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Measurements of exhaled airflow velocity through human coughs using particle image velocimetry

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ABSTRACT

The sudden outbreak of coronavirus (COVID-19) has infected over 100 million people and led to over two million deaths (data in January 2021), posing a significant threat to global human health. As a potential carrier of the novel coronavirus, the exhaled airflow of infected individuals through coughs is significant in virus transmission. The research of detailed airflow characteristics and velocity distributions is insufficient because most previous studies utilize particle image velocimetry (PIV) with low frequency. This study measured the airflow velocity of human coughs in a chamber using PIV with high frequency (interval: 1/2986 s) to provide a detailed validation database for droplet propagation CFD simulation. Sixty cough cases for ten young healthy nonsmoking volunteers (five males and five females) were analyzed. Ensemble-average operations were conducted to eliminate individual variations. Vertical and horizontal velocity distributions were measured around the mouth area. Overall cough characteristics such as cough duration time (CDT), peak velocity time (PVT), maximum velocities, and cough spread angle were obtained. The CDT of the cough airflow was 520–560 m s, while PVT was 20 m s. The male/female averaged maximum velocities were 15.2/13.1 m/s. The average vertical/horizontal cough spread angle was 15.3°/13.3° for males and 15.6°/14.2° for females. In addition, the spatial and temporal distributions of ensemble-averaged velocity profiles were obtained in the vertical and horizontal directions. The experimental data can provide a detailed validation database the basis for further study on the influence of cough airflow on virus transmission using computational fluid dynamic simulations.

1. Introduction

The coronavirus disease suddenly broke out at the end of 2019 and quickly swept the world (COVID-19). According to the World Health Organization (WHO), it has infected over 100 million people and caused over two million deaths by January 28, 2021. This is another major global public health disaster following those caused by the severe acute respiratory syndrome (SARS) 2003 [1], H1N1 influenza epidemic in 2009 [2], and Middle East respiratory syndrome in 2013 [3]. The coronavirus is transmitted mainly by airborne particles and contact. The epidemic cases reported by the WHO demonstrate the importance of understanding the mechanisms of airborne infection. Airborne transmission refers to the transmission of microorganisms from the source to people through aerosols, leading to human diseases caused by infection [4]. The aerosolized disease transmission includes droplet and aerosol transmissions [5]. As early as 1938, Wells and Wells [6] reported that coughs release small microorganism-containing droplets, which can evaporate and remain suspended in the air. The relationship between cough and associated diseases has already been reported [7–9]. As a potential carrier of the novel coronavirus SARS-CoV-2, the exhaled airflow of infected individuals through coughs is considered significant in virus transmission. Numerous studies analyzed the coughing mechanism [10,11], coughing respiratory droplets [12–20], and more directly, the exhaled virus information [21,22]. With the development and widespread application of computational fluid dynamic (CFD) technology, it is possible to utilize CFD to simulate and study the propagation process of droplets exhaled from infected people and the accessibility of viruses in the architectural space. This will be of great significance to control the virus’s transmission and subsequently provide precaution and control methods against infection in the building. It can even provide the design basis for the architectural space from the...
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Nomenclature and abbreviation

| Symbol | Definition |
|--------|------------|
| \(a_1, b_1, c_1, a_2, b_2, c_2, d_2\) | fitting parameters |
| CDT | cough duration time, ms |
| PVT | peak velocity time, ms |
| SD | standard deviation |
| \(x, y, z\) | streamwise, spanwise, and vertical components of the spatial coordinate, respectively, m |
| \(\theta_v\) | vertical cough spread angle, ° |
| \(\lambda\) | wavelength of the laser, nm |
| \(\Gamma(\cdot)\) | gamma probability distribution function |
| \(L_0\) | mouth width, m |
| PV | peak velocity, m s\(^{-1}\) |
| PIV | particle image velocimetry |
| \(t\) | time, ms |
| \(u_x, u_y, u_z\) | components of the instantaneous velocity in the \(x, y, z\)-directions, respectively, m s\(^{-1}\) |
| \(\theta_h\) | horizontal cough spread angle, ° |
| \(\tau\) | nondimensional time |
| \(\langle \cdot \rangle\) | ensemble-average operation |

perspective of environmental health. Therefore, it is essential to elucidate the characteristics of cough and the distribution of its initial velocity, which provides the boundary condition and a validation database for CFD simulation.

Extensive studies have been carried out to characterize the flow behavior of cough and its initial velocity. Mahajan et al. [23] and Singh et al. [24] measured the cough flow rates vary with time using a tussometer. Mahajan et al. show that the flow rates ranged in 200–950 L/min with a mean peak of 300 L/min. Singh et al. found the peak flow rate of females and males were 750 and 1300 L/min, respectively. Gupta et al. [25] measured 25 human subjects and obtained the flow rate and flow direction using a spirometer to describe cough characteristics such as the cough peak flow rate (CFPR), cough expiratory volume (CEV), and peak velocity time (PVT) [23,24,26]. Ren et al. [27] measured the CEV and CFPR from 700 subjects, and utilizing neural network and genetic algorithm to predict CEV and CFPR from sex, heights, weights, ages, and smoking status. They reported that the CEV and CFPR estimation accuracy reached 95% and 94.57%. Regarding the measurement or analysis of the cough initial velocity, Afshari et al. [28] measured the cough airflow velocities of control subjects and subjects with respiratory disease using particle image velocimetry (PIV) in 2002. They reported that the healthy and nonhealthy subjects exhibited different air velocity curves. However, the coughs in their experiment were ‘simulated’ by an electrically controlled hydraulic actuator; they were not real human coughs. Zhu et al. [29] measured the transport characteristics of saliva droplets produced by coughing using a PIV system and reported that more than 6.7 mg of saliva is expelled at speeds up to 22 m/s during each individual cough, which could travel more than 2 m. They also simulated the coughing process to investigate the airborne transport characteristics of airflow in a stagnant indoor environment [30]. Marr et al. [31] measured the coughing flow from a thermal mannequin using PIV and found threefold increase in local turbulence intensity during the exhalation phase of the breathing waveform. Chao et al. [16] measured the droplet size distributions and velocities of healthy volunteers’ expiration air jets during coughing using PIV. The average expiration air velocity was 11.7 m/s, while the geometric mean diameter of the droplets from coughing was 13.5 μm. VanSciver et al. [32] measured the velocity profiles and maximum cough velocities during coughing for 29 subjects using PIV. The maximum cough velocities were in the range of 1.5–28.8 m/s. Their velocity profiles were nondimensionalized and aligned according to the peak velocity at each position. Kwon et al. [4] obtained the average initial velocity (males: 15.3 m/s, females: 10.6 m/s) and angle (males: 38°, females: 32°) of the exhaled airflow from coughing of 17 males and 9 females using PIV. They also reported several instantaneous velocity vector fields of coughed airflow but did not provide detailed velocity profiles. In addition to experiments, Badeau et al. [33] simulated the particle and flow field behavior of a coughing process using the Discrete Phase Model. Zhao et al. [34] simulated the coughs from the mouth with different initial velocities (20 and 100 m/s) and showed that higher initial velocity led to further transport and a higher concentration of particles or droplets. Wang et al. [35] measured the airflow velocity and droplets involved in exhaled cigarette smoke of coughs using PIV and reported the statistical relationship between velocity magnitude with time or coordinate. Dudalski et al. [36] measured the far-field human cough airflows from healthy and influenza-infected subjects, and obtained the time variation of peak velocity in the center of airflow jet but did not discuss the velocity distributions. Wang et al. [37] measured the velocity using PIV and captured droplets on a solid surface that subjects faced when coughing. Although their frequency was very high (12,500 Hz), their research mainly focused on the distribution of droplets while not the airflow characteristics.

These studies revealed some of the cough airflow characteristics. However, there are mainly two deficiencies in the previous cough airflow measurements, which make it difficult to form an effective boundary condition and validation database for CFD simulation of droplet propagation. One is that the detailed distribution of airflow velocity and its temporal and spatial variations need to be further investigated, which is very important to the deep understanding of mechanisms of cough airflow and droplets. Among the above studies, only VanSciver et al. [32] reported the velocity profiles, but the profiles were aligned according to peak velocity position and lost the spatial distribution information. It is challenging to utilize the limited data to provide a validation database and boundary conditions for cough CFD simulation. The other one is that the frequency of PIV was low due to the limitation of equipment, leading to the missing of several airflow characteristics, which relate to a very small time scale. It is essential to employ a high PIV frequency to capture some detailed cough airflow features because several important characteristics were at the time scale of milliseconds. Mahajan et al. [23] reported that the cough air velocity would peak after only a few milliseconds. The temporal and spatial resolution will also be rough when utilizing low frequency, and the turbulence structure caused by large initial velocity near the mouth cannot be captured. The previous studies’ PIV interval was too large (Afshari et al.: 67 m s; VanSciver et al.: 267 m s; Zhu et al.: 70 m s). Therefore, the details of flow may not be captured. Gupta et al. [25] suggested a frequency of 100 Hz or higher. It is worth noting that Bourouiba et al. [38] observed the trajectory of droplets from human sneezes with a very high-frequency PIV (up to 8000 Hz). Wang et al. [35], and Wang et al. [37] utilized a higher PIV (frequency >10,000) to measure the cough but did not explore the detailed velocity distribution.

Therefore, this study aims to measure the initial velocity of cough airflow using a higher PIV frequency and obtain detailed velocity distribution data. This study is the first and essential part, which provides the detailed validation database and probable boundary conditions for the subsequent CFD simulation of droplet propagation in the building environment. To simulate a complete unsteady cough airflow process, the subsequent CFD simulation of droplet propagation in the building environment. To simulate a complete unsteady cough airflow process, the detailed validation database and probable boundary conditions for CFD simulation of droplet propagation in the building environment. To simulate a complete unsteady cough airflow process, the detailed validation database and probable boundary conditions for CFD simulation of droplet propagation in the building environment. To simulate a complete unsteady cough airflow process, the detailed validation database and probable boundary conditions for CFD simulation of droplet propagation in the building environment.
airflow turbulence (this will affect the accuracy of turbulent velocity) more accurately. Repeated cough cases from ten healthy nonsmoking volunteers were measured, and ensemble average operations were carried out to eliminate individual variations and obtain general representative cough airflow results. Overall cough airflow characteristics, including peak velocity time, cough duration time, maximum velocity, and cough spread angle, were measured. Spatial and temporal distributions of cough airflow initial velocity around the mouth area were also obtained and their vertical and horizontal distributions are presented.

2. Measurement methods

2.1. Semi-enclosed chamber filled with stage fog

To measure the exhaled airflow velocity through human coughs, the equipment was installed in a clean darkroom at the Institute of Industrial Science, University of Tokyo. The room temperature and humidity were constant (24 °C, relative humidity: 40–45%) to imitate the coughing situation in the general and representative indoor environment. The main equipment consisted of a chamber and PIV system. The chamber was constructed using transparent acrylic boards and had dimensions of 0.8 m ($x$) × 0.5 m ($y$) × 0.5 m ($z$) (Fig. 1). The left panel of the chamber was constructed using opaque boards to prevent subject harm by the laser. A circular opening (diameter: 0.05 m) existed in the middle of the panel. The chamber contained stage fog (particle diameter: 1–10 μm) and was semi-enclosed (right side remains empty) to assure the air pressure balance during the coughing. During the measurements, the subjects were instructed to sit on an adjustable-height chair in front of the chamber. They could adjust their height to the correct position and place their mouths on the opening. The cough airflow passed through the opening and entered the chamber. The coordinate origin is defined as the position of the mouth center in the middle of the opening. The $x$-, $y$-, and $z$-directions are defined as the streamwise, spanwise, and vertical directions, respectively.

2.2. Setup and accuracy analysis of PIV

For the PIV measurements, stage fog particles were nebulized into the chamber using an oil droplet generator. The parameters of the laser are listed in Table 1. The pulse interval was set to 1/2986 s, according to the camera lens’s capability and maximum airflow velocity. The two sequential images were analyzed into a velocity vector frame by adaptive correlation postprocessing.

The laser lens produced a thin laser sheet, and thus the PIV could be used to avoid laser transmission and mirror reflection. To prevent people exposure to the laser, guard baffles were installed. All people were asked to wear laser safety goggles throughout the measurements. To keep the cough airflow from being affected by the baffle as far as possible, the subjects were introduced to keep the mouth as close to the opening as possible, and keep their heads as steady as possible during coughing. All subjects were introduced to keep their heads in the center of the opening and as horizontal as possible during coughing, but no fixtures were utilized to prevent the coughing unnaturally.

A preliminary analysis on the PIV accuracy was conducted by comparing with the measurement values with hotwire anemometer before the experiment (see Appendix A). We found that the cough jet may blow the fog particles away, and the insufficient concentration of particles lead to a significant measurement error (see Fig. A-1 in Appendix A). Therefore, we added a circular particle supplement tube at the opening (see Fig. A-2 in Appendix A), in which small holes were set at an interval of approximately 1 cm. Particles could be supplemented into the opening during the coughing. The outlet velocity of the particles was lower than 0.1 m/s to avoid impact on the cough airflow. The PIV accuracy was improved when the particle supplement tube was used.

2.3. Experimental subjects and cough cases

Ten young, healthy nonsmoking adult subjects, including five males and five females, were selected for the experiment (Table 2). Each subject repeated coughing three times for the vertical plane measurement and three times for the horizontal plane measurement, with a sufficient rest period between coughs. In total, 60 cough cases were measured in the vertical and horizontal measurements. The experiments were conducted from October to December 2020. The experimental procedures were approved by the University of Tokyo Ethic Committee (Approval number: 20–193) and all subjects have provided written informed contents. Fig. 3 shows the experimental scene and a raw image acquired by PIV. Previous researches reported that several cough characteristics vary including peak flow rate of cough airflow, and PVT, due to the physiological differences caused by sex (e.g., larynx size and the cough power) [24,25]. Therefore, we studied the cough characteristics and velocity distribution of males and females, respectively.
3. Results and discussion

3.1. Overall characteristics of the subject coughs and ensemble average operation

Firstly, comprehensive insights into the airflow characteristics of the coughing process should be checked. According to our preliminary analysis, the measurement error will be larger at positions farther away from the lens due to the refraction of light and perspective (see Fig. A-1 in Appendix A). In addition, velocities near the opening (e.g., $x/\ell_0 = 0.5$) were significantly smaller than that at $x/\ell_0 = 1.0$, which was probably a measurement error due to the insufficient particles near the opening mentioned in Section 2.2, although the supplement tube partly compensated for this phenomenon. Therefore, the position of $x/\ell_0 = 2.5$ was selected as a representative position because it is located in the middle of the camera’s field of view, which is less affected by particle rarefaction and perspective; the accuracy is high. Fig. 4 shows the maximum velocity variation with time at a position of $x/\ell_0 = 2.5$ for an individual cough case. The results indicate that the airflow velocity peaked rapidly with a large acceleration and subsequently slowly decayed. This curve generally represents the typical cough over time from a subject and is similar to the flow rate results reported by Gupta et al. [25]. Fig. 4 does not show the inhalation process before the cough, because it is challenging to capture in our experiment. Furthermore, this process is generally very short and corresponds to less than 1% of the total exhaled airflow [25]. Therefore, the inhalation process was neglected in this study.

| Male subject | Age (years) | Height (m) | Mouth width ($\times 10^{-2}$ m) | Female subject | Age (years) | Height (m) | Mouth width ($\times 10^{-2}$ m) |
|--------------|-------------|------------|-------------------------------|---------------|-------------|------------|-------------------------------|
| M1           | 33          | 1.61       | 4.5                           | F1            | 24          | 1.72       | 4.7                           |
| M2           | 26          | 1.65       | 5.2                           | F2            | 30          | 1.72       | 4.5                           |
| M3           | 37          | 1.73       | 4.8                           | F3            | 29          | 1.52       | 4.1                           |
| M4           | 26          | 1.75       | 5.3                           | F4            | 25          | 1.63       | 4.2                           |
| M5           | 31          | 1.88       | 3.7                           | F5            | 32          | 1.64       | 2.2                           |
| Average      | 30.6        | 1.724      | 4.7                           | Average       | 28.0        | 1.646      | 3.94                          |

Fig. 3. Experimental scene of cough and image acquired by PIV.

Fig. 4. Maximum velocity variation with time at $x/\ell_0 = 2.5$ of one cough case and definitions of PV, PVT, and CDT.

In the velocity variation curve, we can define the peak velocity (PV) at a certain position (e.g., at $x/\ell_0 = 2.5$) as the maximum velocity during the whole cough at the position, peak velocity time (PVT) as the time duration from the time when the airflow reaches this position to that at PV, and cough duration time (CDT) as the time duration for the airflow passing the position, as shown in Fig. 4. These definitions refer to the concept definitions for airflow rate flows in some reports [23,25,26] and can describe the overall cough characteristics. Obviously, the values of PV, PVT, and CDT are different in different positions, we choose the values at $x/\ell_0 = 2.5$ as the representative because of the relatively high
measurement accuracy mentioned previously. Fig. 5 (upper) shows the velocity curves of 15 male cases, and Table 3 lists the variation ranges of PV, PVT, and CDT for all 60 cases at $x/L_0 = 2.5$. The results indicate that, although all cases have similar velocity curves, PV, PVT, and CDT are diverse. The average values are listed in Table 3. Generally, the airflow reached the PV at 18–19 m/s (PVT). The PV for males was approximately 11.8 m/s, which was smaller for females (approximately 10.3 m/s) because the female cough is usually weaker than that of males. The CDT was approximately 500 m/s for both males and females. PV is the peak velocity at $x/L_0 = 2.5$, not the maximum velocity for the whole cough. Table 3 also lists the maximum cough velocity, approximately 15.2 and 13.1 m/s for the males and females, respectively, which generally agrees with the results of Kwon et al. [4]. The raw PV, PVT, CDT values of all cough cases are listed in Table A of Appendix B.

F-tests for PV, PVT, CDT, and maximum velocity between males and females were conducted to validate whether the cough airflows have differences by sex, using the hypothesis of “data between males and females was the same”. The results are shown in Table 3. The p-values varied in the range of 0.16–0.4, implying that the hypothesis was difficult to reject. However, the p-values were also not large enough to prove that the velocity between males and females was the same. In addition, PV and maximum velocity also show differences by sex. Therefore, we consider that the cough airflows varied by sex to a certain extent, and the results will be analyzed by separating males and females in this study.

We nondimensionalized all cough cases and subsequently carried out an ensemble average operation. All cases utilized their PV and PVT at $x/L_0 = 2.5$ for nondimensionalizing the velocity and time, respectively. The lengths were nondimensionalized by the corresponding subject’s mouth width listed in Table 2. Fig. 5 (lower) shows the nondimensional forms of the velocity curves of the 15 male cases. With the rearrangement, all curves coincided when $t/PVT < 1.0$; variations existed in the subsequent decay process, but the tendencies were similar. The vertical and horizontal curves of maximum velocity agreed well. This is because the maximum velocity generally occurred in the center of the airflow (or mouth), which owns the same temporal decaying tendency in the vertical and horizontal directions if considering the jet characteristics of cough airflow. In addition, all cough cases were nondimensionalized by their own representative parameters (PV, PVT) and the subject’s physical characteristics (mouth width) to eliminate individual errors and make them and comparable.

The maximum velocity variations with time at $x/L_0 = 2.5$ for all cough cases measured in vertical or horizontal direction were ensemble-averaged, as shown in Fig. 6. The vertical and horizontal curves well

| Item                      | Male   | Female |
|---------------------------|--------|--------|
| PV variation range (m/s)  | 6.4–18.6 | 5.0–15.7 |
| Average (m/s)             | 11.8   | 10.3   |
| SD (m/s)                  | 3.3    | 3.0    |
| F/Critical F < 0.05 (one tail)/p-value | 1.19/1.86/0.32 |
| PVT variation range (ms)  | 8–35   | 8–39   |
| Average (ms)              | 19     | 18     |
| SD (ms)                   | 7      | 6      |
| F/Critical F < 0.05 (one tail)/p-value | 1.25/1.86/0.28 |
| CDT variation range (ms)  | 277–904 | 343–825 |
| Average (ms)              | 564    | 526    |
| SD (ms)                   | 158    | 131    |
| F/Critical F < 0.05 (one tail)/p-value | 1.46/1.86/0.16 |
| Maximum cough velocity variation range (m/s) | 7.3–20.9 | 8.2–19.1 |
| Average (m/s)             | 15.2   | 13.1   |
| SD (m/s)                  | 3.3    | 3.1    |
| F/Critical F < 0.05 (one tail)/p-value | 1.10/1.86/0.40 |
| Maximum cough velocity by Kwon et al. [4] | 15.3 | 10.6 |

Fig. 5. Raw (upper) and dimensionless (lower) maximum velocity variations with time at $x/L_0 = 2.5$ for 15 male cough cases measured in vertical direction. Every single colorful curve represents the raw or dimensionless maximum velocity at $x/L_0 = 2.5$ varied with time in one cough case. Lower curves were obtained by scaling upper curves via nondimensionalization of velocity and time using PV and PVT, respectively. Colors are for the convenience of distinguishing and do not represent any meaning.

Fig. 6. Ensemble-averaged maximum velocity variation with time at $x/L_0 = 2.5$ in vertical and horizontal directions of all cases with fitted line.
agree, indicating that the velocities in the vertical and horizontal directions owned similar characteristics in both the acceleration and decay process. These curves were similar to the flow rate variation from Gupta et al. [25], in which they reported that the flow rate variation followed the gamma probability distribution. Therefore, it is possible to fit the maximum velocity variation with time at $x/L_0 = 2.5$ in both vertical and horizontal directions using the gamma probability distribution function $\Gamma(\cdot)$, as shown in Equation (1). In the acceleration process, the equation from Gupta et al. [25] was employed, and subsequently, a similar form was utilized to fit the decay process. Here, $t$ represents the time (ms). The coefficient of determination $R^2$ is 0.923 and 0.933 for vertical and horizontal curves. The fitted line indicates that the maximum velocity variation with time closely followed the gamma probability distribution function, similar to the cough flow rate [25].

Fig. 7. Instantaneous distribution of ensemble-averaged velocity vectors of males and females at time of $t/PVT = 1.0, 10.0, \text{ and } 15.0$. The velocity was normalized by PV.
maximal velocity (at \(x/L_0 = 2.5\)) = \[
\begin{align*}
\frac{a_1\tau^{n-1}\exp\left(-\frac{x}{c_1}\right)}{\Gamma(b_1)c_1^{b_1}} & \text{ for } \tau < 1.0 \\
\frac{a_2(\tau + d_2)^{n-1}\exp\left(-\frac{\tau + d_2}{c_2}\right)}{\Gamma(b_2)c_2^{b_2}} & \text{ for } \tau \geq 1.0
\end{align*}
\]
(1)

\(\tau = \frac{x}{PVT}\), \(a_1 = 1.680, b_1 = 3.338, c_1 = 0.428, a_2 = 15.32, b_2 = 0.8435, c_2 = 29.95, d_2 = -0.769\)

Afterwards, all nondimensional cough cases were divided into two groups according to sex, with 15 vertical cases and 15 horizontal cases in each group to analyze the velocity distributions. An ensemble average operation was carried out for each group to eliminate the individual error as fully as possible and acquire the velocity distribution with general characteristics.

### 3.2. Ensemble-averaged velocity distribution

#### 3.2.1. Instantaneous velocity spatial distribution

Fig. 7 shows the two-dimensional distribution of instantaneous ensemble-averaged velocity vectors of males and females at the time of \(t/PVT = 1.0, 10.0, \) and 15.0. The airflow generally formed a diffusion shape from the mouth to the further space. The magnitude of velocity decreased gradually with the change of time. The two-dimensional velocity vectors visually show the shape of velocity distributions; however, the detailed profiles of spatial and temporal variation should be examined.

Fig. 8 shows the vertical and horizontal spatial distributions of the instantaneous ensemble-averaged velocity around the mouth at \(t/PVT = 1.0, 5.0, 10.0, \) and 15.0. All velocities were nondimensionalized by their PVs at \(x/L_0 = 2.5\), while the distances were nondimensionalized by the subjects’ mouth widths \(L_0\) in all cases. The mouth is located at \(x/L_0 = 0, y/L_0 = 0, \) and \(z/L_0 = 0\). For the vertical distribution, only the x- and z-direction components of the velocity were measured by PIV. Therefore, the velocity in the vertical distribution is \(\sqrt{u_x^2 + u_z^2}\), where the bracket \(\langle \cdot \rangle\) represents the ensemble average. Similarly, the velocity in the horizontal distribution is \(\sqrt{u_x^2 + u_y^2}\).

At \(t/PVT = 1.0,\) all coughs reached the PV at \(x/L_0 = 2.5,\) while other positions did not reach or already passed the peak speed at this time. Therefore, the PV at \(x/L_0 = 2.5\) was the largest among all positions. With the increase in \(t,\) a tendency of gradual velocity decay was observed. The averaged velocity curves for males and females were generally identical, which indicates that the male and female airflow characteristics were similar. The averaged velocity partially collapsed; for example, the ensemble-averaged PV at \(x/L_0 = 2.5\) was smaller than one, because the PVs of different cases occurred at different heights owing to the individual differences.

In the \(x/L_0\) range of \(0.5-3.5,\) the vertical ranges of airflow gradually expanded in all distributions, indicating that the airflow from the mouth had a spread angle. The same behavior was observed for the horizontal distributions, as discussed in Section 3.3.

#### 3.2.2. Instantaneous velocity temporal distribution

In addition to the spatial distribution, we also analyzed the velocity variation with time. As stated in Section 3.1, velocity at \(x/L_0 = 0.5\) were underestimated due to the insufficient particles near the opening. In addition, the velocity at \(x/L_0 = 3.5\) were also small and it was difficult to distinguish meaningful profiles, which probably due to the natural decay of the airflow. Therefore, this section analyzes the vertical and horizontal temporal distributions of velocities at the positions of \(x/L_0 = 1.0, 2.0, 2.5,\) and \(3.0,\) as shown in Fig. 9 and Fig. 10. Same as in the last section, the velocity in the vertical distribution is \(\sqrt{u_x^2 + u_z^2}\), while the velocity in the horizontal distribution is \(\sqrt{u_x^2 + u_y^2}\).

At all positions, the velocity initially increased rapidly, and then decreased slowly after it peaked. This tendency well agrees with that shown in Fig. 6. In particular, at \(x/L_0 = 2.5\), the velocity increased from \(t/PVT = 0\) and reached the PV at \(t/PVT = 1\). Subsequently, the velocity gradually decayed. The whole process was advanced at positions of \(x/L_0 < 2.5\) and delayed at \(x/L_0 > 2.5\), because the time origin was defined according to the velocity variation at \(x/L_0 = 2.5\).

Similar to the spatial velocity distribution, the averaged velocity curves for males and females are generally identical, which indicates that the velocity variations with time for males and females are similar. In contrast to the spatial distribution, the vertical range of the airflow was generally constant during the time development. This indicates that the airflow spread with the increase in the distance, but the shape was generally constant over time. Thus, the cough airflow had partial jet flow characteristics, which is consistent with previous reports [16, 25, 31, 32].

The horizontal SD curves varied more sharply than the vertical curves. This probably implies that the measured velocity variation in each case is more violent in the horizontal plane, probably due to measurement errors in the horizontal measurements. One possible reason is the particles’ vertical settlement, which led to the uneven distribution of particles or attachment to the bottom board and caused measurement errors.

#### 3.2.3. PV distribution

Fig. 11 shows the PV distributions at each position in the vertical and horizontal directions. The last line of the horizontal axis caption shows the time at which the PV occurred at the corresponding position. The vertical distributions of the PV at different \(x\)-positions generally indicate the cough directions (or head directions). The horizontal lines represent the fitting line according to the peak velocities at different \(x\)-positions, which shows a downward trend for cough airflows. This tendency was also confirmed in previous studies [25]; i.e., the cough airflow usually shifts downward. Regarding the horizontal distribution, theoretically, the two fitting lines should be horizontal and coincident if the measurement was “perfectly accurate” because the cough direction should be horizontal and toward the center. However, measurement errors led to some deviations (e.g., at \(x/L_0 = 1.0\)), including the uneven distribution of particles mentioned in the last section. In addition, the probability of deviations caused by individual differences should also not be neglected (e.g., heads’ sway during coughing). Fig. 11 also indicates the decaying tendency of the velocity magnitude with the distance, indicating that the airflow energy was damped with the increase in travel distance due to air friction.

#### 3.3. Cough spread angles

The initial cough airflow from the mouth behaves as a jet flow. Therefore, the airflow out of the mouth is usually not completely parallel, but there is a spread angle at the edge of the mouth. The vertical and horizontal cough spread angles are discussed in this section.

The key task to obtain the spread angle is to determine the upper/lower and left/right boundaries of the cough airflow. The previous study [25] determines the boundary by directly checking the raw particle image and drawing the boundary line. This method is intuitive, simple, but obviously with large errors. This study introduced a more quantitative method to determine the airflow boundaries. Considering the jet characteristics of coughing flow, the cough airflow boundary was defined as the position where the velocity decayed to 1% of the maximum value at the airflow center (i.e., velocity is reduced by 99%) in every vertical or horizontal direction. This definition referenced the velocity boundary layer in fluid dynamics. The ordinary least squares fitting line of all boundary points was regarded as the airflow boundary’s edge (Fig. 12).

Subsequently, to eliminate the influence of the head up–down or left–right direction variations in different cases, we utilize the fitting line
Fig. 8. Vertical (left) and horizontal (right) distributions of the instantaneous ensemble-averaged velocity near the mouth.
Fig. 9. Vertical distributions of ensemble-averaged velocity variations with time at various positions of 15 cough cases.
Fig. 10. Horizontal distributions of ensemble-averaged velocity variations with time at various positions of 15 cough cases. Solid line: averaged velocity; dashed line: one SD centered on averaged velocity.
according to the PV at different x-positions introduced in Fig. 11 to determine the head directions. The vertical cough spread angles $\theta_V$ and horizontal cough spread angles $\theta_H$ after excluding the head direction and their averaged values are shown in Fig. 13 and Table 4. The vertical angles varied in the range of $4^\circ$–$27^\circ$, while the horizontal angles varied in the range of $4^\circ$–$31^\circ$, which implies that the individual differences were significant. The averaged values were $\theta_V = 15.9^\circ$ and $17.8^\circ$ and $\theta_H = 16.2^\circ$ and $17.6^\circ$ for males and females, respectively. The difference between averaged vertical and horizontal spread angles was less than $0.3^\circ$. This is very small; therefore, the initial cough airflow exhaled from the mouth was promising to be modeled as a cone, which should be confirmed in the future.

Table 4 shows the averaged $\theta_V$ and $\theta_H$ compared with Gupta et al. [25], in which a large discrepancy was found. In addition to the differences in the methods of determining the airflow boundary mentioned above, several experimental conditions between the current study and Gupta’s were also different, leading to discrepancies. For examples, the number of cases of two studies was quite different (5 for Gupta vs. 15 for the current study); furthermore, subjects’ heads were fixed by an auxiliary device in Gupta’s experiment while heads were free but kept constant as far as possible during coughing in the current study. These differences in experimental conditions could cause the discrepancy of the cough spread angles.

3.4. Discussion on the usage of experimental data

This experiment reported a set of cough airflow data, including
detailed temporal and spatial distributions around mouths, maximum/minimum velocities during time series, ensemble-averaged velocities, and standard deviations, which were seldom discussed in detail in previous studies. In addition to understand human cough characteristics deeply, these data also provide boundary conditions and an accuracy validation basis for CFD validation to model cough airflows for the next step (Table 5). With these data, it is capable of simulating the droplets propagation via cough airflow using CFD. The simulation can help determine the propagation features of droplets (e.g., propagation distances, propagation routes, and concentration distributions), which is essential for the design and research of building space sensitive to social distance hospitals and sanatorium. Furthermore, the simulation is invaluable for evaluating the infection risk in the population in the building environment, which will be further discussed in the next step.

However, some inadequacies of this experiment should be noticed, which limits the utilization of these data to some extent. Firstly, the experimental subjects were healthy young subjects. Therefore, it should be prudent if utilizing these data in modeling the cough airflow from infected subjects or elderly people, because the cough characteristics may change to the difference in the physical condition. In addition, as we reported, the velocity horizontal distribution was noise, and its accuracy may not as high as the vertical distribution, which we should also pay attention to.

4. Conclusions

This study utilized a PIV with the interval of 1/2986 s system to measure the overall characteristics and initial velocity of the exhaled airflow of coughs by five males and five females. The experiment for each person was repeated six times to measure the vertical and horizontal velocity distributions. The measurement results were ensemble-averaged according to sex.

The maximum coughing velocity for females was weaker than that for males, but their PVT or CDT was similar, implying that their cough duration time was almost the same. In addition, the non-dimensional velocity distribution for males and females agreed well in both vertical and horizontal directions, indicating that their cough airflow owns similar characteristics. The temporal variations of maximum velocity at $x/L_0 = 2.5$ can be defined as a combination of gamma-probability-distribution functions. The cough spread angles were analyzed by determining the cough airflow boundaries as the position where the velocity decayed to 1% of the maximum value at the airflow center in every vertical or horizontal direction. The vertical and horizontal spread angles were similar, implying that the initial cough airflow exhaled from the mouth was promising to be modeled as a cone. This should be further studied. The cough spread angles of males and females were also almost the same.

However, several limitations of this study should be noticed. The first is the situation of the subjects (young and healthy) we mentioned obviously, which may limit these data in modeling the cough airflows from the infected subjects (e.g., COVID-19 infected patients) or elderly people. In addition, more objects with different physical conditions should be measured to explore the relationship between airflow characteristics and physical indexes (e.g., ages, weight, and height). Another point is that the study of cough airflow cannot replace the research of pathological organizations. This is because pathogenic organisms exhaled from a cough may act as a different dynamic behavior from the airflow. The characteristics of cough airflow are not enough to grasp the whole transmission mechanisms of the exhaled pathogenic organisms. The effect of environmental temperature and humidity on the droplet transmission and deposit through cough airflows should also be discussed. These should be further studied in the future work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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To see this research data in medley, please click the following link https://data.mendeley.com/datasets/386d3mxxxb/.

Appendix A

The PIV accuracy was analyzed using an air spray and hotwire anemometer. The nozzle of the air spray was arranged at the opening to imitate the human mouth and continuously provided a stable jet flow. The 10-s-time-averaged velocity magnitude was measured using a hotwire anemometer at several positions along the jet flow and was regarded as the benchmark data. The chamber was then filled with fog and PIV was used to measure the velocity field of the jet flow again. Fig. A-1 shows that PIV significantly under-estimated the velocity, because the jet flow blew the fog particles away, so that the measurement error occurred because of the insufficient concentration of particles. After the addition of the circular particle supplement tube (Fig. A-2) at the opening, the accuracy of the PIV significantly improved and was close to that of the hotwire anemometer.
Appendix B

Table A shows the raw PV, PVT, CDT and maximum cough velocity values of 60 cough cases. In the Case names, the first alphabet indicates the subjects, in which “A-E” represents five males, “a-e” represents five females. The second alphabet shows the case was measured in the vertical (V) or horizontal (H) directions. The third number means the experiment case number. Therefore, B–H2 represents the second horizontal measurement of the male subject B.

| Case Name | Age (year) | Body height (m) | Mouth width (m) | PVT (ms) at $x/L_0 = 2.5$ | CDT (ms) at $x/L_0 = 2.5$ | PV (m/s) at $x/L_0 = 2.5$ | Max. Cough velocity (m/s) |
|-----------|------------|----------------|----------------|--------------------------|--------------------------|--------------------------|---------------------------|
| A-V1      | 33         | 1.61           | 0.045          | 20                       | 629                      | 16.0                     | 18.7                      |
| A-V2      | 10         | 3.74           | 1.61           | 19                       | 733                      | 14.9                     | 17.3                      |
| A-V3      | 20         | 4.79           | 1.84           | 33                       | 303                      | 14.5                     | 16.2                      |
| A-H2      | 33         | 27.7           | 14.5           | 11                       | 277                      | 14.9                     | 16.0                      |
| A-H3      | 26         | 1.65           | 0.052          | 23                       | 455                      | 13.9                     | 18.8                      |
| B-V1      | 16         | 5.66           | 12.3           | 18                       | 594                      | 7.0                      | 13.6                      |
| B-V2      | 19         | 5.97           | 10.3           | 11                       | 529                      | 10.6                     | 11.1                      |
| B-H1      | 20         | 4.51           | 9.6            | 9                        | 446                      | 9.6                      | 15.7                      |
| B-H2      | 37         | 1.73           | 0.048          | 27                       | 713                      | 18.6                     | 16.1                      |
| C-V1      | 11         | 5.23           | 11.0           | 8                        | 656                      | 9.7                      | 13.3                      |
| C-V2      | 15         | 7.15           | 10.4           | 16                       | 411                      | 11.8                     | 13.2                      |
| C-V3      | 9          | 4.46           | 9.6            | 19                       | 705                      | 6.6                      | 20.9                      |

(continued on next page)
Table A (continued)

| Case Name | Age (year) | Body height (m) | Mouth width (m) | PVT (ms) at x/L0 = 2.5 | CDT (ms) at x/L0 = 2.5 | PV (m³) at x/L0 = 2.5 | Max. Cough velocity (m/s) |
|-----------|------------|-----------------|-----------------|------------------------|------------------------|------------------------|--------------------------|
| D-V2      | 14         | 590             | 12.9            | 13.8                   |                        |                        |                          |
| D-V3      | 25         | 608             | 10.8            | 11.0                   |                        |                        |                          |
| D-H1      | 22         | 454             | 9.2             | 10.4                   |                        |                        |                          |
| D-H2      | 33         | 493             | 6.4             | 7.3                    |                        |                        |                          |
| D-H3      | 19         | 585             | 8.8             | 13.9                   |                        |                        |                          |
| E-V1      | 31         | 1.88            | 0.037           | 27                     | 904                    | 15.0                   | 11.6                     |
| E-V2      | 35         | 852             | 14.0            | 16.8                   |                        |                        |                          |
| E-V3      | 14         | 881             | 9.6             | 13.8                   |                        |                        |                          |
| E-H1      | 22         | 408             | 7.3             | 11.6                   |                        |                        |                          |
| E-H2      | 14         | 536             | 13.7            | 15.6                   |                        |                        |                          |
| E-H3      | 11         | 446             | 10.8            | 13.4                   |                        |                        |                          |
| a-V1      | 24         | 1.72            | 0.047           | 22                     | 526                    | 9.0                    | 10.2                     |
| a-V2      | 13         | 395             | 8.0             | 9.4                    |                        |                        |                          |
| a-V3      | 13         | 459             | 6.6             | 8.6                    |                        |                        |                          |
| a-H1      | 18         | 744             | 14.4            | 15.2                   |                        |                        |                          |
| a-H2      | 12         | 404             | 12.3            | 15.4                   |                        |                        |                          |
| a-H3      | 12         | 635             | 11.2            | 11.7                   |                        |                        |                          |
| b-V1      | 30         | 1.72            | 0.045           | 24                     | 566                    | 7.1                    | 11.0                     |
| b-V2      | 20         | 583             | 8.2             | 11.3                   |                        |                        |                          |
| b-V3      | 18         | 645             | 5.0             | 10.5                   |                        |                        |                          |
| b-H1      | 11         | 579             | 6.3             | 9.1                    |                        |                        |                          |
| b-H2      | 11         | 557             | 8.1             | 10.3                   |                        |                        |                          |
| b-H3      | 15         | 480             | 8.3             | 9.4                    |                        |                        |                          |
| c-V1      | 29         | 1.52            | 0.041           | 8                      | 605                    | 11.3                   | 14.8                     |
| c-V2      | 19         | 728             | 7.2             | 8.2                    |                        |                        |                          |
| c-V3      | 15         | 825             | 8.7             | 12.0                   |                        |                        |                          |
| c-H1      | 20         | 343             | 15.0            | 16.2                   |                        |                        |                          |
| c-H2      | 17         | 393             | 15.7            | 18.4                   |                        |                        |                          |
| c-H3      | 28         | 400             | 13.6            | 15.4                   |                        |                        |                          |
| d-V1      | 25         | 1.63            | 0.042           | 23                     | 349                    | 8.3                    | 10.0                     |
| d-V2      | 15         | 470             | 12.6            | 16.7                   |                        |                        |                          |
| d-V3      | 28         | 703             | 9.3             | 11.3                   |                        |                        |                          |
| d-H1      | 14         | 444             | 15.2            | 17.8                   |                        |                        |                          |
| d-H2      | 20         | 740             | 9.3             | 12.9                   |                        |                        |                          |
| d-H3      | 39         | 413             | 10.6            | 13.7                   |                        |                        |                          |
| e-V1      | 32         | 1.64            | 0.022           | 22                     | 524                    | 9.9                    | 13.7                     |
| e-V2      | 14         | 449             | 15.4            | 15.4                   |                        |                        |                          |
| e-V3      | 19         | 544             | 9.3             | 16.0                   |                        |                        |                          |
| e-H1      | 12         | 372             | 14.9            | 19.0                   |                        |                        |                          |
| e-H2      | 23         | 472             | 9.6             | 15.8                   |                        |                        |                          |
| e-H3      | 19         | 432             | 9.8             | 13.1                   |                        |                        |                          |
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