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Passenger exposure to respiratory aerosols in a train cabin: Effects of window, injection source, output flow location

Mahdi Ahmadzadeh, Mehrzad Shams

Faculty of Mechanical Engineering, K.N. Toosi University of Technology, Pardis St., Vanak Sq., Tehran, Iran

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ABSTRACT

Nowadays the use of public transportation (PT) has been identified as high risk as due to the transfer of particles carrying the coronavirus from an infected passenger to others. This study puts forward a new computational framework for predicting the spread of droplets produced while the infected passenger talking inside the cabin of a train during various scenarios, including the changes in the outflows’ location and the infected passenger’s position. CFD was used to conduct the study, using the Euler-Lagrange approach to capture the transmission of particles, and Reynolds-averaged Navier-Stokes equations (RANS) to compute the airflow field. The results revealed that opening the window reduces the duration of particles inside the domain. So that when the window is open, the particle’s shelf time can decrease to 25 percent comparing with closed mode. It was found that the passenger sitting next to the infected passenger encountered the highest infection risk. The conclusions made in this work show that the most desirable situation is obtained when the infected passenger is sitting next to the exits, whether the window is closed or open. The results of this paper offer comprehensive insights into how to keep indoor environments safe against infection aerosols.

1. Introduction

Today, humanity around the world is still in the battle against an invisible enemy that knows no boundaries and has increasingly affected the various parts of social and economic life. The severe respiratory viral disease called Covid-19, which results from the SARS-CoV-2 virus. The main route of transmission of this viral infection is through droplets released into the environment through respiratory processes such as breathing, talking, sneezing, coughing, and singing. The typical size range of speaking and cough generated droplets ($d \leq 20 \, \mu m$) allows lingering in the air for O (1 hour) so that they could be inhaled and infected healthy individuals (Vuorinen et al., 2020). Larger droplets carrying viral particles deposit close to the emission source by gravity (droplet transmission), whereas smaller ones follow the airflow, remain suspended in the air for a long time, and distribute meters or tens of meters long distances in the indoor environments (aerosol transmission) and have a long shelf time (Morawska & Cao, 2020). These suspended particles are transported with the airflow in the environment and are the most common cause of people suffering from these particles (Buonanno et al., 2020). COVID-19 pandemic economic impacts on various countries’ economic sectors, including the tourism industry, food and medicine, and trade, have been analyzed more in recent works. For example, (Tang et al., 2021) revealed that the COVID-19 pandemic has a great impact on the consumption expenditure level of various industries and directly affects the public consumption expenditure level in different periods. Thus modifying the physical and built environment is one of the important solutions to reduce a pandemic impact before developing any medication. Anxiety and fear of a pandemic infection, such as COVID-19, have transformed our built environment (Megahed & Ghozneim, 2020). Consequently, assessment and prediction of the virus-laden aerosols dynamics in the indoor environment, specifically in public transportation (PT) as a crowded environment, seems to be a vital solution in order to decrease the mental, social and economic impacts of COVID-19 pandemic. Every year, a large number of people use these systems for transportation, nevertheless, it can be claimed that today PT is one of the sectors that have the greatest impact on the spread of the disease and causes its transmission between different countries and cities in the world. Therefore, it is necessary to reconsider the interactions and the way people travel with passenger PT. The use of facemasks and observing the distance between the occupants are among the first preventive measures (Jayaweera et al., 2020). The distance 1.6–3.0 m has recommended as a safe social distance for aerosol
transmission of exhaled large droplets from talking. However, this distance can be up to over 7 meters for outdoor environments or sneezing and coughing from respiratory activities (Bourouiba, 2020; Sun & Zhai, 2020). Furthermore, Wearing a facemask is an effective, cheap, and easy-to-implement measure especially it is more essential on PT (Chan, 2020). Furthermore, Wearing a facemask is an effective, cheap, and easy-to-implement measure especially it is more essential on PT (Chan, 2020). The other research (Greenhalgh, Schmid, Czypionka, Bassler, & Gruer, 2020) believe that wearing the facemask both in the home, particularly by the person showing symptoms, and outside the home in situations where meeting others is likely (for example, shopping, PT), could have a substantial impact on stopping the transmission chain. Use of the facemask serves primarily a dual preventive purpose: protecting oneself from getting the viral infection and protecting others (Abboah-Offei et al., 2021). In addition, a recent study (Ren et al., 2021) introduces a new and preventative approach, they used a physical barriers with different heights to mitigating COVID-19 infection disease transmission. They found that opening the driver’s window could increase exhaust through the window and door gaps in the back of the bus while opening windows in the middle of the bus could mitigate this phenomenon. (Mesgarpour et al., 2021) performed a novel computational and artificial intelligence framework for the prediction of the spread of droplets produced by sneezing only one standing passenger for different particle sizes in an urban bus. They found out the droplets with
diameters less than 250 micrometers are most responsible for the transmission of the virus. (Zhang et al., 2017) evaluated the performance of different ventilation systems in an aircraft cabin mockup to obtain the local mean age of air, temperature, and velocity distribution under different air distribution systems by using trace gas, thermocouples, and an ultrasonic anemometer measurement system. The results showed that in a comprehensive comparison of mixing ventilation and displacement ventilation, displacement ventilation has high ventilation and heat removal efficiency but it aggravates non-uniformity. They concluded that using a plurality of air inlets could improve the uniformity of air temperature and velocity distribution. Through an analysis of the effects of the dispersion process of respiratory droplets released by coughing of an individual in a fully occupied (by 48 passengers) high-speed rail cabin, (Zhang & Li, 2012) showed that the droplets removal ability is stronger when there is a through-flow from the front door to back. However, in this situation, the droplets can disperse much further and affect more passengers. While these studies provide important insight into factors contributing to transmission rates on PT, detailed analyses are limited to train cabins.

Trains are one of the most common means of PT worldwide, linking them to virus transmission due to the high density of passengers and the lack of strong ventilation. In this study, one of the most common types of train cabins with a capacity of four people is considered. The geometry of the cabin is almost based on the optimized geometry introduced by (Aliahmadipour et al., 2017). Taking into account the seats and other components, the internal volume of the cabin is about 8.2 m³. Here it is assumed that the door is closed also the train resides at the station. Therefore, any effect of train movement has been ignored. Moreover, the sitting position of the passengers (1.4 m height) is considered and tracked virus-carrying droplets released into the domain during the talking of the infected passenger for 10 m. The intake air was modeled to be fresh (i.e. no recirculation) with a relatively high inflow rate of 0.1225 m³/s (T_{inlet}=18 °C and RH = 50%).

The goal of this research is to examine the effects of outflows’ location and injection sources during the close and open window impacts on the spread and transport of the talk-generated small (< 5 μm) particles from an infected passenger in a train cabin. However, there is no study inside a four-capacity train cabin in this field. For turbulent kinetic energy k,

\[
\frac{\partial \rho k}{\partial t} + \nabla \cdot (\rho u_i u_j \frac{\partial k}{\partial x_j}) = \frac{\partial}{\partial x_j} \left( \nu \frac{\partial k}{\partial x_j} \right) - \varepsilon
\]

And for dissipation rate ε,

\[
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\rho \varepsilon u_j) = \frac{\varepsilon}{\kappa} \left( C_1 \frac{\rho k^2}{\rho} - C_2 \varepsilon \right) + \frac{\partial}{\partial x_j} \left( \frac{\varepsilon}{\kappa} \frac{\partial \varepsilon}{\partial x_j} \right)
\]

Where, \( \alpha_k, \sigma_k, C_{1k}, C_2, and C_\varepsilon \) constants. These constants are \( C_k = 0.09, C_\varepsilon = 1.44, C_2 = 1.92, \sigma_k = 1.0, \sigma_\varepsilon = 1.3 \).

Discrete phase: This phase consists of suspended particles and the Lagrangian method has been used to track the propagation trajectory. The aerosol location \( x_p \) is solved by

\[
\frac{dx_p}{dt} = u_p
\]

Where \( u_p \) the aerosol velocity is derived from the balance between inertial forces and external forces applied to the particle.

\[
m_p \frac{du_p}{dt} = \sum F_p
\]

Where \( m_p \) the particle mass and \( \sum F_p \) the result is the forces applied on the particle as calculated below.

\[
\sum F_p = F_{drag} + F_{gravity} + F_a
\]

Where \( F_a \) other additional forces applied on the particle, including the Saffman lift force, the pressure gradient, the mass added the thermophoresis, the Brownian motion effect, and the Magnus. Since the particles are small enough and we do not have severe temperature changes, we consider only the Brownian motion effect and pressure gradient force furthermore, the Saffman lift force may be relatively large near cabins wall for fine indoor particles (Madhavimanesh et al., 2013). The Stokes-Cunningham drag model was used to examine the influence of the drag force in the present model. As a result, the total force on the particle is as follows.


\[ m \frac{du}{dt} = F_{\text{drag}} + F_{\text{gravity}} + F_{\text{aerosol}} + F_{\text{pressure}} + F_{\text{Brownian}} \]  

(12)

In the above equation, the terms on the right-hand side represent the Stokes drag force, gravity/buoyancy force, Saffman lift force, pressure gradient force, and Brownian force respectively. The drag force for submicron size particles \((\text{diameter} = 1 - 10 \, \mu m)\), is set as to:

\[ F_{\text{drag}} = \frac{18\mu_f}{\rho_f d_p^2 C_f} (u_f - u_p) \]  

(13)

\[ C_f = 1 + \frac{2\zeta}{d_p} (1.257 + 0.4e^{-(1.6d_p/2)}) \]  

(14)

\[ m_p = \rho_p \rho_f (\frac{d_p}{d_f})^3 \]  

(15)

\[ F_{\text{aerosol}} = 1.615 \rho_p \sqrt{V_p} \left( u_f - u_p \right) | \frac{du_f}{dy} | \text{sgn} \left( \frac{du_f}{dy} \right) \]  

(16)

\[ F_{\text{pressure}} = -\frac{dp}{dx} \frac{d^2 d_f}{dV} \]  

(17)

\[ F_{\text{gravity}} = (\rho_p - \rho_f) V g \]  

(18)

\[ F_{\text{Brownian}} = m_p G \sqrt{\frac{\pi S_0}{\Delta t}} \]  

(19)

Where, \( C_f \) is Cunningham correction factor (Balachandar & Eaton, 2010) and G represent zero-mean, unit-variance, independent Gaussian random numbers, and

\[ S_0 = \frac{216 \kappa_{\text{Boyle}} T}{\pi^2 \rho_f d_p^2 \left( \frac{d_p}{d_f} \right)^2 C_f} \]

\[ k_{\text{Boyle}} = 1.3806452 \times 10^{-23} J/\text{K} \]

In this phase, a stochastic model accounts for the effect of sub-grid-scale (SGS) flow structures on the aerosols dynamics by adding an eddy fluctuating component to the mean fluid velocity (Bailey, 2017). The stochastic Discrete Random Walk (DRW) model is the most commonly used approach for generating fluid velocity fluctuations. In this model, the generated velocity fluctuations are kept the same for the duration of the eddy lifetime and when the eddy lifetime is finished, a new velocity fluctuation independent of the previous one is produced, thus the generated velocity fluctuations are discontinuous (Mofakham & Ahmadi, 2019). In this model, the fluid velocity at the aerosol location is:

\[ u_f = u_f' + u_f' \]  

(20)

The first term on the right-hand side represents the average velocity of the fluid is obtained by the Reynolds average Navier-Stokes equation (RANS) using the standard \(k-\varepsilon\) turbulence model. In addition to the fluctuating component \(u_f'\) based on the DRW model, is assumed to be isotropic and to follow a Gaussian distribution, which can be obtained by following:

\[ u_f' = \zeta \sqrt{\frac{2\varepsilon}{3}} \]  

(21)

Where \( \zeta \) is a normal random number, which accounts for the randomness of turbulence. In this model, the fluctuating eddy velocity is varying by the length \(L_e\) and the lifetime \(\tau_e\) of the eddy as expressed in Eqs. (22) and (23).

\[ L_e = C_{L_e} \frac{1/2 \rho^{1/2}}{\varepsilon} \]  

(22)

\[ \tau_e = \frac{L_e}{\sqrt{\varepsilon}} \]  

(23)

The time that a particle is in turbulent motion along its trajectory, can be obtained from an integrated time scale.

\[ \tau = \int_0^\infty \langle u_f'(t) \rangle^2 (t + s) \frac{1}{\langle u_f'^2 \rangle} \]  

(24)

The aerosol volume fraction \((\rho_p = \frac{1}{27})\) in the present study is much smaller than \(10^{-6}\), the flow was dilute (Elghobashi, 1994); hence, we utilized a one-way coupling to create coupling between the continuous and particle phases.

### 2.2. Geometry

The geometry details were almost obtained from a real train cabin geometry according to (Ahmadiaipour et al., 2017). The orientation of the domain, the labeled objects (table, passenger, wall, window, inlet, and outlet), and the locations are shown in Fig. 1(a), and the computational grids of the model are shown in Fig. 1(b). The cabin dimensions in the \(x, y, \) and \(z\) directions (i.e., \(L_x \times L_y \times L_z\)) are 1.986 m x 2.48 m x 1.868 m and it contains three inflow fans, which two of them are installed in the plane \(x = 0.21\) m and the other one is installed in the plane \(y = 0.78\) m and three outlets are installed on the aisle wall (at \(x = 1.986\) m). Passengers are sitting in the cabin facing each other (with the distances shown in Fig. 1(a)).

### 2.3. Boundary conditions

The boundary conditions have been illustrated in Fig. 1(a), with the computational domain. The cabin is equipped with three fans is defined as the velocity inlet which pushes down the air into the cabin. While the air goes out from the three outlets at the bottom/top of the airle wall of the cabin. The inlet flow rate is set as 0.1225 m\(^3\)/s and relative humidity is 50%. The turbulence intensity of 10% and the turbulence length scale of 0.015 m are set at the fans for cooled air at 18 °C. Considering the cabin window’s temperature is 30 °C (a summer day), the aisle and ceiling walls’ temperature is 24, 25 °C respectively, and no-slip condition. The remaining surfaces of the cabin are assumed no-slip and adiabatic walls conditions. Four passengers sitting facing together also are represented by rectangular boxes instead of exact three-dimensional shapes to reduce modeling complexity as well as computational costs. Temperatures of the whole body are 36 °C. The mouth has been modeled as a circle slit of diameter 0.03 m. Released droplets from the mouth during talks are accompanied by air gushing out of the mouth at a velocity of 2.5 m/s (Asadi et al., 2019) over a time duration of 300 s. Based on recent numerical and experimental works, it has been determined that particles smaller than 10 microns follow the airflow more than they stick to the boundaries upon contact. For numerical simulations, the particle distribution in this diameter range is modeled on the Weibull function. Furthermore, in the present study, the faces of individuals were examined separately by defining the surface (0.16 m x 0.24 m) on the face of passengers to more accurately assess the risk of infection. For brevity, details of the boundary conditions setup and relevant material parameters are summarized in Table 1.
Fig. 1. (a) Orientation of the domain, the labeled objects and the locations, (b) computational grids of the model and dimensions of the surface defined on the face (marked with a yellow bar); all dimensions in meter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
3. Numerical model

3.1. Simulation

We used ANSYS FLUENT 2020 to simulate the present problem and the Hexa-Cartesian mesh. To coupling between pressure and velocity field SIMPLE scheme and second-order solution, the method has been used. The minimum remaining convergence scale was from the order of $10^{-5}$ for momentum equations and turbulence model, and $10^{-6}$ in solving the flow field. In the present study, first, the continuous phase was solved and then injected the particles by keeping the continuous flow solution constant, and has been performed simulation for 600 s to investigate the spread of particles in the domain.

3.2. Validation

The present numerical model for simulation of particle motion was validated by comparison with (Li et al., 2018). Where two single droplets with sizes 10 and 100 μm at mass flow rates $(5.24 \times 10^{-11}$ kg/s and $5.24 \times 10^{-8}$ kg/s, respectively) and the humidity of 0% in the three-dimensional room $(L \times H \times W = 4 \times 3 \times 2$ m) were used to match the computational conditions. It is assumed that the room temperature is 25°C. As shown in Fig. 2, the predicted time-dependent diameter (solid lines) of droplets expelled by coughing was compared against the theoretical calculations (dot points). A satisfactory agreement was obtained between the numerical results of this study and the data reported in the literature. In addition, it is observed that the present prediction of particle motion is in good agreement with that of (Li et al., 2018). Moreover, we compared the simulation results with a recently numerical study by (Ahmadzadeh et al., 2021) about the transmission of COVID-19 aerosols inside a classroom, after a good agreement, we implemented the solution results.

![Model validation using data of (Li et al., 2018).](image)

3.3. Grid independence

To better analyze the airflow field in the cabin a mesh convergence study was conducted for the airflow velocity and temperature. In this study, four different grid sizes (including 40, 30, 20, and 15 mm) were investigated. Details of the results of the mesh sensitivity analysis and elements number have been presented in Fig. 3. It shows the velocity (first row) and temperature (second row) field in the plane $x = 1.3$ m inside the cabin for different grid sizes. The results using the grid size equal to 20 mm and the 15 are (qualitatively) very similar. Therefore, the grid with size 20 mm was used in all simulations reported below.

3.4. Independence of time step

To test the time step independence, we resolved the problem for time steps of 0.01 s, 0.1 s, and 0.2 s, and then determined the fraction of particles. Fig. 4 shows the results. As shown, the slope of changes between the time steps of 0.01 and 0.1 was lower; hence, we used a time step of 0.1 to simulate particle dispersion with sufficient accuracy in the transient state.

4. Results and discussion

In this section, the simulation results of the different case settings are presented and discussed. Furthermore, due to the symmetry of the flow field inside the cabin, only the injections of passengers 2 and 3 have been investigated. Four different scenarios have been investigated in this study, the details of which are summarized in Table 2. For these scenarios, the window effect (i.e. open and close mode) is separately investigated. Furthermore, for the talking cases, the simulation time has been considered 600 s, with an injection time of 300 s.

This section related to examines the effects of outflows location on the inside domain flow field. As will be seen, the outflows affect the airflow streamlines in the domain, leading to changes in the fraction of suspended aerosols, deposited onto surfaces, and escaped from the domain. Fig. 5 (a)-(d) shows the velocity and temperature distribution contour on plates $x = 0.6$ m and $x = 1.8$ m inside the cabin for the different locations of the outlets including the bottom (left sides figures) and top (right sides figures) of the aisle wall. Figs. 5 (a) and (c) shows the results when the window is closed, while, effects of the open window on the flow field are illustrated in Figs. 5 (b) and (d). In both cases, the field of velocity and temperature have symmetrical conditions and it makes passengers feel the same thermal comfort on both sides. In the case where the outlets are at the bottom the airflow from inlets 1 and 2, travels almost a direct path to the exits and has less effect on the overall cooling of the environment. In contrast, the airflow from inlet 3 plays a significant role in and travels a long distance in the environment to exit, thus this causes the cabin velocity and temperature field to be more affected especially at the right half of the cabin. Despite this when the outlets are installed at the top of the aisle wall, here unlike the previous case, the airflow from inlet 3 has less effect on the flow field of the lower areas, because its output path has been reduced than prior case. This factor leads to low-temperature changes compared to the previous state. Furthermore, as shown, opening the window changes the flow field inside the cabin, which is more noticeable when the outlets are at the top. Even that could be due to leaves the part of the cabin airflows through the window.

The distribution of static temperature around the passengers over the various scenarios is illustrated in Fig. 6 (a)-(d). Comparison figures (a) and (b) with (c) and (d), we could understand the effects of the opening windows. As shown in figures (a) and (c) opening the window has a slight change in the temperature around the people in this case. However, when the outlets are located at the top, the temperature inside the cabin is more affected by the flow of inputs 1 and 2. According to what was discussed in the previous section, as well as due to the location of input 3, with opening a part of the window, a percentage of the flow of
this inlet is out of the window and reduces the cool air of this inlet to the lower parts of the cabin. As a result, in this case, we see a noticeable change in temperature around the body and a relative increase. In addition, by comparing the figures of each row with each other, we can understand the effect of the location of the outputs on the temperature around people. As the results show, the placement of the outlets on top of the wall leads to a decrease in the temperature around the people and it can be stated that this observation is independent of the opening or closing the window. In summary, the flow field inside the cabin when the outputs are at the bottom is more affected by the airflows from input 3, and this flows after leaving and exchanging energy with different surfaces of the cabin (such as the window surface at 30°C, the ceiling at 25°C and the bodies at 36°C) at different temperatures, depending on its position, lose their original coolness and lead to people feeling warmer in this state. On the other hand, when the outlets are at the top, almost all airflows from input 3 leave the environment immediately after entering the cabin and exchanging energy only with the window and ceiling surfaces and has a small chance of being present in the lower areas. In this case, the temperature and the airflow are mostly dominated by the inlet 1 and 2 flows. In addition, as mentioned, the effect of the location of the outlets on the temperature distribution around people when the window is opened should not be ignored. Especially when the outlets are at the top.

Fig. 7 shows the flow streamlines inside the cabin at horizontal (y = 1.5 m) and vertical (x = 1 m) planes. When the outlets are located, at the bottom of the aisle wall (left side of Fig. 7), the airflow is more scattered and this causes strong recirculation zones above the passengers’ heads region, mostly from the left side of the cabin to the right side. This causing deposition of particles to occur near these regions. However, with located the outlets at the top of the wall (right side of Fig. 7), most of the inlet 3 airflows exit from the outlets. In this case, it can be seen that the formation of symmetrical eddy zones that are mostly affected by airflows of the inlets 1 and 2. We can see that the recirculation zones form on both the vertical plane and the horizontal plane. These streamlines are different by moving the position of the outlets, which is expected since the flow field is completely different in these two cases (as shown in Fig. 5).

Fig. 8 shows a comparison between the path-lines of fan 3 inside the cabin. As illustrated, in scenario 1 (left sides) since the outflows are located at the bottom, airflow as soon as the exit from fan 3, move toward the ceiling then arrive at the aisle wall finally leave the cabin by moving down. As a result, the rotation of the airflow inside the cabin will be more and its durability will be higher. In contrast, in scenario 2 (right side), the airflow immediately exits the outlets when it reaches the ceiling and has less opportunity to rotate inside the domain. In addition, these factors affect the formation of vortex areas (recirculation zones) and their differences in the last two modes. Moreover, when the window is opened, we see a decrease in path lines, due to the exit part of the airflows that. In general, it can be concluded that the airflow streamlines

![Fig. 3. Mesh sensitivity analysis for different grid sizes and elements number in the plane x = 1.3 m. Top row: airflow velocity field. Bottom row: airflow temperature field.](image_url)

![Fig. 4. Time step analysis.](image_url)

**Table 2**

Summary of the investigated scenarios.

| Injector passenger | Location of the outflows on the aisle wall | Scenario |
|--------------------|------------------------------------------|----------|
| 2                  | Bottom                                   | 1        |
| 2                  | Top                                      | 2        |
| 3                  | Bottom                                   | 3        |
| 3                  | Top                                      | 4        |
Fig. 5. Flow field contours in planes $x = 0.6$ and $1.8$ m, left side: Outlets located at the bottom, and right side: Outlets located at the top, (a) and (b) velocity distribution when the window is closed and opened respectively, (c) and (d) temperature distribution when the window is closed and opened, respectively.
inside a domain significantly affect the transport and spread of the aerosols. In addition, the presence of any objects (such as tables and even the bodies of passengers), which can obstruct the flow of the inlets, will alter the streamlines drastically (specifically in small environments such as cabin trains). Obstructing the airflows would lead to recirculation zones near these objects, which can cause significant deposition and suspension of aerosols near those objects. In contrast, regions that are free from such objects do not experience significant deposition. Hence, deposition here is being affected more by the change in the airflow streamlines due to the geometry and the multiple airflow outlets.

4.1. Closed window effect

In this section, to clarity evaluate the spread of particles; we examined particle tracking for 300 seconds injected into the domain. According to the results, due to the high rate of inlet airflow and the effect of outflows’ location, more than 99% of the particles are assigned up (trap, suspend, escape) to 180 s after the end of the injection (i.e. within 480 s). Fig. 9 (a)-(c) show the results of the spread of the particles in the domain when the window is closed for different times and scenarios. The fraction of the trapped particles in the domain over time is illustrated in Fig. 9 (a). According to this figure, the fraction of trapped particles increases with time, which is expected, but what is important is that the trend of change remains constant from around 60 s after the end of the injection in all four scenarios. As shown, among the scenarios, scenarios 3 and 2 show the highest and lowest fraction of trapped particles, respectively (percentages corresponding to the end of injection are shown). Details of the fraction of escaped particles from outlets for different times are given in Fig. 9 (b). In addition, by evaluating the effects of the injection source and the position of the outlets, we see that placing the virus-infected person next to the window relative to sitting next to the outlets has increased the escaped particles at the same time (comparison between scenarios 1 to 3 and 2 to 4). Comparing scenarios 1 to 2 or 3 to 4, we conclude that placing the outlets on top of the aisle wall improves the particle exit process. This is due to the nature of the aerosols (their very small mass), which move upwards immediately after injection into the environment and travel less distance to exit under the influence of inlet 3 airflows than scenarios 1 and 3. Moreover, Fig. 9 (c) illustrates the trend of suspended (in fluid) particles’ fractions over time. As shown, the trend of variations is about the same for all scenarios. The fraction of suspended particles in the domain is incremental for about the first 60 s of injection but then decreases as the particles are completely affected by the airflow. Perhaps one of the important points about this behavior is the difference between the peak points of scenario 2 and the other three scenarios. The reason for this difference can be attributed to the higher fraction of particles trapped and escaped during this scenario (meaning that up to 60 s more particles are either trapped on surfaces or escaped from the environment during this scenario as presented in Fig. 9 (a) and (b)). For a better comparison among the scenarios, the results of the fraction of trapped and escaped particles inside the domain in the 300th second have been reported by the vertical dotted line in Fig. 9 (a) and (b). This line is a comparison boundary between before and after the end of the talking and shows particles’ status as soon as starting the talking until ending it during different scenarios. Therefore, according to the results presented in this figure and the above explanations, it can be concluded that among the scenarios discussed, scenario 2 has a better performance in terms of the fraction of escaped and suspended particles than other scenarios, and in contrast, scenario 3 has poor performance. Fig. 10 illustrates the aerosol-cloud profiles at eight instances of time (60–480 s) inside the cabin for different scenarios, while the window is closed. This shows a comparison of how aerosol-clouds are distributed and transmitted inside the cabin. As can be seen in scenarios 2 and 4, most of the particles move upwards after leaving the infected person’s mouth, and most of them accumulate above the passengers’ heads. Nevertheless, in scenarios 1 and 3, depending on the position of the outlets, more particles tend to move down the cabin, especially in scenario 3, and this increases the likelihood of others getting sick.

![Diagram](image-url)
To understand the risk of infection in healthy individuals, the fraction of particles deposited on the face of individuals are compared in different scenarios in Fig. 11. This information was obtained with the help of surfaces defined in people’s faces. These surfaces played an important role in accurately assess the results related to the risk of healthy passengers in this study because the faces (mouth, nose, and eyes) of individuals are one of the main ways in which the virus enters the respiratory system. As can be seen, in all scenarios, the highest fraction of deposited particles is related to the infected person and then the passenger next to that, respectively. In addition, according to the flow patterns that occur during the scenarios, it is concluded that located the outlets at top of the aisle wall (i.e. scenarios 2 and 4) increases the risk of infecting other people.

4.2. Opening window effect

In Section 4.1., the spread and transmission of particles in lack of the open window effects were examined. Here, we will discuss how the trends (aerosol deposition, airborne aerosol numbers, and aerosol removal) change when the cabin’s window is opened for the same scenarios. In this mode, the open window is playing a second path to escape the particles and directly affect the domain airflows. Consequently, in the same previous section, we examined particle tracking for 300 seconds injected into the domain. In addition, the results of distribution and transmission of the particles inside the domain are presented in Fig. 12 (a)-(c). Fig. 12 (a), illustrates the variation of the fraction of the trapped particles for different scenarios over time. As shown, the fraction of trapped particles increases over time, as expected, but the slope of the variations is greater in the first 60 seconds; this behavior can be due to the nature of the aerosol particles. Due to their small mass, the particles tend to move upwards as soon as they are injected and disperse in different areas after being affected by the airflow. While after the injection is timed up the slope of variation due to the exit or deposited particles is decrease and 60 seconds after the last injection the slope is almost zero. Moreover, among the scenarios, scenarios 1 and 4 show the highest and lowest fraction of trapped particles; respectively within the 300 seconds, (percentages corresponding to the end of injection have been shown by the vertical dotted line). Details of the fraction of escaped particles from outlets overtimes are given in Fig. 12 (b). As can be seen, opening the window and the location of the outlets affected the particle exit process. One of the interesting points is the reduction of the range of variation of the escaped particles in this case to the previous case. As the percentages reported in the 300th second show, the difference between the highest (scenario 3) and the lowest (scenario 4) escaped particle fractions is about 6.4%. Therefore, it can be mentioned that by opening the window, the process of changes in the fraction of particles escaping from the domain is very similar in all scenarios. A comparison of the fraction of particles suspended (in fluid) inside the cabin during the scenarios is illustrated in Fig. 12 (c). As shown, the trend of variations is about the same for all scenarios. In the same previous section (closed window case), the fraction of suspended particles in the domain is incremental for about the first 60 seconds of injection but then decreases as the particles are completely affected by the airflow. Perhaps one of the important points about this behavior is the difference between the peak points of scenarios. This point indicates within scenario 3 is faced with the lowest suspended particles than other scenarios. The reason for this difference can be attributed to the higher fraction of particles trapped and escaped during this scenario (meaning that up to 60 s more particles are either trapped on surfaces or escaped from the environment during this scenario as presented in Fig. 12 (a) and (b)). As can be seen in this figure, changing the injection source does not have much effect on these peak points (with comparison scenarios 1 to 3 or 2 to 4). Whereas, changing the position of the outlets has a significant effect on the peak points of suspended particles fraction, especially between scenarios 3 (16%) and 4 (64%). In addition, in scenarios 1 and 3, almost all particles (more than 99%) are assigned around the 360th second, while, in scenarios 2 and 4, particles are assigned about 120 seconds after the injection is completed (420th second). Therefore, according to the results presented in this figure, it can be concluded that among the discussed scenarios, scenario 3 has a better performance in terms of the fraction of escaped and suspended particles than other scenarios, and in contrast, scenario 4 has poor performance. Fig. 13 illustrates the aerosol cloud profiles and their spread tend at eight instances of time (60–480 s) inside the cabin for different scenarios with the open window effect. This helps to assess how aerosol-clouds are distributed and transmitted inside the cabin during different scenarios. As shown in scenario 1 the aerosol-cloud affects the passenger next to the infected person more than the passengers in front. This refers to the effects of window airflows and the location of the outlets, we can point that the particles are often scattered on the side of the infected person and the amount of particle scattering inside the domain reduces compared to the same scenario when the window is closed (Fig. 10). In addition, in scenarios 2 and 4, as illustrated, the effects of the outlet location and open window on the aerosol-cloud lead to the scattering of particles almost whole the domain. Another important effect of an open window can be seen in how the particles are dispersed in scenario 3. As shown in Fig. 13, as soon as the particles leave the infected person’s mouth, affected by the window, the cabin airflow move to the outlets’ side (bottom) as result have less opportunity to disperse throughout the domain. By comparing Figs. 10 and 13, we can understand the open window plays a crucial role in this scenario. In addition, the results of Figs. 9 and 12 confirm this performance.

In a similar previous section, to understand the risk of infection in healthy individuals, the fraction of particles deposited on the face of individuals have been compared in different scenarios in Fig. 14. This
information was obtained with the help of surfaces defined in people’s faces. According to this, in all scenarios, the highest fraction of deposited particles is related to the infected person then the passenger next to that, respectively (similar to the previous section). As shown, according to the flow patterns that occur during the scenarios, it is concluded that the risk of infecting other passengers in scenario 1 is more than others. Furthermore, in scenario 3, we see the lowest risk of infecting healthy individuals.

4.3. Investigating the window effect

In two previous sections, we separately discussed the closed and open window effects on the spread and transmission of aerosol particles released from an infected passenger in specified scenarios. Furthermore, the lowest and highest infection risk scenarios to other individuals in each case were presented. To better assess the window effect, in this section the trends change in these cases (aerosol deposition, airborne aerosol numbers, and aerosol removal) will be compared. Fig. 15 (a)-(c), shows this comparison, solid line and dashed line indicate the closed and open window variations over time for different scenarios, respectively.

As shown, the overall particle fraction variations are almost identical in all figures. In the first 60 s, all three parameters i.e. the trapped, escaped, and suspended particles fraction are increasing with a steep slope. Then the particles are accompanied by the inside airflow and in addition to scattering in the environment, they move towards the outlets, which causes a decrease in the slope of the variations in figures (a) and (b), as well as a negative slope in the variation of figure (c). The important point here is that by opening the window the amplitude of variations in the fraction of the trapped and escaped particles decrease for different scenarios. This difference is shown in figures (a) and (b) after the change process has reached a fixed approach. As can be seen, after assignment about 99% of the particles, the fraction of particles trapped on different surfaces by opening the window has been changed only 4%, while in the closed case the range of changes for different scenarios is up to 38% has been increased. This difference implies that by opening the window, the effect of the injection source and the outlets’ location on the fraction of trapped particles at different levels can be ignored. In the next figure, we see a reduction in the range of variations from 39% in closed window mode to 5% in open window mode. Therefore, it can be stated that the fraction of particles escaping from the environment during the opening

Fig. 8. Path line inside domain from fan 3; left side: Outlets located at the bottom, and right side: Outlets located at the top, (a) closed window mode, (b) open window mode.
of the window is independent of the injection source and the location of the outlets. The important point in this comparison is that by opening the window, the fraction of particles leaving the cabin during all scenarios is higher than scenarios 1 and 2 in the closed window mode, and this reduces the risk of other passengers. One of the most important parameters in choosing the best and worst situation in terms of the risk of the infection is to study and compare the fraction of suspended particles in the air inside the cabin. So that the shorter the shelf life of the particles in the environment, the less likely it is that healthy people will be infected. This comparison is shown in figure (c) for a more detailed study of the effect of open and closed windows on the durability of particles. As can be seen, by opening the window in scenarios 1 and 3 after a period of 360 s (60 s after the infected person stops talking), the fraction of suspended particles reaches below 1%, while in the case of the closed window, the time for the same scenarios is 480 s. Another noteworthy point is the percentage of particles suspended at the peak point. As shown, by opening the window, the fraction of suspended particles during scenario 3 in the 60 s after the injection has reduced from 64% (for closed window mode) to 35%. In addition, all these issues...
Fig. 11. Fraction of the particles trapped on passenger’s faces for different scenarios.

Fig. 12. Comparison of the trend of the released particles during talking over time in different scenarios: (a) aerosols deposited fraction, (b) aerosols removed fraction, and (c) aerosols suspended fraction.

Fig. 13. Aerosol cloud profiles at eight instances of time (60–480 s) inside the cabin for different scenarios: (a) scenario 1, (b) scenario 2, (c) scenario 3, and (d) scenario 4.
In addition, to determine more accurately the risk of infection during different scenarios, in Fig. 17 we have examined the fraction of deposited particles on the face of healthy passengers (i.e. the face of all people except the face of an infected passenger). As can be seen, in scenarios 2 and 4, there is not much difference in whether the window is open or closed. This is while the results are significant for the open and closed window mode during scenarios 1 and 3. By opening the window, the fraction of deposited particles on the face of individuals during scenario 1 has increased 64% (from 0.14% to about 0.39%). However, by shifting the injection location from the side of the window to near the outlets (scenario 3), the deposited particle fraction decreases from 0.18% to 0.05% (72%) as the window opened. These results indicate that during scenarios 2 and 4, the effect of the window can be ignored. However, the effect of opening a window is more evident during scenarios 1 and 3.

5. Conclusion

Currently, protection against COVID-19 and the development of risk assessment plans play a key role in community health and well-being. Understanding the patterns of virus spread and their related parameters is one of the main issues. Importantly, there is a vital need for the

![Figure 14](image1.png)

Fig. 14. Fraction of the particles trapped on passenger’s faces for different scenarios.

![Figure 15](image2.png)

Fig. 15. Comparison of the trend of the released particles during talking over time in different scenarios: (a) aerosols deposited fraction, (b) aerosols removed fraction, and (c) aerosols suspended fraction.

![Figure 16](image3.png)

Fig. 16. Comparison of particle deposition on the face of individuals over various scenarios.
quick assessment of transmission risk in high-occupancy indoor environments such as public transportation. To address this issue, numerical simulations of the airborne dispersion of novel coronavirus-carrying droplets released from the infected passenger is talking inside a train cabin were performed to identify the transmission mechanisms and to assess strategies to reduce infection risk. In the simulations, were investigated the effects of the open and close windows as well as outflows’ locations and infected passenger sources in a four-capacity train cabin with three velocity inlets and three outlets. To observe the thermal comfort of the passengers and the rapid departure of particles, the inlet flow rate has been considered with a high-reliability coefficient. The results revealed that due to the high rate of inlet airflow and the effect of outflows’ location, more than 99% of the particles are assigned to (trapping, suspension, escape) 180 s after the end of the injection (i.e. within 480 s), whereas, with opening the window this time can be reduced to 360 s. The results of this study provide guidelines to set a new protection plan in public transportation, especially in trains, to prevent airborne transmission of novel coronavirus-laden droplets to passengers. In addition to this, the following outcomes emerged from this work.

1. As soon as the injection is completed (i.e. after five minutes), in the open window mode, 3.5% of the aerosols are suspended in the best and worst conditions, respectively.

2. At the first 60 s, with opening the window the fraction of suspended particles decreases up to 40% compared with the closed window mode.

3. The results indicate that within 3 minutes after the falling, the final status of almost all particles, including deposition, suspension, and escape is determined.

4. The location of the infected person plays an important role in infecting healthy passengers, especially in small environments such as train cabins.

5. The results indicate that in opening window mode, sitting the infected person near the exits and the outlets have located at the bottom of the wall, we see an 87% reduction in the risk of infecting healthy passengers.

6. According to these results, the highest fraction of particles deposited on the face of individuals after the injector is related to the passenger sitting next to that.

7. In closed window mode, by changing the location of the outlets from the bottom to the top, the fraction of particles trapped on the faces reduces about 35%.

8. Among the whole scenarios, when the window is open and the injector sits near the outlets furthermore the outlets located at the bottom of the aisle wall, healthy individuals are encountered with at least infected risk.

9. In the closed window case, the desirable mode in terms of the particle deposited fraction on healthy passengers’ faces is when the injector sits near the window, and the outlets have located at the bottom.

**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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