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Research article

Numerical modeling of a sneeze, a cough and a continuum speech inside a hospital lift

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ABSTRACT

The global COVID-19 and its variants put us on notice of the importance of studying the spread of respiratory diseases. The most common means of propagation was the emission of droplets due to different respiration activities. This study modeled by computational fluid dynamics (CFD) techniques a high risk scenario like a hospital elevator. The cabin was provided with an extraction fan and a rack for air renewal. Inside, a sneeze, a cough and a continuum speech were simulated. Inside the lift, two occupants were introduced to observe the risk of propagation of emitted droplets and the impact in diseases spreading risk. The fan effectivity over the droplets ejection was analyzed, as well as environmental condition of a clinical setting. For this purpose the amount of droplets inside were counted during whole time of simulations. The effect of the fan was concluded as able to eject the 60% of small droplets, but also a high performance in spreading particles inside. Among the three cases, the riskiest scenario was the continuum speech due to the saturation of droplets in airborne.

1. Introduction

The symptoms of respiratory diseases usually are coughing and sneezing, which spread a large amount of droplets. The major risk of infection is due to droplets' spreading in public [1]. Cole and Cook [2] reported that most diseases spread in airborne by inhaling ≤6 μm diameter droplets that contains 0.02–0.3 μm viruses. Each pathogen has a different half live. Van Doremalen et al. [3], compared SARS-CoV-2 (COVID-19) half lives in airborne and over different surfaces and discovered infectious copies after more than an hour in ambient, and until 72 h over plastic. According to Dhand et al. [4], a COVID-19 infected person have more than 7 million copies of virus by saliva milliliter. They announced that a 50 μm droplet has a 37% possibility to contain at least one virus replica. This possibility decreases until 0.4% for a 10 μm droplet. Against, the amount of small droplets is orders of magnitude higher. In addition, they concluded that finest particles are able to deep into the lungs by inhalation, aggravating the disease. In this term, particles size has a great importance due to its impact on their paths. Stadnytskiy et al. [5] noted that 100 μm particle can transport tens or hundreds of viruses, but the droplet falls quickly due to gravity force and is not susceptible to be inhaled. On the other hand, 0.1 μm particles can be suspended even days, but as it is smaller than a COVID-19 virus (ranged between 0.05 μm and 0.14 μm) can be discarded. It is expected

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that most hazardous droplets are in 45–15 μm range, which decrease their volume to 15-5 μm.

Sneezing is a frequent respiratory protecting reflex [1]. This reflex allows the evacuation of mucous which contains strange or irritant particles [4]. Usually, a sneeze last from 100 to 500 ms [6–8]. According to Stadnytskyi et al. [5], all the respiratory activities generate droplets, being the sneeze the one which generate more quantity and of larger size. The extreme velocity of air inside the upper respiratory tract (URT) cleans and exhausts undesirable particles in a turbulent flow, carrying droplets of respiratory tract lining fluid (RTLF), which consist in 95% of water. Duguid [9] found that a single sneeze can generate until 46,000 droplets and 30 millions of nuclei. Songu et al. [1] mentioned that most of those droplets have a size less than 5 μm. Wells [10] studied the behavior of different size droplets in a 2 m free fall, and proved that droplets' decreasing ratio was proportional to its size quadratic. This research was the first to define large droplets as those which settle the ground before a complete evaporation, marking ≥100 μm droplets as large droplets. Xie et al. [11] and Wang et al. [12] deepened observing that a droplet evaporation ratio depends on the relative humidity (RH), temperature and relative velocity of the exhaled jet with surrounding air. Thereby, Wells' curve became dynamic, having different values for different conditions. Bourouiba [6] pointed that exhaled air leads small droplets trajectories. Initially, the puff is governed by momentum and buoyancies due to thermal difference. The expelled jet decreases the velocity in relation to the traveled distance. In the same manner, droplets decrease their size until convert in aerosols, turning more susceptible to buoyancy forces and to be inhaled.

Aliabadi et al. [13] found that a high air change per hour (ACH) increases the exposure in a short time, but decreases it in a long time term. Han et al. [14] measured exhaled droplets size during a sneeze using a particle laser sizer located at 5 cm from the mouth. They found two size distribution patterns. Both had lognormal distributions, but one was unimodal (a single curvature with a single peak), and the other was bimodal (two curvatures with two peaks). Unimodal distribution had the most size frequency in 360.1 μm droplets; bimodal distribution size frequency has its peaks in 72 μm and 386.2 μm. They found also that highest velocity of exhaled air occurs between 57 and 110 ms, being the most common time 100 ms. Busco et al. [7] concluded that in relation to pressure, the peak occurred in 0.1 s and had a value of 8 kPa. Total sneeze lasted 0.5 s.

With the background obtained by experimentation and measurement, engineers are able to predict different parameters in different situations. One of the most common techniques is CFD. Rahminejad et al. [15] reproduced the entire URT from trachea to nose and mouth outlets, and found a maximum velocity of 123 m/s in trachea and 48 m/s and 30 m/s in mouth and nose outlets respectively. There exist many studies addressed to health related safe measures. Motamedi Zoka et al. [16] presented a new risk assessment model based on horizontal spreading of droplets and found a low propagation hazard in coughs, but a high droplet spreading for sneezes. According to this study, a low RH achieves more droplets spread but in lower concentrations than a high RH, case where the volumetric concentration is higher but in zones near to the source. CFD technique permits also modeling real and concretionary scenarios. Csaba and Ferenc [17] modeled a Budapest underground car with 11 people inside where one occupant coughed and sneezed. They set different conditions like with/without air conditioning (AC) or facemask, and the opening or closure of windows. They found that the risk of contagious in an underground car can be reduced and controlled using a good AC configuration. Opening windows spreads more the exhaled air, reducing its concentration, but in a random manner, so it can be harmful depending on the situation. Also, they recommended wearing face mask due to its breaking potential in relation to exhaled air.

Other CFD researches were focused on the behavior of droplets. Busco et al. [7] set up a sneeze simulation recreating head movements and pressure dynamics and their effect on droplets' spreading under different situations of RH and temperature. According to this study, the angular movement of the head together to the dynamic pressure can spread droplets twice as far as previously though, reaching distances of 4 m in downstream. They also concluded that in dry and cold conditions, all the droplets were completely evaporated in 15–20 s. In contrast, there still existed floating droplets after 50 s when the environment was hot and wet. Akagi et al. [18] simulated a sneeze against a facial shield, concluding that it is not a safe device, due to generated vortexes and their penetration to the gap between face and shield, introducing the 4.4% of the exhaled droplets. Moreover, the shield carrier can inhale these droplets generating a flow stream in the gap produced by his respiration. Ugarte-Anero et al. [19] deepened in this device and found that in case of a soft breeze the amount of incoming particles to the gap was larger; moreover if the sneezer was lower than the person who wore the shield.

Other experimental researches focused their efforts to investigate droplets generated by coughs. Fairchild et al. [20] sized exhaled droplets from different activities. They found that exercises that forced more the respiration generated bigger sized droplets, but in all cases more than 98% of droplets were smaller than 1 μm. These results were ratified time after by Papineni and Rosenthal in Ref. [21]. Yang et al. [22] studied the cough droplet size distribution by using an aerodynamic particle sizer (APS) and found that the 82% of particles were in 0.74–2.12 μm size range for a total distribution of 0.62–15.9 μm. They described the distribution as multimodal with peaks in 1 μm, 2 μm and 8 μm. Mahajan et al. [23] achieved the exhaled air velocity profile during cough, and described it as a lineal increase until the maximum, at 30–35 ms from the beginning, with a lineal decrease with some irregularities until zero in 300 ms. Chao et al. [24] obtained a maximum velocity in their experiments of 11.7 m/s. Instead, other literatures obtained larger maximum velocities of 22 m/s and 28.8 m/s in Refs. [25,26] respectively.

Using the described literature about coughing droplets, several CFD studies have modeled remarkable cases. Kou et al. [27] reproduced a human URT in CFD to research interior physics. They set up a mass flow dynamic inlet with a peak of 6 L/s at the bronchi, and a pressure outlet at mouth. They found the higher pressure value at the bronchi of more than 10^5 Pa and a maximum velocity value of almost 64 m/s. Hayasi et al. [28] configured the ventilation of a contaminated room provided of supply air inlet at the bottom and outlets placed in front at the top and the bottom of the wall. A recirculation of indoor air appeared, meanwhile a continuous contaminated air was exhausted. In the case of occupancy by a standing up person, its respiration inhaled from the bottom contaminated air. Hoque and Omar [29] simulated a two dimension room to explore the best ventilation configuration, according to inlet an outlet height positions for an emitted cough. Pursuant to this study, for good ventilation paths, inlet and outlet must be in the same height, and avoiding as possible to set the inlet above the outlet. Elhadary et al. [30] also concluded that better ventilation configuration was to set up the outlet on the ceiling. Liu et al. [31] structured a CFD case of an exhalation and a cough directly focused over other human. They executed different simulations varying the distances between occupants, their heights, and also performed common paths to avoid droplets propagation such as coughing directly on the elbow or wearing surgical masks. Their remarkable conclusions were that the exposition was susceptible to the distance and relative humidity. In wet environments, the evaporation can be 10 times slower. In literature also are present more concrete simulations. Zhang and Li [32] build simulations recreating a high speed rail train where a passenger located at the middle of the coach coughed. According to them, the best scenario to take out droplets was when there existed a front side supply air, and a backside exhausting outlet. In contrast, it was also the configuration which spread more droplets. Sen [33] recreated cough scenarios in an elevator case where a downstream ventilator was placed in the center. The study modeled a high RH case with high temperature, as is usual in a lot of zones in India. This research found that in these conditions the downstream leads droplets to settle on the ground, avoiding direct infections.

Several studies were focused on research speech droplets behaviors. In these terms, Chao et al. [24] recollected images of people counting from 0 to 100, and found a maximum velocity value of exhaled air of 4.6 m/s and a mean value of 3.1 m/s also concluded that speech droplets were smaller than cough droplets; the mean value was 16 μm, in a lognormal distribution, which matched with the investigation of Duguid [9]. Xie et al. [34] proposed the experiment of also counting from 1 to 100 inside a small box, where droplets impacted over glass slides. They found that the mean size peaks were between 50 μm and 75 μm They also carried out the experiment but counting into a plastic bag covered by tissues and wearing surgical mask. The results showed great discrepancies at weighting tissues and mask, so no definitive conclusion was determined. Kwon et al. [35] measured the velocity of the exhaled air during coughs and speech under 23 °C and 50% RH conditions. Theirs results were similar to the Chao et al. [24] ones, although discrepancies between subjects were notable. They concluded that higher persons had higher exhalation velocities for any case. Also found a relation between cough and speaking exhalations velocities, pointing the speech velocity as 22–27% of cough velocity. Gupta et al. [36] characterized the airflow exhaled from reading a passage during 2 min. They concluded that flow was irregular, but similar to a continuous exhaust. The flow value was similar to breathing flow (27 L of air in 2 min). They also recommended representing the mouth opening as a continuum opening of 1.8 cm^2.

This study is focused on one of the most riskiest scenarios for a breathing pandemic, such a hospital lift. This is a small cabin with high traffic of occupants. For this purpose, a hospital lift was modeled (2.1 m length, 1.5 m wide and 2 m high). The lift had a 30 cm diameter exhausting fan located in the center of the ceiling. One wall of the lift stood a ventilation rack of 1.5 m long, positioned at the

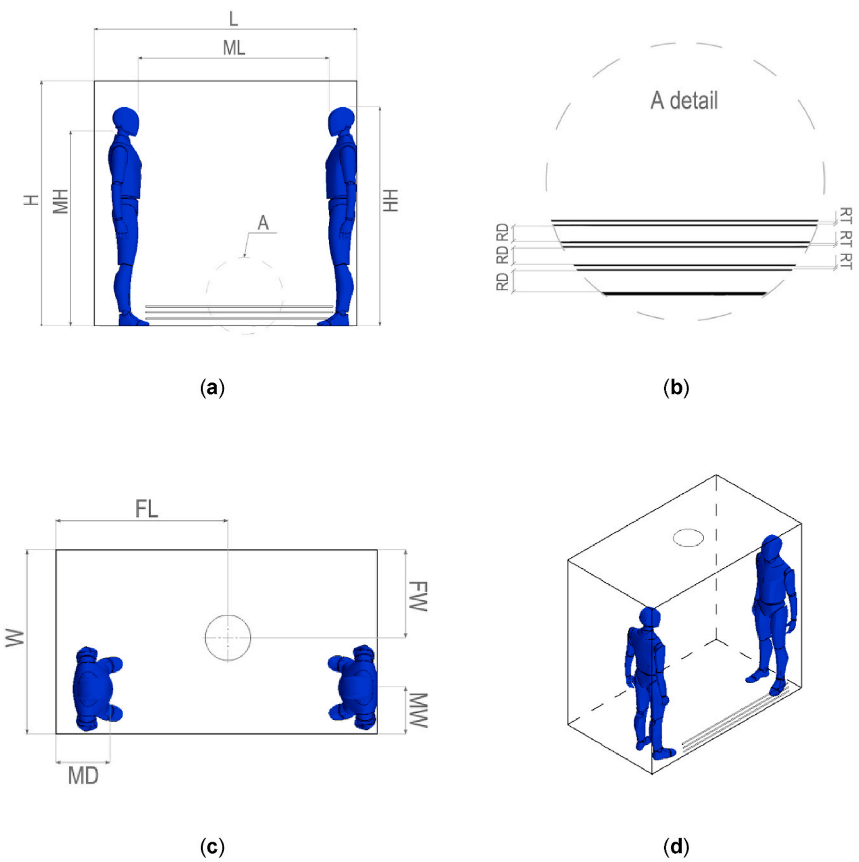


Fig. 1. Dimensions of boundaries: (a) Front view; (b) A Detail of racks (c) Plan; (d) Perspective view.

bottom. The rack consisted in three openings of 1 cm wide which permitted the entering of supply air. Inside the lift were two 1.75 m tall enfaced occupants. They were situated at the two corners of the rack wall.

The main target of the research was to evaluate numerically the efficiency of the fan in terms of removing droplets under three different situations inside a clinic elevator: during a sneeze, during a cough and during a short speech. The safety of an exhausting device was assessed in terms of decreasing particle concentrations. At the same time, evaporation, concentration zones and buoyancy were studied under clinic temperature and RH conditions; meanwhile they were affected by a centered upstream.

2. Numerical method

2.1. Case description

The presented scenario consisted in a hospital lift which measures were the minimum recommended measures according to EN 81−20 and EN 81−50 regulations. The lift possessed an exhausting fan situated at the center of the roof. The fan was modeled to exhale 1100 m^3 air per hour through a 30 cm diameter. To recreate this condition, the modeled ventilator was set up as pressure outlet, and defined in −35 Pa. To renovate the exhausted air, three 1.5 m long ventilation slots were modeled. These openings, of 1 cm wide, were centered over the 2.1 m long wall. Racks were positioned horizontally, at 15 cm from the ground the first, and 15 cm of distance one above other. They were configured as stagnation inlet, to introduce air with the same parameters of the indoor environment, not to alter the conditions.

Inside the lift, two human bodies were introduced as transmitter and receptor representation. Both were 1.75 m tall, located face to face at 1.5 m distance. They were not positioned centered, if not stuck to the wall with racks modeled over it. One of the human bodies had a mouth designed with the purpose of exhaling droplets and air, simulating a breathing activity such a sneeze, a cough and a speech, accordingly to the proposed case. The dimensions of the mouth was the same used in Ref. [37], namely, 40 mm wide and 5 mm height, in concordance with the advises of Dbouk and Drikakis in Ref. [38] for modeling a cough. Busco et al. [7] found a mouth opening of almost 1.3 cm^2 for a single subject during a sneeze. According to Gupta et al. [36], a male mouth maintains a continuous area during a speech of 1.2 ± 0.52 cm^2. As mouth dimensions deeply depends on the subject characteristics, authors considered the same opening as valid for sneeze and speech cases. Fig. 1(a) displays the length dimensions of the elevator. Fig. 1(b) shows the measures of the racks. Fig. 1(c) demonstrates the measurements in width and Fig. 1(d) simply shows a perspective view. The meanings and values of different measures in Fig. 1 are presented in Table 1.

The temperature inside was defined in 24 °C in accordance to UNE 100713:2005 normative [39]. In paragraphs of this normative, is recommended to maintain the RH between the 45% and 55%. For this study, RH was defined at 50%.

Computational domain was discretized through a trimmer mesh of 877,006 cells. Mesh was subdivided in five volume controls (VC) of different cell refinement, being coarser in zones of less activity. The finest VC was near to the mouth, until 45 cm downstream. The other important zone was the path to the ceiling outlet. Fig. 2 displays the mesh in XZ plane. The quantity of cells in each VC were VC1 = 224,316, VC2 = 533,968, VC3 = 109,928, VC4 = 7902 and VC5 = 892.

The grid verification study was performed comparing the variation of a 110 μm diameter droplet size in freefall. To simulate a direct fall, gravity axes were modified, transforming the X axis as gravity force vector, maintaining the mouth inlet and taking out the second human from the domain. The droplet tracking last until 1.75 m, where the front wall was located. Values were compared to the obtained in experimental results of Hamey et al. [40]. Mesh independency study was carried out according to generalized Richardson extrapolation [41,42]. Three meshes were studied: fine (877,006 cells), medium (456,042 cells) and coarse (218,906 cells), with a cell number increment r = 2. The achieved R value was positive and less than 1, which means that a monotonic convergence was obtained, [43]. The grid verification study was conducted in a similar way of Ugarte-Anero et al. [44]. Details can be found in Appendix A.

2.2. Description of modeled breathing activities

For this work, three different simulations were carried out to numerically compare the effectiveness of the fan; specifically a sneeze,

Table 1
Computational domain measures.

Dimension	Meaning	Value
H	Height	2 m
L	Length	2.1 m
W	Width	1.2 m
HH	Human height	1.75 m
MH	Mouth height	1.56 m
ML	Mouth length	1.55 m
MD	Mouth distance	0.34 m
MW	Mouth center width position	0.3 m
FL	Fan length	1.05 m
FW	Fan width	0.6 m
RD	Rack distance	0.15 m
RT	Rack thickness	1 cm

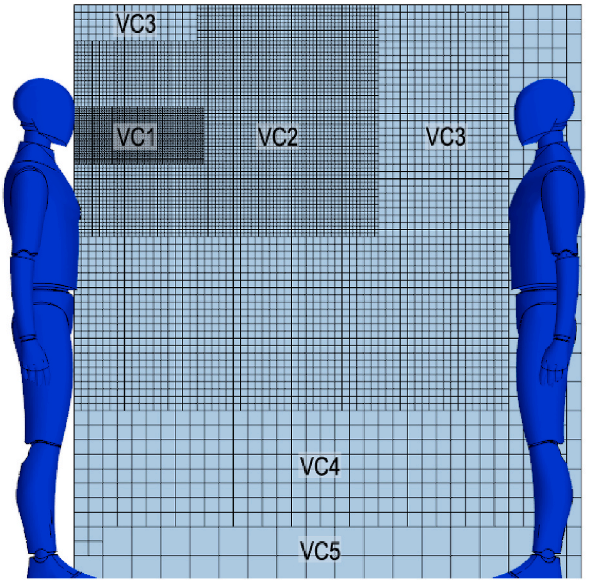


Fig. 2. Computational domain discretization.

a cough and a short speech. The selected parameters were chosen in accordance to experimental literatures.

2.2.1. *Sneeze case description*

Droplets were defined as H_2O particles in a range of size from 0 to 1000 μm, in a lognormal distribution where the mean value was 360.1 μm with a standard deviation of 1.5. These values were taken from Han et al. [14] results. The simulated sneeze lasted 0.465 s. The droplets were introduced to the domain from 40 × 5 mm velocity inlet surface. Initial temperature of droplets and exhaled air was fixed in 35 °C. Velocity was fitted as sinusoidal function based on the experimental study of Busco et al. [7], where maximum velocity had a value of 70 m/s, see Eq. (1). The values for variables are shown in Table 2.

$$Vel = A_1 \sin(B_1 t + C_1) + A_2 \sin(B_2 t + C_2) + A_3 \sin(B_3 t + C_3) + A_4 \sin(B_4 t + C_4) + A_5 \sin(B_5 t + C_5) \tag{1}$$

where t is the value of timing of the sneeze, from 0 to 0.465.

The total injected mass was 6.7 mg, based on the Zhu et al. [25] findings. This value was validated in Ugarte-Anero et al. [19]. As velocity, mass injection was also a dynamic function, maintaining the curve–shape. According to Busco et al. [7], a sneeze can be divided in two sections. The first half of a sneeze expels air and droplets, meanwhile in the second half only air is expelled. In this terms, the injection of saliva occurred up to 0.22 s. Fig. 3 describes inlet velocity and mass injection.

2.2.2. *Cough case description*

The initial droplet size distribution was modeled in concordance with the obtained results in Xie et al. [34]. This study concluded that size distribution was a Rosin−Rammler function. For this study, the range was set in a range from 10 to 300 μm. Reference size was 80 μm and the exponent 8 μm. The cough was modeled to last 0.5 s in a velocity profile similar to the obtained by Mahan et al. [23]. In this research, an instantaneous peak was observed in 0.03 s, followed by an irregular and fast velocity decrease until 0.26 s and a final slight air exhausting until 0.5 s. For the current study, authors considered to represent the velocity profile with linear increase to 17.7 m/s, a continuum decrease until 3.9 m/s followed by a decrease until 1.5 m/s in an attempt of approximation to a real case, represented in Fig. 4. The total mass injection was 6,7 mg of saliva, based on the work of Zhu et al. [25]. The injection lasted 0.26 s, the time of the powerful considered exhalation. The profile was modeled to imitate the velocity profile but ending in zero.

Table 2
Values for variables.

Suffix	A	B	C
1	61.22	2.08	2.167
2	8.6990	19.83	−1.887
3	32.79	34.73	−3.261
4	81.18	40.27	−1.929
5	54.25	42.6	0.4481

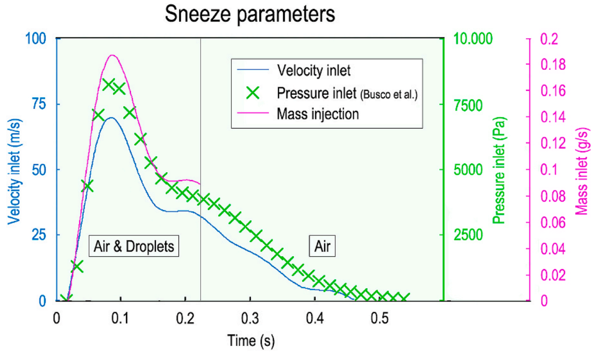


Fig. 3. Exhaled parameter values of a sneeze. Blue line represents the used inlet velocity values for this study, in m/s. Green X markers represent experimental pressure values obtained from Busco et al. [7]. Magenta line shows the time dependent injected mass function, in g/s. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

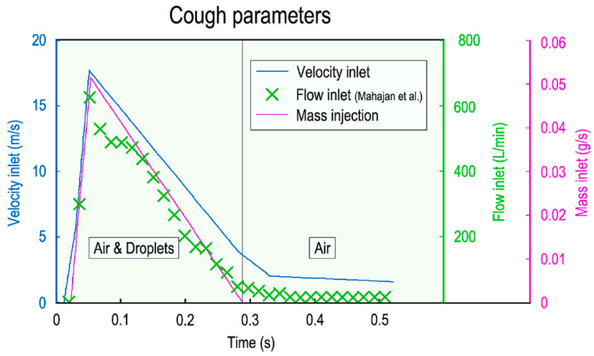


Fig. 4. Exhaled parameter values of a cough. Blue line represents the used inlet velocity values for this study, in m/s. Green X markers represent experimental flow values obtained in Mahajan et al. [23], in L/min. Magenta line shows the time dependent injected mass function, in g/s. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.2.3. *Speech case description*

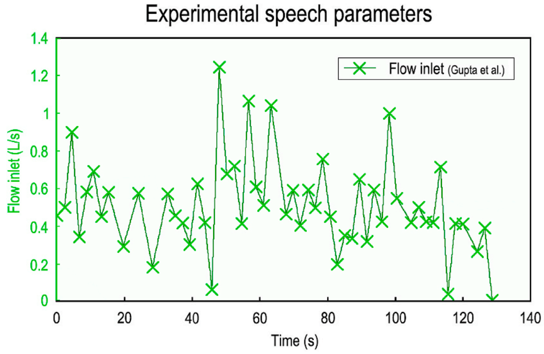
In this case, the droplet size distribution was modeled according to the obtained results in the experiments of Chao et al. [24]. They concluded that during a speech, the size of exhaled particles is in a range between 0 and 600 μm, and a mean value of 16 μm in a lognormal function. Gupta et al. [36] found the exhaled flow profile as randomly irregular but comparable to a continuous flow rate. The obtained mean value was 0.225 L/s, but with big differences depending on the height of the subject. Kwon et al. [35] concluded that speech air exhaling velocity represents between 22–27% of the cough velocity, and defined a mean value of 4.11 m/s. The selected velocity value for the current study was 4 m/s, which represents the 23% of the modeled velocity in cough case. The injection ratio was set in 0.33 mg/s in a continuous rate. To select this value, the authors took 10 s to read 50 syllables of a random passage, and were based on Xie et al. [34] were a mean value of 0.66 mg per syllable was obtained. The total physical time for this case was 15 s. Fig. 5 (**a**) shows the experimental flow rate and Fig. 5 (b) illustrates the modeled speech mass and velocity parameters.

2.3. *Eulerian model*

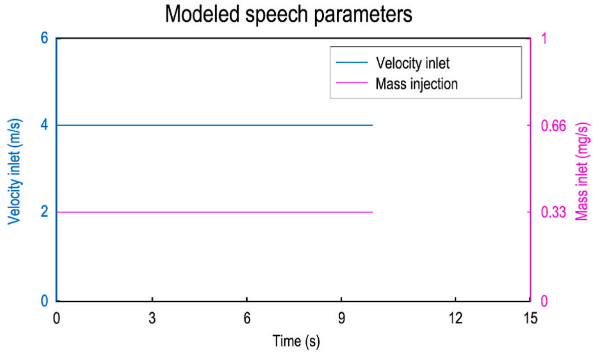
Defined velocity for the ambient inside the lift was considered as negligible. The unique remarkable velocity in this phase was the stream generated by the exhausting device, since the cabin was an isolated place from natural streams. Static temperature was defined in 21 °C, and the imposed mathematic model was Reynolds Averaged Navier Stokes (RANS) with Shear Stress Transport (SST-K-omega) turbulence, developed by Menter [45]. The Antoine equation was used to calculate saturation pressure for any temperature, and achieve the equilibrium pressure.

2.4. *Lagrangian model*

Lagrangian equations define the physics of particles, in this case, related to droplets. This case was a pure lagrangian simulation, where the physics of movement and evaporation of droplets were studied. This mathematical model, presented in Ref. [46] permitted to find out the position and state of droplets in different times, solving energy and mass equations. To reach an accurate result, it was necessary to define the Courant number which is a dimensionless number that relates velocity, cells of computational domain and



(a)



(b)

Fig. 5. Exhaled parameter values of a speech. (a) experimental flow values obtained in Gupta et al. [36]. (b) modeled speech velocity inlet (blue line) and mass injection (magenta line). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

selected time steps. This number was fixed in a maximum value of 0.7 for the first instants of all modeled cases. Eq. (2) defines the Courant number.

$$C = \frac{U \cdot \Delta t}{\Delta x} \tag{2}$$

where C is Courant number, Δx is the minor cell length and Δt is the value of the time step. To maintain the same courant number for all the cases, the time step was differently modeled for each simulation. In the case of sneeze, the selected time step was $6{\cdot}10^{-5}$ s; $2.3{\cdot}10^{-4}$ s for the case of cough and 10^{-3} for speech case.

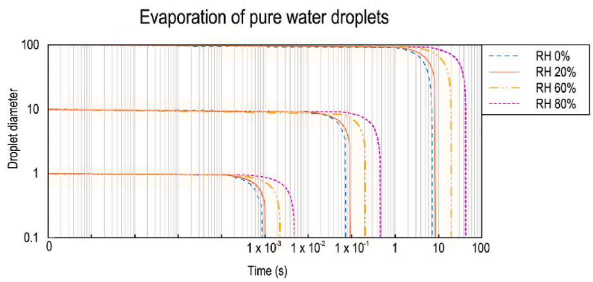


Fig. 6. Evaporation of pure water droplets under different relative humidity environments for the mathematical models used in the current study. The initial temperature of droplets was 37 °C. The environment temperature was 20 °C.

2.5. Validation

The validation procedure presented in Redrow et al. [47], Morawska [48], Li et al. [49] and Ugarte-Anero et al. [44] was used for the validation of the present work. A study in which different diameters of droplets of pure water (1 μm 10 μm and 100 μm) with a temperature of 310.15 K are subjected to an environment of 293.15 K and RH varies to see the evaporation time. The numerical results presented in Fig. 6 are similar to those shown by the aforementioned works. Furthermore, the investigation of Hamey et al. [40] has been also used as validation. Hamey study consists of two droplets of water (one of 110 μm and another of 115 μm of diameter) at a temperature of 289 K within an environment at 293 K where the path of a droplets of pure water was studied. Figs. 6 and 7 show the results obtained by comparing the numerical simulations with experiments.

3. Results

In the current study, three CFD cases about breathing activities were carried out. Simulations reproduced a hospital lift with two occupants inside, where one of them sneezed, coughed and spoked, in a clinic environment. The lift was equipped with an exhausting fan and a ventilation slot to introduce supply air. After finishing the simulations, the results were analyzed for a numerical and visual interpretation. In this way, the amount of droplets along the time was graphically represented in diameter size ranges, according to each case. In addition some scenes were presented for a better comprehension of the behavior of particles in certain instants.

3.1. Sneeze case

Fig. 8 represents the number of particles for different size stretches. At the beginning a lineal increase was observed by the time of principal droplet injection in 0.11 s. The injection reduced its ratio but adding new parcels until 0.22 s, when larger droplets amount started to reduce their amount, unless less than 50 μm particles, which increased their amount until 0.81 s. From that moment on, lighter particles decreased their amount drastically in exponential shape with some irregularities until 3.6 s afterwards, the number of parcels was maintained almost constant, and recovered a considerably reducing ratio from 4.7 s onwards. Other sized parcels were reduced in quantity, in a linear shape with slow decrease for the entire simulated time.

Droplets, represented in parcels, were violently ejected from the mouth and heaviest impacted over the occupant in 0.12 s from the beginning of the sneeze, without any influence of the fan. The slowest particles, those ejected at the final steps of the sneeze, were attracted by the fan at the first moments of their ejection, overall the lighter parcels. In whole, no parcel larger than 200 μm had the necessary buoyancy to maintain their selves in suspension, and hit the occupant if their momentum dynamics allowed, or fall on the ground if not. The first exhausted parcel was a light parcel and occurred in 0.85 s, which matched with first decrease of small particles in Fig. 6. Onwards, droplets were removed from the domain by the fan and divided in two volumetric groups. These two groups, one placed upstream and the other downstream suffered recirculation caused by fan stream motions. The recirculation dispersed the parcels in whole lift, more concentered upstream by the position of the healthy occupant. Fallen droplets were gathered in healthy occupant feet. Fig. 9 shows the parcels positions in 1 s, 2.5s and 5 s, differenced in size by colors. Fig. 9(a)–(c) demonstrate the droplet dispersion from a point of view in perspective. Fig. 9(d)–(f) shows the dispersion in top view.

3.2. Cough case

Fig. 10 shows the evolution of the amount of particles for 10 s. Diameter size ranges where subdivided in 4 stretches; diameters smaller than 50 μm, between 50 and 75 μm, between 75 and 100 μm and larger than 100 μm. An initial growing peak appeared due to saliva injection. The droplets in range 75–100 μm started to decrease instantly. Meanwhile, the smaller droplets increased their amount. Before 6th second particles 75–100 μm had a major decreasing ratio as well as 50–75 μm started to decrease their quantity. Particles smaller than 50 μm increased their amount slowly until last moments of the simulation, when a slight decrease seemed to appear.

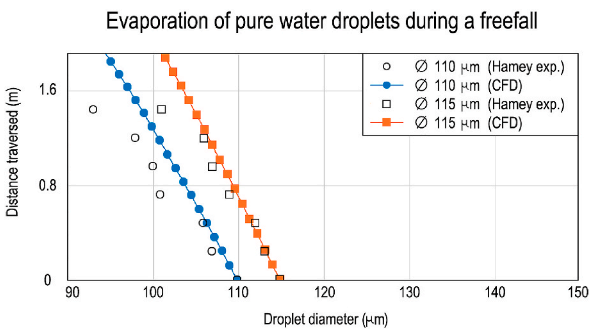


Fig. 7. Evaporation of pure water droplets in 70% RH and 20 °C environment during an experimental freefall and CFD simulations. Two initial diameters were studied (110 μm and 115 μm).

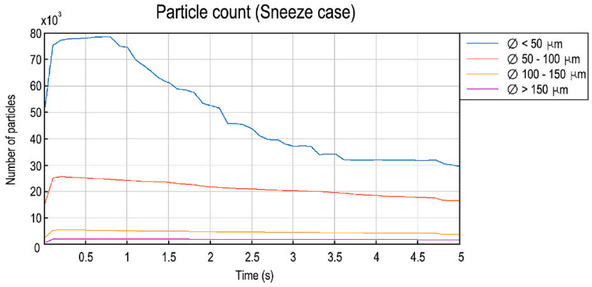


Fig. 8. Sneeze particle counting along 5 s. Counts are subdivided in 4 diameter size ranges: less than 50 μm; between 50 and 100 μm; between 100 and 150 μm and more than 150 μm.

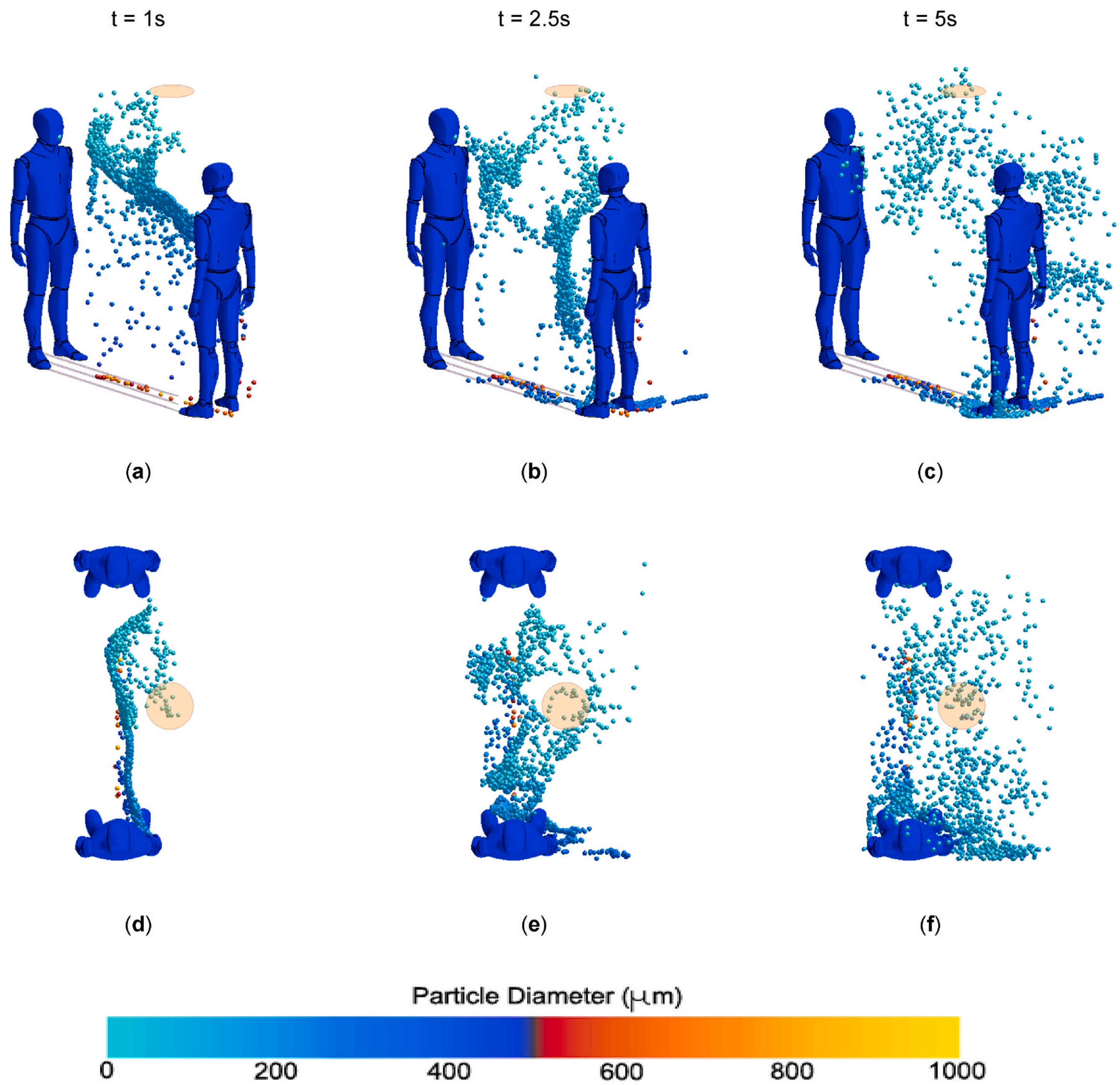


Fig. 9. Sneeze particle pictures: (a), (b) and (c) shows a whole point of view for 1 s, 2.5 s and 5 s respectively; (d), (e) and (f) shows a top view for 1 s, 2.5 s and 5 s respectively.

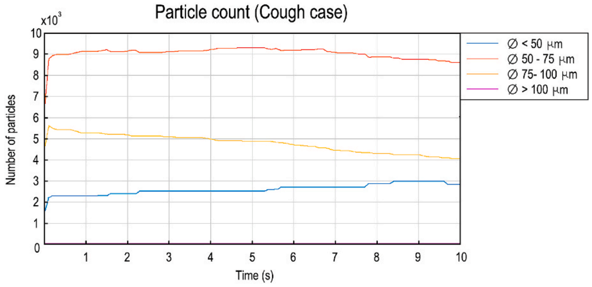


Fig. 10. Cough particle counting along 10 s. Counts are subdivided in 4 diameter size ranges: less than 50 μm; between 50 and 75 μm; between 75 and 100 μm and larger than 100 μm.

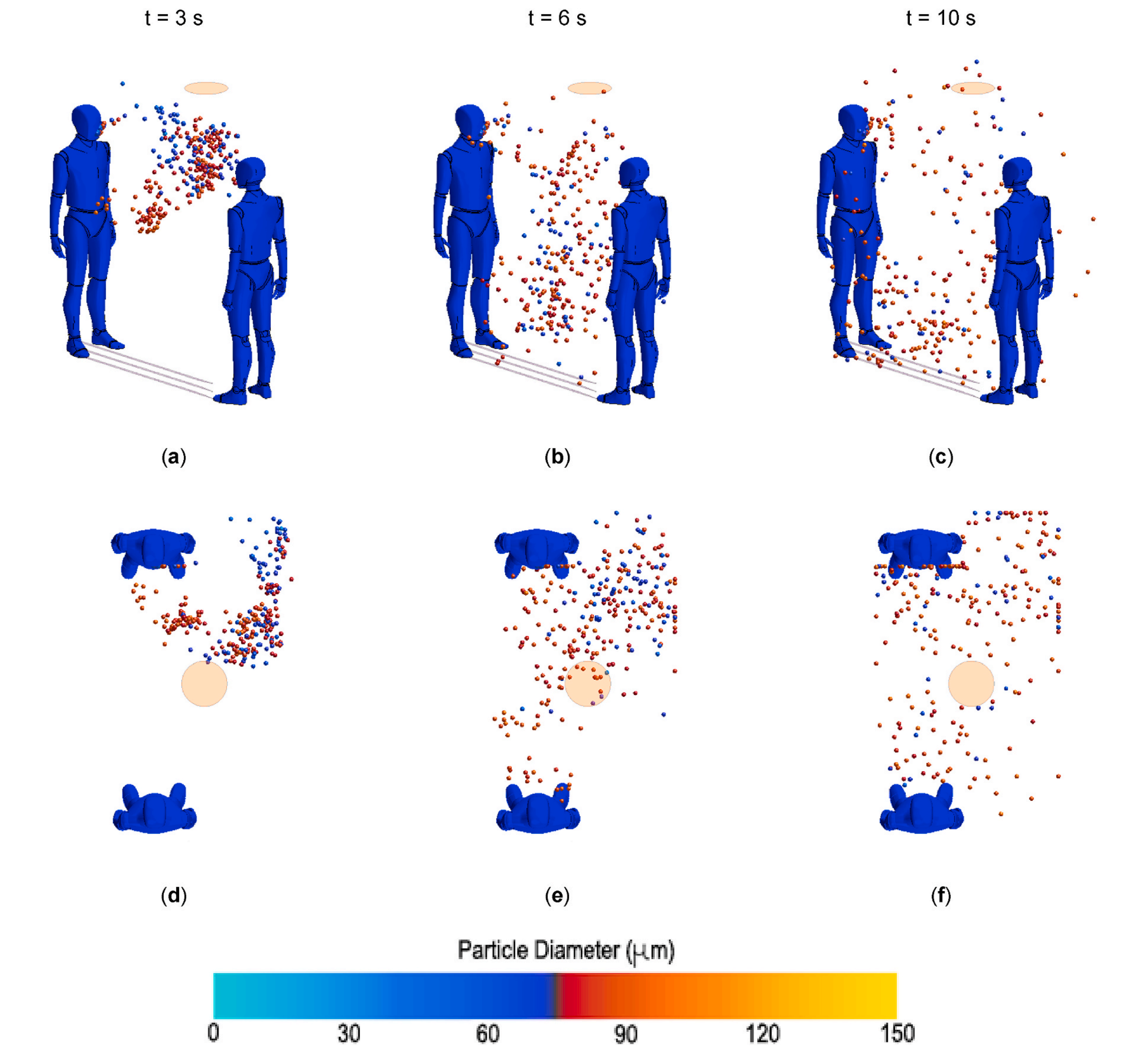


Fig. 11. Cough particle pictures: (a), (b) and (c) shows a whole point of view for 3 s, 6 s and 10 s respectively; (d), (e) and (f) shows a top view for 3 s, 6 s and 10 s respectively.

Fig. 11 displays the position for different sized parcels along the simulation, and their evolution. Fig. 11(a)–(c) show a whole point of view for 3 s, 6 s and 10 s respectively and Fig. 11(d)–(f) represent a top view for 3 s, 6 s and 10 s respectively. At the beginning a single droplet cloud was observe. At the first second, the cloud was divided in two parts, both distancing from the emitter to his left. One, in head had the heavier droplets and went upstream. The lighter parcels were affected by a vortex created from the fan which lead them backward and upward creating a recirculation ring. Around the second 2, all parcels were dispersed in random trajectories governed by the streams inside. The first exhausted parcel occurred in second 5.5, which matched with the initial decreasing ratio of 75–100 μm. The droplets located at the top of the elevator continued being exhausted meanwhile the bottom droplets were recirculated until they got in upward stream that lead them to the top, being in some cases exhausted through the fan. The most of stuck droplets were near the zone of the emitter.

3.3. Speech case

Fig. 12 shows the amount of droplets along the simulated 15 s during a 10 s speech inside the lift. For this case, diameter ranges were subdivided in 4 size stretches; droplets smaller than 50 μm, droplets of sizes comprehended between 50 and 75 μm, between 75 and 100 μm and droplets larger than 100 μm. For this case, a great amount of parcels smaller than 50 μm was observed. This range of size appeared in the first moment and increased linearly its amount until second 3, when rose greatly in quantity until the 5th second. Afterwards, the amount increased in slower size until the end of droplet emission in second 10. During the last 5 s, this range decreased the sum gradually. Secondly, larger particles, namely 50–75 μm droplets almost were not counted until after than second 3, when suddenly appeared in a continuum value. At second 9, they started to increase their amount until the end of the simulation. Larger droplets than 75 μm were almost showed up.

Fig. 13 exposes the different size droplets in seconds 3, 10 and 15. Fig. 13(a)–(c) represents an isometric point of view for different times. Fig. 13(d)–(f) display the top views. The particles larger than 150 μm fell directly to the ground in parabolic motion being stuck there. Finer droplets recirculated inside the lift. In second 3 two recirculation movements were detected. Both were clearly affected by the fan. The primary had the center disposed near to the lift. The secondary had the lift located at its perimeter tending to go backward. The streams generated from the racks below originated turbulences which impacted to the small droplets raising and lowering them randomly. In second 15 parcels were more scattered inside the domain than in second 10, although it is also appreciated that concentrations were minors due to the exhausting of droplets through the fan.

4. Discussion

The current study researched, by CFD media, the behavior of expelled droplets under three breathing activities such as sneezing, coughing and speaking. The selected scenario was a hospital lift, in clinic environment, provided by an exhausting fan and three air inlet slots to provide air to indoor.

Parameters were chosen following different sources. Sneeze was modeled as a dynamic inlet velocity in sinusoidal shape, in concordance with Busco et al. [7], with a 70 m/s peak [14]. Size distribution was the proposed by Han et al. [14]. Cough was the same model validated in Chillón et al. [37] but with an inlet velocity profile near to the results of Mahajan et al. [23]. To represent a 10 s speech, a continuum velocity mass inlet was configured according to researches of Gupta et al. [36] and Chao et al. [24].

Even assuming the experimental results of different authors, this work represents a specify case, because each subject have particular parameters as exhaling velocity, droplet size distribution or amount. In this study, some simplifications were adopted. The exhausting fan was modeled as a circular shaped outlet positioned on the ceiling, so produced streams were an approximation. Even more, a unique breathing activity was assumed, without adopt the human inhalation and exhalation from respiration, neither physics movements nor mimics, which could change the results here obtained. Human plumes also were not designed, so the droplets movements depended only on the streams generated by the fan, being human figures mere visual representations. The last simplified set up was the selected shape for the emitting mouth, which had a continuum form during the droplet expelling and was the same for the three cases.

For the three cases, results showed that certain amounts of small droplets (<100 μm) were exhausted through the fan. Differences in the results of droplet size, amounts and concentration zones were observed among three simulations. Authors recommend testing new fan dispositions, diameter sizes and aspiration ratios. The small volume of an elevator becomes it a room where the concentration of droplets can be very high, which increases the risk of infections inside. Deeping in this issue should be mandatory to consider a lift as safe.

5. Conclusions

In the current study, a hospital lift has been modeled using CFD techniques. The lift was equipped with an exhausting fan located over the center of the ceiling with a ratio of 1100 m^3 per hour. Three racks were also modeled on a wall at the bottom to provide renewed air. Inside the lift, two human models were included. Three simulations were carried out, where in the first, a human sneezed; in the second he coughed and finally, a 10 s speech occurred. The goal of the research is to investigate the suitability of a fan which exhaust the exhaled droplets. According with the obtained results, four conclusions were achieved.

- In the case of sneeze, the fan seemed to have more impact over the exhausting of droplets. In this case, about the 60% of droplet smaller than 50 μm and around the 28% of droplets 50–100 μm were expelled from the domain. In the rest of cases, the effectivity

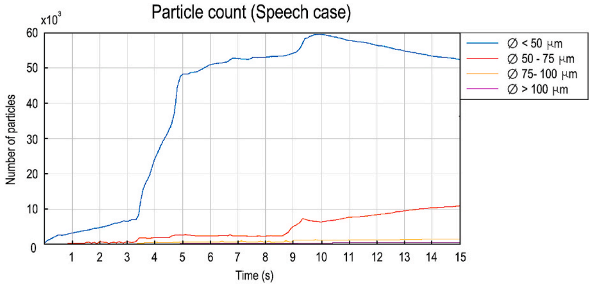


Fig. 12. Speech particle counting along 15 s. The speech lasted 10 s, the final 5 s no particle was emitted. Counts are subdivided in 4 diameter size ranges: less than 50 μm; between 50 and 75 μm; between 75 and 100 μm and larger than 100 μm.

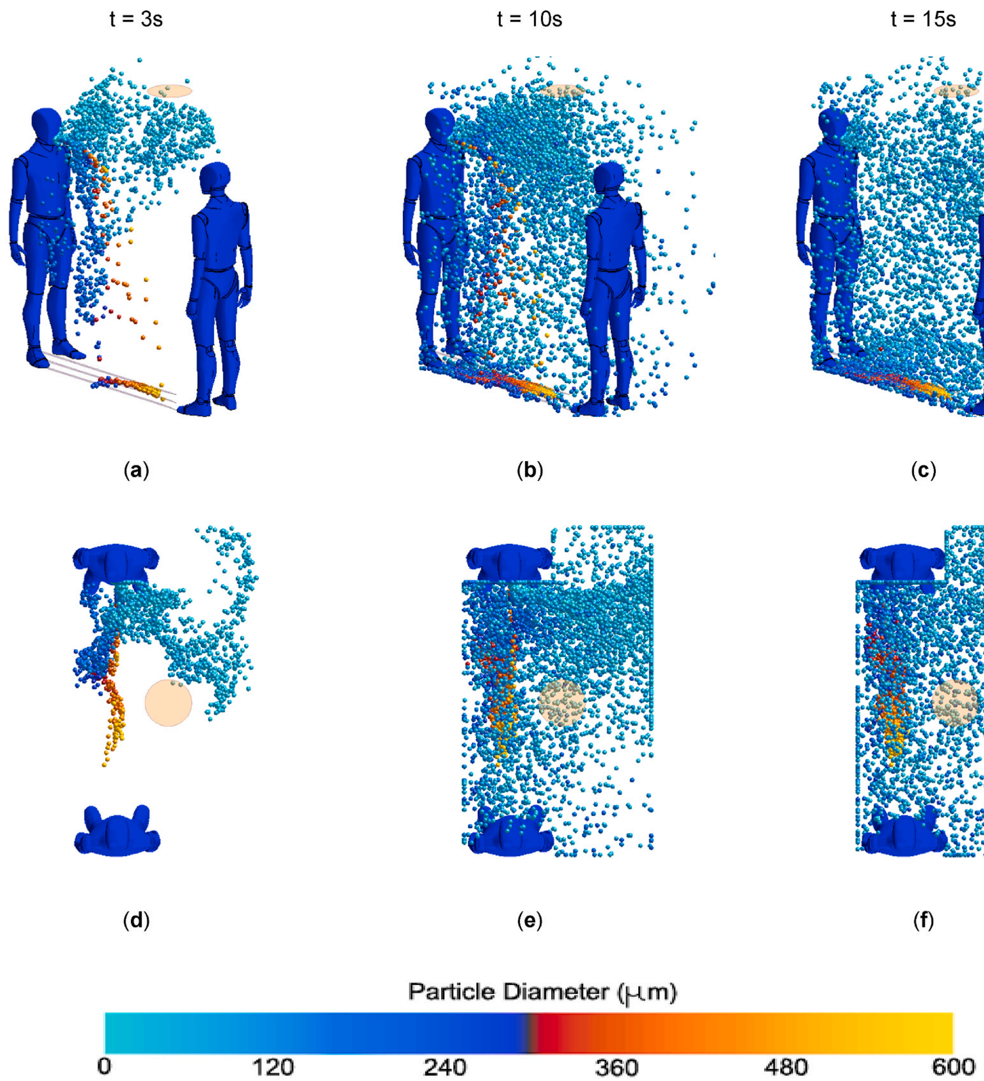


Fig. 13. Speech particle pictures: (a), (b) and (c) shows a whole point of view for 3 s, 10 s and 15 s respectively; (d), (e) and (f) shows a top view for 3 s, 10 s and 15 s respectively.

was not so important. In cough case, the majority of ejected droplets were larger than 50 μm; in contrast to speech case, where the exhaled droplets were smaller than 50 μm. From this data, authors concluded that a minimum inertia was necessary to get in the updraft generated by the fan.

- The setup of a ventilator fan dispersed the particles in the domain, generating concentered zones which could be dangerous respect to breathing diseases transmissions. Anyway, the installation of this device would clean the inside but in longer time terms. Authors saw appropriated to switch on the fan during long times when it is empty of occupation.
- Among three simulated cases, the worst scenario was the speech. The continuum emitting ratio surpassed the capacity of the fan to eject droplets, saturating the environment of particles in high concentrations. It would be advisable not to talk in closed small interiors and to wear surgical masks in times of pandemic.
- Clinic conditions (RH 50% and 24 °C) avoided the drying of droplets. Particles increased in size and mass due to hygroscopic effects as it could be elucidated from speech case, where the amount of droplets of smaller range decreased meanwhile the quantity of the next size range increased. The streams generated by the fan could have any effect in drying droplets by convection but in a minor range.

Author contribution statement

Sergio A. Chillón: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Unai Fernandez-Gamiz: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Ekaitz Zulueta: Conceived and designed the experiments; Analyzed and interpreted the data.

Ainara Ugarte-Anero: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Oskar Urbina-Garcia: Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no competing interests.

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Appendix A

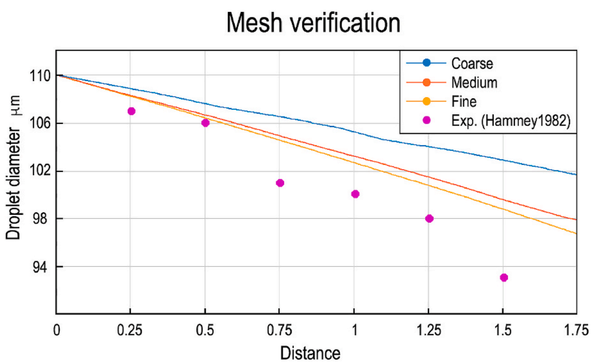

Figure A1. The change of diameter of pure water droplet vs traveled distance. The experimental evaporation of a 110 μm diameter droplet achieved in Hamey et al. [40] was evaluated for numerical validation.

Table A2. Results of Richardson extrapolation for 110 μm diameter droplet validation for fine mesh.

Mesh				Richardson extrapolation for fine mesh		
	Traveled distance					
Diameter	Coarse	Medium	Fine	RE	p	R
109,12	0,1902	0,1323	0,1237	0,1252	2,7539	0,1482
108,22	0,3836	0,2681	0,2493	0,2530	2,6215	0,1625
107,32	0,5503	0,3981	0,3742	0,3786	2,6719	0,1569
106,42	0,7685	0,5343	0,4995	0,5056	2,7539	0,1482
105,51	0,9578	0,6695	0,6226	0,6317	2,6215	0,1625
104,59	1,0947	0,7919	0,7444	0,7532	2,6719	0,1569
103,67	1,3302	0,9297	0,8646	0,8772	2,6215	0,1625
102,75	1,5139	1,0638	0,9841	1,0013	2,4960	0,1773
101,82	1,7063	1,1862	1,1091	1,1225	2,7539	0,1482
100,88	–	1,3271	1,2342	1,2522	2,6215	0,1625
99,94	–	1,4403	1,3539	1,3699	2,6719	0,1569
98,99	–	1,5745	1,4722	1,4900	2,7539	0,1482
98,04	–	1,7083	1,5888	1,6120	2,6215	0,1625
97,08	–	–	1,7049	1,7251	2,6719	0,1569

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