Sneeze and cough pathogens migration inside aircraft cabins

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Transmission of respiratory infectious airborne diseases, such as influenza, H1N1, Severe Acute Respiratory Syndrome (SARS) and COVID-19 inside any closed environment like the aircraft cabins has always been a topic to be studied, because the respiratory droplets produced when a passenger with a certain infections talks coughs or sneezes have harmful effects on other occupants. They have the ability to take flight and hang in the surrounding air or land on passengers or surfaces in short time. This work presents the results of a study of airflow behavior of coughing and sneezing droplets that are produced from a moving passenger in wide-body aircraft cabin section at different velocity rates. In addition, it compared between transmission of different flow rates and velocities in order to show how can these diseases transported from a moving and standing passenger to other passengers. This numerical simulation used computational fluid dynamic (CFD) modeling simulation. The results showed that the airflow of coughing and sneezing droplets produced from the moving passengers could reach seated passengers; however, sneezed droplets had more harmful impacts than coughed droplets, also both travelled for a long distance inside the cabin. In addition, when comparing the droplets spread range resulting from the moving passenger and stand-still one, it was found that the quicker the passenger moves, the further the droplets spread.

Influenza, H1N1, Severe Acute Respiratory Syndrome (SARS) and coronavirus disease 2019 pandemic (COVID-19) are infectious diseases that may infect humans either through droplets or airborne particles carrying these diseases [1]. The droplets or particles are produced from an infected person during coughing, sneezing or talking. Moreover, these droplets are transmitted from one person to another person through inhalation [2]. Computational Fluid Dynamics (CFD) numerical simulations as well as practical experiments are used to study the effects of transmission of the droplets inside closed environments. **Table 1** summarizes the studies of the transmission of the airborne particles or droplets and their behaviors.

Regarding respiratory infectious diseases, there are three ways to spread; direct and indirect contacts besides airborne transmission [9]. This happens inside aircraft cabins. In direct contact, the droplets that are coming from the passenger's mouth and nose during coughing, sneezing and talking and containing viruses need only a close contact to transport [4]. Moreover, in indirect contact droplets transmitted from the surfaces like cabin's chair or windows to the passengers [11]. There are many parameters that should be taken into consideration in order to simulate the dispersion and deposition of the expiratory droplets using computational fluid dynamics (CFD). These parameters are [8]:

- Coughing or sneezing flow rate
- Coughing or sneezing direction
- Mouth area
- Temperature of coughed or sneezed droplets
- Size of coughed or sneezed droplets

Concerning the impacts of transmission of diseases due to the movement of passenger, Poussou et al. [12] and Mazumdar et al. [13] studied the impact of moving a passenger or cabin crew through the exhaled droplets that are generated from a seated passenger. In addition, Khalil and Kotb [14] simulated the spreading of coughed particles induced from a moving passenger inside the aircraft cabin. This investigation attempted to use computational fluid dynamic (CFD) simulation, dynamic mesh analyses technique, and Lagrangian equations model to compare between the behaviors of cough and sneeze particles induced from a passenger while moving and standing under different velocities and flow rates.

Mathematical Modeling

The Governing Equations

In this investigation, ANSYS FLUENT V18.1 CFD commercial software was used to solve mass, momentum, and energy equations that are required to simulate the case.

Continuity Equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

Momentum Equation:

$$\frac{\partial(\rho u)}{\partial t}+\nabla\left(\rho u\vec{V}\right)=-\frac{\partial P}{\partial x}+\nabla(\mu grad\ u)+S_x \qquad (2)$$

$$\frac{\partial(\rho v)}{\partial t}+\nabla\left(\rho v\vec{V}\right)=-\frac{\partial P}{\partial y}+\nabla(\mu grad\ v)+S_y \qquad (3)$$

$$\frac{\partial(\rho w)}{\partial t}+\nabla\left(\rho w\vec{V}\right)=-\frac{\partial P}{\partial z}+\nabla(\mu grad\ w)+S_z \qquad (4)$$

Energy Equation:

$$\frac{\partial(\rho T)}{\partial t}+\nabla\left(\rho T\vec{V}\right)=\nabla+\nabla\left(\frac{\lambda}{c_P} grad\ T\right)+S_T \qquad (5)$$

Table 1. *A brief summary the studies of the transmission of the airborne particles or droplets and their behaviors.*

Author	Method	Results
Afshari et al. [3]	Experimental investigation	Illustrated the characteristic differences between the airflow produced during coughing of a healthy person and an infected person.
Zhao et al. [1]	Numerical investigation	Showed that the airborne particles that are generated from a person inside a closed room during normal talking can be transmitted to a short distance, while coughed and sneezed particles can travel to a distance longer than 3 meters.
Leder, and Newman [4]	Theoretical investigation	Concluded that the spread of airborne pathogen transport can happen inside an aircraft cabin due to the infectious air exhaled by an infected passenger and inhaled by another passenger.
Gao and Niu [5]	Numerical investigation	Reported that the possibility of spreading and transmission of respiratory droplets that are produced from a human during a normal breathing process inside a room with a displacement ventilation system is low, nevertheless if two persons face each other, infection may be occurred due to the contaminated air.
Yan et al. [6]	Experimental and numerical investigation	Revealed that the airborne particles can be controlled by the airflow of the ventilation system. Moreover, the location of the infected passenger affects the airborne pathogens transport inside the aircraft cabins.
Gupta et al. [7]	Experimental investigation	Proposed new boundary conditions that can be used to simulate the behavior of coughed droplets using computational fluid dynamics (CFD).
Gupta et al. [8]	Experimental investigation	Clearfield that breathing and talking processes have a great effect on infections transmission, because they have higher event frequency than coughing process.
Han et al. [9]	Experimental investigation	Analyzed and measured the sneezed droplets and their sizes in order to be used as CFD boundary conditions. Moreover proposed a geometric mean of sneezed droplets.
Yan et al. [10]	Numerical investigation	Reported that the droplets mass fraction and the distributions of local air velocity strongly affected by the human body heats.

Moreover, a dynamic mesh analysis in ANSYS program was used in ANSYS FLUENT in order to present the passenger movement inside the aircrafts cabin. Due to moving of the passenger an integral form of conservation equation is used [15]:

$$\frac{d}{dt}\int_{V} \rho\phi dV + \int_{\partial V} \rho\phi(\vec{U} - \vec{U_g}).d\vec{A}$$

$$= \int_{V} S_{\phi} dV + \int_{\partial V} \Gamma \nabla \phi . d\vec{A} \quad (6)$$

The model that was used during the simulation to calculate the airflow of the particles and the ventilated cabin is the realizable $K - \varepsilon$ model, as the performance of this model is better than the standard $K - \varepsilon$ model [16], and it is more accurate than RNG $K - \varepsilon$ model [16]. The transport Equations for the Realizable $K - \varepsilon$ Model are as follows [16]:

$$\frac{\partial}{\partial t}(\rho K) + \frac{\partial}{\partial x_j}(\rho K u_j)$$

$$= \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_x}{\sigma_K})\frac{\partial K}{\partial x_j}\right] + G_K + G_b - \rho_\epsilon - Y_M + S_K \quad (7)$$

$$\frac{\partial}{\partial t}(\rho \in) + \frac{\partial}{\partial x_j}(\rho \in u_j)$$

$$= \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\epsilon})\frac{\partial \in}{\partial x_j}\right] + \rho C_1 S_\epsilon - \rho C_2 \frac{\epsilon^2}{K + \sqrt{\nu\epsilon}} - C_{1\epsilon}\frac{\epsilon}{K} C_{3\epsilon} G_B - S_E \quad (8)$$

Where, $\vec{V}$ is the velocity vector, P is the pressure, u, v, w are flow velocity in the directions of x, y and z axis, t is the time, V is the control volume, ϕ is a general scalar, ρ is the fluid density, $\vec{U}$ and $\vec{U_g}$ are flow velocity vector and mesh velocity of the moving mesh, respectively, Γ is the diffusion coefficient, S_ϕ is the source term of ϕ, G_K is the turbulence kinetic energy, G_b is the turbulence kinetic energy that is generated due to buoyancy, Y_M is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, σ_K and σ_ε are the turbulent Prandtl numbers, S_K and S_E are terms that can be defined by the user, C_1 and C_2 are constants.

Calculations of Cough and Sneeze Droplets

To investigate the behaviors of the cough and sneeze droplets induced from the moving passenger, the discrete phase model was used in ANSYS FLUENT in order to predict the trajectory of the droplets; this can be done by integrating the force balance on the droplets [15].

Droplets Force Balance Equation

The forces balance of the droplet equals the droplet inertia with all forces that affect the droplet, it can be written (for the x-direction, as an example) as [15]:

$$\frac{du_d}{dt} = F_D(U - U_d) + g_X\frac{(\rho_d - \rho)}{\rho_d} + F_X \quad (9)$$

Where, $F_D(U - U_d)$ is the drag force per unit droplet mass, U_d is the velocity of the droplet, ρ_d is the density of the droplet, g_X is the force of gravity on the droplet in x-direction, μ is the molecular viscosity and F_X is an additional force.

Model validation

In order to validate this study, ANSYS FLUENT v18.1 CFD commercial program was used. Validation process is to test the reliability and accuracy of the ANSYS Fluent CFD program that was used to simulate a numerical case. This can be done by comparing the generated CFD results with experimental data. During this investigation, the experimental data were selected from Kühn et al. [17] study that was focused on analyzing and measuring the forced and mixed convection heat transfer inside AIRBUS 380 upper-deck cross section cabin mockup. The cross section of this aircraft has a length of 6 meters, a width of 5.1 meters, and a depth of 2.2 meters. Moreover, 20 dummies were added inside the cabin to simulate the passengers. Inner heaters surrounded these manikins in order to simulate their thermal load reflection and four electrical panels were added on the top of each side of the cabin to simulate the heat input of the light. ANSYS design modeler (DM) was used to draw the cabin, as shown in **Figure 1**. A half of a cross-section of the cabin was created in order to speed up the CFD progress. Consequently, we used the same boundary conditions that were used during the experiment. **Table 2**. shows the validation boundary conditions.

ANSYS design modeler (DM) was used to create the 3D model of the cabin. The dimensions of the upper deck cross section cabin are 5.1×2.2×6 meters. **Figure 1** shows the 3D model of the upper deck cabin; nevertheless, a half of the cross-section cabin was used during the simulation in order to perform the simulation in short time.

Table 2. *The validation boundary conditions.*

Temperature of the incoming air	21 C
Temperature of the manikin bodies	33.5°C
The total power of the four electrical heating panels	1.8 kW
The number of air inlets that worked together	24
The total air volume flow rate	300 dm³/s
The total volume flow rate at inner ceiling A inlets	150 dm³/s
The total volume flow rate at lateral air inlets	150 dm³/s
Heat flux of each manikin	55 W

Moreover, by using ANSYS, about 6835652 tetrahedral mesh cells and 8628058 nodes were generated. In addition, we used the realizable $K-\varepsilon$ model. Kühn et al. [15] illustrated the results of the velocity magnitude profile of A50/50 air inlets configuration at x = 1190 mm. also used an equation to illustrate the temperature magnitude at x = 1120, as shown in **Figure 2.** The temperature equation is:

$$\Delta T_{loc} = (T - T_{in})\frac{(\Delta T)}{\Delta T} \tag{10}$$

Where, ΔT_{loc}, $(T - T_{in})$, (ΔT) and ΔT are the corrected and actual measured local temperature difference to the incoming air temperature.

From the comparison of the experimental velocity and temperature data and the CFD results in **Figure 2**, it was found that the argument between them is good and can be accepted.

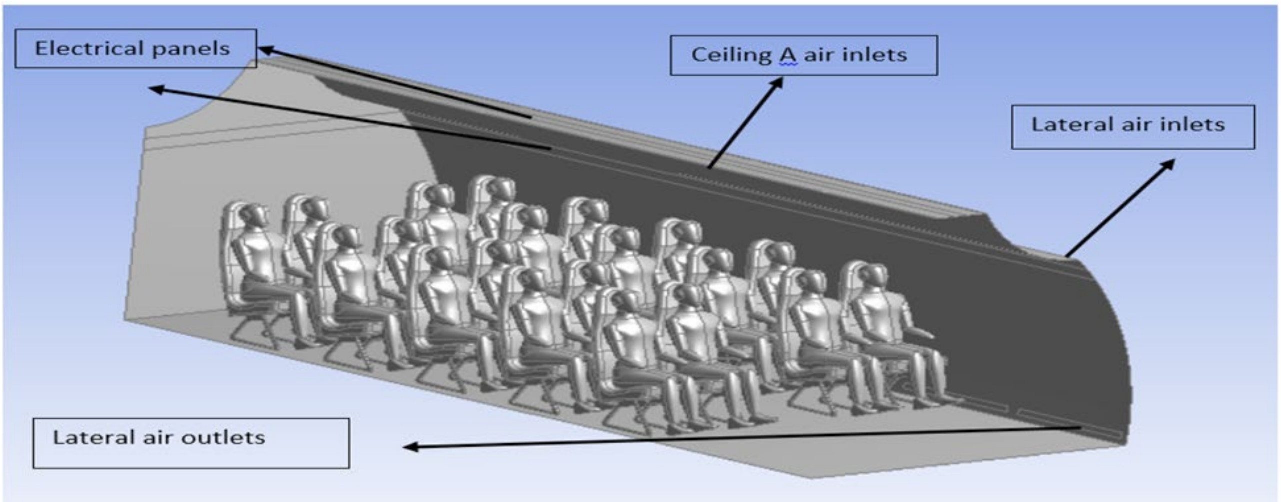


Figure 1. 3D model of the A380 upper-deck cabin.

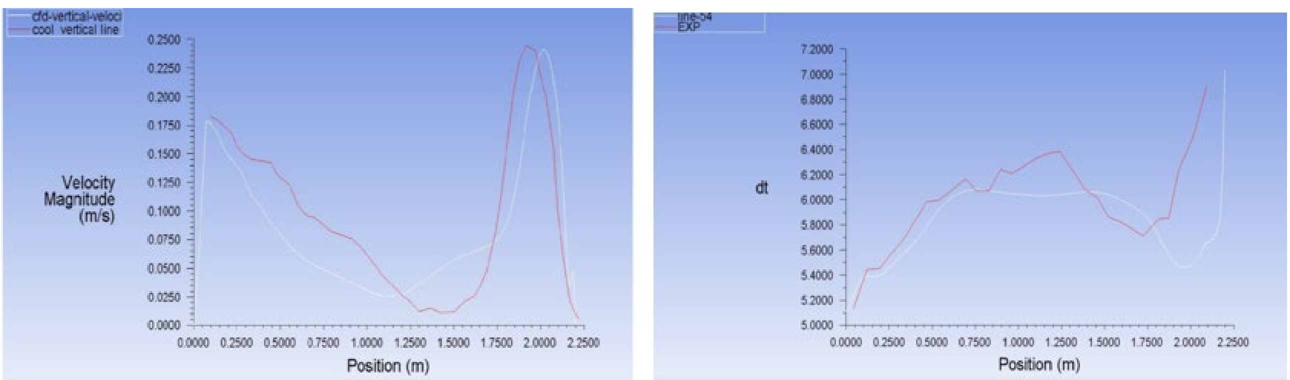


Figure 2. A comparison between the experimental velocity and temperature magnitude and the CFD results.

Numerical model

Proposed model

The dimensions of the geometric model are also based on the model used by Kühn et al. [15]. **Table 3** shows the simulation boundary conditions of the case study. We selected this aircraft cabin, because the probability of diseases transmission inside its cabin is higher than any other aircrafts due to including large number of passengers during long flights. Moreover, a dummy was installed in the middle of the cabin's aisle in order to simulate the exhalation of the coughed and sneezed droplets during the movement. This dummy has a length of 1.67 m and a width of 0.45 m besides its mouth area is 4 cm², as recommended by Gupta et al. [7]. **Figure 3** shows the 3D model of the moving passenger inside the cabin. Throughout our CFD simulation, the realizable $K-\varepsilon$ model and coupled pressure-velocity coupling were used.

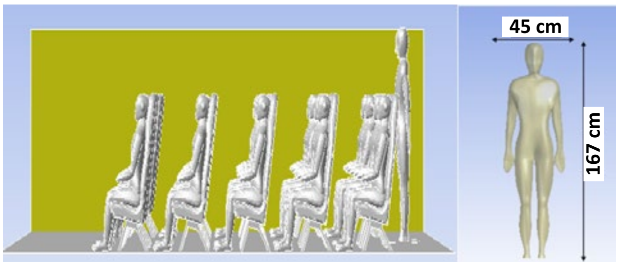


Figure 3. 3D model of the cabin and moving passenger.

Table 3. *The simulation boundary conditions.*

CFD software	ANSYS FLUENT V18.1
Turbulence model	The realizable $K-\varepsilon$ model
Moving passenger's height	1.67 m
Moving passenger's width	0.44 m
The total air volume flow rate	300 dm³/s
The total volume flow rate at inner ceiling A inlets	150 dm³/s
The total volume flow rate at lateral air inlets	150 dm³/s
Temperature of supply air flow	18°C
Temperature of ceilings	22°C
Temperature of electrical lights	27°C
Temperature of the moving passenger	36°C
Temperature of the seated manikins	34.5°C
Back wall temperature	22°C
Floor temperature	24°C
Mass flow rate of the moisture from the mouths of the passengers	0.05 kg/s
Speed of the moving passenger	0.6 m/s

Design Case Setup

Economy class in the A380 aircraft cabin was selected because of the higher density of passengers inside it, which may cause a risk of pathogen diseases transmission. This study focused on transmission of coughed and sneezed droplets or particles that are produced by a passenger in case of moving with a constant speed between passengers and without any movement. To perform an accurate CFD investigation, coughed and sneezed droplets properties were used, as illustrated in **Table 4.**

Concerning modeling turbulent dispersion of droplets, stochastic discrete- particle model that enables us to predict the behavior of the droplets through integrating the trajectory equations for the individual droplets or particles using instant fluid velocity along the droplet path during the integration [15].

Design Case Studies

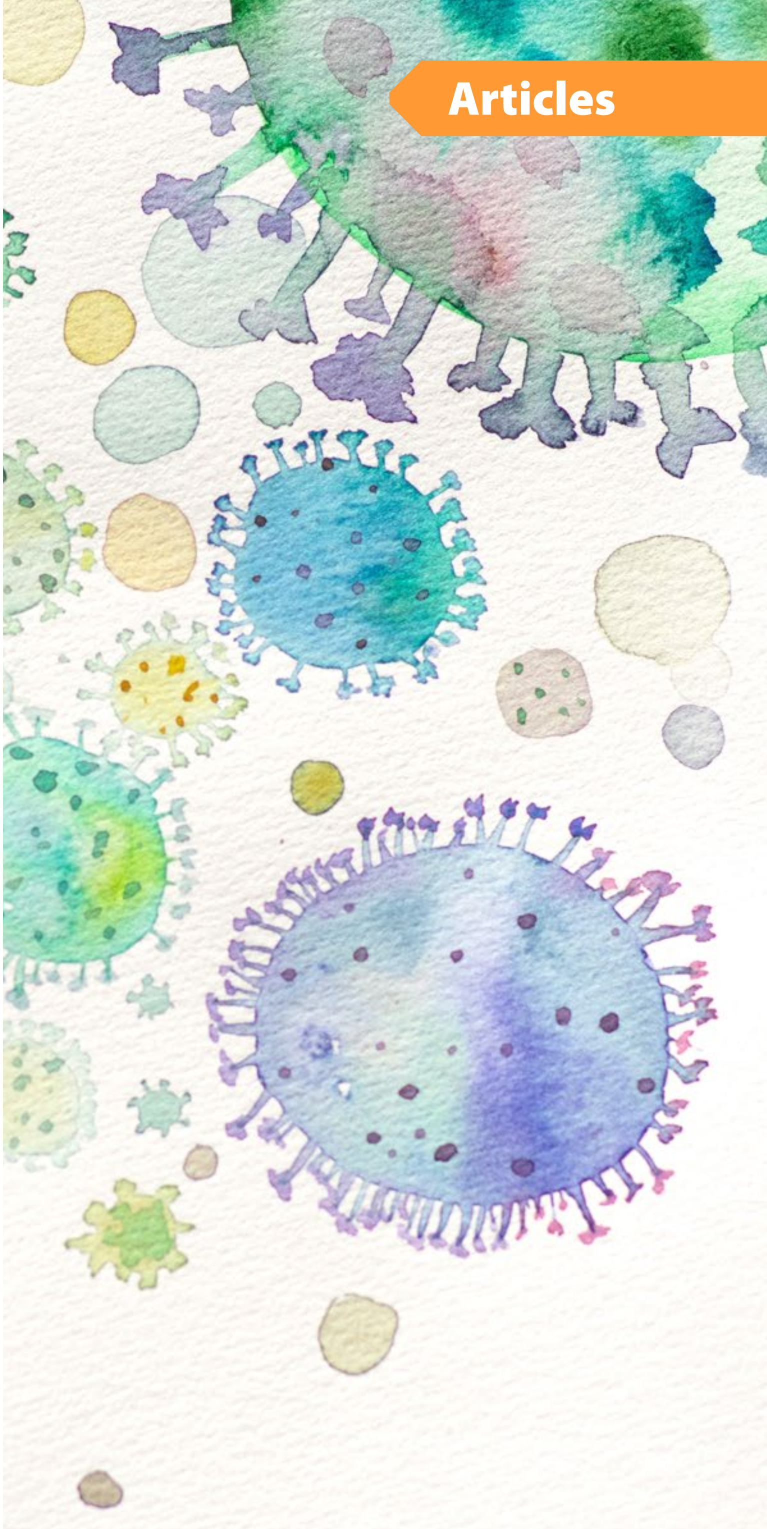
Two cases were simulated during this investigation each case has two scenarios. They can be described as follows: In cases one and two, transmission behaviors of sneezed and coughed droplets or particles produced from a passenger or cabin crew member were investigated during standing without any movement and moving with a constant speed up to 0.6 m/s. In long flight that may extend up to 7 hours, too many passengers leave their seats to do different activities; therefore, these scenarios can be happened. During this investigations, different coughing and sneezing flow rates were used, moreover, different velocities, as illustrated in **Table 5.**

Table 4. *Properties of coughed and sneezed droplets.*

Zhao et al. [1]	Coughing velocity	20 – 100 m/s
Zhu et al. [18]	Coughing velocity	6 – 22 m/s
Zhu et al. [18]	The total cough volume	0.8 – 2.2 dm³
Mahajan et al. [19]	The total cough volume	5 dm³
Gupta et al. [7]	• Mouth area for men • Mouth area for women • Cough flow rates for men • Cough flow rates for women • Coughing period • The cough jet direction	4 cm² 3.370 cm² 3 – 8.5 dm³ 1.5 – 6 dm³ 0.3 sec 40°
Jennison [20] Duguid [21] Buckland & Tyrrell [22]	Coughing and sneezing droplets size	• 7-100 µm • 1-2000 µm • 50-850 µm

Table 5. *Coughed and sneezed droplets characteristics.*

Parameters	Sneezing	Coughing
Temperature of the droplets	35	35
Exhaled period	1 sec	0.3 sec
Exhalation velocity	30 m/s	11.5 m/s
Max droplet diameter	500 µm	500 µm
Min droplet diameter	50 µm	50 µm



Results and their Discussions

This CFD study investigated the behavior of coughed and sneezed droplets and their transmission in the aircraft cabin during the flights using ANSYS FLUENT software.

Case One

Sneezing during Standing

Figures 4 & 5 show the transmission of the sneezed droplets that were produced from the passenger mouth for one second during his/her standing. These droplets' spread in *x*, *y*, and *z* positions were analyzed for 4 seconds during the CFD investigation, as shown in **Figure 5** where *x* and *y* represent width and height of the cabin. From the results, after exhaling the sneezed droplets with a speed of 30 m/s and their sizes are ranged from 50 – 500 µm. **Figure 5** shows that the droplets transported to more than 1.7 meters in *x*-direction and 1.8 meters in *y*-direction at the end of the simulation process. Moreover, these droplets traveled from the first to the second row.

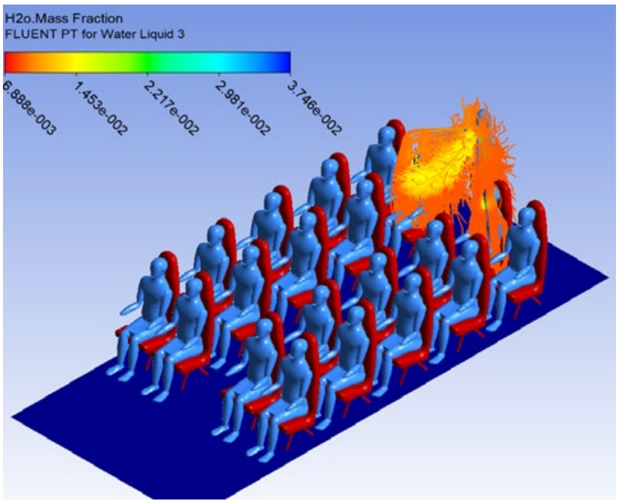


Figure 4. Transmission of the sneezed droplets during standing still.

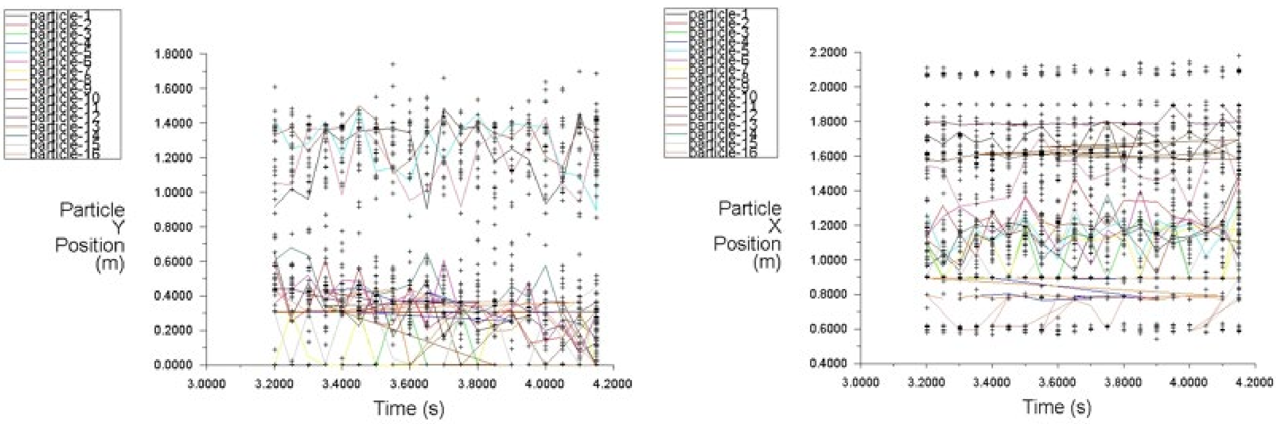


Figure 5. Transmission of the sneezed droplets in x- and y-directions during standing still.

Coughing during Standing

Moreover, **Figures 6 – 7** show the spread of the coughed droplets that were produced from the passenger mouth for one second during his/her standing with a speed of 11.5 m/s [18]. These droplets' transmission was simulated for 3 seconds during the CFD investigation, as shown in **Figure 6** after exhaling the coughed droplets their sizes are ranged from 50 – 500 µm. **Figure** 7 shows that the droplets traveled to more than 1.1 meters in *x*- and *y*-direction at the end of the simulation process. Moreover, these droplets traveled from the first to the second row.

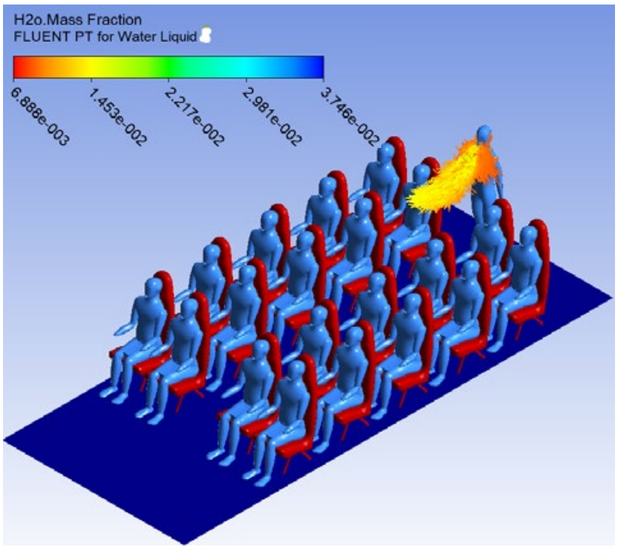


Figure 6. Transmission of the sneezed droplets ▶ during standing.

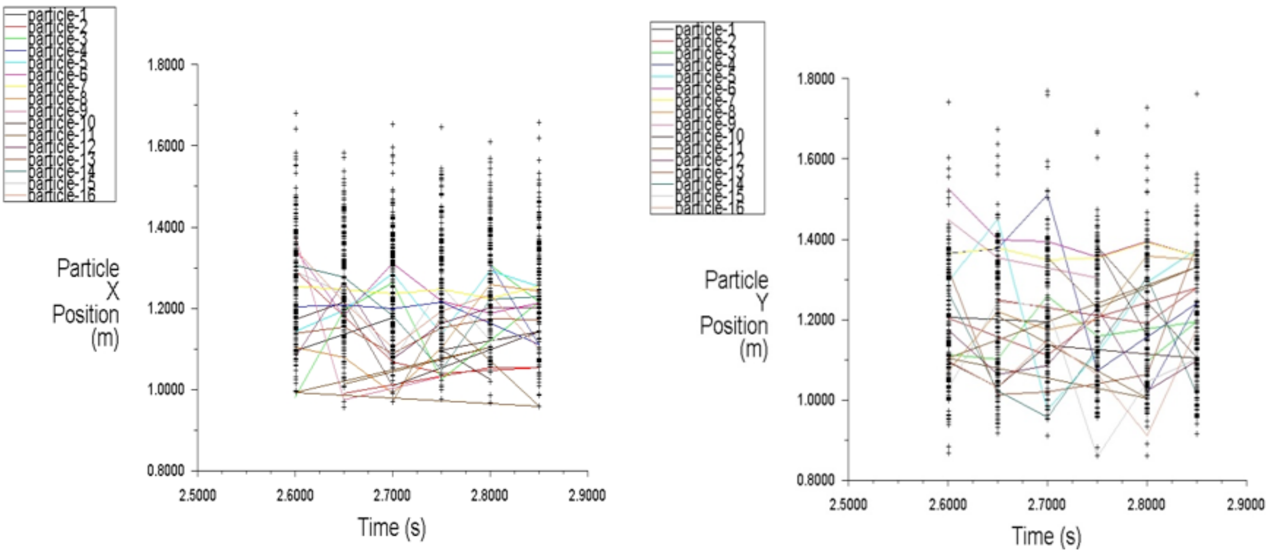


Figure 7. Transmission of the coughed droplets in x- and y-directions during standing.

Photo by Elizaveta Galitckaia / Shutterstock

Case two

Sneezing during Motion

Regarding sneeze during passenger's movement, the moving passenger started to sneeze for 1 second with a velocity of 30 m/s during the CFD simulation as shown in **Figures 8 – 9.** The sneeze droplets were able to take a flight, reach the surrounding passengers directly, and still had the ability to reach other passengers as they were still in the air. Moreover, these droplets spread to 2 m in *x*-direction and 1.5 m in *y*-direction at the end of the simulation process that extended for six seconds.

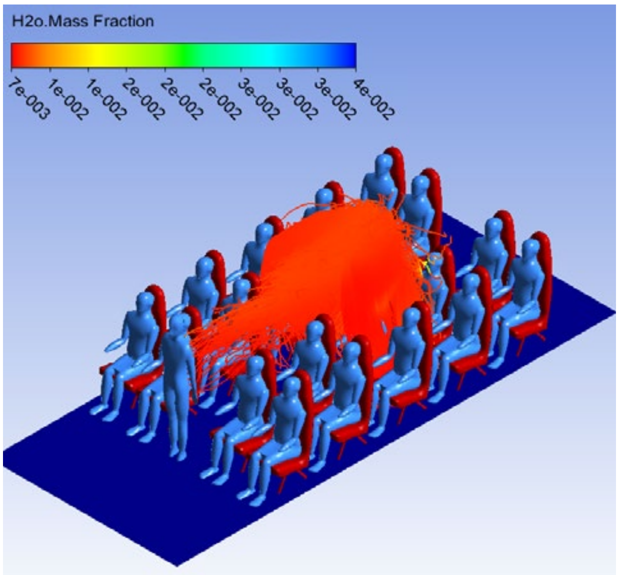


Figure 8. Transmission of the sneezed droplets during motion. ▶

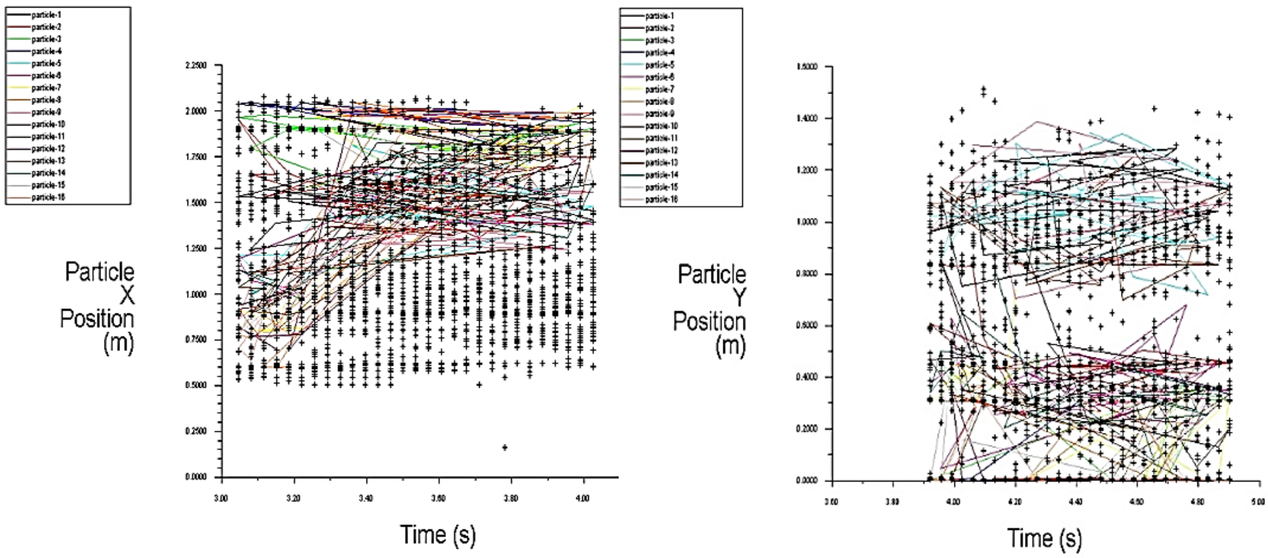


Figure 9. Transmission of the sneezed droplets in x- and y-directions during moving.

Coughing during motion

The moving passenger started to cough after 3.4 seconds of moving up to 3.4 seconds, and the exhalation velocity was 11.5 m/s. **Figures 10-11** shows the same droplets after 6 seconds of the passenger's movement. Moreover, at the end of the injection period that extended for 0.3 seconds, these ranges rose to 1.75 m in *x*-direction and 1.4 m in *y*-direction.

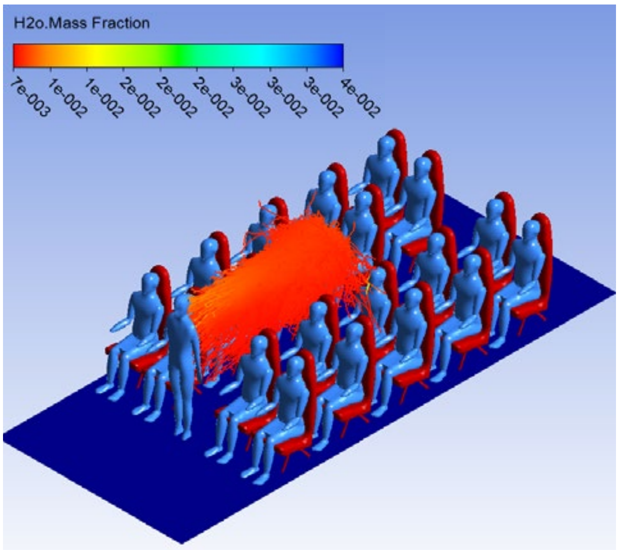


Figure 10. Transmission of the coughed droplets during motion.

Conclusions

Based on the present CFD simulation for the behaviors of the sneezed and coughed droplets that produced from a moving passenger inside the aircraft cabin, the relevant conclusions are as follows:

1. The transmission of the sneezed droplets that were exhaled from the standing passenger could reach the seated passengers in the first and second rows and still have the ability to travel and reach more passengers, while the coughed droplets could travel up to 1.1 meters without any movement from the passenger.

2. During the movement of the passenger with a constant speed, the droplets spread widely inside the aircraft cabin and managed to attacked many passengers inside it.

3. The impacts of the sneezed droplets on the seated passengers were much stronger than the coughed droplets. ■

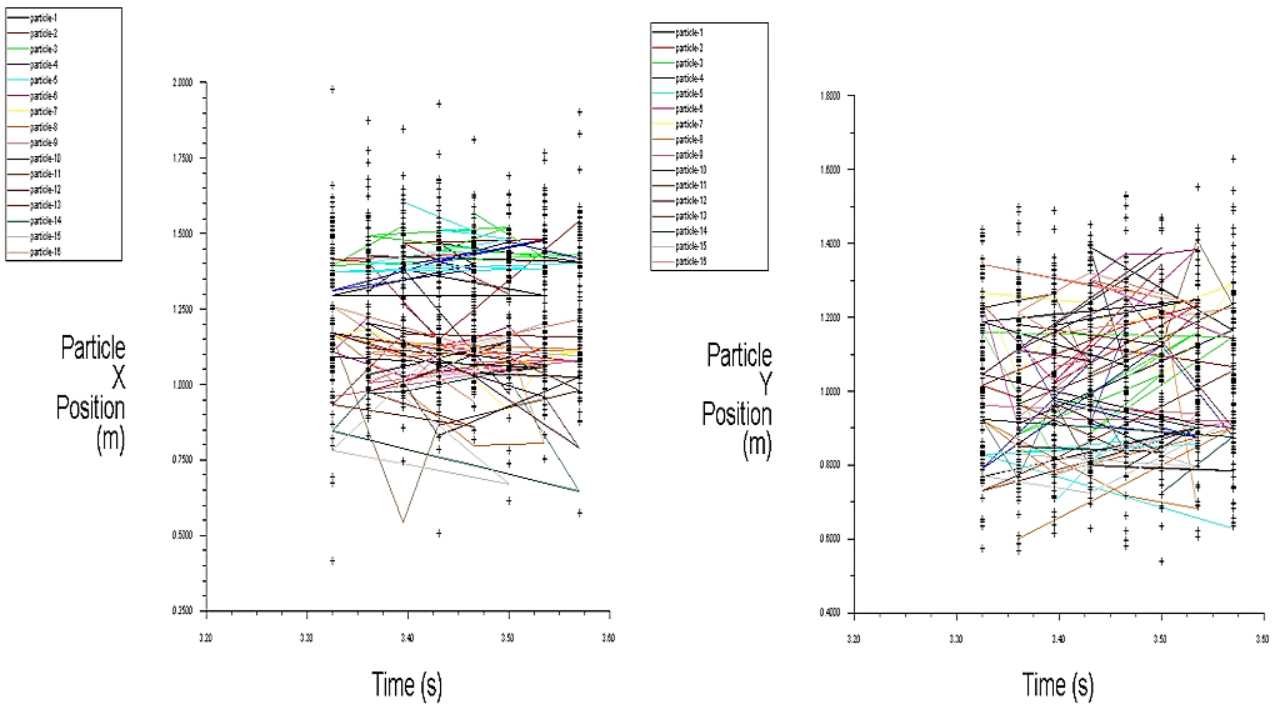


Figure 11. Transmission of the coughed droplets in x- and y-directions during moving

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