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Transient CFD simulation of the respiration process and inter-person exposure assessment

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Abstract

It is known that the person-to-person spreading of certain infectious diseases is related with the transmission of human exhaled air in the indoor environments, and this is suspected to be the case with the severe acute respiratory syndrome (SARS) outbreak. This paper presents the numerical analysis of the human respiration process and the transport of exhaled air by breathing, sneezing, and coughing and their potential impact on the adjacent person in a modeled room with displacement ventilation. In order to account for the influence of the thermal plume around the human body, a three-dimensional computational thermal manikin (CTM) with an accurate description of body geometry was applied. Some of the results were compared with those from former simulations and experiments. It was found that personal exposure to the exhaled air from the normal respiration process of other persons is very low in a modeled room with displacement ventilation. Personal exposure to pollution caused by sneezing or coughing is highly directional. When two occupants face each other the cross-infection may happen due to the long transport distance of the exhalation.

Keywords: Human body; Computational thermal manikin; Inhalation; Exhalation; Human exposure

1. Introduction

The outbreak of severe acute respiratory syndrome (SARS) in over 25 countries around the world between November 2002 and June 2003 resulted in unprecedented international efforts to control the disease. Ever since the onset of the outbreak, there have been many debates on the possible transmission modes of the disease. In general, infectious respiratory diseases, such as the common cold, flu, and tuberculosis, can be transmitted by droplets transmission and/or airborne transmission, the former referring to membrane contact of pathogen-containing large droplets, and the latter referring to infection caused by inhalation of fine droplets. The WHO consensus report [1] is inclined towards the conclusion that person-to-person transmission of SARS was via large droplets. The current medical practice of infection control in hospital differs for diseases of these two transmission modes [2]. However, in either case, understanding the movement of the droplets generated by human respiration may lead to more effective control measures, which may include proper ventilation system design and operation and the proper use of personal protection equipments.

Li et al. [3] pointed out that most studies on transport of human exhalation were not conclusive. The dispersion and deposition of bio-aerosols caused by breathing, coughing, and sneezing is a fundamental process that has not been well understood. More than one million droplets with diameter up to 100 μm generated by sneezing could travel a distance of up to 3 m in the initial few micro-seconds due to the inertia of the droplets. The diameter of the droplets will decrease because of evaporation. Then these droplets can be suspended in

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the air when the size is smaller than 5–10 μm, since the aerodynamic drag force, which can be determined by the Stokes' law [4], can easily overcome the gravity force. As turbulence normally exists, these droplets can remain suspended in the air over prolonged periods. Zhao et al. [5] showed that the concentration of the droplets created by the respiration process reduces to below 0.001% of the initial concentration within 1.0 m away from the human body and droplets produced by sneezing or coughing could transport horizontally a distance of 3 m with an outlet velocity of 20 m/s.

In most previous numerical investigations of personal exposure the presence of the human body is excluded for simplicity. However, the existence of a person in a ventilated room may modify the local flow field and consequently the local contaminant field which determines the actual human exposure. A resting human body may act as a heat source generating convective upward flow and an obstacle to the ambient room flow [6]. Strictly speaking, the detailed real geometry of a human body should be used if the local air movements around occupants are the focus of the study [7]. Since the inhalation region and the transport of human exhalation result from the complex interaction between different airflows, including room airflows, respiration flow, warm rising flow around the human body, and air movement due to physical activity, the application of a computational thermal manikin (CTM) can potentially lead to some insight into these processes. The development of CTM engineering is in its preliminary stage [8], but a CTM can predict personal exposure to air pollutants and airborne pathogens, and it is also useful for the study of local thermal comfort and for the development of personalized ventilation.

In this paper, to account for the influence of the thermal plume around the human body, a three-dimensional CTM with an accurate description of body geometry is applied, so that the transient airflow around the nose and mouth during respiration, the inhalation region, the exhaled air transport, and the sneezing process can be analyzed.

2. Outline of CFD method

The detailed numerical geometry of the thermal manikin is obtained from a physical thermal manikin by using a three-dimensional laser scanning technique. The geometry of the CTM is a real and accurate representation of a nude seated female occupant. The surface area is 1.5696 m^2. Two human bodies represented by such a CTM facing each other are placed in a displacement ventilated room (Fig. 1). One is the polluting source and the other is exposed. The distance between the nose tips is about 1.2 m. The ventilation air is supplied from the sidewall at the floor level, with an inlet facial velocity of 0.2 m/s, and the supply air temperature is 22 °C, and the turbulent intensity I is assumed to be 20%. The ventilation rate is 0.024 m^3/s and it provides the room with 5.54 air changes per hour, which approximates a practical displacement ventilation design. No other heat sources are present in this modeled room, except the convection heat loss from the two human bodies. The exhaust grill is located at the ceiling level. In this case, there is no strong buoyancy-driven convection flow, so the airflow pattern in this modeled room will be close to a uni-directional flow, which is desirable for achieving better ventilation effectiveness. In reality, if there are other more intensive convection heat sources, such as other office appliances, and warm window/wall surfaces, the hot plume generated by these sources may generate recirculation.

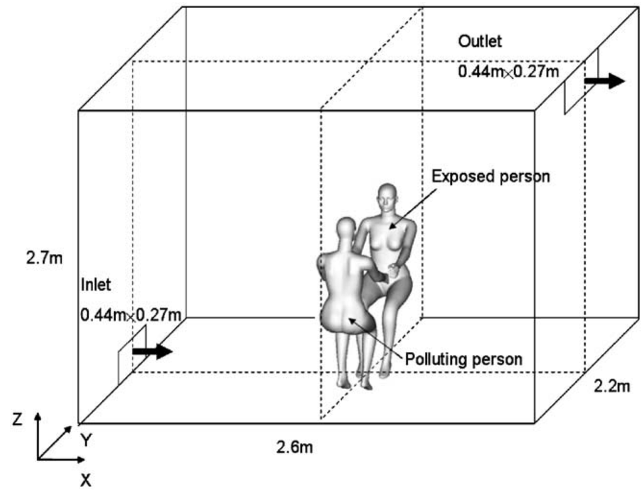

Fig. 1. Schematic of the displacement ventilated room and sitting positions of the two persons.

The ventilated room is divided into two parts: a cuboid enclosing the human bodies and the remaining room space for grids generation. The cuboid is broken with unstructured grids (tetrahedral cell topology) due to the complex geometry of the human body while the remaining room space is discretized with structured grids (Fig. 2). In order to express the complex human body geometry especially the extremities of the head, the cells with the length scale of centimeters, even millimeters, should be applied. Since gradients of the air velocity field and the temperature field surrounding the body are high four boundary layers are created around the human body with the first layer height of 0.2 mm. The total number of cells is 2,525,729. The RNG k–ε model including a differential formula for effective viscosity to account for low-Reynolds-number effects, combined with enhanced wall treatment which integrates a two-layer model with enhanced wall function, is used in this simulation [9] because the airflow around the human body sitting in the displacement ventilated room is not a fully developed turbulent flow. The value of $y+$ of the grids close to the human body is less than 1. The location of the first grids to the wall is of great importance in the accurate simulation of convective heat transfer if wall functions are used. Normally the value of $y+$ should be in the range of 30–100 if the standard wall function works. However, the small length scale of the grids close to the body mentioned before limits the value of $y+$. Therefore here the enhanced wall treatment is applied which requires at least 10 cells within the viscosity-affected near-wall region. Detailed boundary conditions are listed in Table 1.

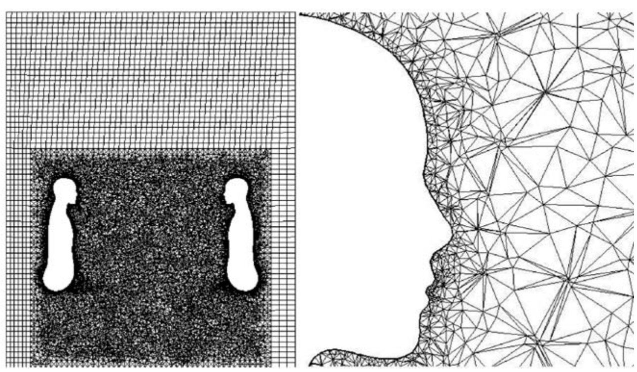

Fig. 2. Grids system.

Table 1
Numerical scheme and boundary conditions

Turbulence model	RNG k–ε model including low-Reynolds-number effect
Numerical scheme	Upwind second-order difference, transient state with full buoyancy effect, enhanced wall treatment
Room air inlet	$V = 0.2\,\text{m/s}$, $T = 22\,°\text{C}$; $I = 20\%$; $D = 0.335\,\text{m}$ (I is turbulence intensity, D is hydraulic diameter)
Room air outlet	Pressure outlet
Room wall	Adiabatic wall
Human body	$T = 31\,°\text{C}$
Nose/mouth	Velocity: a time function

The real respiration process of the polluting CTM is approximated by a sinusoidal curve (Fig. 3). We assume the frequency of respiration under light physical work is 17 times per minute with a time-mean rate about 8.4 l/min [10]. The transmission of the exhaled air is calculated by tracer-gas diffusion analysis. Tracer gas of concentration C_{ex} 1000 ppm is added into the exhaled air and its transient spreading in the room space is calculated based upon the governing conservation equation for chemical species in the following form:

$$\frac{\partial}{\partial t}(\rho\varphi) + \text{div}(\rho\vec{U}\varphi - \Gamma_\varphi \times \text{ grad } \varphi) = S_\varphi, \tag{1}$$

where t is time, ρ is air density, φ is tracer gas concentration, $\vec{U}$ is velocity vector, Γ_φ is diffusion coefficient, and S_φ is the source term. Once the tracer gas concentration φ for a nodal point is obtained, the mass fraction f of the exhaled air can be subsequently calculated by the following equation:

$$f = \varphi / C_{\text{ex}}. \tag{2}$$

The mass fraction f basically means the fraction of exhaled air at that point.

For normal breathing process, using tracer-gas diffusion analysis is reasonable since the number of droplets in the exhalation is almost zero. As to the sneezing or coughing process, simulating droplets transport by concentration conservation equation means shear stress, gravitational setting, and electrostatic force effect are not taken into account. However in the initial several seconds after sneezing or coughing, application of the tracer-gas method is rational due to the same high velocity of droplets and the exhaled air and the fact that the momentum, heat, and mass exchanges between droplets and room air can be neglected. After this initial period the evaporation and cohesion phenomenon will be significant and aerodynamic investigations on droplets or particles are necessary. In this regard, the simulated tracer gas movement in this study will more closely represent the fine droplets, especially those with an aerodynamic

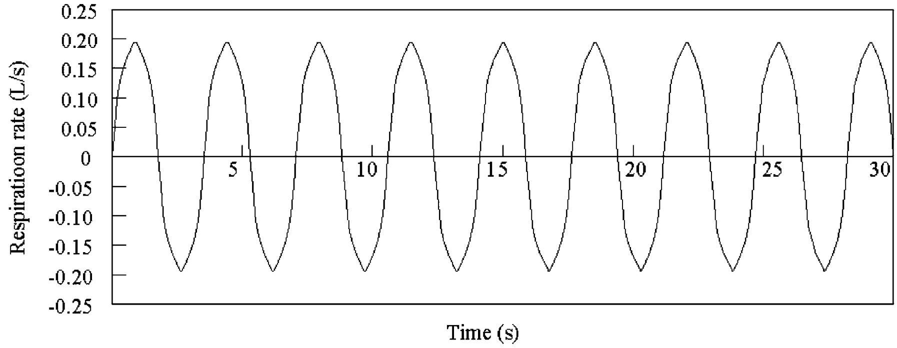

Fig. 3. Approximation of the transient respiration process.

diameter less than 2.5 μm. Modeling the movement of larger-size particles requires the more complicated particle trajectory modeling approach, or the Eulerian approach taking into account the gravity settling effects.

The transient process of the exposed CTM is simplified to a steady inhalation process with an inhaled air rate of 0.14 l/s. Three different cases for the polluting CTM, respectively representing the normal respiration through the nose or mouth, and sneezing or coughing process, are studied. The opening area of the nose and mouth is 1.5 and 2.5 cm^2, respectively. The direction of the exhaled airflow from the nose and mouth is 30° downward and horizontal respectively. The temperature of exhalation is 34 °C and the density is 1.15 kg/m^3 [11,12]. The assumed duration of sneezing is 1 s with the volume flow rate of 250 l/min [13]. For simplicity only one sneezing process is modeled, although people may sneeze more than once in a cycle of sneezing or coughing.

3. Results and discussion

3.1. The transient respiration process

Figs. 4 and 5 show the airflow vectors at the facial region when the occupant breathes through the nose and mouth, respectively. Due to the relatively small airflow rate of respiration the inhaling and exhaling processes have almost no influence on the room airflow pattern. When breathing through the nose the potential flow of inhalation is besieged by the natural convection surrounding the body. Small swirl flows are generated beside the mainstream of the intermittent exhalation jet. When breathing through the mouth the exhaled air is brought away at the direction of about 45° upward in front of the face gradually. The tracer-gas concentration in the room space 0.8 m away from the head is almost zero. This indicates that human exposure to the exhaled air by normal respiration of the others is minimal in this displacement ventilated room. This result is in line with the previous investigation on exhaled droplets transport [5]. While Figs. 4 and 5 show the three cycles of breathing simulated, it can be expected that, with the time elapsing, the pollutants in exhalation may accumulate indoors and reach a quasi-steady concentration level. But the distribution will strongly depend on the ventilation or the air distribution methods. With mixed ventilation, i.e., when air is supplied from a high-velocity, high-entrainment diffuser located at the ceiling level, a relatively uniform pollutant concentration will exist in the room space. In the present simulation, the room has a quasi-unidirectional flow pattern, and our

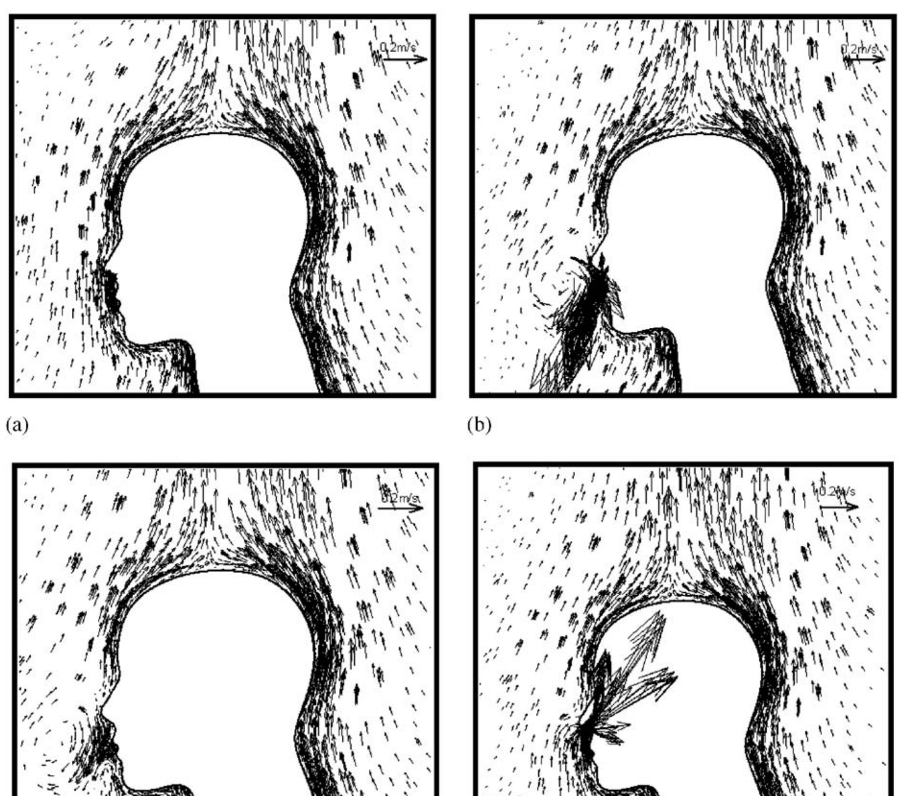

Fig. 4. Velocity vector distributions in respiration area around the nose, (a) $t = 7.04$ s, (b) $t = 7.92$ s, (c) $t = 8.80$ s, (d) $t = 9.68$ s.

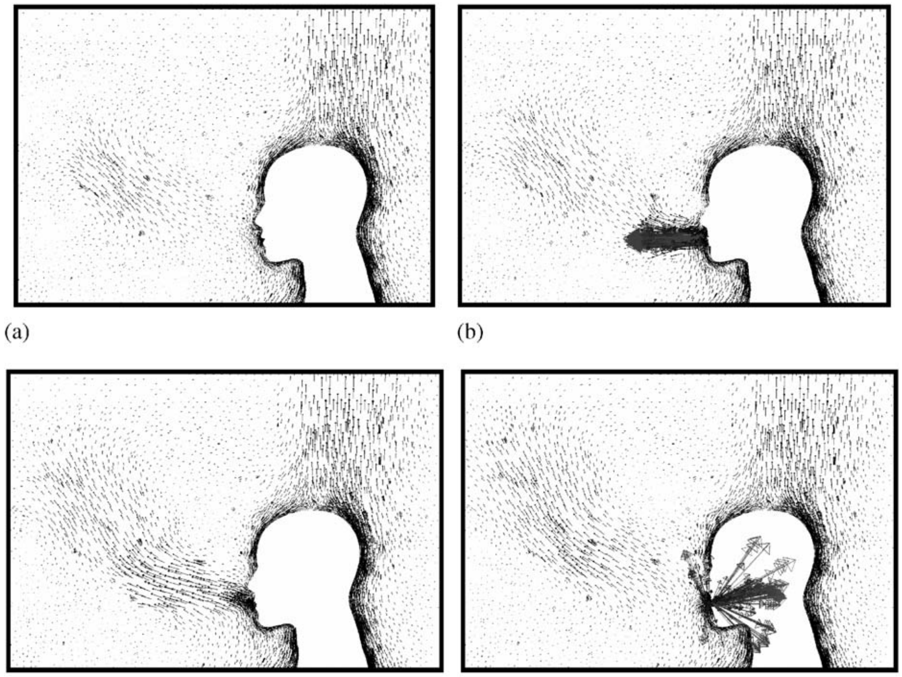

Fig. 5. Velocity vector distributions in respiration area around the mouth: (a) $t = 3.52$ s, (b) $t = 4.40$ s, (c) $t = 5.28$ s, (d) $t = 6.16$ s.

steady-state simulation indicates that the concentration of exhaled air is only present above the occupied zone, so that human exposure to the others' exhalation is also close to zero since the exhaled air is promptly exhausted at the ceiling level.

Fig. 6 shows that the warm rising airflow under the jaw close to the human body is diverted to the cheeks. Zhu et al. [14] emphasized that the influence of jaw cannot be ignored when examining flow field in respiration area.

Figs. 7 and 8 illustrate the path-line descriptions of the inhaled and exhaled air through the nose and mouth, respectively. The exhaled air through the mouth is able to get away from the enclosure of the warm rising airflow around the human body since the exhaled airflow is highly directional in horizon at a high momentum level. In contrast the exhaled air through the nose is entrained upward by the thermal plume because its downward direction reduces the momentum. In both situations the inhaled air is from the lower level of the displacement ventilated room in front of the body by natural convection. BjØrn and Nielsen [15] pointed out that the exhalation stratified at the breathing height in the displacement ventilated room if the vertical temperature gradient was high enough, i.e. 0.5 °C/m or above. However, it is not observed in the current numerical study, presumably due to the low convection heat present in the modeled room.

Figs. 9 and 10 show the temporal variations of mass fraction f at the nose and mouth when breathing through the nose or mouth, respectively. Results of three breathing cycles are shown. The mass fraction f during the exhalation periods are obviously 100% of the exhaled air as it should be, and the mass fraction f during the inhalation periods is an indication of the percentage of re-inhalation of one's own exhaled air. Most of the exhaled air is brought away while a small portion is re-inhaled by the occupant. When breathing

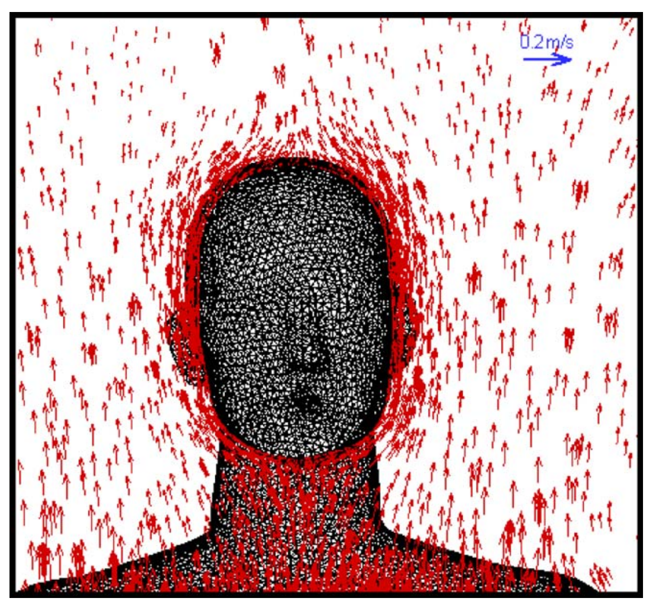

Fig. 6. Velocity vector distribution at the jaw region.

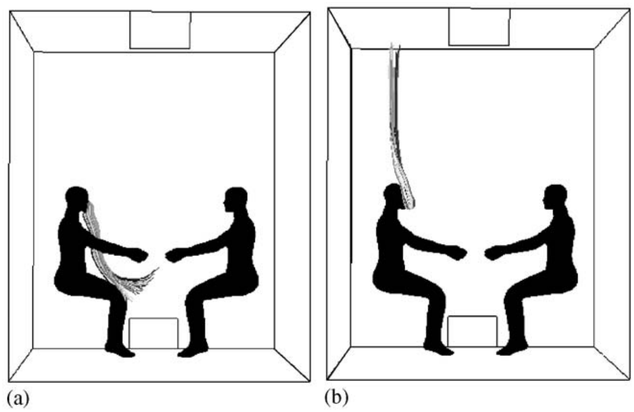

Fig. 7. Path-line descriptions of inhalation and exhalation only through the nose: (a) inhalation, (b) exhalation.

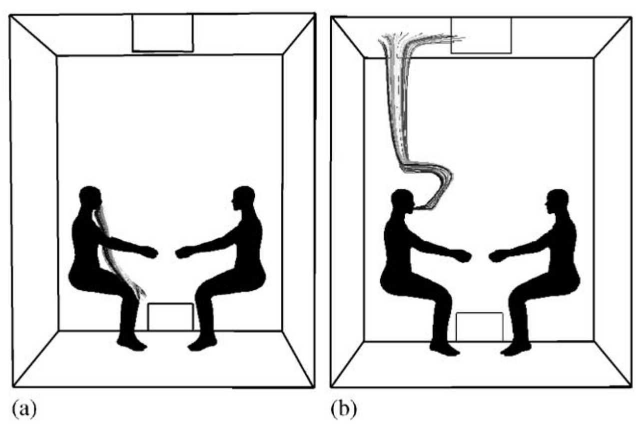

Fig. 8. Path-line descriptions of inhalation and exhalation only through the mouth: (a) inhalation, (b) exhalation.

through the nose the mean re-inhalation rate is about 10%, which is lower than the value of 16.2% in the simulation of a standing human body by Murakami [16]. The discrepancy may be due to the different parameter settings such as respiration frequency, exhaled air condition and direction, body posture, and nose nostril area. When breathing through the mouth the re-inhalation rate is almost zero. The reason is that the horizontal buoyant jet from the mouth can penetrate the envelope of the thermal plume and be taken away by the room air.

3.2. The sneezing process

Fig. 11 shows the spreading of the exhaled air during and after sneezing. It is obvious that a long transport distance of exhalation is induced by sneezing or coughing. In the present scenario where two occupants face each other at a distance of about 1.2 m, the exhalation by sneezing approaches the other person step by step. The time of 1 s is enough for it to reach the breathing region of the exposed person. Because of the

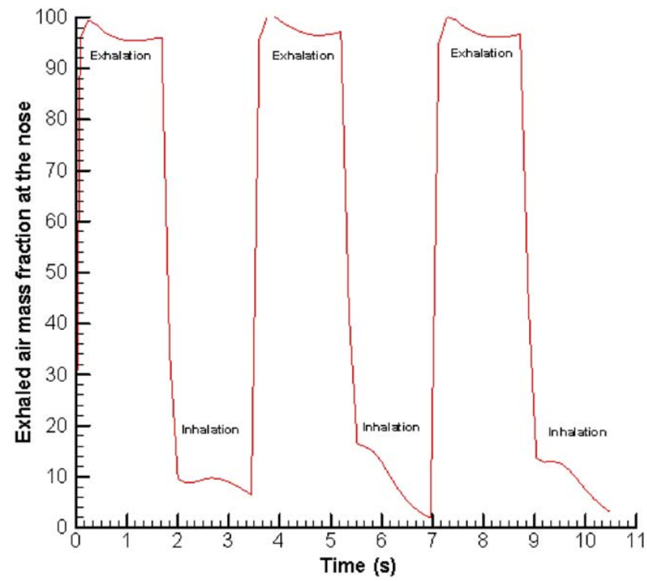

Fig. 9. Temporal variation of mass fraction f of the exhaled air when respiring only through the nose (the value of f during the inhalation periods represents the re-inhalation of the previously exhaled air).

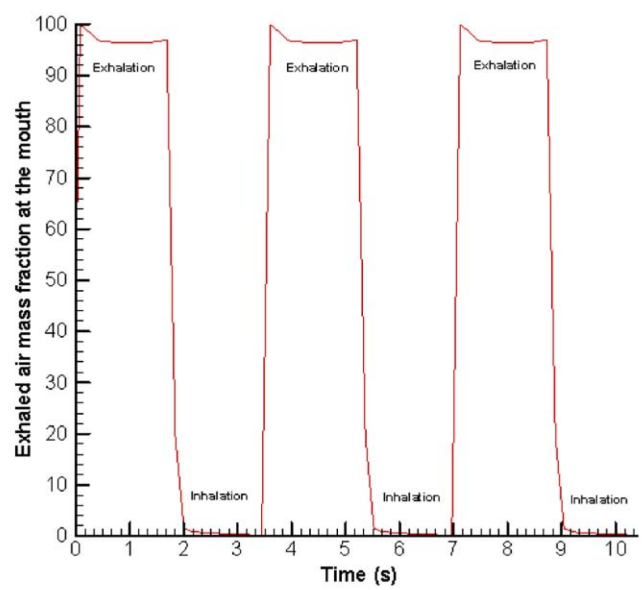

Fig. 10. Temporal variation of mass fraction f of the exhaled air when respiring only through the mouth (the value of f during the inhalation periods represents the re-inhalation of the previously exhaled air).

high velocity the exhaled air flows indoor almost horizontally. This horizontal airflow is able to penetrate the protection of the boundary layer flow enclosing the exposed person. It proves the fact that if the thermal plume is peeled off or penetrated, its positive function on inhaled air quality by drawing fresh air from the lower level of the displacement ventilated room will disappear. Fig. 11(g) indicates that the exhaled air can get across the human body, impinge on the wall and

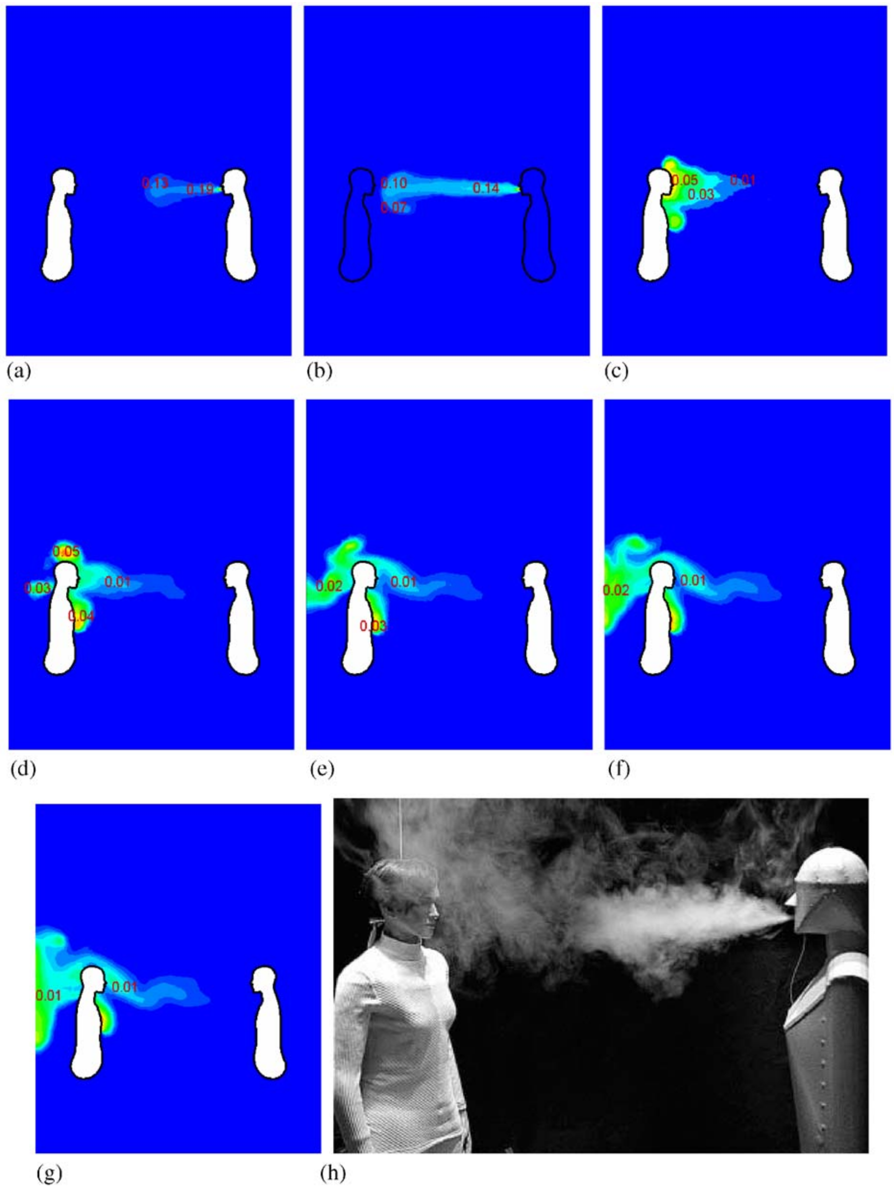

Fig. 11. Distributions of the mass fraction of the sneezed air during and after sneezing: (a) $t = 0.5\,\mathrm{s}$, (b) $t = 1.0\,\mathrm{s}$, (c) $t = 1.5\,\mathrm{s}$, (d) $t = 2.0\,\mathrm{s}$, (e) $t = 2.5\,\mathrm{s}$, (f) $t = 3.0\,\mathrm{s}$, (g) $t = 3.5\,\mathrm{s}$, (h) smoke visualization of exhalation flow from the mouth [15].

finally be exhausted. These simulation results correspond well with the smoke visualization (Fig. 11(h)). However the smoke is shown to be rising above the head of the exposed occupant due to the buoyancy effect and there is no smoke blocked by the chest. This is because the exhaled air velocity is much lower in the experiment and consequently the value of Gr/Re^2 is higher than in the present simulation.

Fig. 12 shows the fraction of the sneezed air in the inhaled air at different moments after a sneezing. In the period from 1.0 to 2.5 s the concentration in the inhalation of the exposed person is greater than 1%. It is well known that the health impact of a gaseous pollutant to the human body is closely related to the received dose and exposure time. For example, US EPA defined Acute Exposure Guideline Levels as the threshold concentrations of one-time-only exposure over a certain period [17]. Here we put forward the conception of ''infection index'' η by the following equation:

$$\eta = \int_0^\infty V \rho_{\mathrm{in}} C \mathrm{d}t, \tag{3}$$

where V is the inhalation rate ($\mathrm{m^3/s}$), ρ_{in} the inhaled air density ($\mathrm{kg/m^3}$), and C the mass fraction of the sneezed air in the inhaled air. As to current simulation the value of η in regard to the exposed person is 800 μg. This value can be compared with the safety threshold, which is the maximum exposure that cannot cause infection. It is obvious that for different airborne infectious diseases

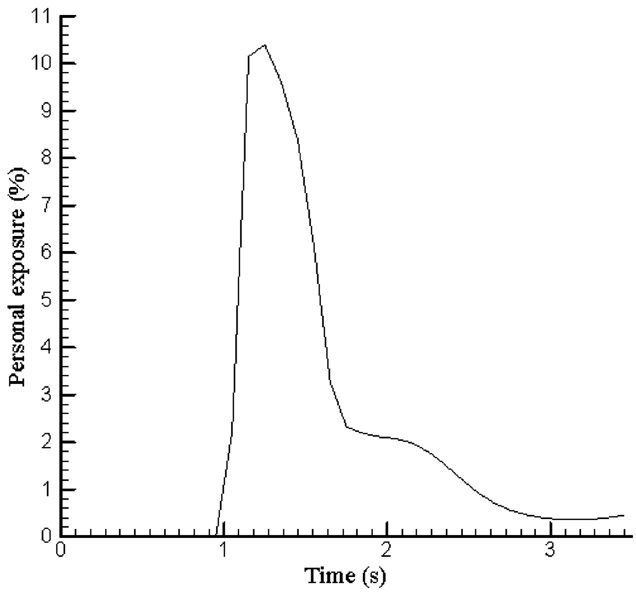

Fig. 12. Sneezed air mass fraction in the inhaled air of the exposed person during and after sneezing.

the value of the safe threshold is different. Also it should be borne in mind that the adoption of the infection index must be accompanied by the virus concentration in the exhaled air. Toxicology demonstrates that human beings differ in sensitivities to every virus and the response spectrum follows a normal distribution [18]. All these issues are out of the scope of this study. Present modeling proves pollution created by sneezing may cause cross-infection indoors. The traditional courtesy of "covering your mouth with a handkerchief when sneezing" may also have its merit in reducing infection. In regard to the control strategies good personal hygiene habits such as wearing a mask and personalized air supply are important. Further studies on their effects on preventing the transmission of respiratory diseases are needed.

It should be noted that the exposure to sneezing or coughing is highly directional. It can be envisaged that if one is at the back of the sneezing person the direct exposure will be much less. In the current case with displacement ventilation the large percentage of pollutants can be exhausted by the ventilation air quickly.

4. Conclusions

A three-dimensional CTM with the real body geometry is applied to study the inhalation region, transmission of the exhaled air, and personal exposure. The following main conclusions can be drawn:

1. It appears that personal exposure to the exhaled air from the normal respiration process of other persons is very low in the present modeled room with displacement ventilation. This conclusion agrees with the steady-state simulation, and also agrees with the notion that displacement ventilation has better ventilation effectiveness than mixed ventilation. This result may well support that better ventilation system design in building spaces may well reduce infectious disease spread.
2. The percentage of exhaled air in the next inhalation when respiring respectively only through the nose and mouth is 10% and 0%, respectively, which agrees with conventional wisdom that one should inhale though the nose and exhale through the mouth.
3. When two occupants face each other cross-infection may happen due to the long transport distance of the sneezed air, but this exposure is highly directional. The practical implication is that displacement ventilation may still have an effect in minimizing the indirect exposure to pollutants contained in exhaled air.

This study demonstrates how CFD simulation can potentially reveal the spread mechanisms of exhaled pollutants. Further studies are required to investigate how the inhalation region and exhalation transmission are influenced by the metabolic rate, breathing frequency and flow rate, exhaled air temperature and density, and body posture and orientation. Researches on the diffusion of the droplets generated by the sneezing or coughing process are also imperative since they, especially the larger-sized ones, have different aerodynamic behaviors from the gas phase.

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