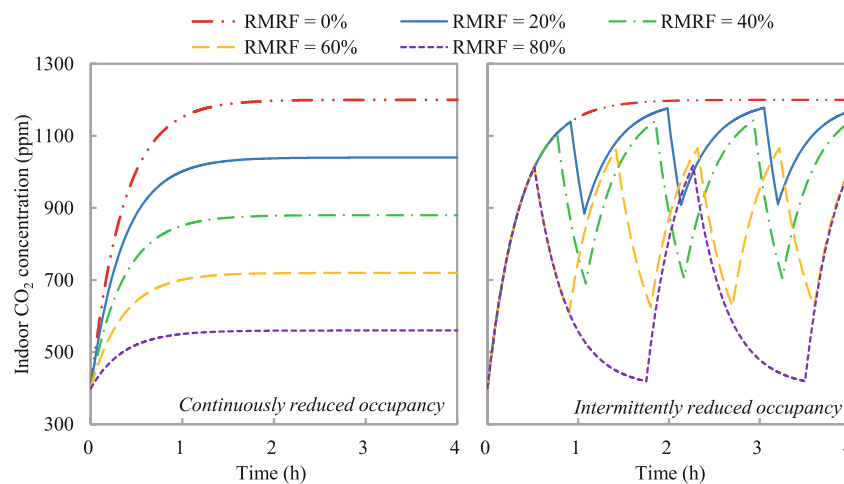

Fig. 11 Indoor CO_2 concentrations of continuously and intermittently reduced occupancy methods at different targeted reduced mean rebreathed fractions (RMRF) under Scenario 1
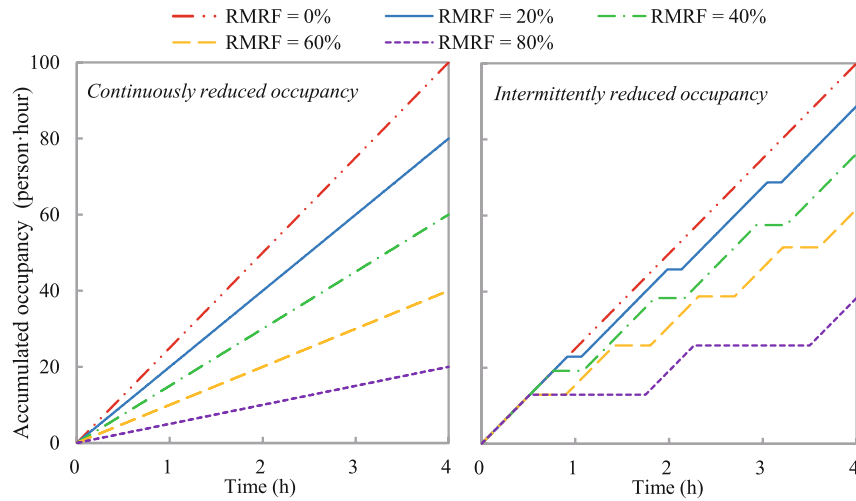
Fig. 12 Accumulated occupancies of continuously and intermittently reduced occupancy methods at different targeted reduced mean rebreathed fractions (RMRF) under Scenario 1
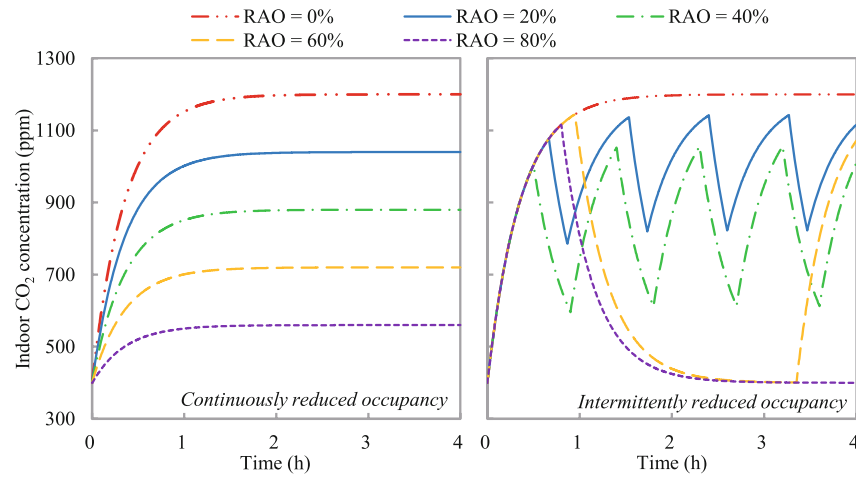

Fig. 13 Indoor CO_2 concentrations of continuously and intermittently reduced occupancy methods at different targeted reduced accumulated occupancies (RAO) under Scenario 2
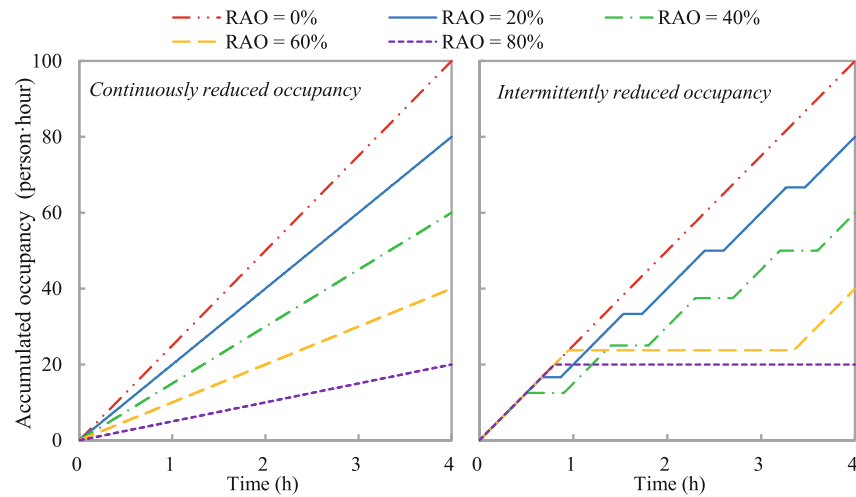

Fig. 14 Accumulated occupancies of continuously and intermittently reduced occupancy methods at different targeted reduced accumulated occupancies (RAO) under Scenario 2
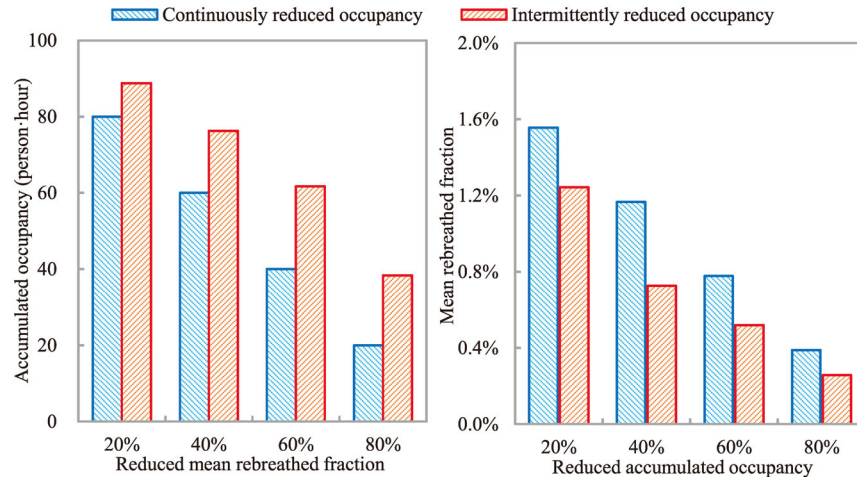
Fig. 15 Performance comparisons between continuously and intermittently reduced occupancy methods

under Scenario 2 is nil, it means that the indoor environment is operated with normal occupancy with reduced airborne infection risk of zero and reduced working productivity of zero, where the two occupancy-aided ventilation methods also perform the same.

Figure 16 shows the reduced mean rebreathed fraction positively and linearly related to the reduced accumulated occupancy with the continuously reduced occupancy method. In contrast, when the intermittently reduced occupancy method is implemented, the reduced mean rebreathed fraction is in a positive and quadratic function with the reduced accumulated occupancy. This means the effectiveness in improving the airborne infection risk control performance is linearly related to the reduced working productivity when the continuously reduced occupancy method is implemented, but is non-linearly related to the reduced working productivity when the intermittently reduced occupancy method is implemented. The linearity under the continuously reduced occupancy method has been explained in Section 2, and the non-linearity under the intermittently reduced occupancy method is explained as follows. The working time of the intermittently reduced occupancy method can be divided into three phases, i.e., (1) the starting phase with the indoor CO_2 concentration increasing from the initial value to the upper limit, (2) the occupancy-reduced phase with the indoor CO_2 concentration reducing from the upper limit to the lower limit, and (3) the occupancy-increased phase with the indoor CO_2 concentration increasing from the lower limit to the upper limit. Figures 5, 8, 11 and 13 show that compared with the continuously reduced occupancy method, during the starting phase, the intermittently reduced occupancy method is inferior because of the high indoor CO_2 concentration. During the occupancy-reduced phase, the intermittently reduced occupancy method is superior because of the mean rebreathed fraction of zero.

During the occupancy-increased phase, the intermittently reduced occupancy method might perform better than the continuously reduced occupancy method and might worse depending on the targeted airborne infection risk control performance and the targeted working productivity. The interaction of the three phases results in the non-linearity under the intermittently reduced occupancy method. Nevertheless, the intermittently reduced occupancy method is more effective than the continuously reduced occupancy method since it achieves less reduction in the accumulated occupancy at a given reduced mean rebreathed fraction under Scenario 1, and achieves more reduction in the mean rebreathed fraction at a given reduced accumulated occupancy under Scenario 2.

This study uses the rebreathed fraction to indicate the airborne infection risk which has the advantages of requiring
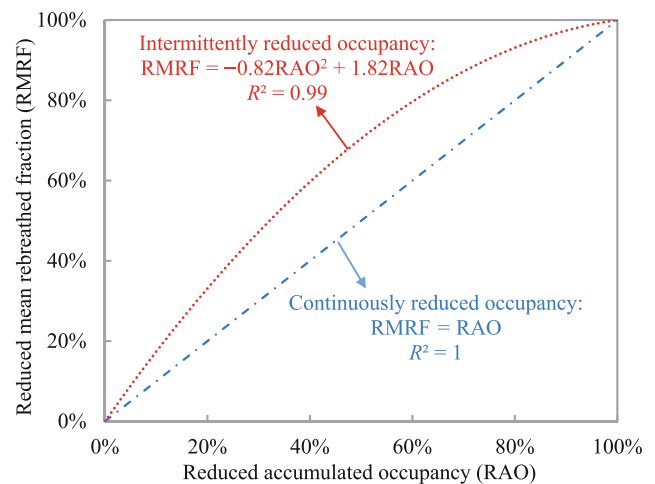

Fig. 16 Variations in reduced mean rebreathed fraction with reduced accumulated occupancy of continuously and intermittently reduced occupancy methods (the benchmark is the normal occupancy method)

no information of the airborne transferability of infectious respiratory disease (Rudnick and Milton 2003; Andrews et al. 2013; Zhang et al. 2021b; Li et al. 2022). The airborne transferability is generally indicated by the quantum generation rate (Dai and Zhao 2020). The quantum is an infectious dose unit, and one quantum is the quantity of pathogens required to cause an infection risk of 63.2% (i.e., $1-e^{-1}$) (Cheng et al. 2022c). The airborne transferability of a specific respiratory disease is difficult to obtain since the airborne transferability of a specific respiratory disease can vary largely. For example, the airborne transferability of COVID-19 has been reported to vary largely with the quantum generation rate of 14 h^{-1} (Dai and Zhao 2020) to 1023 h^{-1} (Cheng et al. 2022c). When the airborne transferability is not exactly known, the rebreathed fraction can be used to indicate the airborne infection risk (Rudnick and Milton 2003; Andrews et al. 2013; Zhang et al. 2021b; Li et al. 2022). The airborne infection risk can be calculated from the rebreathed fraction by Eq. (9) (Rudnick and Milton 2003; Zhang et al. 2021b). For example, when the quantum generation rate of the studied COVID-19 case is 142 quanta/h and all occupants wear masks with the efficiency of 75% (Zhang and Lin 2021), based on the rebreathed fractions of the normal occupancy method, continuously reduced occupancy method, and intermittently reduced occupancy method in Section 3.2 (i.e., 1.94%, 1.55%, 1.24%, respectively), the corresponding airborne infection risks can be calculated by Eq. (9) as 2.72%, 2.18%, and 1.75%, respectively. As a result, the intermittently reduced occupancy method outperforms the continuously reduced occupancy method by 19.8% (i.e., further reducing the airborne infection risk by 19.8%). Similarly, with Eq. (9) and its required input parameters (e.g., quantum generation rate), the relationship between the reduced mean rebreathed fraction and reduced accumulated occupancy in Figure 16 can be transferred to describe the relationship between the reduced airborne infection risk and reduced accumulated occupancy (e.g., with the quantum generation rate of 14 quanta/h in Figure 17 and with the quantum generation rate of 1023 quanta/h in Figure 18).

$$P = 1 - e^{-\frac{(1-\varphi)\text{RF}Iqt}{n}} \qquad (9)$$

where P is the airborne infection risk; RF is the rebreathed fraction; I is the number of infectors; q is the quantum generation rate (h^{-1}); t is the exposure time (h); n is the total number of occupants; φ is the removal efficiency of virus by masks, filters, air cleaners, etc.

There are multiple transmission routines, e.g., airborne transmission and contact transmission (Li 2021a). Like many existing studies (Dai and Zhao 2020; Morawska et al. 2020; Stabile et al. 2021; Wang et al. 2021; Zhang and Lin 2021;
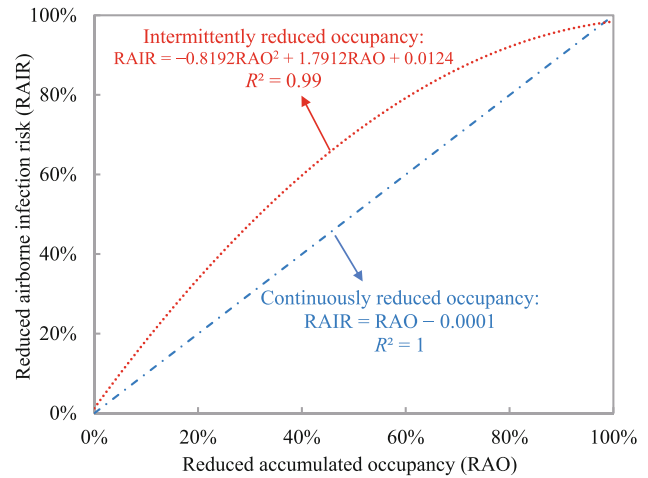

Fig. 17 Variations in reduced airborne infection risk with reduced accumulated occupancy of continuously and intermittently reduced occupancy methods: quantum generation rate is 14 quanta/h (the benchmark is the normal occupancy method)
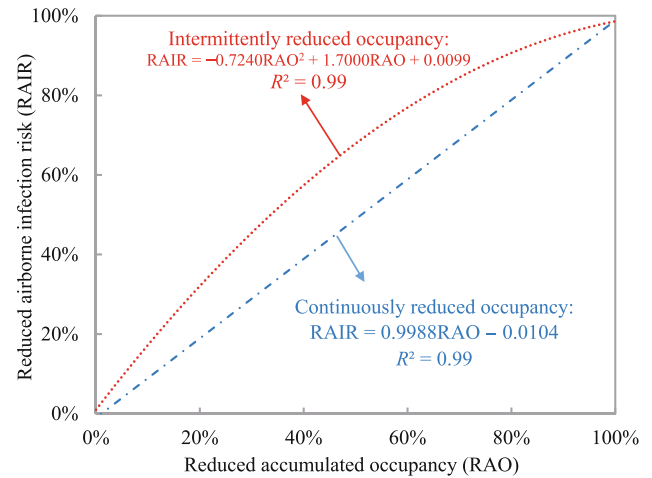

Fig. 18 Variations in reduced airborne infection risk with reduced accumulated occupancy of continuously and intermittently reduced occupancy methods: quantum generation rate is 1023 quanta/h (the benchmark is the normal occupancy method)

Fan et al. 2022; Wang et al. 2022; Zhang et al. 2022b;), this study focuses on the airborne transmission in a room which has regular cleaning and disinfection of contact surfaces for the infection risk control of contact route. The intermittently reduced occupancy method is compatible with the method for the infection risk control of contact route. The reduced-occupancy period of the intermittently reduced occupancy method can be used for cleaning and disinfection of contact surfaces. When considering the infection risk control of contact route, the unit period of reduced occupancy (Figure 3) of the intermittently reduced occupancy method should satisfy the minimal time length required for cleaning and disinfecting contact surfaces. In this way, the intermittently reduced occupancy method

outperforms the continuously reduced occupancy method for the compatibility with the infection risk control of contact route.

Although this study focuses on mixing ventilation with a uniform indoor thermal environment, the two-scenarios-based evaluation framework (Section 2.2) can be used to compare the performances of the two occupancy-aided ventilation methods under non-uniform air distribution such as stratum ventilation (Cheng et al. 2022a), attachment ventilation (Yin et al. 2021) and displacement ventilation (Fan et al. 2022) in the future. This study evaluates the airborne infection risk from the perspective of the individual indicated by the mean rebreathed fraction as the existing studies do (Rudnick and Milton 2003; Andrews et al. 2013; Li et al. 2022). However, when the airborne infection risk of a group of people is concerned, the mean rebreathed fraction normalized by the number of occupants in the indoor environment can be used to indicate the airborne infection risk, which will be studied in the future. Moreover, the unoccupied period lessens the requirement for thermal comfort (Wu et al. 2021). Energy saving can be harvested from the lessened thermal comfort requirement by enhancing/lowering the room air temperature during the unoccupied period under the cooling mode/heating mode (Zhang and Lin 2020; Li and He 2021), which will also be studied in the future.

5 Limitations

There are three simplifications in this study. First, for the airborne infection risk control performance evaluation, the rebreathed fraction is used rather than the airborne infection risk (Rudnick and Milton 2003). Since the infectious pathogen of the respiratory diseases is contained in the exhaled contaminant, the rebreathe fraction that describes the rebreathed ratio of the exhaled contaminant can reasonably indicate the airborne infection risk (Andrews et al. 2013). The CO_2-based rebreathed fraction used in Section 2 has been verified and well recognized by existing studies (Rudnick and Milton 2003; Liao et al. 2005; Andrews et al. 2013; Richardson et al. 2014; Vouriot et al. 2021). The CO_2-based rebreathed fraction is practically convenient because it does not require information about the infectious virus and CO_2 concentration is practical to obtain (Rudnick and Milton 2003; Liao et al. 2005; Andrews et al. 2013; Richardson et al. 2014; Vouriot et al. 2021). However, the CO_2-based rebreathed fraction is subject to the assumption of being well-mixing (Rudnick and Milton 2003; Liao et al. 2005; Andrews et al. 2013; Richardson et al. 2014; Vouriot et al. 2021). The assumption of being well-mixing generally applies to the widely used ventilation method, i.e., mixing ventilation (Rudnick and Milton 2003; Liao et al. 2005; Andrews et al.

2013; Richardson et al. 2014; Vouriot et al. 2021), which has also been validated in Figure 4. When other advanced ventilation methods are used, e.g., displacement ventilation and stratum ventilation, ventilation efficiency should be introduced to revise the assumption of being well-mixing (Sun and Zhai 2020; Lu et al. 2022b). Second, the working productivity is indicated by the accumulated occupancy merely. The working productivity evaluation is complex and affected by many objective and subjective parameters (Dall'Ora et al. 2016; Collewet and Sauermann 2017). The accumulated occupancy representing the space utility is a major parameter affecting working productivity, and generally larger accumulated occupancy indicates the workers have more time to conduct the assignments with larger working outputs (Collewet and Sauermann 2017). The occupancy-aided ventilation affects the working productivity mainly via adjusting the accumulated occupancy (Section 2). Thus, this study reasonably uses the accumulated occupancy to indicate working productivity. The existing studies (Zhang et al. 2021b; Melikov et al. 2020) also have used the accumulated occupancy to indicate working productivity. Third, the occupant movement of the intermittently reduced occupancy method can change indoor airflow pattern (Ren et al. 2022), thereby affecting the airborne infection risk. However, similar to the existing studies (Melikov et al. 2020; Zhang et al. 2021b), this study has not considered the effect of the occupant movement since the occupant movement is finished within a short time and mixing ventilation used in this study is insensitive to the occupant movement. It has been experimentally verified that the effect of short occupant movement on mixing ventilation is negligible (Wu and Lin 2015). However, when advanced air distribution like displacement ventilation is studied in the future, the effect of occupant movement should be considered since displacement ventilation is sensitive to the occupant movement (Feng et al. 2021).

6 Conclusions

This study develops a two-scenario-based evaluation framework to compare the effectiveness of two occupancy-aided ventilation methods, i.e., the continuously reduced occupancy method and the intermittently reduced occupancy method, regarding the airborne infection risk control performance indicated by the mean rebreathed fraction and the working productivity indicated by the accumulated occupancy. The findings are summarized as follows.

- For the continuously reduced occupancy method, the improvement in airborne infection risk control performance linearly increases with the decreasing working productivity.
- For the intermittently reduced occupancy method, the improvement in the airborne infection risk control

performance quadratically increases with the decreasing working productivity.

- At a given targeted airborne infection risk control performance, the working productivity of the intermittently reduced occupancy method is larger than that of the continuously reduced occupancy method by up to 92%.
- At a given targeted working productivity, the airborne infection risk of the intermittently reduced occupancy method is lower than that of the continuously reduced occupancy method by up to 38%.

This study would improve the decision-making of airborne infection risk control strategies for healthy buildings with high working productivity.

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