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Human exhalation characterization with the aid of schlieren imaging technique

Chunwen Xu a,b, *, Peter V. Nielsen b, Li Liu b, Rasmus L. Jensen b, Guangcai Gong c

a College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao 266580, China
b Department of Civil Engineering, Aalborg University, Aalborg 9000, Denmark
c College of Civil Engineering, Hunan University, Changsha 410082, China

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ABSTRACT

The purpose of this paper is to determine the dispersion and distribution characteristics of exhaled airflow for accurate prediction of disease transmission. The development of airflow dynamics of human exhalation was characterized using nonhazardous schlieren photography technique, providing a visualization and quantification of turbulent exhaled airflow from 18 healthy human subjects whilst standing and lying. The flow shape of each breathing pattern was characterized by two angles and averaged values of 18 subjects. Two exhaled air velocities, \( u_m \) and \( u_p \), were measured and compared. The mean peak centerline velocity, \( u_m \), was found to decay correspondingly with increasing horizontal distance \( x \) in a form of power function. The mean propagation velocity, \( u_p \), was found to correlate with physiological parameters of human subjects. This was always lower than \( u_m \) at the mouth/nose opening, due to a vortex-like airflow in front of a single exhalation cycle. When examining the talking and breathing process between two persons, the potential infectious risk was found to depend on their breathing patterns and spatial distribution of their exhaled air. Our study when combined with information on generation and distributions of pathogens could provide a prediction method and control strategy to minimize infection risk between persons in indoor environments.

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1. Introduction

Airborne infection has always been a worldwide concern for medical profession and building management professions. Many diseases including tuberculosis, influenza, measles, anthrax and meningitis could be transmitted via air in indoor environments [1]. The outbreaks of severe acute respiratory syndrome (SARS) in 2003 and H1N1 flu in 2009 have further increased concerns about the life-threatening transmission of aerosol infection [2].

Airborne diseases are spread when droplets of pathogens are expelled into the air during human exhalation [3,4]. To control and reduce the contamination risk of these infectious aerosols, many studies have been focusing on characterizing the dynamics of exhaled airflow and behaviors of aerosol containing droplets in indoor environments [5–40]. These studies on exhaled airflow behaviors are the first step to understand the potential of airborne transmission and could provide a way to predict and control disease infection. In previous studies, detailed information on exhaled airflow dispersion as an indicator of potential airborne disease transmission have been investigated using three types of objects: human volunteers [11–18], breathing thermal manikins [19–27] and computer simulated persons (CSPs) [28–40]. Although studies based on breathing behaviors of manikins or CSPs can provide relatively comprehensive prediction of airflow patterns and infection prone zones, there could be errors with the use of these two techniques for prediction of real breathing conditions without a proper understanding of breathing characteristics of actual human subjects [13,16].

There has been little information on airflow dynamics of human exhalation. Chen and Zhao [37] reported that the initial exhaled velocity could greatly influence the dispersion of droplets in the range of 0.1 μm–200 μm in terms of trajectories and distances. To predict the evaporation, dispersion and transportation of respiratory droplets in indoor environment using Computational Fluid Dynamics (CFD), boundary conditions such as expelled airflow velocity are necessary [14]. Different techniques have been used to estimate exhaled velocities during different expiration behaviors...
such as coughing, sneezing and breathing. Various results have been reported with different methods of study, providing little data in previous literature. Some studies [30, 37] used approximate values of exhaled velocities produced during different respiratory activities (e.g. normal breathing 1 m/s, talking 5 m/s, coughing 10 m/s, and sneezing 20–50 m/s). Chao et al. [12] applied the particle image velocimetry (PIV) technique for measuring expelled velocities during coughing (11.7 m/s) and speaking (3.9 m/s). Tang et al. [16] used schlieren imaging technology to determine the maximum nasal and mouth breathing velocities of 1.4 m/s and 1.3 m/s, respectively. The maximum expiration air velocities for coughing and sneezing was found to be 4–5 m/s. Gupta et al. [13] developed a source modelling of air flow rate, flow direction and area of mouth/nose opening using human subjects for boundary settings for CFD simulations. Xu et al. [17] pointed out that even though the boundary settings complied with real human breathing characteristics, there could still be differences in the exhaled airflow of a complicated manikin than real persons. Similar problems could also occur in CSPs. The preclusion of using hazardous lasers, toxic tracer gases or particles on human subjects, which can otherwise be applied to the manikins, has so far limited research on these systems. The preclusion of using hazardous air has been provided. One method of studying real human exhaled airflow without the aid of hazardous techniques or materials is the use of schlieren photography [2,15,16].

Schlieren photography technique has been widely used in visualizing the flow of fluids of varying density, such as a gas jet [41], water jet [42] or flame jet [43]. Tang et al. [15, 16] expanded this technique to quantify human exhaled airflow in order to assess their contamination potentials. Some other methods have been used in previous studies to achieve similar purpose, like the particle imaging velocimetry (PIV) [12, 14] and using smoker subjects to visualize their breaths [13]. Schlieren imaging relies only on density differences to refract the light beam to visualize an airflow [44]. Human exhaled flow differs from the surrounding air in density, especially when air is immediately expelled from the mouth or nose [17, 45]. No invasive or potentially irritant tracers are needed, so human volunteers are quite safe [2, 15, 16]. The implementation of schlieren imaging technique on human volunteers can further enhance our understanding of the behavior of real human respiration and the potential contamination risk of these breathing activities. The accuracy for the prediction of the transmission behavior could be further improved by using other additional techniques, such as CFD or breathing manikins, to provide a powerful tool for evaluating the infection risk of respiratory pathogens.

Infection risk assessment is very useful in understanding the transmission dynamics of infectious diseases and in predicting the risk of these diseases to the public, while a number of factors could also influence the transmission process and outcome [46], such as dispersion and distribution of airborne pathogens, ventilation strategies, droplet sizes, air turbulence etc. These factors have contributed to the complexity of these exposure and risk assessment of infectious pathogens on human beings. The Wells–Riley model has been one of the most extensively used models for quantitative infection risk assessment of respiratory infectious diseases in indoor premises [47]. However, the Wells–Riley model assumes a uniform airborne pathogen distribution at a steady-state condition, which could yield errors in the assessment.

In our study, the respiratory activities between two human subjects were visualized using schlieren photography technique. The spatial variation and unsteady distribution of exhaled contaminants in the microenvironment between two persons are illustrated.

The goal of this present study is to characterize the dispersion of human exhaled airflow by schlieren technique and provide accurate information in three aspects: flow shape, exhaled velocity and interactions of exhalations between two persons. This investigation could provide accurate information on boundary conditions of human breathing for CFD simulation and could be helpful to validate the accuracy of risk prediction of airborne disease transmission.

2. Methods and design

2.1. Schlieren experimental setup

The schlieren imaging technique was used to visualize the real-time breathing process of human subjects. The temperature differences between the exhaled air (32–36 °C at the mouth or nose opening) [17] and the laboratory environment controlled at around 23 °C, would lead to a refraction of the light ray when passing through the media of different densities. The different components of exhaled air that have different densities to the room air would contribute to the refraction of light for our experimental investigation.

The schematic of the schlieren experimental setup is shown in Fig. 1. A standard schlieren structure with a beam splitter was constructed, consisting of a spherical concave mirror of astronomical telescope quality (0.61 m diameter and 7 m focal length) and a high-speed camera (Chameleon CMLN-1352C, resolution of 1296 by 964 pixels). The breathing images were captured by a camera with a speed of 15 frames per second (fps) for a lasting of 2 min for each breathing pattern and these were downloaded to a laptop. The software, PointGrey FlyCap 2, installed on the laptop was used to control the high-speed camera remotely and download the shadowgraph images.

2.2. Characterization of breathing behavior of human subjects

The breathing characteristics of human subjects whilst standing and lying were investigated in this study. Fig. 2 shows the placement of a human subject in front of a concave mirror. The relative distance between the subject and the mirror would affect the size of these images. The reduced scale of these images were thence calibrated for every subject and every breathing pattern. In normal standing conditions, these human subjects were asked to stand approximately 0.5 m in front of and to one side of the mirror. A height-adjustable holder was used to support the subject’s head in case of any movement during the experiment. A special bed with adjustable height was placed first in parallel and then perpendicular to the mirror, forming respectively a side and front view of a lying person to the observer as shown in Fig. 2. A soft cushion and a pillow were placed on the bed and a heavy quilt was used to cover the subject up to the neck position to block the thermal plume arising from the body and mimic the sleeping condition of a normal person to the most extent. The subject was asked to lie on the bed quietly for about 10 min before the experiment.

The basic information of 18 healthy young adults participated in the experiment is given in Table 1. All participants were of Chinese ethnicity. Three breathing modes were tested for both standing and lying positions: (a) nose breathing only; (b) inhaling through the nose and exhaling through the mouth and (c) mouth breathing only. These subjects were instructed to breathe naturally for a relatively long time (above 10 min) with each breathing pattern. However, these subjects constantly complained about their dry mouth due to saliva evaporation during their mouth only breathing with a nose clip restricting breathing from their nose. Interruption by shutting up their lips and saliva swallowing were permitted as a part of their breathing pattern. The camera recorded each breathing
process for about 2 min without the subject realizing the beginning of the recording. When a subject was instructed to inhale through the nose and exhale through the mouth; the air from his or her lung was actually expelled from the nose and mouth simultaneously (see Appendix A), as the nasal and oral cavities are connected and air leaks into these cavities even when a person is not intended to exhale with his/her nose.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2016.11.032.

2.3. Velocity measurement

2.3.1. Centerline velocity

In this study, a hot sphere anemometer (Dantec 54N50, DANTEC Dynamics A/S) with an accuracy of ±0.01 m/s was placed near the mouth or nose opening to measure the initial velocity at a frequency of 10 Hz. The anemometer was calibrated in a standard jet-wind tunnel positioned in both horizontal and vertical directions, in the presence of 22 °C conditioned air.

The influence of exhaled air temperature and humidity on measurements was ignored in this work, which has been explained in Ref. [17]. A coordinate was built from the mouth/nose opening. For mouth breathing, the anemometer was horizontally placed in front of the mouth at a distance of about 0.03 m. When the person performed nose breathing, the anemometer was vertically placed approximately 0.03 m down to the nostrils. The variation in the position of the anemometer was adjusted by the movement of a robot arm and according with the schlieren photography to ensure that the probe would be exactly positioned within the exhaled airflow and close to the center of the airflow.

The determination of the centerline of the airflow is shown in Fig. 3. For mouth only breathing in standing posture, the velocity decays along the centerline. The mean peak air velocity at the centerline of the airflow was defined as $u_m$. In this study, the $u_m$ at the nearest measuring points from the mouth/nose opening (around 0.03 m) was expressed as $u_{0.03}$ and was used to indicate the initial velocity of exhalation.

2.3.2. Propagation velocity

The visible propagation distance $d$ was derived from schlieren images frame by frame along the centerline of exhaled flow. The propagation velocity, $u_p$, was expressed as $\Delta d / \Delta t$, in which $\Delta t$ is the time interval. Note that $d$ differs from $x$ and $x$ is the horizontal component of $d$, see Fig. 3.

3. Results and discussion

3.1. Flow shape characterization

3.1.1. Thermal plume around human body

The movement of body plume and exhaled air can be clearly...
observed with the aid of schlieren photography technique. For a standing person, the thermal plume would arise along the body height and continue to develop above the person’s head. The plume velocity was measured using a hot-sphere anemometer placed along different vertical heights above the subject’s head. The maximum velocity measured was approximate 0.23 m/s.

Murakami [28] and Melikov [48] indicated that the majority of inhaled air for a standing still person would be directly from the limited area below the nose (nose breathing) or the mouth (mouth breathing) and in the front part of the body. The rising thermal plume can be inferred to contribute to the inhaled air to a large extent for a standing person. Whilst the upward stream around the body collides with the expelled air, causing possible velocity decrement immediately at the mouth/nose opening when the exhaled plume enters the thermal boundary layer of the body [26,29].

A curved flow affected by the rising thermal plume, especially at low initial exhaled velocities was observed. For a person lying on his or her back, the plume would rise vertically from the exposed part of the body (i.e. head, face and neck) without the heavy quilt covering and then mix with the exhaled air. Comparing the airflow during the standing posture to the air movement with a person lying flat; the upward thermal stream could somehow accelerate the vertical movement of the exhaled airflow instead of blocking it. This was due to the identical dispersal direction of these flows.

3.1.2. Flow direction and development

Schlieren images within one breathing cycle for each subject were extracted from a series of high contrast images captured by the camera within a recording time of around 2 min. The extraction was conducted randomly among the 20–50 breaths (depending on breathing frequency) for each breathing pattern and each subject. These 2-D images were stacked together with a time interval of 1/20 s or 2/15 s to illustrate the development of exhaled flow within one breathing cycle as shown in Fig. 4. The boundaries of these exhaled flows were connected, forming a region that the exhalation could affect.

From Fig. 4, the expelled airflow was shown to be turbulent full of vortex rings and the periodic exhaled flow was shown to have similar characteristics with a constant jet in terms of flow shape. The width and length of the airflow was shown to grow with increasing distance from the origin by mixing with the surrounding air. Therefore, the velocity and concentration of exhaled contaminants could also be reduced by the development of the exhaled flow. There are obvious individual differences in the exhaled airflows in terms of flow shapes, propagation distances and dispersal directions.

The angles would be needed to define the breathing direction of a nose or mouth as shown in the side or front view in Fig. 4. These angles did not vary much among our human subjects. The measured breathing angles of male and female subjects were combined for our analysis. These breathing angles were measured in each breathing pattern and have an approximately normal distribution verified by statistics (Statistical Product and Service Solutions, SPSS). Table 2 shows the average of these measured angles with a confidence limit of 95% and the confidence interval for the means was always tight with a maximum of 14°.

The direction of $\theta_1$ for the side view condition was defined in Fig. 4(a–d). This was positive when the centerline of the airflow was below the x axis as shown in Fig. 4(a and b) or to the right of the x axis (Fig. 4(c and d)). Otherwise, $\theta_1$ would be negative, which means the exhaled airflow would have an upward dispersal trend. For nose breathing, the averaged downward angle between nostrils and horizontal line was about 57°, and this corresponds with Gupta et al.’s average of 60° [13]. For mouth only breathing, most measurements were found with a downward flow trend with an averaged $\theta_1$ of about 14°, even though in most conditions of the airflow in the mouth breathing was considered horizontal [12–14,19–24,28–35]. This might be due to the longitudinal asymmetry of the mouth cavity structure.

From Table 2, the $\theta_1$ and $\theta_2$ of the mouth only and nasal only breathing that were obtained from the side view did not vary much between different postures. As expected, the exhaled airflow from the nose or mouth was not a regular cone because the spreading angles of $\theta_2$ that were observed respectively from the side and in front of the body are considerably different. The $\theta_2$ is significantly wider in the front view than the side view in the lying posture. The value is also bigger than that obtained by Gupta et al. [13].

3.2. Velocity characterization

3.2.1. Initial exhaled velocity

Fig. 5 shows typical centerline velocity variations over time during moth only breathing of a subject. Because the hot sphere anemometer can only measure the velocity magnitude without direction, the measurements are always positive. Fig. 5 shows the repeated breaths of one male subject with a breathing frequency of about 10 min⁻¹ and variations of amplitudes of exhaled velocities over time. The peak value of each breath was extracted and then averaged for the definition of the mean peak velocity, $u_{m}$. The ratio, $u_{m}/u_{am}$, of the standard deviation of amplitudes to the mean value was used to indicate the fluctuation degree of a person’s breathing [17]. In this work, the $u_{0.05}/u_{am}$ was at $x = 0.03$ m with a variation of merely 9% to about 160%, meaning that some people was breathing regularly and some did not. The irregularity of the breathing could further increase the turbulence degree of the exhaled air. This $u_{0.05}$ should be lower than the real initial velocity that was obtained from the immediate mouth/nose opening; as there could be velocity decay with increasing distance from the origin when the measured point did not fall within the constant velocity core [17].

The $u_{0.02}$ for the male and female subjects and their range values are given in Table 3. One main reason for the wide spread of measured velocities could be due to the wide variation in our
human subjects used in the current study. The physiological parameters of a person: exhaled minute volume (MV, the volume of exhaled air from a person’s lungs per minute), breathing frequency (BF) and mouth/nose shape and area could contribute to the variation; and these could be different from person to person. In spite of smaller MV, the initial velocities of female subjects were shown to be higher than those of male subjects mainly due to higher RF and smaller mouth/nose opening [13,17]. The air leakages from the nose could result in relatively lower mean initial velocity from the mouth when people inhale with their nose and exhale with their mouth as shown in Table 3. Human postures could also affect the breathing by influencing the activity of abdominal muscle [13], but no significant relationship between postures and breathing velocities was found in our present study.

The mean value of $u_{0.03}$ was found to be even higher than the maximum breathing velocity measured from nose/mouth opening obtained by Tang et al. [16] by schlieren photography. The main reason of the deviation lies in different methods used to evaluate

### Table 2

Average spreading angles of exhaled airflow with 95% confidence limit.

| View angle       | Breathing route       | This study | Gupta et al. [13]a                      |
|------------------|-----------------------|------------|----------------------------------------|
|                  |                       | $\theta_1$ | $\theta_2$                           |
| Standing side view | Mouth only            | 14° ± 14’  | 36° ± 6’                              |
|                  | Nose only             | 57° ± 6’   | 29° ± 3’                              |
| Lying side view  | Mouth only            | 9° ± 6’    | 29° ± 3’                              |
|                  | Nose only             | 51° ± 5’   | 32° ± 3’                              |
| Lying front view | Mouth only            | 34° ± 8’   | 61° ± 12’                             |
|                  | Nose only             | 43° ± 6’   | 21° ± 8’                              |

a These angles were measured by Gupta et al. [13]; both male and female volunteers were sedentary rather than in lying or standing position.
the exhaled velocity. Our study employed the mean peak velocity as depicted in Fig. 5, while Tang et al. [16] used the visible propagation distance divided by the propagation time as shown in Fig. 4. The latter method describes the propagation speed of the exhalation flow measured at the leading front edge of the flow within certain time interval rather than the initial pulsating flow generated by a person. This could also be the reason why velocities of sneezing and coughing reported by Tang et al. (4–5 m/s) [16] are significantly lower than the generally recognized velocities of sneezing and coughing (e.g. sneezing 20–50 m/s, coughing 10 m/s) [18]. The maximum propagation velocity obtained by quantification given by schlieren images should not be considered as the exhaled velocity as this might cause underestimation for boundary setting of CFD simulation. The propagation velocity of the exhaled airflow will be further discussed in Section 3.2.3.

3.2.2. Centerline peak velocity decay

Our previous study [17] found that $u_m$ decayed with $x$ in the form of a power function, as defined by Equation (1).

$$u_m = ax^b$$  

The mean peak air velocity of female subjects’ breathing from the mouth was found initially higher than that of male subjects; but the air velocity of females’ breathing decayed more rapidly than the males’ along the centerline [17]. In our work, different human subjects were used in the present study compared to the previous study to validate the applicability of the regression equation. Fig. 6 shows that the $u_m$ of mouth only breathing corresponds well with the regression equation reported [17]. The dashed line forms a region where scattered points of exhaled velocities could be located. As shown in Fig. 6, although the exhaled air velocity, $u_m$ at $x = 0.4$ m for most human subjects was reduced to below 0.1 m/s; this was equivalent to the turbulence level of room air, and the exact maximum propagation distance of the exhaled flow would be difficult to determine. The regression equation would suggest a measurable $u_m$, could continue well beyond the region where experimental data were collected, but this is likely to be an artifact of the fitted curve. Although Tang et al. [16] reported the observed maximum propagation distance of mouth only breathing and nose only breathing was 0.8 m and 0.6 m, respectively; it is still difficult to know exactly where the exhaled airflow should stop; if it stops, it must be dependent on the surrounding turbulence level of the airflow in the room.

Similar decay trends of CO2 in the exhaled air were also found,

| Breathing patterns         | Male                | Female               |
|----------------------------|---------------------|----------------------|
|                            | Standing $u_{0.03}$ (m/s) | Lying $u_{0.03}$ (m/s) | Standing $u_{0.03}$ (m/s) | Lying $u_{0.03}$ (m/s) |
| Nose only                  | 1.08 (0.45–2.00)    | 1.82 (1.00–2.52)     | 1.63 (0.34–2.58)    | 1.52 (0.9–2.27)     |
| Nose in and mouth out      | 1.22 (0.31–2.27)    | 0.81 (0.31–1.55)     | 1.53 (0.36–2.80)    | 1.35 (0.46–2.25)    |
| Mouth only                 | 1.56 (0.95–2.03)    | 1.56 (0.67–2.02)     | 1.64 (0.50–2.63)    | 1.64 (0.40–3.22)    |

**Fig. 5.** Pulsating velocity measured during a subject’s mouth only breathing. The mean peak velocity (red dashed line) is defined as $u_m$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Fig. 6.** Velocity decay along the centerline in the mouth only breathing for (a) male subjects and (b) female subjects.
indicating a reduced exposure level of contamination to the receptor with increasing distance apart. Chen and Zhao [14] reported that the exhaled droplets with a diameter smaller than 10 μm could travel to some distance along in a room. The long-distance transportation of small droplets could largely depend on turbulence level and air distribution in the room [49–54].

3.2.3. Propagation velocity

The propagation images obtained from side view, as shown in Fig. 4(a–d), were extracted and analyzed. The observed propagation distance was dependent on the temperature difference between the exhaled air and ambient air. However, to recognize the maximum propagation distance in this work is difficult due to the size limitation of the mirror and the resolution limitation. Hence, d was derived merely within the viewable area of the camera and the distinguishable propagation boundaries. This could result in some underestimation of the maximum propagation distance. Fig. 7 shows the visible propagation distance, which was increased correspondingly with time. The recognized maximum propagation distance was around 0.4 m, corresponding to the velocity decay distance shown in Fig. 6. Many equations were tested for the fitted decay curve but the linear one was found to perform the best (the R-square always above 0.97). The slope of the connected line of the propagation distance over time, that is the slope of the linear fitting equation, would be recognized as the averaged propagation velocity within the viewable area given by the camera. The maximum length of the airflow propagation could be even longer than the concave mirror boundary and could not be clearly visible. Despite the limitation of the schlieren imaging technique, the propagation velocity was still useful and valid for the prediction of exhaled flow dispersion speed [16]. These two velocities, \( u_m \) and \( u_p \), should be clearly distinguished for use. The \( u_m \) was derived from certain measurement points along the centerline of the airflow, while the \( u_p \) was obtained by tracing the airflow movement to the leading front edge of the image of the exhaled air. From Fig. 7, \( u_p \) for our male subjects and female subjects in standing posture and with mouth only breathing, varied from 0.2 m/s to 0.6 m/s and from 0.3 m/s to 0.8 m/s, respectively, which is significantly lower than the \( u_m \) measured near the mouth opening (about 0.03 m). Even for the maximum \( u_p \) derived close to the mouth/nose opening [16], \( u_p \) was still lower than the mean peak velocity \( u_{0,03} \) listed in Table 3. Fig. 8 shows that the front of a single exhalation cycle was similar to a vortex like airflow or to a puff. The peak exhaled air velocity \( u_{0,03} \) in a point close to the mouth was measured when the vortex airflow passed this point, and this was typically larger than the propagation velocity of the same vortex. This would be the typical situation for a vortex as illustrated by Akhmetov [55].

The \( u_p \) would be high when a person exhaled with high MV at a high BF. The \( u_p \) should be correlated to MV and BF. Robinson [56] and Gupta et al. [13] reported a linear relationship between MV and the body surface area (BSA). Regression analysis was performed to obtain the correlation between the \( u_p \) and the BSA × BF. Fig. 9 shows that the \( u_p \) would be increased with an increase in BSA × BF for both genders. Fig. 9 also shows that the \( u_p \) was basically linear in relation to the BSA × BF. A linear regression equation

Fig. 7. Visible propagation distances of mouth only breathing and nose only breathing over time: (a) male, standing posture; (b) male, lying posture; (c) female, standing posture and (d) female, lying posture.
was assumed as given by Equation (2). Table 4 gives the regression analysis results of the slope \( k \), the correlation coefficient \( r \) and the \( t \)-test for \( r \). The \( r \) for all test groups was found to be more than 0.7 for a \( p < 0.05 \), which shows that the \( u_p \) is linearly related to the BSA × BF. However, due to the small number of points, the equation should be further validated by more measurements.

\[
u_p (\text{m/s}) = k \times \text{BSA (m}^2\text{) × BF (min}^{-1})
\]

3.3. Infection prone zones between two persons

As respiratory infection cases are often transmitted due to obvious proximity relationship to the index case, to enable further understanding of the exposure risk of contamination between two persons, the exhaled flows generated by talking and breathing between two subjects were visualized and captured by the high speed camera.

The dispersion of the visualized exhaled flow would be recognized as an indicator of infection transmission especially for droplets smaller than 1 \( \mu \text{m} \) with good air following performance. As

| Postures and breathing patterns | \( k \) | Correlation coefficient \( r \) | \( t \)-test | \( t_{0.025} \) |
|--------------------------------|-------|-----------------|--------------|-------------|
| Male                           |       |                 |              |             |
| Standing mouth                 | 0.019 | 0.82            | 3.52         | 2.45        |
| Standing nose                  | 0.010 | 0.74            | 2.67         | 2.45        |
| Lying mouth                    | 0.011 | 0.81            | 3.09         | 2.57        |
| Lying nose                     | 0.011 | 0.71            | 2.45         | 2.45        |
| Female                         |       |                 |              |             |
| Standing mouth                 | 0.018 | 0.76            | 3.06         | 2.36        |
| Standing nose                  | 0.019 | 0.84            | 4.11         | 2.36        |
| Lying mouth                    | 0.015 | 0.88            | 4.49         | 2.45        |
| Lying nose                     | 0.010 | 0.73            | 3.00         | 2.31        |

Fig. 8. Image of an exhalation airflow produced by a female subject (a) and details of the airflow in a vortex (b). The front of a single exhalation is typically corresponding to a vortex like flow and the peak velocity in the vortex is larger than the propagation velocity of the vortex.

Fig. 9. Variation of \( u_p \) with BSA × BF of (a) the male subjects and (b) the female subjects.
airflow patterns could vary between subjects, flow interactions between two different pairs of female subjects (Group I - 0.34 m apart and Group II - 0.41 m apart) were studied, as illustrated in Fig. 10. These subjects were situated on the edge of the concave mirror. Their head positions were not fixed as in previous tests. Corresponding real-time video clips are shown in Appendix B.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2016.11.032.

During a free conversation, the exhaled airflows from two pairs of subjects was shown to be relatively short compared to mouth or nose only breathing. Air flows expelled from both nose and mouth during talking were observed and flow directions from the mouth varied due to the content of the conversation. Most of the time, expiration airflows from opposite subjects would remain separate and were brought up by a constantly rising thermal plume around their bodies (with a thickness of approximate 10 cm), although occasionally the flow was shown to interact with the receptor’s thermal plume layer and interfered with the breathing zone. Mouth breathing (nose in and mouth out) was shown to have a higher potential to transmit diseases to receptor subject as the flow generated by mouth breathing could spread over a longer distance as compared with talking and are more horizontally directed than nose breathing.

For Group I, the female subject on the right hand side was shown to perform a downward mouth exhalation and the flow was shown to enter the breathing zone of opposite person. While for Group II, the upward flow from the person on the right side, was shown to directly bend up over the head of the opposite person without interacting with the breathing zone, demonstrating the potential of mouth-breathing to transmit infection, which could vary among individuals and also dependent on relative frequencies in an unsteady state.

From our analysis of the infectious prone zone between two persons using schlieren technique, the exposure level and hence the infectious risk posed by respiratory pathogens were not at a steady condition and always expected to have spatial variation. The spatial distribution of airborne pathogens would govern the exposure level of the receptor person. However, no existing models could predict the complicated disease transmission process and the infectious risk accurately by simply considering the spatial variation alone.

CFD would be a very promising tool to overcome existing shortcomings of current risk evaluation models and would provide useful information for infection control. Full understanding of respiratory characteristics of real human subjects could play an important role for accurate prediction using CFD simulation. More work should be done to enhance our understanding of flow dynamics of human breathing.

4. Conclusions

How airborne pathogens disperse and distribute in the room air could govern the exposure levels of susceptible persons to infectious diseases. Accurate prediction of airborne disease transmission and characterization of infection prone zones can aid infection control. This work characterized the exhaled airflow behaviors of human subjects and provided accurate boundary conditions for CFD simulations of human breathing or by using manikins. The main conclusions of this study are summarized as follows:

- The expelled air could interact with the constantly rising body plume from human subjects in different ways whilst standing or lying. The spreading angles of the exhaled plume was shown to have minimal variations between human subjects. The \( \theta_1 \) and \( \theta_2 \) of mouth and nasal breathing measured from side view were consistent in different postures with little variation. The measured mean angles obtained in our study could be used to describe the average level of the physical geometry of human breathing.

- The \( u_p \) and \( u_m \) could be used to describe the breathing velocity from different aspects. The \( u_p \) would be significantly lower than the measured initial velocity \( u_{0, up} \). However, \( u_p \) would not be useful as velocity boundary condition for CFD settings as it could cause underestimation of the exhaled velocity. The \( u_m \) would decay with increasing horizontal distance along the centerline and the decay could be predicted by a power function. The mean \( u_p \) within the observed region was found to be correlated to human physiological parameters. Although the maximum propagation distance of exhaled airflow by measuring \( u_m \) or \( u_p \) would be difficult to determine, as the exhaled airflow over 0.4 m would interact with turbulent room air. We suggest more measurements with human subjects to validate the prediction method for the \( u_m \) and \( u_p \).

- The interaction of exhaled airflows with opposite (facing) subjects could vary between subjects and breathing patterns, implying possible complexity in prediction of infectious risk exposure of human occupants in close proximity in room air. The information on spatial distribution of airborne pathogens in the microenvironment between two persons is particularly important for identifying and implementing infection control strategies.

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