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Experimental measurements of airflow features and velocity distribution exhaled from sneeze and speech using particle image velocimetry

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A B S T R A C T

Airflow exhaled from sneeze and speech is an important source of viruses and droplets in daily life and may cause imperceptible virus propagation. The velocities of sneeze and speech airflow exhaled from 10 healthy young participants repeatedly using high-frequency (2986 Hz) particle image velocimetry are measured. The parameters for describing the dynamic process of sneeze airflow, such as sneeze duration time (SDT), peak velocity time (PVT), maximum velocities, and sneeze spread angle, are analyzed. The sneeze airflow lasts 430 ms (SDT) and reaches the peak velocity in the first 20 ms (PVT). The maximum sneeze airflow velocity is approximately 15.9 m/s. The temporal variation of the sneeze velocity exhibits the gamma distribution. For speech airflow, the maximum instantaneous velocity and maximum time-averaged velocity are reported. The maximum instantaneous velocity is approximately 6.25 m/s, whereas the time-averaged value is only 0.208 m/s owing to the extremely small airflow velocity among syllables. The vertical/horizontal spread angles of the airflow are 15.1°/42.9° for sneeze and 52.9°/42.9° for speech. The difference in airflow features based on gender is generally slight for both sneeze and speech. Subsequently, an ensemble-average operation is conducted to obtain the general and representative velocity distributions. We report each component of the temporal and spatial velocity distributions of the sneeze airflow and the time-averaged velocity distribution of the speech airflow. These detailed distribution data can provide a comprehensive understanding of sneeze and speech airflow movement mechanisms as well as a detailed database for future sneeze and speech computational fluid dynamics simulations.

(continued on next column)
1. Introduction

The current coronavirus disease (COVID-19), which caused over 1.6 million infectors and 3 million deaths by May 2021, has become a significant global public health disaster. During the past two years, researchers revealed that the novel coronavirus (SARS-CoV-2) is transmitted mainly by airborne particles via airflow exhaled from the infectors, especially from the infectors’ coughs, which is a primary symptom of the infections. Therefore, the world has paid full attention to human coughs during epidemic prevention and control. Meanwhile, many studies were also focused on human coughs, including the cough airflow features [1,2] and the exhaled droplets via coughs [3–8].

However, researches also revealed that SARS-CoV-2 has an incubation period of 5–14 days [9,10], and in several individual cases, it can approach 27 days [11]. During the incubation period, the infectors may not show any symptoms and thus propagate the virus during daily communications (e.g., sneeze and speech) and eventually cause cluster infections, especially in the enclosed building interior space. Therefore, as a potential carrier of the novel coronavirus, the exhaled airflow and droplets via daily sneeze and speech should also be noted in studying the virus transmission in the built environment.

In previous studies, most researchers have focused on measuring exhaled droplets via sneeze [12–15] and speech [16–18], which are primary routes of virus propagation. However, exhaled airflow via sneeze and speech is equally important when investigating virus transmission from infectors. This is because small droplets or viruses are suspended in the air directly and propagate with the airflow movement. Owing the development of computational fluid dynamics (CFD) technology, virus propagation via exhaled airflow from infectors in a certain space can be simulated. This is extremely beneficial for investigating and controlling virus transmission and subsequently providing precaution and control methods. Therefore, detailed airflow features and velocity distribution data are essential for the simulation of sneeze and speech: they provide the fundamental boundary conditions and a validation database.

However, to the best of our knowledge, few studies have focused on measuring exhaled airflow features and the velocity distribution of sneeze. Nishimura et al. [19] attempted to measure and visualize sneeze airflow by tracing cigarette smoke from the mouth using a high-speed camera. Tang et al. [20] reported a maximum sneeze velocity of 4.5 m/s, which was derived by measuring the maximum visible distance of sneeze plumes using a high-speed camera. Bourouiba et al. [21] reported a sneeze duration time of 200 ms and an airflow spread angle of 14.8°. Bahl et al. [22] introduced a method to visualize droplets expelled through sneezing using light-sheet illumination. In their method, the airflow velocity can be measured at some points by analyzing the droplet movement; however, the sneeze airflow features and detailed velocity distribution are difficult to obtain. Fontes et al. [23] simulated airflow and droplets through a network of nasal and buccal passages via sneezing and investigated the relationship between droplet dispersion and human physiological factors. Additionally, they reported several temporal slices of the velocity vector and droplet distributions around the mouth.

Additionally, researchers have measured airflow features from speech. Chao et al. [24] measured speech airflow using particle image velocimetry (PIV) and reported an average expiration airflow velocity of 3.9 m/s, as well as maximum velocities of 4.6/3.9 m/s for male/female. Gupta et al. [25] reported a peak airflow rate and spread angle of 1.61/s and 30° during speech, respectively. Kwon et al. [26] measured the initial velocity of the speech airflow of 17 males and 9 females using PIV and obtained average initial speech velocities of 4.07 and 2.31 m/s for males and females, respectively. Additionally, they reported exhaled airflow spread angles of 49° and 78°, respectively. Giovanni et al. [27] reported that different syllables produced various average velocities in the range of 0.3–1.8 m/s. Tan et al. [28] measured the peak velocity, vortexes, and plumes using a high-speed camera when participants were pronouncing several specific syllables.

Although these previous studies investigated some parameters that provide a general description of the sneeze and speech airflows (e.g., the maximum velocity, flow rate, and spread angle), detailed initial velocity distributions of sneeze and speech airflows have not been reported to the best of our knowledge. In addition, investigations regarding sneeze and speech airflow features are insufficient, such as that studies regarding the dynamic variation process features of sneeze airflow are scarce. Meanwhile, previous speech measurements mainly focused on the relationship between syllable types and speech airflow features, whereas the general airflow features of daily speech were rarely discussed.

Therefore, the exhaled airflow from sneeze and speech was measured using high-frequency PIV in this study. We discussed the parameters for the airflow of the dynamic sneeze process comprehensively, such as the peak velocity, peak velocity time, sneeze duration time, and so on. In addition, we reported the detailed temporal and spatial distribution of sneeze airflow velocity and spatial distribution of time-averaged speech airflow velocity for the first time. In addition to providing a comprehensive understanding of the dynamic process of human sneezing and speech airflows in daily life, these data can provide the boundary conditions and an accuracy validation basis for CFD validation to model sneezing and speech airflows in future studies. This is invaluable for evaluating the infection risk among a population in the built environment. High-frequency PIV is employed to capture characteristics associated with small time scales and small-scale airflow turbulence more accurately. Repeated sneeze and speech experiments were conducted on 10 healthy nonsmoking volunteers to measure the exhaled airflow velocity. The essential characteristics of the sneeze and speech airflows were measured. Different data processing methods were applied to sneeze and speech airflow data, depending on the characteristics of sneeze and speech. Finally, nondimensionalization and ensemble-average operations were performed to eliminate individual variations and obtain their general representative and detailed airflow velocity distributions.

2. Measurement methods

2.1. Experimental equipment and participants

The experimental equipment was installed in a clean darkroom at the Institute of Industrial Science, University of Tokyo. The ambient environment temperature and humidity influence the movement behavior of airflow and droplets, such as the buoyancy on the airflow and droplets, and the evaporation and size change of droplets. However, this is not what we focus on in this study. The commonly-used temperature and relative humidity range used in previous experiments were approximately 20–26°C and 15%–73% [5,19,23–27,29,30]. Based on this fact, we referred to the common indoor air-conditioner parameters and maintained the room temperature and humidity to a relative middle value in this study, at 24°C and 40%–45%, to mimic general indoor environments. The main equipment comprised a semi-enclosed chamber and a PIV system. The chamber (xyz = 0.8/0.5/0.5 [m]) was constructed using transparent acrylic boards (Fig. 1(a)), and the front panel was constructed using opaque boards to prevent the participants from being harmed by the laser. A circular opening (diameter 0.05 m) was set in the middle of the panel, through which the participants can sneeze or speak into the chamber. The chamber was filled with stage fog (particle diameter of 1–10 mm) and was semi-enclosed to ensure air pressure balance during sneezing or speaking. Ten healthy nonsmoking adult participants, including five males and five females, were selected for the experiments (average age, 30.6±28.0 years; average height, 1.72±1.65 m; and average mouth width, 4.7±3.9 cm for males/females, respectively). The physical attributes of the participants are listed comprehensively in Table A-1 in the Appendix. During the measurements, the participants were instructed to sit on an adjustable-height chair in front of the chamber. They can adjust their height to the correct position and
place their mouths on the opening. The sneeze or speech airflow passed through the opening and entered the chamber. The coordinate origin was defined as the position of the mouth center in the middle of the opening. The $x$-, $y$-, and $z$-directions were the streamwise, spanwise, and vertical directions, respectively.

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 based on the capability of the camera lens and the maximum airflow velocity. The two sequential images were analyzed to obtain a velocity vector frame using adaptive correlation post-processing.

PIV can only detect two-dimensional velocity on a thin laser sheet illuminated by a laser. Therefore, vertical and horizontal distribution measurements were conducted to obtain the three-dimensional spatial distribution of the velocity (Fig. 1(b,c)). Movable boards wrapped with a black flannelette were installed on the bottom and backside of the inner surface of the chamber to avoid laser transmission and mirror reflection. All participants were instructed to wear laser safety goggles throughout the measurements to prevent them from being exposed to the laser. Additionally, the participants were instructed to maintain their heads as horizontal and as steady as possible during sneezing or speaking. However, to prevent unnatural sneeze or speech airflow, no fixtures were utilized.

A PIV accuracy analysis was conducted using a hotwire anemometer prior to the experiment. The analysis results show that a significant measurement error occurred when the current PIV system was used because the sneeze or speech airflow blew the fog particles away and resulted in an insufficient concentration of particles. We introduced a kind of circular particle supplement tube set at the opening to compensate for this phenomenon in previous work [31]. Particles from the tube can be supplemented into the opening through small holes arranged in the tube during the sneeze or speech with a small velocity. The particle supplement tube was applied in our previous cough experiment, and the results showed that the PIV accuracy can be improved significantly using the particle supplement tube [31].

2.2. Sneeze experimental cases and data processing

For the sneeze experiment, one sneeze was conducted for each measurement, and the entire sneezing process was fully recorded. A sufficient rest duration was allocated between every sneeze to mimic the strength of an actual sneeze. Pepper was provided when necessary to ensure that the participants sneezed more naturally. Each participant repeated the sneeze three times for each of the vertical and horizontal plane measurements. Therefore, 60 sneeze cases were measured for the vertical and horizontal measurements.

Because sneezing is a dynamic process, the time-varying features of the sneeze airflow should be investigated first. However, it is difficult to describe the total airflow field; we selected $x/L_0 = 2.5$ as a representative position to analyze the airflow time-varying features. The relevant discussions are provided in Section 3.1. Additionally, several other parameters were analyzed in Section 3.1 to describe the overall sneeze.
airflow features. The position $x/L_0 = 2.5$ was emphasized because it was located in the middle of the camera’s field of view, which was affected less by particle rarefaction, the camera perspective, and the chamber boundary; hence, the accuracy was relatively high [31].

Subsequently, all the sneeze cases were nondimensionalized and ensemble-averaged to eliminate individual errors to the maximum extent and to acquire the velocity distribution with general features. Hence, the ensemble-averaged temporal and spatial distributions of the airflow velocity were obtained, as discussed in Section 3.2. Deviations from the ensemble average are discussed as well. The ensemble-average operation is defined as follows:

$$f = \langle f \rangle + f'$$

(1)

where $f$ represents the physical quantity (e.g., instantaneous velocity), $\langle f \rangle$ the ensemble-averaged value, and $f'$ the deviation from the ensemble-average operation.

Regarding the sneeze airflow dynamic process, the ensemble-averaged velocity was defined as the ensemble-averaged value of the instantaneous scalar velocity for all cases, as follows:

$$\langle u \rangle = \frac{1}{3} \sum_{j=1}^{S} u_j, \langle v \rangle = \frac{1}{3} \sum_{j=1}^{S} v_j, \langle w \rangle = \frac{1}{3} \sum_{j=1}^{S} w_j$$

(2)

where $u_j, v_j,$ and $w_j$ represent the $x$-, $y$-, and $z$-direction components of the instantaneous velocity of the $j$th experimental case, respectively; $S$ is the number of cases.

2.3. Speech experimental cases and data processing

Speech is typically a continuous vocal process, and people rarely utter only one or two syllables in daily communication. Therefore, in the speech experiment, the dynamic variation process of the airflow of a single syllable was not measured; however, the speech airflow for a duration was recorded and its time-averaged value was obtained. In the speech experiment, participants were introduced to count continuously in English, beginning from one. Speech airflow within 10 s was continuously measured in one case. The participants were instructed to speak using their accustomed speed, rhythm, and volume. In addition, syllable types were not specifically selected (e.g., we did not specifically select plosives to strengthen the airflow). These measures ensured that the participant spoke as they would in their daily communication. Similar to the sneeze experiment, a sufficient rest duration was allocated between each measurement. Three vertical plane measurements and three horizontal plane measurements were conducted. A total of 60 speech cases were measured for the vertical and horizontal measurements.

In the data processing, a time-average operation for the 10 s speech airflow was conducted for each case. Subsequently, all the time-averaged results were nondimensionalized and ensemble-averaged to eliminate individual errors. Hence, we obtained the spatial distributions of the ensemble-averaged and dispersed results of the time-averaged speech airflow velocity. The definition of the ensemble-average operation is the same as that shown in Equation (1), and the time-average operation is defined in Equation (3):

$$f = \langle f \rangle + f'$$

(3)

Each component of the ensemble-averaged results for the time-averaged velocity is defined as follows:

$$\langle f \rangle = \frac{1}{T} \sum_{i=1}^{T} \left( \frac{1}{S} \sum_{j=1}^{S} f_i^j \right)$$

$$\langle f' \rangle = \frac{1}{T} \sum_{i=1}^{T} \left( \frac{1}{S} \sum_{j=1}^{S} f'_i^j \right)$$

$$\langle \pi \rangle = \frac{1}{T} \sum_{i=1}^{T} \left( \frac{1}{S} \sum_{j=1}^{S} \pi_i^j \right)$$

(4)

where $u_j^i, v_j^i,$ and $w_j^i$ represent the $x$-, $y$-, and $z$-direction components of the instantaneous velocity at the $i$-th sampling time of the $j$-th experimental case, respectively; $T$ and $S$ are the numbers of sampling times and cases, respectively.

According to Kikumoto [32], well-known steady CFD simulation methods (e.g., Reynolds-averaged Navier–Stokes, RANS) ensemble averages each velocity component, but not the scalar velocity. Therefore, the ensemble-averaged results of each component were reported, based on Equations (2) and (4), for the convenience of further CFD validations and comparisons in the future.

3. Results of sneeze airflow measurements

3.1. Overall sneeze airflow features and ensemble-average operation

First, a comprehensive insight into the overall airflow features of a sneezing process was conducted. Fig. 2 shows the temporal variation of the maximum velocity at the representative position of $x/L_0 = 2.5$ for one sneeze case. The velocity curve shows the typical sneeze airflow variation pattern: the airflow velocity peaked rapidly with a high acceleration and subsequently decayed slowly. This curve reflects the sneeze airflow velocity variation from the bottom surface of the throat within the upper respiratory tract reported by Fontes et al. [23].

Duration and maximum velocity are two well-known indices for describing sneeze airflow characteristics [33]. However, using only these two indexes is insufficient to comprehensively discuss the dynamic variation process of the sneeze airflow. The sneeze airflow pattern shown in Fig. 2 is similar to the velocity variation [31] or flow rate [34] of an exhaled airflow from coughing. Therefore, in addition to the maximum velocity, we employed the peak velocity (PV), peak velocity time (PVT), and sneeze duration time (SDT), which are frequently utilized in cough airflow analysis [31], to describe the overall sneeze characteristics. In the velocity variation curve, the PV can be defined as the maximum velocity at $x/L_0 = 2.5$ during the entire sneezing process; PVT as the duration from the time when the airflow reaches $x/L_0 = 2.5$ to the time when the PV occurs; and SDT as the entire time duration for the airflow to pass $x/L_0 = 2.5$ completely. It is noteworthy that the values of PV, PVT, and SDT were different at different positions, and we selected the values at $x/L_0 = 2.5$ as the representative values because of the relatively high measurement accuracy mentioned previously.
Table 2 lists the statistical results of the PV, PVT, and SDT for all sneeze cases. The results indicate that the PV, PVT, and SDT were similar between the male and female participants. Generally, the airflow reached the PV in 20 ms (PVT), which is similar to the PVT for cough airflows [31]. The PV for the males/females was approximately 12.2/11.1 m/s. The SDT was 400–470 ms. It is noteworthy that the PV is the peak velocity at $x/L_0 = 2.5$ and not the maximum velocity for the entire sneeze airflow region. Table 2 shows that the maximum sneeze velocity was approximately 16 m/s for both the male and female participants.

We nondimensionalized all the cough cases using the PV and PVT of each case at $x/L_0 = 2.5$ for the velocity and time, respectively, and the mouth width of the participant for the length. Fig. 3(a) shows the nondimensional form of the maximum velocity curves at $x/L_0 = 2.5$ of all cases. Owing to the rearrangement, all curves coincided when $t/PVT < 1.0$, and the similar tendencies were exhibited in the decay process, although variation appeared. Subsequently, the ensemble-average operation was conducted for all sneeze cases to eliminate individual errors and acquire a velocity distribution with general features. The results shown in Table 2 and Fig. 3(a) imply no significant difference in the sneeze airflow features between the males/females; therefore, all the male and female cases were ensemble averaged together.

Fig. 3(b) demonstrates the ensemble-averaged temporal variations of maximum velocity at $x/L_0 = 2.5$ in vertical or horizontal directions. The

| Item                              | Male Cases | Female Cases | All Cases |
|-----------------------------------|------------|--------------|-----------|
| PV at $x/L_0 = 2.5$ [m/s]         | variation range 5.40–18.3 | 4.64–19.0 | 4.64–19.0 |
| ensemble-averaged value           | 12.2       | 11.1         | 11.7      |
| SD                                | 2.71       | 3.38         | 3.56      |
| PVT at $x/L_0 = 2.5$ [ms]         | variation range 7–30 | 5.43 | 5.43 |
| ensemble-averaged value           | 19         | 20           | 19        |
| SD                                | 6          | 9            | 8         |
| SDT [ms]                          | variation range 123–828 | 150–794 | 123–828 |
| ensemble-averaged value           | 473        | 396          | 434       |
| SD                                | 171        | 155          | 167       |
| Maximum instantaneous velocity [m/s] | variation range 9.88–23.5 | 10.0–21.7 | 9.88–23.5 |
| ensemble-averaged value           | 16.2       | 15.6         | 15.9      |
| SD                                | 3.96       | 3.28         | 3.62      |

Fig. 3. Temporal variations of dimensionless maximum velocity of all cases at $x/L_0 = 2.5$ (upper) and ensemble-averaged value (lower).
vertical and horizontal curves well agreed, indicating that the vertical and horizontal velocities owned similar features in both the acceleration and decay process. These curves were similar to the maximum velocity variation of cough airflow reported by Han et al. [31] and Gupta et al. [34], in which they reported that the velocity variation followed the gamma-probability distribution. Therefore, we fitted the velocity variation curves, employing their equation. The equation utilized the gamma-probability distribution. Therefore, we fitted the velocity variation with time closely followed the gamma probability distribution, similar to the cough airflow. 

The fitted line indicates that the maximum velocity varied more rapidly at \( \tau < 1.0 \), which is consistent with Fig. 3(b).

The maximum velocity (at \( x/L_0 = 2.5 \)) is

\[
\begin{align*}
\text{max velocity} & = \begin{cases} \\
\frac{a_1 \tau^{b_1} \exp \left( -\frac{\tau}{c_1} \right)}{\Gamma(b_1)c_1^{b_1}} & \text{for } \tau < 1.0 \\
\frac{a_2 \tau^{b_2} \exp \left( -\frac{\tau}{c_2} \right)}{\Gamma(b_2)c_2^{b_2}} & \text{for } \tau \geq 1.0
\end{cases}
\end{align*}
\]

\( \tau = \frac{\text{t}}{\text{PVT}} \), \( a_1 = 1.680 [-] \), \( b_1 = 3.338 [-] \), \( c_1 = 0.428 [-] \), \( a_2 = 8.184 [-] \), \( b_2 = 0.590 [-] \), \( c_2 = 16.720 [-] \).

3.2. Temporal and spatial distribution of ensemble-averaged velocity

Fig. 4 and Fig. 5 show the vertical and horizontal temporal distributions of the instantaneous ensemble-averaged nondimensional velocity at positions \( x/L_0 = 1.0, 2.0, \) and 3.0. The time, velocities, and distances were nondimensionalized by the PVT and PV of the corresponding case, and the participant’s mouth width \( L_0 \), respectively. The velocity was obtained by ensemble-averaging all the cases to eliminate individual errors. It is noteworthy that for the vertical distribution, only the \( x- \) and \( z- \) direction components of the velocity were measured using PIV; therefore, only \( \langle u \rangle \) and \( \langle w \rangle \) are reported for the vertical distribution. Similarly, \( \langle u \rangle \) and \( \langle v \rangle \) are reported for the horizontal distribution. The mouth was located at the coordinate origin (e.g., \( x/\text{L}_0 = 0, y/\text{L}_0 = 0, \) and \( z/\text{L}_0 = 0 \)). In addition to the ensemble-averaged velocity represented by solid lines, the maximum and minimum instantaneous velocity at each position are also displayed by horizontal bars. Meanwhile, the dash lines are used to show the \( \pm 0.5 \) standard deviation (SD) from the ensemble-average operation, which implies the range with a confidence interval of 38.3% (when the nondimensionalized ensemble-averaged velocity was one). Notice that sneeze airflow of each case varied to a certain extent due to individual differences, leading that it was difficult to measure the uncertainty of the experiment. Therefore, Figs. 4 and 5 shows \( \pm 0.5 \) SD to describe it to a certain extent by considering the results of multiple experiments accord with the normal distribution.

It was discovered that \( \langle u \rangle \) was significantly higher than \( \langle v \rangle \) and \( \langle w \rangle \), indicating that the streamwise direction component was the main region of the sneeze airflow. In all positions, the velocity first increased rapidly and then decayed gradually when it peaked. This tendency is consistent with the curves shown in Fig. 2. This trend became more pronounced at \( x/L_0 = 2.0 \) (in fact, the trend was the most apparent at \( x/L_0 = 2.5 \) because the time was nondimensionalized by the PVT of \( x/L_0 = 2.5 \)).

When approaching \( t/\text{PVT} \sim 10 \), the velocity attenuated significantly at all positions, and it was difficult to determine the precise curve shape. This implies that although Table 2 shows that the complete duration of sneeze airflow (e.g., SDT) is approximately 20 times that of the PVT, the first 10 PVTs were more critical for the velocity distribution. The velocities at \( x/L_0 = 3.0 \) were extremely small during the entire SDT, which suggests the spatial range of the sneeze airflow to some extent.

The temporal distribution could not reflect the spread shape and spatial range of the sneeze airflow; therefore, the spatial distribution of instantaneous ensemble-averaged velocity at times \( t/\text{PVT} = 1.0, 3.0, \) 6, and 9 were analyzed, as shown in Fig. 6. The velocity in the vertical distribution does not contain the spanwise component, whereas the velocity in the horizontal distribution does not contain the vertical component, similar to the temporal distribution. Same as Figs. 4 and 5, \( \pm 0.5 \) SD (confidence interval of 38.3%) were also shown in Fig. 6.

At \( t/\text{PVT} = 1.0 \), the sneeze airflow reached the PV at \( x/L_0 = 2.5 \), whereas the other positions did not reach or had already passed the peak speed. Therefore, the PV at \( x/L_0 = 2.5 \) was the highest among all positions investigated; however, this is dependent on the nondimensional parameters selected. Notice that PV at \( x/L_0 = 2.5 \) was smaller than one
avoid using any auxiliary fixtures to ensure that the sneezing airflow is head centered and stable as much as possible during the experiment, we direction in both temporal and spatial distribution. This was because rical, and the peak velocity of each location deviated from the horizontal distribution. However, the results were not strictly symmet-rically, the sneeze airflow direction should be toward the center in the positions

Fig. 5. Horizontal profiles of ensemble-averaged velocity variation with time at positions \( x/L_0 = 1.0, 2.0, \) and 3.0.

because the PVs of different cases occurred at different heights because of individual differences. As \( t \) increased, a gradual velocity decay was observed. The averaged velocity collapsed partially. Both vertical and horizontal velocity distribution were not symmetrical. Vertical airflow usually has a downward trend, caused by the structure of the mouth and the head movement when sneezing [20,23]. On the other hand, theo-reetically, the sneeze airflow direction should be toward the center in the horizontal distribution. However, the results were not strictly symmetrical, and the peak velocity of each location deviated from the horizontal direction in both temporal and spatial distribution. This was because heads swayed left and right slightly when sneezing, and it was difficult to completely avoid. Although the subjects were asked to keep their head centered and stable as much as possible during the experiment, we avoid using any auxiliary fixtures to ensure that the sneezing airflow is as natural and authentic.

In the spatial range of \( x/L_0 = 0.5-3.5 \), the vertical ranges of airflow increased gradually in all the distributions. The same behavior was observed for the horizontal distributions. This indicates that the airflow expanded as the distance increased, but the shape remained relatively constant over time. This causes the sneeze airflow to exhibit partial jet flow characteristics and a spread angle, consistent with Bourouiba’s findings [21]. The values of the spread angles are discussed comprehensively in the following section.

### 3.3. Sneeze spread angles

The initial sneeze airflow from the mouth resembled a jet flow; hence, the airflow out from a mouth is typically not entirely parallel, but a spread angle exists at the edge of the mouth, as indicated in the previous section. The vertical and horizontal cough spread angles are discussed in this section.

To obtain the spread angle, the sneeze airflow’s upper/lower and left/right envelopes must be determined. In previous studies, the enve-lope was usually determined by directly verifying the raw particle image and drawing the boundary line [21], which is straightforward, but sig-nificant errors were generated. In this study, a more quantitative method introduced by Han et al. [31] was used to determine the airflow enve-lopes and investigate the spread angles of cough airflows. The airflow envelope boundary was defined as the point at which the velocity decayed to 1% of the maximum value of the airflow center (i.e., the velocity was reduced by 99%) at the corresponding \( x \)-position. Subse-quentlv, the head’s up-down or left-right sway directions were deter-mined by calculating the spatial forward direction of the maximum velocity in the center of the airflow. This was performed to eliminate the effect of the head sway on the airflow spread angle during sneezing.

The statistical values of the vertical/horizontal sneeze spread angles \( \theta_v/\theta_h \) after excluding the effects of head sway are shown in Table 3. The angles varied extensively in both the vertical and horizontal directions. This implies that the individual differences were significant because the speech spread angle can be affected by many factors, such as the organ structure, physical attributes, and psychological factors. However, the ensemble-averaged angles indicate few differences in terms of direction. Table 3 also lists the vertical spread angles measured by Bourouiba et al. [21], which is close to the results of this experiment. The deviation is considered mainly due to the different angle calculation methods dis-cussed above. In Bourouiba et al.’s experiment, they calculated the vertical spread angle based on the visualization image, which shows the smoke shape exhaled from the mouth via one subject’s sneeze. In addition, differences in the temperature and humidity of the two experiments also affected the airflow behaviors to some extent.

### 4. Results of speech airflow measurements

#### 4.1. Overall features of speech airflow

The overall characteristics of the speech airflow were investigated, as shown in Table 4. The maximum instantaneous velocity varied signifi-cantly, accompanied by different individual physical attributes and speaking habits. The ensemble-averaged maximum velocity of the male participants was slightly higher than that of the female participants. In particular, the males yielded greater velocity variations than the females. The maximum velocity obtained in this study was higher than that obtained by Chao et al. [24]. The exact reason is yet to be eluci-dated. One possible attribution is individual differences. The statistics of physical situations between our participants and Chao’s may differ because the number of participants in both experiments was not suffi-ciently high; as such, it was difficult to represent the general situation.

In addition to the maximum instantaneous velocity, the maximum values of the time-averaged velocity are discussed in Table 4. The time-averaged values were significantly lower than the instantaneous velocity (approximately 1/20). This is because almost no airflow was exhaled from the mouth between the two syllables; hence, the velocity during this period was extremely small negligible, as shown in Fig. 7. This caused the time-averaged velocity level to be significantly smaller than the maximum instantaneous velocity. However, the time-averaged values were more consistent with the actual airflow velocity in daily
Fig. 6. Vertical (left) and horizontal (right) instantaneous distribution of ensemble-averaged velocity at times $t/PVT = 1, 3, 6,$ and 9.
communication than the maximum instantaneous velocity. This is because people typically utter continuously when speaking, rather than only uttering one or two syllables. It is noteworthy that the speaking speed and strength of different people vary significantly. Therefore, the number of emitted syllables in a certain period is diverse and time-variable. The distribution of the time-averaged velocity is discussed comprehensively in the following section. Similar to the sneeze experiment, the maximum time-averaged velocity at \( x/L_0 \) was utilized as the nondimensionalized velocity.

4.2. Ensemble-averaged results of time-averaged velocity distribution

Fig. 8 shows the distributions of time-averaged vectors in the vertical and horizontal directions. They typically correspond to the results of a steady simulation (e.g., RANS) and hence should be analyzed. A significant velocity gradient was observed from the mouth toward the airflow envelope. In the vertical distribution, an upward tendency of the airflow was clearly observed. This tendency has been reported in other speech airflow PIV experiments [24]. It may be a potential feature of speech airflow and hence should be further confirmed by eliminating the interference of head sway during speaking in the future. In the horizontal distribution, the airflow was more horizontal compared to the sneeze airflow, because the power of speech was less than that of sneeze and the heads were affected less by the left–right sway. However, it was still difficult to keep the airflow perfectly horizontal during the experiment.

Fig. 9 shows the profiles of \( \langle u' \rangle \) and \( \langle w' \rangle \) in the vertical distribution and those of \( \langle H \rangle \) and \( \langle V \rangle \) in the horizontal distribution. Their ±0.5 SD (i.e., \( \langle u' \rangle, \langle v' \rangle, \text{and} \langle w' \rangle \)) are shown as well, which implies the range with a confidence interval of 38.3% (when the nondimensionalized ensemble-averaged velocity was one). At all positions, it is clear that \( \langle u' \rangle \) was greater than \( \langle V \rangle \) and \( \langle w' \rangle \), indicating that the streamwise direction components dominated the speech airflow, similar to the sneeze airflow. The airflow decayed significantly as the x-distance increased, and the airflow profile was difficult to distinguish at \( x/L_0 = 3.5 \). In addition, the vertical spatial range of the airflow spread from \( z \approx -0.9 \delta \) to \( z \approx 0.9 \delta \) at \( x/L_0 = 0.5 \) to \( z \approx -1.5 \delta \) to \( 1.5 \delta \) at \( x/L_0 = 3.5 \). The horizontal distribution exhibited the same spread tendency, which implies that vertical and horizontal airflow are significant.

**Table 3**

| Items                        | \( \theta_v \) [°] | \( \theta_h \) [°] |
|------------------------------|-------------------|-------------------|
| Males Variation range        | 6.73–23.2         | 8.12–21.7         |
| Averaged/SD                  | 14.9/4.98         | 13.6/4.48         |
| Females Variation range      | 7.09–25.7         | 3.66–30.4         |
| Averaged/SD                  | 15.4/5.66         | 17.2/7.49         |
| All Cases Averaged/SD        | 15.1/5.25         | 15.4/6.31         |
| Bourouiba et al. [21], \( ^a \) | 14.8              | –                 |

\( ^a \) Spread angle was measured based on the visualization image of the smoke spread shape exhaled from the mouth of one person’s sneeze at the temperature of 23 °C and relative humidity of 19.1%.

**Table 4**

| Item                                      | Male Cases | Female Cases | All Cases |
|-------------------------------------------|------------|--------------|-----------|
| Maximum instantaneous velocity [m/s]      | variation  | 1.23–25.3    | 2.63–11.6 | 1.23–25.3 |
| SD                                        | 4.55       | 2.10         | 3.53      |
| Chao et al. [24]                           | 4.6        | 3.6          | –         |
| Maximum time-averaged velocity [m/s]      | variation  | 0.0771–0.511 | 0.0948–0.550 | 0.0771–0.550 |
| ensemble-averaged value                   | 0.206      | 0.210        | 0.208     |
| SD                                        | 0.115      | 0.106        | 0.110     |
| Maximum time-averaged velocity at \( x/L_0 = 2.5 \) [m/s] | variation  | 0.0368–0.217 | 0.0612–0.294 | 0.0368–0.294 |
| ensemble-averaged value                   | 0.105      | 0.117        | 0.111     |
| SD                                        | 0.0466     | 0.0576       | 0.0523    |
4.3. Speech spread angles

The method used to determine the speech spread angles was generally the same as that to determine the sneeze spread angles. However, the airflow envelope was calculated using time-averaged velocity distributions for each case. The results of the speech spread angles are listed in Table 5. The spread angles of speech varied between 12° and 97°; the male/female participants’ averaged spread angles were 50.9°/54.9° for the vertical direction and 44.6°/41.2° for the horizontal direction, which shows deviations from Kwon et al.’s results [26]. It is highly probable due to subjects’ different pronunciation conditions. The angles were measured when subjects were instructed to pronounce the words “dul” in Kwon’s study. In this study, the spread angles were the 10s time-averaged values of subjects’ pronunciation of several words by counting from one to ten. In addition, the speech spread angles were significantly larger than those of sneezing and coughing [31], which tendency agreed with Kwon et al.’s research [26]. The speech spread angles’ variations were also significant. This may be due to the diversity of syllables, which leads to the diversity of vocal methods and mouth shapes. However, it is noteworthy that the spread angles were general values calculated based on a time-averaged value of several words in 10 s. If we focus on a single occurrence syllable, then the spread angle may vary significantly with the shape of mouths uttering different syllables, as stated previously.

5. Conclusions

In this study, the overall characteristics and detailed velocity distributions of sneeze and speech airflows were measured using high-frequency PIV, since those airflows are important sources of imperceptible virus propagation from infectors. Measurements of 60 sneeze and sixty 10 s speech cases from 10 healthy young participants, including five males, were measured. The overall airflow parameters for describing the dynamic process of the sneeze airflow were obtained, such as the maximum velocity, PVT, PV, and SDT. For the speech airflow, the maximum instantaneous velocity and maximum time-averaged velocity were reported. The spread angles for both the sneeze and speech airflows were investigated. Nondimensionalization and ensemble-average operations were conducted for both sneeze and speech airflow velocities to eliminate individual errors and obtain general and representative velocity distributions.

The sneeze airflow reached the PV in 20 ms (PVT), and the entire airflow lasted approximately 430 ms (SDT). However, the velocity variation during the first 10 PVTs was the most significant. The maximum sneeze airflow velocity was approximately 15.9 m/s. The
temporal variation in the sneeze velocity reflected a gamma distribution. For the speech airflow, the maximum velocity was significantly weaker, i.e., approximately 6.25 m/s. The time-averaged velocity was only 0.208 m/s as almost no airflow was exhaled in the intervals between syllables. The vertical/horizontal sneeze spread angles were 15.1°/15.4° for the males/females. Whereas the speech spread angles were significantly larger (approximately 52.9°/42.9°), due to the diversity of vocal methods and mouth shapes when speaking. The difference between the sneeze and speech airflows based on gender was slight. In addition, the temporal and spatial velocity distributions of the sneeze airflow and the time-averaged velocity spatial distributions for the speech airflows were reported comprehensively.

These velocity distributions can provide a detailed database for further investigations into the mechanism of droplet/virus transmission through daily sneezing and speech airflows, as well as for validating the transmission via CFD simulations. Furthermore, the results of this study can provide the potential boundary conditions for transmission simulations (e.g., the temporal variation function, spread angles, etc.).

However, this study has several limitations. First, the participant sample size was not sufficiently large; therefore, the relationship between the participants’ physical situations and the airflow characteristics could not be established. Furthermore, elderly and infected people, whose sneeze and speech airflows are likely to differ from those of young, healthy people, were not included in the experiment. This aspect should be considered in future studies. Additionally, these limitations should be considered when using the results in CFD simulations. Therefore, next we plan to simulate human sneeze and speech airflow utilizing these data obtained to confirm the experimental data’s applicability as simulation boundary conditions and validation basis.

**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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**Appendix**

Table A lists the physical attributes of the experiment participants.

**Table A**

| Male participant | Age [years] | Height [m] | Mouth width [× 10⁻² m] |
|------------------|-------------|------------|--------------------------|
| M1               | 33          | 1.61       | 4.5                      |
| M2               | 26          | 1.65       | 5.2                      |
| M3               | 37          | 1.73       | 4.8                      |
| M4               | 26          | 1.75       | 5.3                      |
| M5               | 31          | 1.88       | 3.7                      |
| Average          | 30.6        | 1.72       | 4.7                      |

| Female participant | Age [years] | Height [m] | Mouth width [× 10⁻² m] |
|--------------------|-------------|------------|--------------------------|
| E1                 | 24          | 1.72       | 4.7                      |
| E2                 | 30          | 1.72       | 4.5                      |
| E3                 | 29          | 1.52       | 4.1                      |
| E4                 | 25          | 1.63       | 4.2                      |
| E5                 | 32          | 1.64       | 2.2                      |
| Average            | 28.0        | 1.65       | 3.9                      |

**Research data**

Data pertaining to this study are available online at [https://data.mendeley.com/datasets/5jd9srw5k6](https://data.mendeley.com/datasets/5jd9srw5k6).

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