

Characteristics of physical blocking on co-occupant's exposure to respiratory droplet residuals

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Abstract: Existed evidences show that airborne transmission of human respiratory droplets may be related with the spread of some infectious disease, such as severe acute respiratory syndrome (SARS) and H1N1 pandemic. Non-pharmaceutical approaches, including ventilation system and personal protection, are believed to have certain positive effects on the reduction of co-occupant's inhalation. This work then aims to numerically study the performances of mouth covering on co-occupant's exposure under mixing ventilation (MV), under-floor air distribution (UFAD) and displacement ventilation (DV) system, using drift-flux model. Desk partition, as one generally employed arrangement in plan office, is also investigated under MV. The dispersion of 1, 5 and 10 μm droplet residuals are numerically calculated and CO_2 is used to represent tracer gas. The results show that using mouth covering by the infected person can reduce the co-occupant's inhalation greatly by interrupting direct spread of the expelled droplets, and best performance can be achieved under DV since the coughed air is mainly confined in the microenvironment of the infected person. The researches under MV show that the two interventions, mouth covering and desk partition, achieve almost the same inhalation for fine droplets while the inhalation of the co-occupant is lower when using mouth covering for large droplets.

Key words: mouth covering; desk partition; respiratory droplets; exposure; ventilation method

1 Introduction

The outbreaks of epidemic and pandemic viral infections, including the emergency of severe acute respiratory syndrome (SARS) during 2003 and H1N1 pandemic in 2009 and 2010, pose serious threats to human's well-beings physically and mentally, and also result in huge economic losses worldwide. Up to now, different approaches have been investigated to interrupt or reduce the spread of infectious disease. Although antiviral drugs and vaccines are believed to be the mainstay [1], they might be limited or not available at the beginning. Non-pharmaceutical measures, such as ventilation methods and personal protection, are simple and low cost interventions and might reduce the transmission of epidemic respiratory viruses effectively [2].

One systematic review [3] concluded that air conditioning schemes possessed strong associations with the transmission and spread of infectious disease, such as measles, tuberculosis, chickenpox, anthrax, influenza, smallpox and SARS. The numerical studies of GAO and NIU [4] demonstrated that displacement ventilation (DV)

might minimize the indirect exposure to the sneezed droplets, and GAO et al [5] also stated that the dilution of sneezed droplets was dominant primarily by indoor air movement in the breathing zone. MUI et al [6] found that the droplet dispersion and mixing under DV were much weaker compared with mixing ventilation (MV). WAN et al [7] investigated the transport characteristics of the exhaled droplets under two idealized floor-supply ventilation systems, and concluded that smaller droplets were much easier to be extracted by the uni-directional upward system, while the floor-supply and floor-return system performed better for larger droplets. These studies were mainly focused on the dispersion of exhaled droplets and less attention was paid to the co-occupant's exposure. Meanwhile, a long-term stay of the co-occupant in enclosed environment should be considered since some viruses contained in the airborne droplet residuals could survive for several hours [8].

Another review by JEFFERSON et al [2] stated that higher intervention effectiveness could be obtained when person with suspected symptoms were wearing face masks or gowns. Although one study [9] showed that paper surgical mask, even worn in multiple layers (up to five), had lower filtration efficiency, the research of

TANG et al [10] demonstrated that wearing a surgical mask could redirect and decelerate exhaled airflows from the infected individuals and might minimize the pathogen-laden viruses entering the breathing zone of others. It then can be estimated that mouth coverings including masks and gowns may mitigate the transmission of infectious disease. However, the efficiency of these barriers under different ventilation methods is less studied.

This work, therefore, aims to investigate the performance of mouth coverings on co-occupant's inhalation under different ventilation systems. Meanwhile, the effects of mouth covering and desk partition are also studied under MV.

2 Methods

Figure 1 illustrates the configuration of the simulated office, and the arrangements of mouth covering and desk partition under MV. The office dimensions are 4.0 m in length, 3.0 m in width and 2.7 m in height. There are two people working there, sitting face to face with a roughly 1.5 m distance between their nose-tips. The one on the right is assumed to be the infected person who emits pathogen-laden droplets and the other is called the co-occupant. In front of the

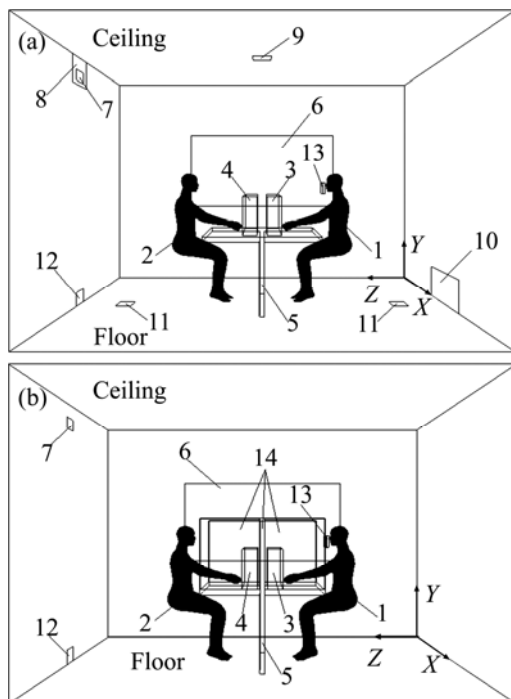


Fig. 1 Configuration of simulated office with mouth covering for infected person (a) and arrangements of mouth covering and desk partition under MV (b) (Room length (Z) 4 m, Width (X) 3 m, Height (Y) 2.7 m; 1–Infected person; 2–Co-occupant; 3, 4–Computer; 5–Desk; 6–Window; 7–MV inlet; 8–DV outlet; 9–UFAD outlet; 10–DV inlet; 11–UFAD inlet; 12–MV outlet; 13–Mouth covering; 14–Desk partition)

infected person, a rectangular slab (0.20 m (length) \times 0.12 m (height)) is set to represent mouth covering and located at about 0.03 m ahead of the mouth. There are desk partitions in the middle of the two people to build a private environment for each and the upper level of the partitions is 1.5 m above the floor. Boundary conditions for the computer, desk, window, human body, and walls are listed in Table 1.

Table 1 Details of numerical methods

Model and boundary	Condition
Turbulence model	Renormalization κ - ϵ [11]
Wall treatment	Standard wall function
Droplet distribution	One-way coupling drift-flux model
Droplet deposition	Lai and Nazaroff deposition model [12]
MV inlet	Air flow 57 L/s, temperature 16 °C
UFAD inlet	Air flow 57 L/s, temperature 20 °C
DV inlet	Air flow 57 L/s, temperature 20 °C
MV/UFAD/DV outlet	Velocity and temperature: free slip
Window	Uniform heat flux 200 W
Floor, ceiling, walls	Adiabatic
Human body	Uniform heat flux 60 W
Computer	Uniform heat flux 120 W
Desk	Adiabatic

Three ventilation methods, including MV, UFAD and DV, are investigated. The temperature of inlet airflow is set to be 16 °C, 20 °C and 20 °C, respectively, with the same air change rate of 6.4 times per hour. The swirling diffuser under UFAD is simulated by eight small square cells [13]

Although a normal respiration process follows a sinusoidal cycle, steady inhalation for the co-occupant is assumed in this simulation. The breathing rate for the steady respiratory process is 8.4 L/min through nostrils, and the direction of inhaled jet is 45° upward. As to the infected person, a horizontal pulsating jet from the mouth at a velocity of 22 m/s [14] lasting 0.5 s, is assumed to simulate several consecutive coughs. The pulsating flow rate is 4.8 L/s and the concentration in the exhaled air for each droplet size is 0.05 g/m³. The temperature of expelled air is set to be 35 °C [15].

3 Results

3.1 Effects of mouth covering under different ventilation systems

Before the numerical simulation of expelled droplets' dispersion, indoor thermal comfort must be ensured at first and the related parameters are evaluated.

The temperature distribution under MV is quite even, about 24 °C. Temperature stratification can be observed under UFAD and DV, while the temperature at head level is both maintained at 24 °C to ensure the comparison basis for the three systems.

To embody the effect of mouth covering, Fig. 2 illustrates the distribution of 10 μm droplets for cases with and without mouth covering under MV at the first second with the normalized concentration not less than 0.001, when droplets concentration in the exhaled air of the infected person is denoted to be 1. The pathogen-laden droplets from the infected person could reach the co-occupant directly when there is no covering, while the coughed air will be redirect to the region behind the infected person by using mouth covering. Fig. 2 clearly shows that mouth covering can reduce the co-occupant’s inhalation by avoiding the direct exposure.

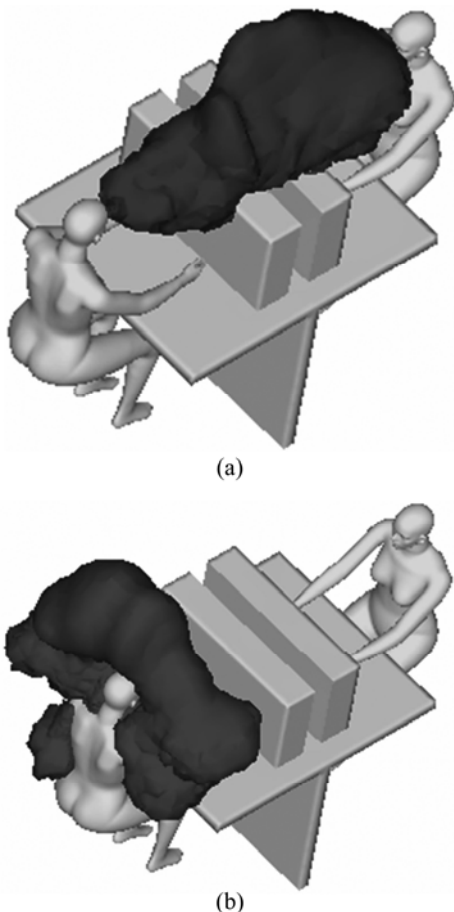


Fig. 2 Dispersion of 10 μm droplets in cases with and without mouth covering under MV at the first second with normalized concentration not less than 0.001 (Droplet concentration in exhaled air of infected person is denoted as 1.0): (a) Coughing without mouth covering; (b) Coughing with mouth covering

The normalized inhaled concentration of the co-occupant under three ventilation systems is shown in Fig. 3 when the infected person coughs directly and in Fig. 4 when coughs with mouth covering. Since the

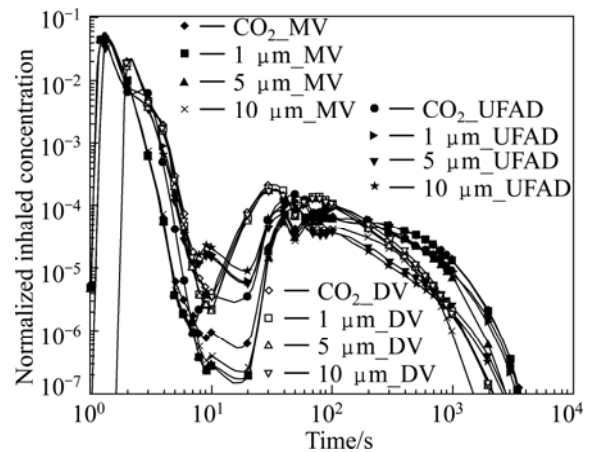


Fig. 3 Normalized inhaled concentration of co-occupant under three ventilation methods with infected person coughing without mouth covering

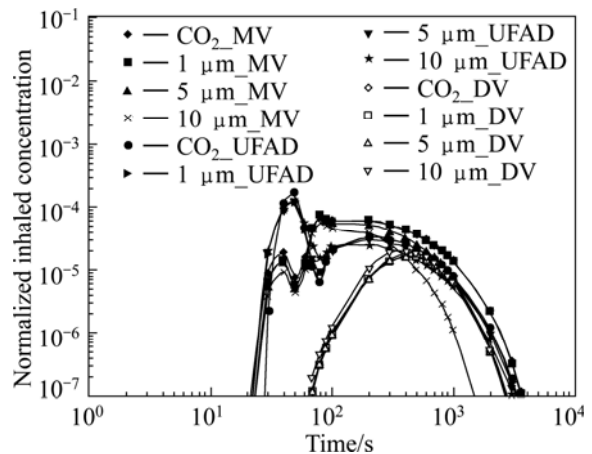


Fig. 4 Normalized inhaled concentration of co-occupant under three ventilation methods with infected person coughing with mouth covering

coughed air can approach the co-occupant immediately when there is no blocking, the exposed contaminant concentration is quite higher. Due to the mainly upward air movement under DV which hampers the horizontal transportation of the coughing air, the inhaled concentration reaches its peak at the first stage about 1 s later compared with MV and UFAD. With the time elapsing, this higher momentum coughing jet dissipates, and ventilation system distributes the dispersed droplet residuals gradually, leading to the decreasing inhaled concentrations. In the situations with mouth covering, the expelled air is thwarted and cannot reach the co-occupant directly, as shown in Fig. 2. Ventilation system then is the primary force to deliver these pathogen-laden droplets to the breathing zone of the co-occupant and result in a relatively lower inhaled concentration.

The inhaled dose of the co-occupant during the whole exposure process is shown in Fig. 5. Inhaled dose refers to the fraction inhaled by the co-occupant of the

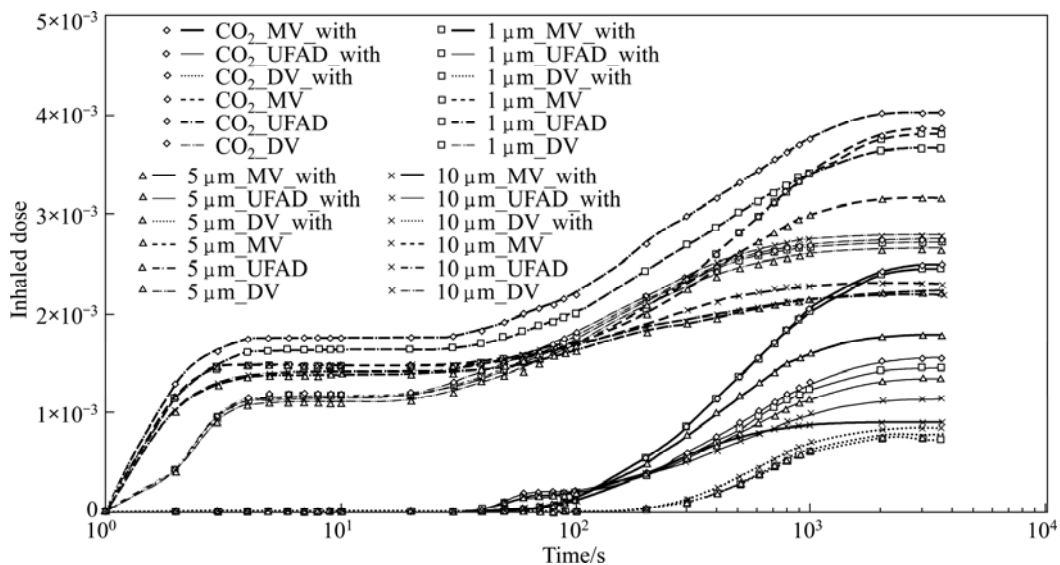


Fig. 5 Inhaled dose of co-occupant when infected person coughs with and without mouth covering under MV, UFAD and DV

total pollutant mass exhaled by the infected person. It can be observed that a short-term direct exposure without mouth covering can still pose higher health risk to the co-occupant. By employing a mouth covering, direct impact from the infected person can be avoided and a smaller inhaled dose of the co-occupant can be achieved. It is necessary to be mentioned that the inhaled dose under DV is lower for smaller droplets but higher for larger droplets for cases without mouth covering, while the lowest exposure can be achieved for all investigated droplets by wearing a mouth covering. Meanwhile, lower inhalation for smaller droplets under UFAD can also be maintained except 10 μm droplets compared with MV.

3.2 Effects of physical blockings under MV

To assess the performances of two physical interventions, namely mouth covering and desk partition, the dispersion of 10 μm droplets at the 2nd second is shown in Fig. 6, as well as the velocity vector in the centre plane ($X=1.5$ m). It can be seen that the exhaled air can reach the co-occupant directly and will cause high direct exposure when there is no barrier between the two people, while using mouth covering or desk partition can both interrupt the horizontal dispersion of the expelled droplets and may mitigate the co-occupant's exposure. However, these two blockings may show different efficiencies in reducing the co-occupant's exposure. As shown in Fig. 6, the coughed air when wearing mouth covering is redirected to the region behind the infected person where the coughed droplets can be extracted efficiently. Using desk partition, on the other hand, can thwart the exhaled air to the middle of the office which is located in the recirculation region.

In order to evaluate the exposure of the co-occupant, the normalized inhaled concentration of the

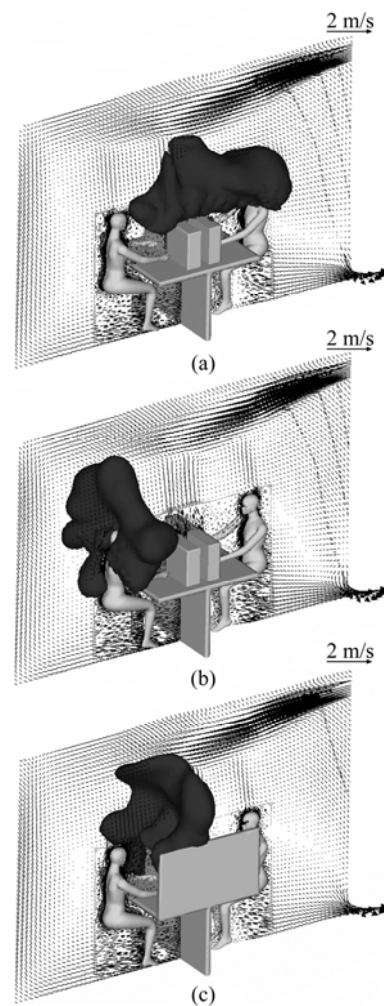


Fig. 6 Velocity vectors in centre plane ($X=1.5$ m) and concentration distribution profile of 10 μm droplets at 2nd second with normalized concentration not less than 0.001 (exhaled concentration of infected person is denoted to be 1.0): (a) Coughing without interventions; (b) Coughing with mouth covering; (c) Coughing with desk partition

co-occupant under different situations is shown in Fig. 7, and Fig. 8 illustrates the inhaled dose for the whole exposure process. If no blocking is employed, the coughing jet can approach the co-occupant directly, as shown in Fig. 7, and therefore leads to higher exposed concentration in the first 10 s. When mouth covering or desk partition is arranged, the direct impaction from the pathogen-laden coughing jet can be avoided and the exhaled droplets are mainly reflected to the region close to the infected person, as shown in Fig. 6. Later, air ventilation system distributes those droplets gradually, and the exposed contaminant concentration increases first and then decreases because of extraction and deposition of the droplets, as shown in Fig. 7. Because of the interruption of horizontal traveling of the exhaled droplets, the inhaled dose is decreased apparently. However, the dispersion of exhaled droplets due to ventilation system can still result in an un-negligible inhaled dose.

Comparing the inhaled dose of these cases, it is clear that these two physical blockings can only reduce

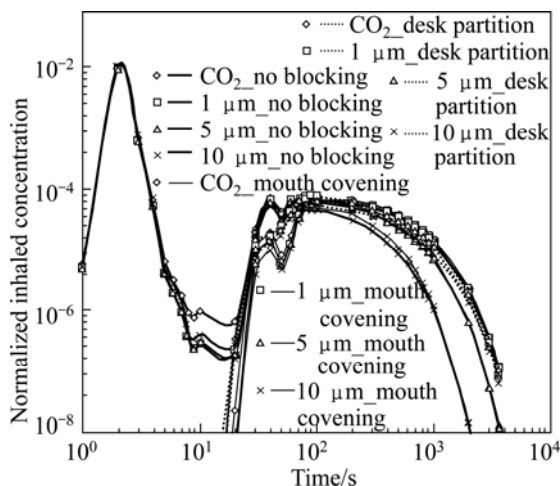


Fig. 7 Normalized inhaled concentration of co-occupant without physical blocking, with mouth covering, and with desk partition

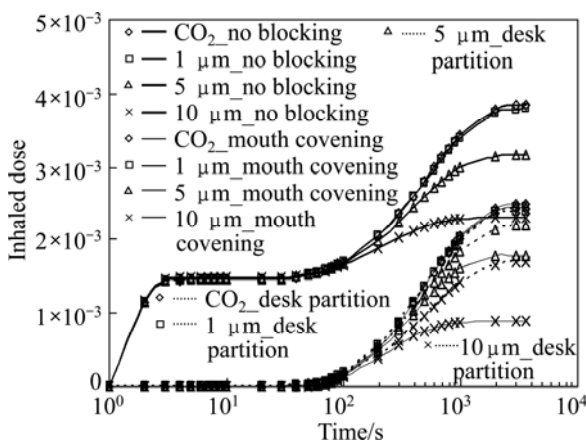


Fig. 8 Inhaled dose of co-occupant without physical blocking, with mouth covering, and with desk partition

the co-occupant’s direct exposure to the exhaled droplets under MV, while have limited effects on the airborne transmission of infectious viruses carried in droplet residuals. As to the performance of the two blockings, the co-occupant’s inhaled dose is almost the same for fine droplets, while the inhalation is lower for larger droplets when using mouth covering. This is for the reason that the coughed air, when adopting desk partitions, is reflected to the recirculation region of the office, which may hinder the deposition of larger droplets.

4 Discussion

It is well known that respiratory droplets evaporate very fast in indoor environment. For droplets with initial diameter smaller than $80 \mu\text{m}$, it takes them less than 1 s to evaporate completely [16–17]. Because of the high traveling velocity of coughing air and short distance between the physical blockings and the infected person, the evaporation processes and droplets deposition onto the barriers should be considered. An empirical equation [18] is employed to estimate the deposition rate for $10 \mu\text{m}$ droplet residuals assuming with a $20 \mu\text{m}$ initial size. The results show that the total deposition rate on the blocking can be about four orders of magnitude lower than the total emission. It will then be feasible not including droplets evaporation process in cases with mouth covering, assuming that the coughed air is redirected and released from the edges of mouth covering [8].

Apparently, wearing a mouth covering by the infected person may protect the co-occupant from direct exposure to the infectious coughed air and then reduce total inhalation. The efficiency of using this physical blocking may vary for different ventilation systems. As shown in Fig. 5, this covering functions more effectively under UFAD and DV, especially under DV. Unlike the cases without mouth covering under DV, in which the coughed air is released at a higher velocity and the extraction of the exhaled droplets relies on the upward-driven air flow, using mouth covering can confine most of the expelled air in the microenvironment of the infected person, which can facilitate moving those pathogen-laden droplets upward by thermal plume. Although the contaminant trapping phenomenon in the breathing zone [19, 5] may increase other occupants’ exposure risk under DV, covering mouth when breathing, coughing or sneezing, can ensure its best performance in the reduction of health exposure.

As mentioned before, although desk partition can protect the co-occupant from direct exposure to the coughed droplets, the inhaled dose of larger droplets for the occupants is higher than that with mouth covering.

This can be attributed to the reason that the coughed air is captured in the recirculation region, as shown in Fig. 6, which may slow down the deposition of larger droplets. Although MV can distribute the exhaled droplets to be evenly dispersed in built environments [5], contaminants deposition can be influenced once they are released to the recirculation zone. Rearranging the inlet and outlet diffusers are possible ways to eliminate or reduce the dead zone in order to facilitate the extraction of contaminants in cases with desk partition.

5 Conclusions

1) Wearing mouth covering by the infected person or employing desk partition can effectively protect the co-occupant from direct exposure to the coughed virus-carried droplets, and reduce the total inhaled dose. The two blockings show almost the same effects for fine droplets, while mouth covering performs better for larger droplets.

2) The co-occupant's inhalation under UFAD is almost the same as MV for all the droplets investigated when the infected person coughs without mouth covering. The total inhaled dose decreases apparently when mouth covering is used.

3) Among the three ventilation systems, the adoption of mouth covering under DV presents a cheering reduction on the co-occupant's inhalation, and the inhaled dose remains the lowest for all investigated droplets.

Acknowledgements

The project is funded by Research Grant Committee of the Hong Kong SAR government (RGC No. PolyU5265/08E).

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(Edited by YANG Bing)