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Quantify impacted scope of human expired air under different head postures and varying exhalation rates

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ABSTRACT
Many researches indicate human respiration flow and background ventilation are two important aspects leading to possible respiratory disease spread. However, current studies on respiration flow and the resulted exhaled pollutant dispersion are limited, because different head postures, respiration mode, breath rate, room ventilation and so on, can exert profound impacts that are not understood very clearly.

To evaluate the role of head postures on transmission of human exhaled pollutants, this study uses a computational fluid dynamics (CFD) program to study the exhalation flow of a sitting adult in a calm indoor office. Four different head postures are considered: sitting upright viewing front, sitting upright but head tilted viewing upward, sitting upright but head turned viewing the lateral, and sitting but pillowing head on a table. Based on the decay percentage of a gas concentration, the impacted scope of expired air is identified. The common posture by sitting upright viewing front is selected to investigate the change of impacted scope with increasing exhalation rates. The experimental test is also carried out using a breathing thermal manikin. This study finds out that the impacted scope of expired air under different head postures is different. The horizontal impacted distance is highly dependent on the specified threshold concentration. If a person sits around at a table and makes a deep exhalation, other people shall be apart from him/her with a larger distance to be free from the exhaled pollutant exposure, once his/her thermal plume is blocked by the table.

1. Introduction

With an increasing rate for human engaged in indoor activities, more concerns have been raised on indoor health, especially on how to control and prevent possible airborne disease transmission. The historical outbreaks of airborne contagious diseases like various types of influenza have severely strike the global economy and deprived hundreds of human lives. By July 8, 2009, over 94,000 influenza A (H1N1) cases and 429 influenza A-related deaths from 136 countries have been reported [1]. Not only the influenza could be deadly, there were 8098 people infected by the Severe Acute Respiratory Syndrome (SARS) and 774 of them died in 2003 [2]. The loss of the world economy due to SARS is close to 40 billion US dollars [3]. Some researches [4] reveal that the respiratory infectious disease seems to transmit through the airborne routes. An infected person may discharge the pathogens to the surrounding air by breathing, talking, coughing and sneezing, etc. Accompanied by strong expired air jets, pathogens can be transmitted away a certain distance. Apparently, it would be very helpful for controlling and preventing the disease transmission if the impacted scope of expired air from an infected person can be quantified accurately.

Toward the above aims, this paper investigates human expired air motion and the associated airborne pollutant transmission. The impacted scope of human expired air by the nose is determined quantitatively. The relationship of impacted region changing with increasing exhalation rates are to be revealed as well, by taking account of different head postures.

2. A brief overview of human expired air dispersion

A person inhales the ambient fresh air (typically in volume ratio oxygen possesses: 20.9%, carbon dioxide: 0.04%, water vapor: 0.75%, nitrogen: 78.4%) with adequate oxygen and exhales the pulmonary air to sustain human metabolism. The exhaled air is featured by high concentration of carbon dioxide (4.2%) and water vapor (6.2%) [5]. The remnant pulmonary air components include oxygen (15.3%), nitrogen (74.3%), and droplets that are atomized on mucous membrane of respiratory tracts, etc. The droplets can carry
millions of germs and are thus believed to be responsible for many infectious disease contagions through respiration [6]. The release of droplets is accompanied by various human respiratory activities, which can be as mild as the normal breathing during gently work, or as intense as talking, coughing and even sneezing, etc. The intense upper respiratory activities can discharge larger content of germs than the normal breathing [7]. If there is no cover, a coughing or sneezing in a calm environment can puff away the droplets horizontally two to three meters [8,9]. Due to very evident sick symptoms emerged during talking, coughing and sneezing, the healthy people are usually more alert on the possible contraction and thus tend to keep themselves away from the infectious sources. However for the normal breathing, especially in the disease incubation period without showing any symptom, people would lose alert on the possible cross infection. Therefore, though much lower intensity, the normal breathing can be a non-ignorable path for disease transmission as it has higher event frequency. For example, when breathing for 2 h the total volume of exhaled air reaches 1600 L, which corresponds to the air discharged by 100 coughs [10]. The release of droplets during normal breathing (in the order of 10^3/j) is non-neglectable, either [11]. Undoubtedly, the expired air dispersion by the normal breathing shall be paid with significant attention.

Four common breathing modes exist, such as inhalation/exhalation through: (1) nose/nose, (2) nose/mouth, (3) mouth/nose, and (4) mouth/mouth [12]. The transient respiration process may be approximated into a sinusoidal wave [10,13,14] or simplified into a trapezoid [15,16]. Usually, the breath rate and frequency vary depending on the human metabolism. At light work, the pulmonary ventilation is about 5–6 l/min with 10–20 breaths/min; however, if the work strength increases, the flow rate can be up to 20 times larger and the frequency can reach 45 breaths/min [17]. For simplicity, when studying only the exhaled pollutant dispersion, the inhalation process may be omitted and consider the exhalation through nose or mouth only. For example, Özcan et al. [18] visualized the constant exhalation flow in the breathing zone. Zhao et al. [8] modeled the exhalation through the nose to study the transport of exhaled contaminants. Similarly, Bjørn and Nielsen [19] investigated the exhaled air motion through nose and mouth, respectively, as well as the resulted personal exposure.

The exhaled air jet from the mouth can be treated as horizontal when sitting or standing upright [10,19,20]. However, the two exhaled jets from the nostrils are more complicated. They are usually inclined downwards about 45° from the horizontal and keeping a separation angle of 30° between each other [12,20]. Because the total opening area of the nose is only about a half of the mouth’s [12,20], the discharge momentum through the nose is much stronger and directional. This paper has thus put a focus on the exhalation through the nose. The exhaled air speed has a wide span due to the sinusoidal-like respiration rhythm. If the mean area of the nose is thought to range from 0.46 to 0.94 cm² for an adult and a typical peak expiratory flow rate is taken as 0.4 l/s [10], the theoretical peak discharge velocities at the nostrils are among 4.3–8.7 m/s. However, for a forced expiration, the discharge velocities can be larger by at least one order of magnitude. This is because the peak expiratory flow rate in a force expiration can reach 10.4 l/s based on the measurement from an early work [21], which are comparable to paired coughs.

The motion of exhaled jets in the ambient air is the result of combined interaction of many factors. These factors include jet delivery momentum, exhaled air temperature, human thermal plume, background ventilation, room geometry and layout, and so on. In a calm ambient environment, the human exhaled air jets tend to go downward first and then rise up due to buoyancy effect [18]. This is because the surrounding air temperature is commonly lower than that of the exhaled air, which is generally kept between 32 °C and 33 °C [19] and varies with temperature of inhaled air [22]. The thermal plume around a human body plays a role in tending to prevent the exhaled air jets from being spread out and aids the rising motion of the jets [23]. The respiration flow itself may somehow disturb the rising body thermal plume in the breathing zone, but has no significant impact above the breathing zone [24].

The impacted region of exhaled air depends on the motion of expired air jets. Knowing such impacted region is of great importance. However, based on the available published literature, the quantitative results on circumscription of the impacted region seems controversial, regarding in whether the expired air penetrates the body thermal plume or not. Johnson et al. [25] conducted tests both for a breathing thermal manikin and a volunteer adult in an almost calm chamber using a laser Doppler anemometer, and claimed that the expired air through the nose does not break through the surrounding thermal boundary layer. Homma and Yakiyama [23] have obtained similar findings, though they carried out test with an indirect method using an infrared thermogram. The transient CFD simulation by Gao and Niu [13] also supports that the exhaled air through nose is confined into the human thermal boundary layer. Despite of the above, some opposite findings are also reported. For example, Bjørn and Nielsen [19] did the smoke visualization for a breathing thermal manikin and found that the exhaled air can penetrate the thermal plume and impose exposure to the other manikin standing at 0.4 m away. The visualization by Melikov and Kaczmarczyk [12] has also clearly shown that the expired jets from the nostrils of a seated breathing manikin have definitely broken the thermal boundary layer. The more precise particle image velocimetry (PIV) test by Özcan et al. [18] shows that the down–upward exhaled jets have permeated through the thermal plume, too. In addition, the numerical study by Zhao et al. [8] illustrates that the exhaled droplets (1 μm) through normal respiration can be transported 0.6 m away, which is already beyond the thermal boundary layer. The thickness of thermal boundary layer near the human head is around 0.15–0.2 m [23,26,27], which does not seem too difficult to penetrate through. Only when the exhaled jets are discharged at very low speed such as less than 1.0 m/s, may the exhaled air be fully confined within the thermal boundary layer and then be entrained upwards [7].

The above controversy may be explained by the following aspects. (1) There is meaningful difference in test subjects which may not be disregarded. For example, different subjects have distinct respiration mode, pulmonary ventilation rate, breath frequency and rhythm, nose structure and geometry, nostril opening area, expired jet direction and temperature, body geometry and shape, posture, clothing condition and surface temperature distribution, etc. This means the non-identical test subjects may lead to different test results. (2) Current techniques in representing human subjects may not be blameless. Different skills and precision in manufacturing breathing thermal manikins exist. Inappropriate treatment of respiration mode and process, poor control of exhalation flow and temperature, rough approximation of exhaled air components, etc., may bring errors that are not well understood. (3) Test or numerical simulation methods may not be accurate as they perform in the calibration procedure. Sometimes the instrument operation brings some unknown errors. The associated turbulence effect in the breathing zone imposes difficulty in accurately measuring. The current numerical simulation methods may not be able to fully represent the realistic human characteristics, either. (4) Different background environmental conditions employed in tests may lead to slightly different results.

In despite of the above aspects, probably no one would deny that the impacted region is dynamic mainly depending on the human exhalation flow. With a larger exhalation rate or intenser...
discharge momentum, the impacted region shall be larger. However, the quantitative relationship of impacted region varying with increasing exhalation rates is still unclear. In addition, head posture is critical to exhaled airborne pollutant dispersion, because it determines the directions of exhaled jets. But there is a lack of literature that has considered more complicated head postures other than the reported common type by sitting or standing upright. On the other hand, to make the human-related research works produced from different parties comparable and reproducible, Melikov [20] has proposed to standardize a series of important characteristics for breathing thermal manikins. For example, the exhaled jets from the nose are suggested to be inclined downwards with 45° from the horizontal plane; the two jets are thought to keep a separation angle of 30° between each other; and the nostril opening holds a round shape with a diameter of 0.8 cm, etc. The standardization procedure may aid better communication and promote recognition of research works among different parties.

By adopting the suggested standards, this study has mainly used a validated computational fluid dynamics (CFD) program to investigate the expired air dispersion. The manikin has a body profile similar to a male adult but is not exactly identical. The prototype of the numerical model stems from a breathing thermal manikin in our indoor environment chamber as illustrated in Fig. 2(a). More details of the physical manikin will be addressed later in the part of numerical model validation. The numerical manikins are designed with four different head postures: (1) sitting upright viewing front (Fig. 1(a)), where the exhaled jets separate from each other in 30° and keep 45° downward from the horizontal; (2) sitting upright but head tilted viewing upward and maintaining the exhaled jets along the horizontal discharge (Fig. 1(b)); (3) sitting upright but head turned 60° from the front (Fig. 1(c)); and (4) head pillowed on a table (Fig. 1(d)), in which one of the nostril jet is kept horizontal.

No matter what head posture is considered, appropriate representation of the respiration process is critical to expired air dispersion. The realistic respiration process is close to a sinusoidal wave. If the pulmonary ventilation rate for a sedentary adult is assumed to be 6.0 l/min and the frequency is 10 min⁻¹, the tidal volume (the air volume expired in a single breath) is 0.6 l and the duration of each breathing cycle lasts 6 s. Typically, there is a short break after each inhalation or exhalation process. If the short break is assumed to be 0.5 s, and also suppose the duration for each inhalation and exhalation is identical, the time spent in each inhalation or exhalation is 2.5 s. Holding the same tidal volume, one

3. Numerical models

A simplified numerical model for a breathing thermal manikin seated on a chair, as shown in Fig. 1, is created to investigate the expired air dispersion. The manikin has a body profile similar to a male adult but is not exactly identical. The prototype of the numerical model stems from a breathing thermal manikin in our indoor environment chamber as illustrated in Fig. 2(a). More details of the physical manikin will be addressed later in the part of numerical model validation. The numerical manikins are designed with four different head postures: (1) sitting upright viewing front (Fig. 1(a)), where the exhaled jets separate from each other in 30° and keep 45° downward from the horizontal; (2) sitting upright but head tilted viewing upward and maintaining the exhaled jets along the horizontal discharge (Fig. 1(b)); (3) sitting upright but head turned 60° from the front (Fig. 1(c)); and (4) head pillowed on a table (Fig. 1(d)), in which one of the nostril jet is kept horizontal.

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may use alternate rectangles as shown in Fig. 2(b) to replace the sinusoidal wave. Under such circumstance, the constant exhalation rate would be 14.4 l/min, which corresponds to the same pulmonary ventilation rate of 6.0 l/min in the sinusoidal respiration process. If the focus is on the expired air dispersion, the steady exhalation process illustrated by the dashed line in Fig. 2(b), may be used to replace the sinusoidal wave for simplicity [20]. However, the exhalation rate can take the same value as the rectangular respiration process. This investigation has adopted the exhalation rate of 14.4 l/min as the baseline for the steady exhalation, and then gradually increases the rate into its twofold and trifold to evaluate the effect of an increasing rate to expired air dispersion.

For a fixed exhalation rate, the size of nostril openings is closely related to the discharge jet speed. According to the suggested standardization procedure [20], the nostril opening is assumed to be a circle with a diameter of 0.8 cm. Under the constant exhalation rate of 14.4 l/min, the exhaled air speed normal to the nostril opening is close to 2.4 m/s. The exhaled air temperature can be thought as 32 °C, and the exhaled components are supposed to be the same as air. To mimic the thermal plume around the human body, the manikin surface temperature shall be specified appropriately. For simplicity, a uniform temperature of 30.3 °C is assigned to the whole body parts, which corresponds to the total sensible heat dissipation rate of 75 W in a comfortable indoor environment. Table 1 has summarized some of the manikin details and other boundary parameters.

Table 1 has summarized some of the manikin details and other boundary parameters.

To investigate expired air dispersion in a calm environment, the proposed manikin model is put to an office served by an underfloor air distribution system as shown in Fig. 3. The dimensions of the room are 7.5 m in length, 5.6 m in width, and 3.6 m in height. The manikin is seated on a chair in the center of the office. There is a computer simulator on a table nearby. Except for four overhead fluorescent lamps to provide illumination, there is no other furniture or occupant inside the room. This is to eliminate other factors which may exert impacts in interrupting expired air dispersion. The conditioned outdoor air is supplied to the room through four perforated under-floor panels and then extracted out by the two ceiling exhausts. The total air supply rate is 56.0 l/s. The slightly cool air (22.5 °C) is supplied to room to maintain the indoor temperature at around 23 °C. Due to very small cooling load, temperature stratification should not be very evident. To identify the impacted region of expired air, a dummy tracer gas is introduced to the manikin exhaled air. The gas concentration at the nostrils is assumed to be 1.0 unit. The impacted region of expired air will then be quantified based on the percentage of gas concentration decay.

Considering the very complicated geometric details and the involved complex flow, heat and mass transfer phenomena, CFD seems an appropriate tool to fulfill the research task. The commonly used RANS (by solving the Reynolds—averaged Navier—Stokes equations) CFD solves a series of differential equations that can be casted into the general scalar form as:

\[
\frac{\partial}{\partial t}(\rho \phi) + \frac{\partial}{\partial x_j} \left( \rho u_j \phi \right) = \frac{\partial}{\partial x_j} \left( \Gamma_{\phi,eff} \frac{\partial \phi}{\partial x_j} \right) + S_{\phi}
\]

where \( \rho \) is the air density, \( \phi \) is a scalar variable, \( t \) is time, \( u_j \) is the velocity component in three directions \( (x_j; j = 1, 2, 3) \) of a Cartesian coordinate system, \( \Gamma_{\phi,eff} \) is the effective diffusion coefficient, \( S_{\phi} \) is the source term. By supplementing different values for \( \phi \), the above equation can represent the continuity, momentum, energy, turbulence and contaminant concentration equations, respectively. Indoor airflow is generally turbulent and hence turbulence modeling is required. In the eddy-viscosity turbulence model family, many models may be appropriate for indoor flow simulation. However, after extensively comparing a couple of eddy-viscosity models, Chen [28] and Zhang et al. [29] finally recommended the renormalization group (RNG) \( k-\epsilon \) model due to its generally good accuracy, robustness and affordability. This study has thus adopted the RNG \( k-\epsilon \) model proposed by Yakhokh et al. [30] for turbulence simulation.

Three distinct numerical solution techniques are available for CFD: finite difference, finite element, and finite volume method. The finite volume method is the most well-established and widely used in commercial CFD codes due to a clear relationship between
the numerical algorithm and the underlying physical conservation principle. Hence, this investigation has employed the finite volume method. The finite volume method divides the domain into many CFD cells, and then integrates the governing equations over all CFD cells (control volumes). The integral equations are discretized with a variety of finite-difference-type approximation that converts the integral equations into a system of algebraic equations. The solution for boundary cells can be simplified by adopting the standard wall function method. Finally, these algebraic equations are solved with suitable solvers via the semi-implicit method for pressure-linked equations (SIMPLE) algorithm.

This study used a commercial CFD software, GAMBIT, to build the geometry domain of the cases and generate the cells for simulation in the solver, FLUENT. Both combined structured (hexahedral grids) and unstructured (tetrahedral grids) meshes were created in all cases using the “Tet/Hybrid” scheme with “Hex core”. For each case, the room is divided into two sub volumes for grid generation. The small rectangular sub volume is centered by the manikin with a dimension of 1.4 m \times 1.58 m \times 1.5 m; while the remnant space constitutes the other sub volume. Different grid sizes are employed in the two sub volumes. Due to the complicated geometric details of the manikin, the minimum grid size of 0.002 m is generated in the exhalation region, while in the other body parts the grid size has been increased into 0.01 m. To reduce the computing resource demand, nonuniform grid meshes are created in these two sub volumes by using size control functions. Originating from the manikin body surface, the spacial grid size inside the small sub volume is further gradually increased to 0.05 m. However, in the big sub volume the maximum grid size of 0.1 m is used. Though such big difference in grid size for these two sub volumes, meshes are switched gradually on the boundary interfaces.

The final grid number in the small sub volume is around 650 thousand, and 460 thousand in the big sub volume. To check if the grid-independent results have been obtained, the finer grids with a total number of 1,427,417 were also tested but did not show meaningful differences. The flow and temperature distribution were solved first and then the flow was frozen for tracer gas concentration solution. The continuity and momentum equations were thought to reach convergence when the ratio of the sum of the mass gain and loss on all boundaries to the overall mass gain in the room was less than 1.0e-6. In a similar method the convergent ratio limit for energy was 3.0e-3, and 1.0e-6 for gas concentration.

4. Validation of a CFD program

Because the RANS CFD modeling uses a significant amount of approximations, it is necessary to validate the CFD program together with the users to ensure the reliability of results. This validation has adopted a self-fabricated breathing thermal manikin as shown in Fig. 2 to mimic a sitting adult. A manikin for clothing show in shop is wounded with electric-resistance wires and then dressed up. To generate the steady exhalation flow, a micro fan located outside of the manikin drives air through two plastic tubes to the nostrils. The plastics tubes are fixed between the heated wires and the clothing to maintain a suitable temperature as human expired air. The measured exhaled air jets as shown in Fig. 4(a) are inclined 42° downwards from the vertical and separating each other in 32°, which is slightly different from the suggested standardization. The total heat provided to the manikin is controlled at 75 W via a voltage regulator. The clothing surface temperature is around 30 °C. More details on the fabrication of the thermal manikin can refer to our previously published paper [31].

The manikin is put to an indoor environment chamber served by an under-floor air distribution system. The chamber layout and dimensions are the same as those shown in Fig. 3. To quantify the impacted region of expired air, this investigation uses the sulfur hexafluoride (SF6) as a tracer gas by introducing it to the micro fan intake. For simplicity, the mouth was kept shut and the respiration cycle was simplified into the constant, steady exhalation only. The measured exhaled air speed at the nostrils is 1.6 m/s. The nostril opening is simplified into a round shape with a diameter of 0.8 cm, so the corresponding steady exhalation rate is 9.7 l/min. Table 2 lists out a part of thermo-fluid boundary information in the test. Both thermo-flow parameters and SF6 concentration are measured on several vertical poles in direct front of the manikin. The air velocity together with air temperature is measured by a three-dimensional ultrasonic anemometer (type DA-650&TR-92T; Kaijo Sonic, Japan). The resolution of the anemometer is 0.005 m/s with 1% uncertainty for velocity, and 0.025 °C with 1% repeatability for temperature. The SF6 concentration is measured by an SF6 leakage detector (type GD6000; Shanghai General Detection Research Institute, China). The resolution of the detector.

![Fig. 3. An office environment with an under-floor air distribution system to investigate expired air dispersion by a seated breathing manikin.](image)

![Fig. 4. Breathing thermal manikin for experimental test: (a) exhaled jet directions; (b) the test chamber.](image)
than in the exhaled jet center, so the velocity levels are much lower.

Fig. 5 shows the quick decay of exhaled air momentum and the air speed in a section across the manikin and measuring poles. It resulted in a commercial CFD software by creating the geometry as shown in Fig. 3 and generating appropriate CFD meshes. The total number of grids is $1,197,244$. The two-equation RNG $k\epsilon$ turbulence model with the standard wall function is employed to solve the flow and pollutant dispersion.

Fig. 5(a) shows the comparison of SF$_6$ concentration along a vertical pole 20 cm in direct front of the nose (left sub figure) and 30 cm in direct front of the nose (right sub figure). There is a peak in the concentration profile at around $Z = 1.15$ m, but the peak value decays quickly even the both poles separate in only 10 cm from each other. This is because the exhaled jets from the both nostrils have a spread angle of around $32^\circ$ in the horizontal plane, where the both poles are not located in the exact discharge jet center but the jet recirculated region. Nevertheless, the computed SF$_6$ concentrations match the experimental data very well. Similarly, due to the jet effect, air velocity in the height of about 1.15 m reaches the peak at a vertical pole 5 cm in direct front of the nose (Fig. 5(b) left). However, in 15 cm direct front of the nose (Fig. 5(b) right), the velocity peak decays below 0.1 m/s. Fig. 5(d) also shows the air speed in a section across the manikin and measuring poles. It clearly shows the quick decay of exhaled air momentum and the rising motion of exhaled jets with the thermal plume. Again, note these two poles are located in direct front of the nose rather than in the exhaled jet center, so the velocity levels are much lower than their initial discharge. The temperature profiles shown in Fig. 5(c) have also presented a small temperature jump at the exhalation height. In general, the temperature stratification along height is not very evident because of very small dissipation rate by heat sources and hereby a small cooling load.

The above comparison shows the simulated results have obtained the excellent agreement in both concentration and temperature profiles, and reasonably good agreement for velocity profiles. Considering the measurement uncertainty from test apparatus operation and also flow instability, this validation procedure concludes that the CFD program and the users are capable of providing reasonable results in modeling expired air dispersion.

### 5. Results and discussions

The quantification of impacted region by the expired air is not easy. By plotting the pathlines originating from the human mouth and nose is a simple and intuitive method. However, such method is not accurate because the expired air may quickly mix with the surrounding air and the strong diffusion effect is nontrivial, which is unable to be represented by the pathlines. On the other hand, only the actual inhalation dose by a person does actually indicate the threshold level to be symptomatic. The local pollutant concentration should be known to obtain the inhalation dose. For simplicity, this investigation has proposed to quantify the impacted region of expired air according to the percentage of concentration decay, by assuming the baseline concentration at the initial release.
as 1.0 unit. Before we present the quantitative impacted region of expired air, let us first analyze the effect of head postures to exhaled air dispersion.

5.1. Effect of head postures to expired air dispersion

Fig. 6 shows the distribution of concentration in terms of decay percentage. Such decay percentage is equivalent to the normalized concentration by the gas concentration at the nose. The result shown in Fig. 6(a) is on the symmetric plane just across the head when the occupant is sitting upright viewing front. The exhaled pollutant goes downward first to a small distance and then rises up quickly with the thermal plume. If taking 10% as the threshold line, the main impacted scope in the horizontal can be identified as 23 cm in direct front of the occupant. The pollutant has just broken through the thermal boundary layer. Such findings are consistent with the measurement results presented in the part of numerical model validation.

When the occupant is sitting upright viewing upward, the main horizontal impacted scope is a little smaller as shown in Fig. 6(b). The exhaled pollutant is discharged out horizontally from the both nostrils and then it quickly rises up because of higher temperature of exhaled air than the ambient and also by the action of rising thermal plume around body. The situation for the head turned with 60° from the front as shown in Fig. 6(c) is similar to that viewing front as shown in Fig. 6(a). However, because of a little stronger depressing effect by the thermal plume at the human lateral side, the horizontal impacted distance is a little smaller than that viewing front. When the head is pillowed on the table, Fig. 6(d) shows the pollutant is mainly transported to the side region of the occupant along the table. The plotting of the result is on a vertical plane along the horizontal exhaled air jet. Because the table behaves as a block to restrain the human thermal plume, the exhaled air can easily break through the plume boundary layer and therefore the pollutant can be transported farther in the horizontal. The effect of table is also investigated by the other researchers [32], which is found very effective to block the free convection flow around a human body.

The above results reveal that under a normal exhalation rate of 14.4 l/min, the human thermal plume aids to restrict the pollutant within a small distance (less than 25 cm if taking 10% of concentration decay as the threshold) around a sitting adult. The pollutant plume can nearly penetrate through the body thermal boundary layer but without going too far. However, when a person pillows head on a table, the pollutant can be transmitted much farther (45 cm if taking 10% as the threshold) once the table blocks the body thermal plume.

5.2. Quantitative impacted distance under different head postures

The previous analysis has shown that the impacted region by the expired air has a close relationship with the specified threshold percentages of concentration decay. Theoretically, the smaller the
set threshold, the larger the impacted region. This study has adopted 1%, 5%, 10%, 15% and 20% as different benchmark threshold values to quantify the horizontal impacted distance of expired gas pollutant from the exhalation point (i.e. the nose). Fig. 7 shows the quantitative impacted distance varying with the concentration decay percentage. Clearly, the impacted distance increases gradually with the decrease of the decay percentage. The increasing extent is much severer for the case when pillowing head on the table. Such phenomena can also be found in Fig. 6 as explained in the above section. The impacted scope when pillowing head is the largest among the four cases. When a person sits upright viewing front, the impacted scope is smaller but still larger than those in the rest two cases. A sitting person when viewing upward and when viewing lateral can only deliver pollutant to the smallest scope. Coincidently, the impacted distance between viewing upward and viewing lateral is identical. If taking 20% as the threshold line, 0.15 m can be identified as the safe separating distance for other people from a sitting adult. However, if the threshold value reduces to 1%, a healthy person shall be apart at least 0.35 m away from a sick adult who sits viewing front, upward or lateral, and 0.8 m away if a sick person who pillows head on the table.

The above analysis concludes the highly dependent nature of impacted distance with the set threshold values. The impacted distance when one pillows head on the table is the largest. A healthy person shall be apart away from a sick adult with a certain distance which varies with the defined threshold concentration.

5.3. Effect of increasing exhalation rates to impacted distance

It is known that the impacted scope of expired air may be larger with an increasing exhalation rate. For example, when a person makes a deep exhalation, the exhaled pollutant may be transmitted farther away. This investigation has selected the posture of sitting upright viewing front to evaluate the effect of exhalation rates to the horizontal impacted distance. Such posture is the most common type in office work or during entertainment. Three steady exhalation rates are assumed, the baseline rate of 14.4 l/min, its twofold and trifold. Fig. 8 illustrates the relationship of impacted distance versus the specified threshold values. When the threshold percentage is greater than 10%, the impacted distance is generally less than 0.35 m. The impacted scope difference among each other is very small. Some difference presented in the figure may be due to the numerical uncertainty or instable flow. However, when the threshold percentage is less than 5%, much clearer difference emerges. Generally, the larger the exhalation rate, the longer the impacted distance. Taking the threshold value of 2% as an example, the impacted distance for the exhalation rate of 14.4 l/min is 0.3 m; whereas the impacted distance increases to 2.0 m when the rate is doubled, and 2.3 m when tripled. It shall point out that under a steady exhalation rate of 43.2 l/min, the well-mixed pollutant concentration is 1.29% (see Table 1 for boundary setting), which is a little smaller than the threshold value. However, at a threshold of 1%, the pollutant is able to reach the whole room throughout; while for the exhalation rates of 14.4 l/min and 28.8 l/min, the impacted distance is only 0.33 m and 3.9 m, respectively, which are not shown in Fig. 8.

The above results reveal that when a large threshold percentage is adopted, there is minimal difference in impacted distance if the exhalation rates are increased. However, with a small threshold value, the larger the exhalation rate, the larger the impacted scope. For a steady exhalation rate of 43.2 l/min, the whole room may be risky for exposure if the threshold line is taken as 1%.

We would like to remind that the exhaled air components may change when a person’s exhalation rate increases. The simplification of unsteady breathing into the steady exhalation and the involved unstable mixing process between the expired air jets and the background air, may exert some unknown effects that are awaiting to further identify. This paper has assumed the background air is almost stationary. The conclusions of this investigation may thus only be valid for the steady exhalation in a calm indoor environment, in which the expired air components do not change over time.

6. Conclusions

In order to evaluate the role of head posture and exhalation rate on expired air dispersion, this study used a validated computational fluid dynamics (CFD) program to investigate the human expiration flow and gaseous pollutant dispersion exhaled out by a sitting adult. Basic findings include:

1. After comparing with the experimental data obtained in a test using a simplified breathing thermal manikin, the numerical models are found to be able to predict the exhalation flow and gas pollutant concentration distribution with good accuracy.
2. The impacted scope of expired air under different head postures is different. Under a normal steady exhalation rate of 14.4 l/min, the human thermal plume aids to restrict the pollutant within a small region. However, when a person pillows head on a table, the pollutant can be transmitted much farther away and beyond the human thermal boundary layer.
3. The identified horizontal impacted distance is highly dependent on the threshold concentration decay percentage specified. If taking 1% as the safe threshold, a healthy person shall be apart at least 0.8 m away from a sick sitting adult under a steady exhalation rate of 14.4 l/min.
4. When the exhalation rate is increased to the twofold (28.8 l/min) and trifold (43.2 l/min), there is minimal difference in impacted distance if a large threshold decay percentage (bigger than 10%) is adopted. However, under a small threshold percentage, the larger the exhalation rate, the larger the impacted scope.
5. Care should be taken if a person makes a deep exhalation and sits around at a table when his/her thermal plume is blocked. In such context, a larger separating distance for other people is needed to be free from the exhaled pollutant exposure by that person.

![Fig. 8. The varying impacted distances under the three different steady exhalation rates.](image-url)
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