21st International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
27-30 September 2022, Aveiro, Portugal

NUMERICAL DISPERSION MODELLING OF THE DROPLETS EXPIRED BY HUMANS

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Abstract: Owing to the COVID-19 pandemic, in the last two years the attention of the scientific community has focused on the study of the dispersion of small droplets ejected by humans during different respiratory activities. The properties of the droplets used as input data in numerical simulations and models that forecast the dispersion of the expired particle-laden air cloud are of major importance in order to obtain reliable results. Recent numerical simulations highlighted that a lack of knowledge concerning droplet size and velocity distributions still exists. Indeed, only few works tackled this problem, since it is particularly difficult to measure droplet sizes over a wide range and to measure sizes and velocities simultaneously. Consequently, the droplet velocity is generally assumed to be either zero or equal to the air velocity. In this work, the dispersion of droplets expired by humans have been simulated numerically using as input experimental data collected during two measurement campaigns concerning speaking and coughing. The size and the 3 velocity components of the ejected droplets have been measured simultaneously for particles down to 2 μm using an extended version of the Interferometric Laser Imaging Droplet Sizing technique.

Key words: *Droplet dispersion, droplet velocity, droplet size, airborne disease***.**

INTRODUCTION

The airborne disease transmission is strictly linked to the dispersion of the droplet-laden air cloud emitted by humans during different respiratory activities. The dispersion process of the ejected cloud and the distances traveled by the droplets have been assessed by means of experiments, numerical simulations and simplified models (e.g., Bourouiba et al, 2014; Abkarian et al, 2020; Bahl et al, 2021; De Padova and Mossa, 2021; Dbouk and Drikakis, 2020; Busco et al, 2020; Li et al, 2022; Xie et al, 2007). Realistic input data (air velocity and droplets size and velocity at the emission point) must be provided to models and numerical simulations to obtain reliable results to be used in guidelines, as occurred during COVID-19 pandemic. Therefore, the experimental characterization of the source is of major importance. Even though several works concerning the source characterization have been reported in the literature (e. g. Asadi et al, 2019; Johnson et al, 2011; Chao et al, 2009; Duguid, 1946; Gupta et al, 2010; Kwon et al, 2012), several features still hue to be elucidated (Rosti et al, 2020; Seminara et al, 2020). In particular, a discrepancy among the measured droplet size distributions emerges from the literature (Bourouiba, 2021; Johnson et al, 2011; Seminara et al, 2020). Besides, several works reported measurements of the velocity (or the airflow) of the ejected air (e.g., Kwon et al, 2012; Chao et al, 2009; Abkarian et al, 2020; Gupta et al, 2010), but only a few detected the droplet velocity (Bahl et al, 2020; Nishimura et al, 2013; de Silva et al, 2021; Bahl et al, 2021). The simultaneous measurement of droplet size and velocity could also provide interesting information, as the velocity of the droplets at the source could depend on their size. Due to its complexity this kind of measurement is very rare and was notably carried out in two recent works for the respiratory activity of coughing (de Silva et al, 2021; Bahl et al, 2021), even if limited to droplets larger than 30 μm and to two of the three velocity components. Concerning human droplet emissions, note that most of the studies focused on extreme respiratory events such as sneezing and coughing, while less works concerned the activity of speaking, despite its importance in airborne pre-symptomatic or asymptomatic transmission. In this work we carried out detailed measurement to characterize the droplet emission during the respiratory activity of speaking. Namely, simultaneous measurements of the size and the three velocity components of the droplets have been performed for particles down to 2 μm. The experimental data have been used as input in numerical simulations performed by means of Computational Fluid Mechanics.

MATERIALS AND METHODS

Measurement campaign

The measurement campaign has been carried out in the Laboratoire de Mécanique des Fluides et d'Acoustique of the Ecole Centrale de Lyon. It has been asked to 20 volunteers to count from "one" to "one hundred" in order to simulate the respiratory activity of speaking. The size and the three velocity components of the ejected droplets have been measured simultaneously by means of the Interferometric Laser Imaging for Droples Sizing (ILIDS) technique. In the ILIDS the droplets are illuminated by a laser light sheet and out-of-focus images of them are taken by means of system of lenses and a camera. The light scattered by the liquid spherical droplets is characterized by regular interference fringes, from whose spacing the droplet size can be deduced. The velocity of each of the detected droplets is obtained by measuring their displacement in two consecutive images, for a given time lag. More details about ILIDS can be found in Mees et al (2011). The ILIDS setup (and the related image treatment) have been improved with respect to the classical application to measure droplet sizes down to 2 μm – absolute limit of the ILIDS technique – and the three velocity components (Grandoni et al, 2022).

Numerical simulation setup

ANSYS Fluent 18.2 (ANSYS, 2011) has been employed to simulate numerically the dispersion of the droplets ejected during the respiratory activity of speaking. The simulation domain is a regular box 3 m high, 2 m wide and 2 m long, representing a portion of an indoor environment. Although the process of speaking is highly unsteady due to the variety of phonemes, it can be modelled as a continuous turbulent jet (Abkarian et al, 2020). Therefore, a steady emission of particle-laden air cloud is assumed in the simulations. The emission of air and droplets occurs from a surface of 0.013 m x 0.013 m representing the mouth, which is located on the left side of the domain at 1.6 m above the floor (i.e., the average height of the human mouth). The air is continuously ejected from the mouth at a speed of 0.5 m/s (*velocity inlet* boundary condition). Different values of the air speed are reported in the literature; 0.5 m/sis taken from the work by Abkarian et al (2020). The other boundary conditions used are the following: *wall* at the floor, at the ceiling and at the side faces; *pressure outlet* at the face opposite to the mouth; *velocity inlet* with a velocity of 0.01 m/s at the face all around the mouth. The temperature of the air ejected by the mouth is set to 306.15 K (Xie et al, 2007), i.e., higher than the ambient temperature (~ 293.5 K). The temperature of the ambient air is maintained by imposing at the side walls and around the mouth a fixed temperature of 293.5 K, while the floor and the ceiling are adiabatic. The mesh consists of ~ $7 \cdot 10^6$ hexahedral cells, whose maximum size is of 0.013 m; the cell size reduces getting closer to the mouth.

The number of particle streams (i.e., groups of droplets with the same features) injected in the domain from the surface simulating the mouth is 1024, approaching 10240 droplets. The droplets are modelled as inert spherical water particles; therefore, evaporation is not taken into account. The droplet size and velocity distribution given as input to the simulations are obtained from the measurement campaign.

A standard k-ε turbulence model has been used to solve the airflow, considering the buoyancy effect only for the production of turbulent kinetic energy. For the particle motion a Lagrangian model (Discrete Phase Model with Discrete Random Walk activated) has been employed. The simulations have been stopped once all the residuals were lower than 10^{-6}.

RESULTS AND DISCUSSION

Size distributions and injections

In Figure 1a the droplet size distribution obtained from the experimental data is shown. Most of the droplets lie in the range 2-4 μm; the number of droplets rapidly decreases until a relative maximum occurs between

25 and 30 μm. From the experiments, the velocity distribution of the droplets appears to vary with their size, mostly the longitudinal component (x), i.e., the component parallel to the mean airflow ejected from the volunteers' mouth. The five size distributions obtained for five different droplet size classes are depicted in Figure 1b (more details on the experimental results are reported in Grandoni et al., 2022). In Figure 1c the considered droplet injection is shown. Droplets of different sizes are randomly distributed within the mouth surface; the velocity is assigned to the droplets, so that different droplet size classes are characterized by different velocity distribution.

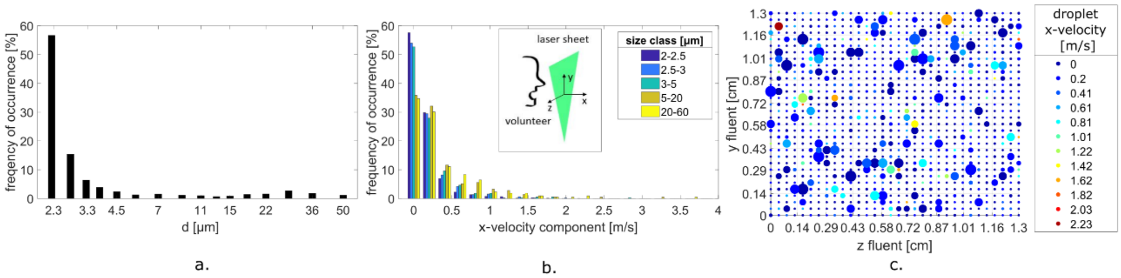

Figure 1. a. Droplet size distribution and b. x-component velocity distributions for five different droplet size classes obtained from the experimental data. c. Injection considered as input for numerical simulations; the area of the graph coincides with the area of the mouth surface from which the injection takes place; each circle corresponds to an injected droplet; the size of the circle is proportional to the size of the droplet, while the color is related to droplet velocity (only the longitudinal velocity component is represented for the sake of brevity)

Simulation results

The airflow exiting the mouth forms a jet, which is initially horizontal. Moving away from the mouth the jet velocity decreases until its buoyancy – due to the temperature difference between ejected and ambient air – prevails and the jet starts rising. Because of the low ejection velocity, the air jet moves horizontally only for a short distance. Once the air has reached the ceiling, it spreads and exits the domain. According to the boundary conditions, the air exits mainly through the *pressure outlet* face (right side).

As expected, larger – heavier – droplets quickly fallout from the air jet and start settling. Droplets of sizes d~ 28 - 60, ~ 22 and ~ 18 μm start falling out from the air jet at 5, 15 and 25 cm from the mouth, respectively. On the other hand, smaller droplets are advected by the air towards the ceiling. In general, only droplets of d > 16 μm settle within 2 m from the mouth (Figure 2a). The mean, minimum and maximum distances traveled by the droplets before settling are depicted in Figure 2b. The distance decreases with d, i.e., droplets of d ~ 50 μm are removed from the air within 50 cm from the mouth, droplets of d ~ 36 μm within 1 m, the others settle at a distance x ≥ 2 m. Droplets smaller than 16 μm rise with the gaseous phase; however, only the smallest remain close to the ceiling, while the larger tend then to move downwards. In fact, the sizes of the droplets exiting the domain from the lower and the upper part of the *pressure outlet* face and from the ceiling vary (Figure 2c). Namely, the prevailing size of the droplets exiting the domain from the ceiling is d ~ 2 μm, while the prevailing sizes are d ~ 5 μm e d ~ 18 μm for the upper and the lower part of the *pressure outlet* face, respectively.

Figure 3 depicts droplet number concentration fields on sections transversal to the mean airflow (i.e. parallel to the mouth surface) at 5, 25 and 40 cm from the mouth. Concentration is expressed as percentage of the concentration at the mouth. Droplet concentration decreases (along with potential risk of infection) moving away from the mouth; however, the area contaminated by the droplet obviously becomes wider due to the spread of the particle-laden air cloud. Far from the mouth, the droplets are approximatively completely mixed in the air; this situation corresponds to a concentration within a transversal section of ~0.0028 % (less than 1 particle per cubic centimetre). The dark blue line in Figure 3 indicates the concentration of 0.0028 %. Therefore, closer to the mouth the risk is higher due to zones of higher droplet concentrations. The high droplet concentration area moves upwards due to buoyancy effects, so that at about 40 cm from the mouth its height is greater than the zone where a common person breath (> 2 m). Droplet concentration at mouth height (~ 1.6 m) decreases from ~ 15 % to ~ 0.0073 % and to ~ 0 % at 1 mm, 25 cm and 40 cm from the mouth, respectively. The presence of droplets below the mouth height is due to settling droplets. Note that, in the concentration fields in Figure 3, no distinction among different droplet sizes is considered. However, the concentration fields vary with droplet size.

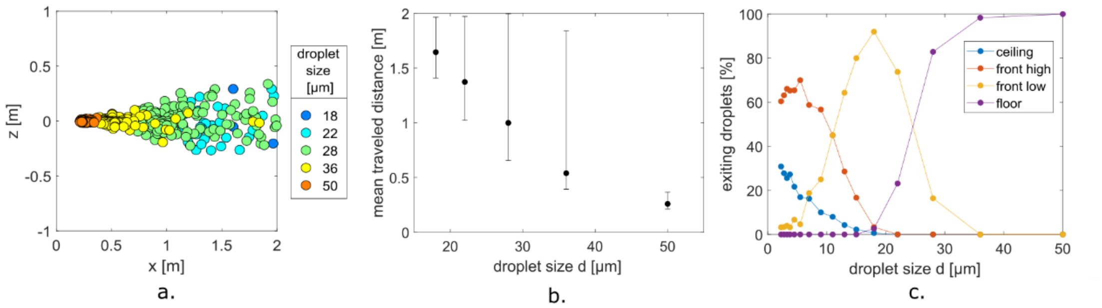

Figure 2. a. Settled droplets; each circle corresponds to a droplet, circle color is related to droplet size, b. mean, maximum and minimum traveled distances before settling and c. percentage of particles of each size class exiting through different domain zones

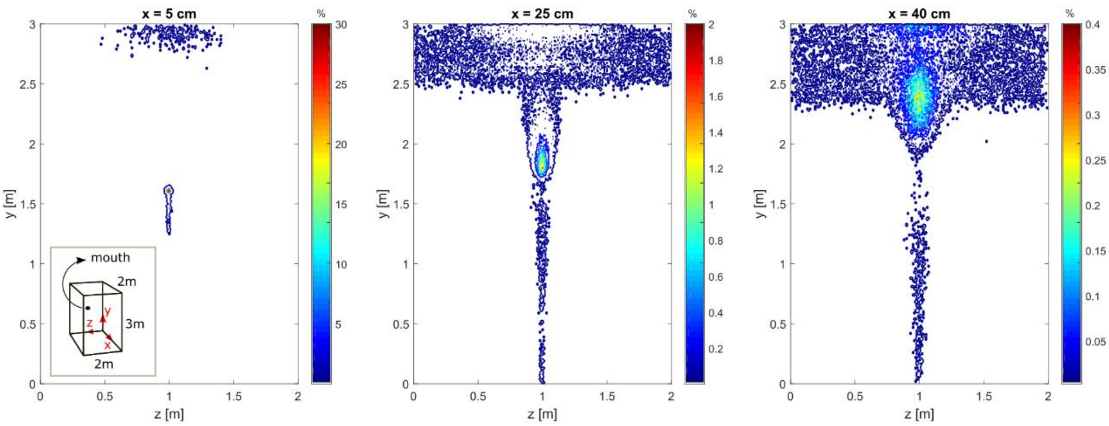

Figure 3. Droplet number concentration fields on transversal sections at 5, 25 and 40 cm from the mouth

CONCLUSIONS

Numerical simulations have been carried out to model the dispersion process of droplets ejected by humans while speaking. Detailed input data consisting in droplet velocity and size distributions have been obtained from a measurement campaign involving 20 volunteers. The ejected particle-laden air cloud moves horizontally for a short distance, then it starts to rise due to buoyancy effects. Larger heavier droplets quickly fallout from the cloud and start settling, while smaller – lighter – particles are transported by the air towards the ceiling. Only droplets larger than 16 μm settle on the floor; droplets of size d ~ 50 μm and 36 μm are removed from the air within 50 cm and 1 m from the mouth, respectively, the others can travel longer distances or remain suspended. Droplet concentration reduces moving away from the mouth due to settling and cloud spread. Closer to the mouth, the infection risk is higher than far from the ejection, where droplets are almost uniformly distributed in the ambient air; concentrations higher than the completely mixed condition are found within 30-40 cm from the mouth. Note that the considered ambient air temperature is typical of a winter condition. Other simulations are worth to be carried out to assess a summer condition, where the buoyancy effect is weaker. Besides, other simulations are needed to test the sensibility of the results to the detail of the provided input data.

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