Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Transient CFD simulation of the respiration process and inter-person exposure assessment

Naiping Gao*, Jianlei Niu

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

Received 1 March 2005; received in revised form 25 April 2005; accepted 11 May 2005

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.

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
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 m². 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 m³/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.

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...
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 8.41/min [10]. The transmission of the exhaled air is calculated by tracer-gas diffusion analysis. Tracer gas of concentration $C_{\text{ex}}$ 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:

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

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

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

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

---

Table 1: Numerical scheme and boundary conditions

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

---

**Fig. 2.** Grids system.

**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 cm², 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/m³ [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-speed, 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.](image-url)
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. Björn 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...
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 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...
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” $\eta$ by the following equation:

$$\eta = \int_0^\infty V \rho_m C dt,$$

where $V$ is the inhalation rate (m$^3$/s), $\rho_m$ the inhaled air density (kg/m$^3$), and $C$ the mass fraction of the sneezed air in the inhaled air. As to current simulation the value of $\eta$ in regard to the exposed person is 800 $\mu$g. 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
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 inhala-
tion 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 other cross-infection
may happen due to the long transport distance of
the sneezed air, but this exposure is highly direc-
tional. 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 fre-
quency 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.

Acknowledgements

The project is funded by the Research Grant
Committee of the Hong Kong SAR government, under
the Project no. PolyU5031/01E. The authors also wish
to thank Miss Josephine Lau and Dr. David T.W. Chan
for their assistance in the laser scanning of the thermal
manikin.

References

[1] WHO, Consensus document of the epidemiology of severe acute
respiratory syndrome (SARS), Department of Communicable
Disease, Surveillance and Response, WHO/CDS/CSR/GAR/
2003.11.
[2] ASHRAE, HVAC design manual for hospital and clinics,
ASHRAE Special Project 91, 2003. American Society of Heating,
Refrigerating, and Air-conditioning Engineers.
[3] Li Y, Huang X, Yu ITS, Wong TW, Qian H. Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. Indoor Air 2005;15(2):83–95.

[4] Vincent JM. The motion of airborne particles. Oxford: Pergamon; 1995 Aerosol science for industrial hygienists p. 72–113 [Chapter 4].

[5] Zhao B, Zhang Z, Li X. Numerical study of the transport of droplets or particles generated by respiratory system indoors, Building and Environment 2004;40(8):1032–9.

[6] Nielsen PV, Bjørn E, Brohus H. Contaminant flow and personal exposure. Heating/Piping/Air conditioning Engineering 2002;74(8):40–5 63.

[7] Topp C, Nielsen PV, Sorensen DN. Application of computer simulated persons in indoor environmental modeling. ASHRAE Transactions 2002;108(2):1084–9.

[8] Aalborg University and International Center for Indoor Environment and Energy, http://www.cfd-benchmarks.com.

[9] Fluent Inc. Fluent 6.1 User Manual, 2003.

[10] Huang DY. Physical diagnostics. China Commerce Publishing Co; 1977.

[11] Höppe P. Temperatures of exhaled air under varying climatic conditions. International Journal of Biometeorology 1981;25:127–32.

[12] Bjørn E. Dispersal of exhaled air in stratified surroundings-CFD studies. Proceedings of the ROOMVENT2002, Copenhagen, Denmark, 2002, p. 285–88.

[13] Badeau A, Afshari A, Goldsmith T, Frazer D. Preliminary prediction of flow and particulate concentration produced from normal human cough dispersion. Proceedings of the second joint EMBS/IBMBE Conference, Houston, TX, USA; 2002, p. 23–6.

[14] Zhu S, Kato S, Murakami S, Hayashi T. Study on inhalation region by means of CFD analysis and experiment. Building and Environment 2004, in press.

[15] Bjørn E, Nielsen PV. Dispersal of exhaled air and personal exposure in displacement ventilated rooms. Indoor Air 2002;12(3):147–64.

[16] Murakami S. Analysis and design of micro-climate around the human body with respiration by CFD. Indoor Air 2004;14(7):144–56.

[17] US EPA, Proposed temporary Acute Exposure Guideline Levels (AEGLs). United States Environmental Protection Agency 2001.

[18] Li X, Yang J, Sun W. Strategy to optimize building ventilation to aid rescue of hostages held by terrorists. Indoor and Built Environment 2005;14(1):39–50.