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Jet Fans in the Underground Car Parks and Virus Transmission

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ABSTRACT

Jet fans are increasingly preferred over traditional ducted systems as a means of ventilating pollutants from large spaces such as underground car parks. The spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) -which causes novel coronavirus disease (COVID-19)- through the jet fans in the underground car parks has been considered a matter of key concern. A quantitative understanding of the propagation of respiratory droplets/particles/aerosols containing the virus is important. However, to date, studies are yet to demonstrate the viral (e.g. SARS-CoV-2) transmission in the underground car parks equipped with jet fans. In this paper, the numerical simulation has been performed to assess the effects of jet fans on the spreading of viruses inside the underground car parks.

Keywords: Air circulation; Car Park; COVID-19; Jet fans; OpenFOAM; SARS-CoV-2

1. INTRODUCTION

Since December 2019, novel coronavirus disease (COVID-19) has become a major concern for the global population. It has led to 1,092,144 deaths worldwide as of October 15, 2020 [1]. It simulated the clinical course of infection with two previously reported human coronaviruses – including severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV) which was named severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) by the Coronavirus Study Group of the International Committee on Taxonomy of Viruses [2]. Studies have reported that severe acute SARS-CoV-2 spreads mainly through respiratory droplets and aerosols [3-7]. These respiratory droplets can be exhaled during coughing, sneezing, or even talking [8].

The increase in mortality rates of COVID-19 has evoked scientists to evaluate all aspects of viral transmission. Considering the characteristics of respiratory droplets/particles/aerosols transmission on the wind condition, there will be a large number of viruses within an underground car park when a confirmed case sneezes near the jet fan. Underground car park ventilation will cause cross-infection through respiratory droplets/particles/aerosol

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transmission among people if appropriate design were not taken. However, underground car park design and viruses' control has rarely been studied directly.

The jet fan ventilation system has been developed to ventilate the underground car parks for carbon monoxide (CO) removal during the normal condition as well as smoke extraction in the emergency scenario such as fire [9-12]. Under normal condition, jet fans can spread the sneeze-originated respiratory droplets in the airflow direction and increase the risk of viral transmission increases. In this regard, the number of people in underground car parks and jet fans velocity plays a key role in the risk of viral transmission.

A comprehensive review of COVID-19 transmission via respiratory droplets was conducted by Carelli [13], Drossinos and Stilianakis [14], Chen [15], and Chen *et al.* [16]. Sun and Zhai [17] analyzed the infection probabilities of COVID-19 via large respiratory droplets and recognized 1.6–3.0 m as a safe social distance. Dbouk and Drikakis [18] numerically studied airborne droplet transmission during coughing. They found that respiratory droplets could travel unexpected considerable distances depending on the high-speed wind conditions. Dbouk and Drikakis [19] also demonstrated that respiratory droplets from coughing or sneezing traveled a distance less than 2 m in the case of zero-wind conditions. Bourouiba [20] found that expelled respiratory droplets during human sneezing could travel up to 7–8 m at 36 km/h - 108 km/h wind speeds. Various researchers recommended the use of face masks in the public environment, and some of them believed that social distancing of 2 m may not be adequate during the COVID-19 outbreak [21].

Infection control and prevention depend on disrupting the transmission of pathogens (viruses) from the infected human to a new human. Understanding routes of disease transmission and how it contributes to the spread of viruses allows for the identification of effective prevention and control measures. The transmission of viruses can be divided into the following five main routes: direct contact, fomites, aerosol or airborne, oral, and vector-borne. Surprisingly, the SARS-CoV-2 pathogens may be transmissible through unexpected daily activities, for example, the turbulent flow induced by toilet flushing [22], the male-oriented urinals [23], and exhausted aerosol from the cleanroom heating and ventilation conditioning systems [7]. Transmission via each of these three routes is important and depends on various factors (e.g. the particle distribution, the turbulent intensity, the humidity, and the temperature). Among these, SARS-CoV-2 mainly has airborne transmission potential [24]. Continuous airflow of jet fans can increase the transmissibility of virus-containing droplets/particles/aerosols in the underground car parks. A better understanding of how respiratory droplets/particles/aerosols spread due to the continuous airflow of jet fans may provide insight that contributes to mitigating SARS-CoV-2. To the best of our knowledge, the problem of spreading viruses in underground car parks has not been investigated previously. All previous works of literature focused on the CO control. The main aim of our work is to present predictions of the respiratory droplets/particles/aerosols spreading resulting from the continuous airflow of jet fans. This helps investigators gain a deep understanding of the behavior of complex air flows inside the underground car parks, which are engaged with the dynamics of viruses. The simulations were carried out at a low-speed of jet fans (daily applications or normal condition) with various configurations of the sneeze source. Finally, we suggest six tips to reduce the risk of infection through respiratory droplets transmission during the use of the jet fan air conditioning system in the underground car parks.

2. KEY ISSUE OF JET FAN AIR CONDITIONING SYSTEMS WITHIN THE UNDERGROUND CAR PARKS IN THE COVID-19 SITUATION

The ventilation system in the underground car parks consists of jet fans, fresh air ducts and exhaust ducts, CO detection sensors, and a control panel [25]. This system -which operates in a similar way to a ducted system- is based on placing a set of axial impulse fans all along the underground parking area. When jet fan conditioning system is installed on the ceiling, it moves the air towards the exhaust ducts by effectively creating a continuous flow and impeding the creation of stagnant zones. Therefore, the jet fan system -with continuous flow- can easily spread the viruses inside the underground car parks. For example, when an infected person sneezes near the jet fan, the respiratory droplets/particles/aerosols spread through the jet fan system. **Figure 1** represents the schematic view of the computational domain, including the fresh air ducts, exhaust ducts, and the configuration of the jet fans, and we assumed four different locations as the sneeze sources inside the underground car parks. The spreading patterns of the viral particles after a human cough or sneeze near the jet fan have been demonstrated in **Figure 2**.

3. FORMULATION OF THE JET FAN FLOWS IN THE UNDERGROUND CAR PARKS

The ventilation process of underground car parks involves continuous incompressible form of the air, in a process of jet fan fluid flow. To track the viral dynamics, we applied the Reynolds Averaged Navier-Stokes (RANS) method for the modeling of interactions between jet fan fluid flow and created respiratory particles. The jet fan flows turbulent effects are modeled using the Reynolds-averaged form of equations (1-3) are called RANS equations along with the standard $k - \omega$ turbulence model. In addition, the transmission of respiratory droplets/particles/aerosols containing the virus under the action of jet fans is tracked by the discrete phase model (DPM), which is a Lagrangian tracking approach [26].

A. RANS MODEL

The relevant equations of motion are the continuity equation, the momentum conservation law, and temperature equation in their incompressible form, respectively represented as [27]:

$$\frac{\partial}{\partial x_j} (\rho u_j) = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} [\mu (\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})] + \frac{\partial}{\partial x_j} (-\rho u_i' u_j') \quad (2)$$

$$\rho C \frac{DT}{Dt} = \nabla \cdot (k \nabla T) + \frac{1}{2} \tau : (\nabla u_i + \nabla u_j^T) \quad (3)$$

Where p , u , and T are the pressure, the fluid velocity, and the temperature of fluid, respectively.

B. DISCRETE PHASE MODEL (DPM)

The DPM is adopted in this paper to simulate the virus particle movement under the effect of continuous airflow of jet fans within the underground car parks. Recently, Dbouk and Drikakis [18], Li *et al.* [22], and Wang *et*

al. [23] used this model to simulate a human cough-induced particle movement, turbulent induced toilet flushing, and urinals transmissions, respectively. The flow pattern of a particle is calculated from the following equation [28]:

$$\frac{du_p}{dt} = F_D (\bar{u} - \bar{u}_p) + \frac{g(\rho_p - \rho)}{\rho_p} + F_{Brownian} + F_{Saffman} \quad (4)$$

Where d is the diameter of the sneezed respiratory droplets/particles carrying viruses between $1 \mu\text{m}$ and $13 \mu\text{m}$; The resulted Stokes drag force equation is adopted to calculate F_D as follows [29]:

$$F_D = \frac{18\mu}{d^2 \rho_d C_c} \quad (5)$$

Where the Stokes-Cunningham slip coefficient C_c under atmospheric conditions is calculated to be from the following equation [30]:

$$C_c = 1 + \frac{2\lambda}{d} (1.257 + 0.4e^{-(1.1d/2\lambda)}) \quad (6)$$

Where λ is the molecular mean free path of the gas. In addition, because of the size of the respiratory particles, the Brownian force and Saffman lift force are taken $F_{Brownian}$ and $F_{Saffman}$, respectively. The components of the Brownian force are modeled as a Gaussian white noise process with spectral intensity $S_{n,ij}$ given by [31,32]:

$$S_{n,ij} = S_0 \delta_{ij} \quad (7)$$

Where δ_{ij} is the Kronecker delta function, and

$$S_0 = \frac{216\nu\sigma T}{\pi^2 \rho d_p^5 \left(\frac{\rho_p}{\rho}\right)^2 C_c} \quad (8)$$

T is the absolute temperature of the fluid, ν is the kinematic viscosity, and $\sigma = 1.38 \times 10^{-23}$ is the Stefan-Boltzmann constant. Amplitudes of the Brownian force components are of the form [32]:

$$F_{Brownian} = \xi_i \sqrt{\frac{\pi S_0}{\Delta t}} \quad (9)$$

Where ξ_i are zero-mean, unit-variance-independent Gaussian random numbers. The amplitudes of the Brownian force components are evaluated at each time step.

C. SAFFMAN'S LIFT FORCE

The Saffman's lift force can be defined as follows [32]:

$$F_{Saffman} = \frac{2K v^{1/2} \rho d_{ij}}{\rho_p d_p (d_{ik} d_{kl})^{1/4}} (\vec{u} - \vec{u}_p) \quad (10)$$

Where $K= 2.594$ and d_{ij} is the deformation tensor as well as d_{ik} and d_{kl} .

4. NUMERICAL TECHNIQUE AND BOUNDARY CONDITIONS

The open-source field operation and manipulation (OpenFOAM) for computational fluid dynamics (CFD) software package version 5 was used to perform the numerical simulations. The OpenFOAM codes were written in C++ programming language using the finite-volume numerical technique to solve the conservation of mass, energy, and momentum along with the equation of state in their Reynolds-averaged form [33,34]. The second-order upwind scheme was used to handle the convective terms. The Gauss-linear second-order approach was employed to address the diffusion terms. The Pressure-Implicit with Splitting of Operators (PISO) algorithm was applied to couple the pressure and the velocity. The under-relaxation factors for the pressure, momentum, and energy equations were 0.7, 0.7, and 0.6, respectively. In addition, the minimum residuals for convergence of pressure, velocity, and temperature were 10^{-10} , 10^{-11} , and 10^{-12} , respectively. In order to simulate the particle movement during the normal condition of jet fans within the underground car parks, two assumptions were adopted in this article: (1) the generation of the respiratory particles is ignored, (2) The size and other physical properties of the respiratory particles remain constant during simulation.

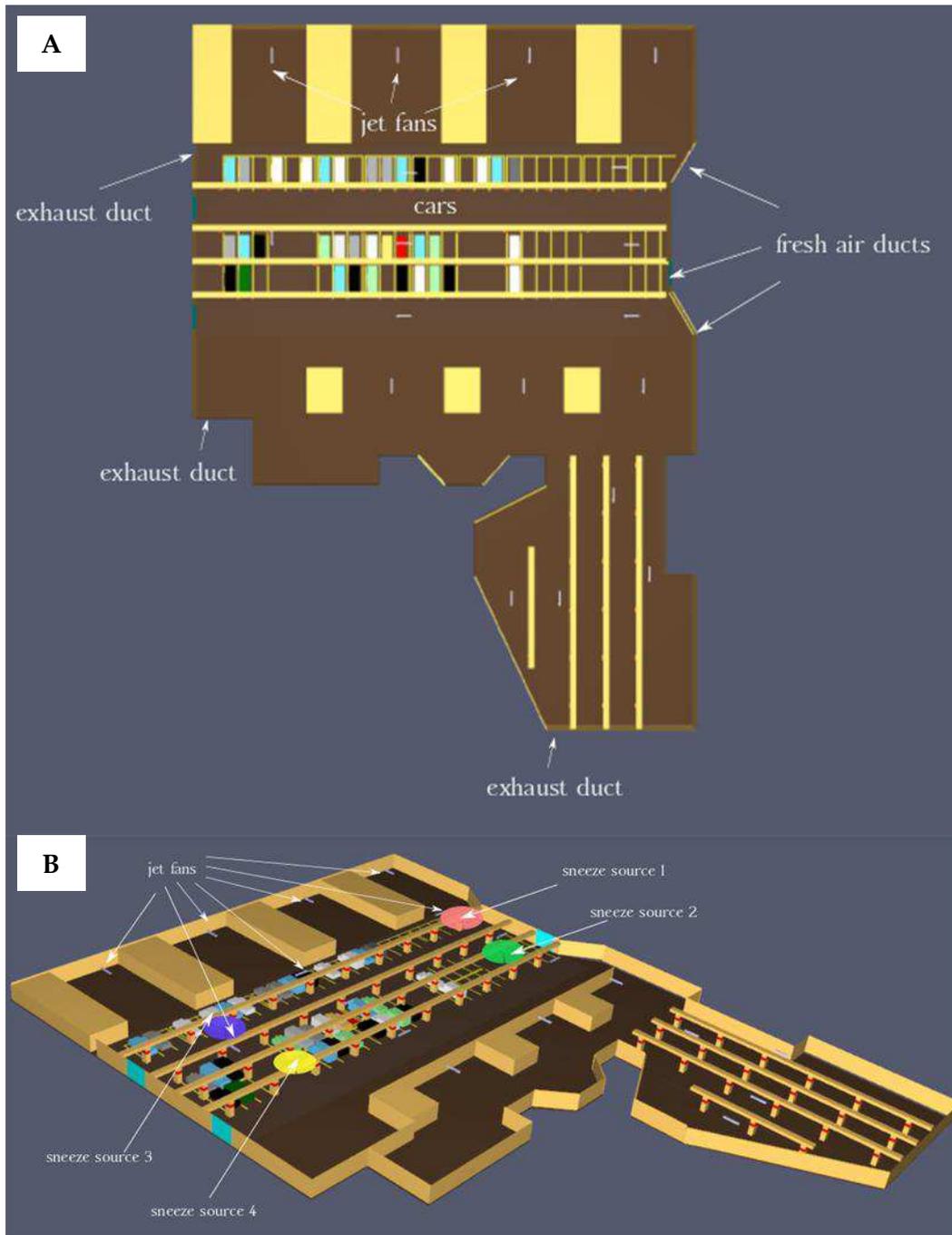


Figure 1. Schematic view of the underground car parks containing fresh air ducts, exhaust ducts, jet fans, and cars (A) and locations of the sneeze sources (B).

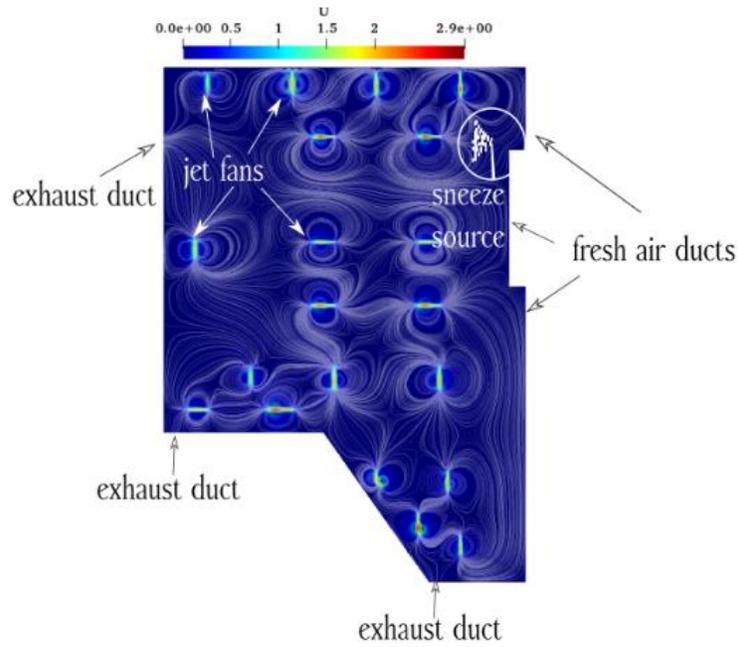


Figure 2. Schematic view of the created streamline due to the continuous jet fan air flows and sneeze sources.

The fixed-value and fixed-flux pressure conditions are imposed at the fresh air ducts. The outlet-inlet is employed to model the exhaust ducts. Our case study can control CO by jet fans within the underground car park without the air circulations. Afterward, we focus on the viruses spreading inside the car park.

5. VALIDATION OF RESULTS

Figure 3 demonstrates the comparison of our data with the experimental visualizations presented by Collela *et al.* [35] for the two-dimensional numerical simulation of the discharged velocity for the jet fans. The discharged airflow temperature was set to 20 °C, and the ambient pressure, p_∞ , was 100 kPa. The maximum relative deviation of the discharged velocity for the two cases in **Figure 3** was approximately 4.5%.

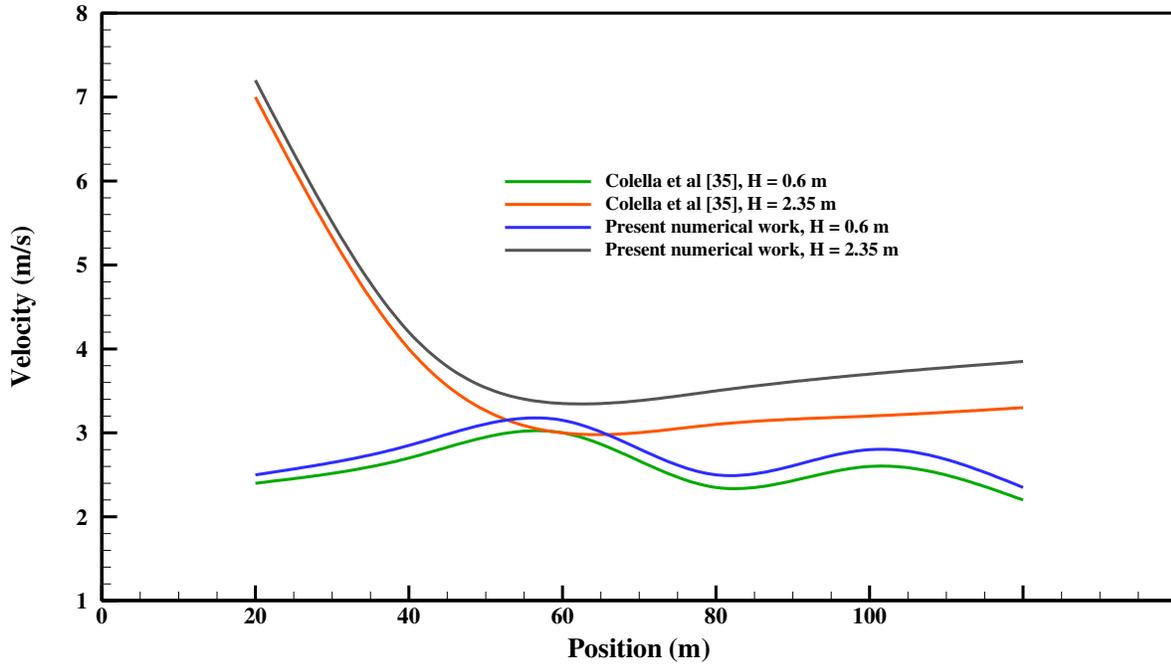


Figure 3. Comparison of the jet fan discharged velocity with the results of Collela et al.'s study.

The *grid independence test* was carried out to compute the required number of numerical cells to obtain convergent results. To obtain the grid-independent results, simulations have been carried out on three different mesh topologies at the low-speed jet fan velocity of 10 m/s. **Figure 4** presents the jet fan discharged velocity using the three mentioned numerical coarse, fine, and finest meshes. Grids 800000 and 900000 produce almost identical results for the jet fan discharged velocity with a relative error of less than 0.5%. Hence, a numerical grid 700000 chose to have a convergent solution with the optimized computational cost. A summary of the output of the grid independence test is shown in **Figure 4**.

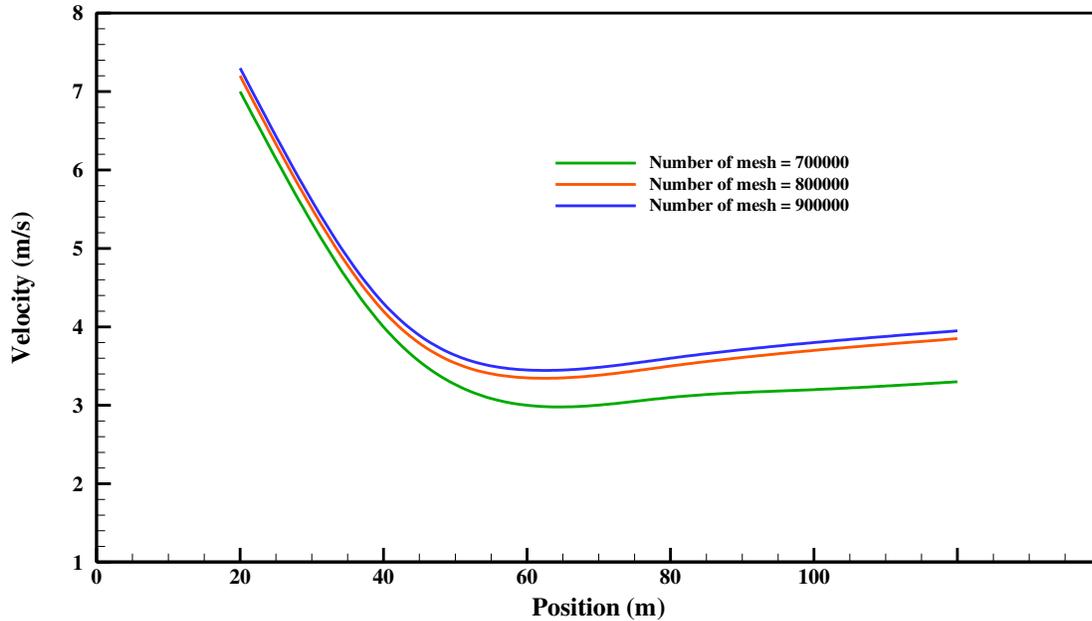


Figure 4. Jet fan discharged velocity obtained using coarse mesh 700000, fine mesh 800000, and finest mesh 900000.

6. RESULTS AND DISCUSSION

The spreading of respiratory viruses such as SARS-CoV-2 increases when sneeze occurs near the fresh air ducts. The respiratory particles concentrations in the underground car parks depends on the jet fan air velocity. Of note, when more than one person exists in the car park, the transmission of virus-containing particles (e.g. SARS-CoV-2) significantly increases. By determining safe and short pathways for exiting attendings in the car park, the risk of transmission will decrease. Clearly, these safe pathways should be near the fresh air and far away from the jet fan flow direction. Currently, the crucial protective effect of face mask against SARS-CoV-2 has been highlighted by scientific authorities [36-38]. The persons inside the underground car parks should wear the face mask. However, if only one person exists inside the car park, the continuous airflow of jet fans extracts the viral particles from the underground car parks, rapidly. Another solution to reduce the viral transmission by the continuous airflow of jet fans is the usage of the high-efficiency particulate air (HEPA) filters and ultraviolet light emitters inside the jet fans boxes. Airflow patterns within the underground car parks carry viruses from the sneeze source(s) through the jet fans. Usage of the HEPA filters and ultraviolet light emitters inside jet fan boxes decrease the concentration of viruses.

Figure 5 indicates the spreading patterns and recirculation of the respiratory particles using the air velocity contours at the four sneeze (infection) sources. Continuous air flow of jet fan transmission is defined as the transmission of infection by sneezed respiratory droplets/particles that are similar to the airborne transmission and can remain suspended in the underground car park for a short time. over this short time, the discharged particles potentially expose a much higher number of susceptible individuals at a much greater distance from the source of sneeze within the underground car park. By comparison of **Figure 5**, the distribution of respiratory

droplets/particles within the underground car park depends on the location of the sneeze source. Furthermore, the multiple suction and discharge of the respiratory droplets/particles by jet fans convert these particles to the much smaller aerosols that may move further away.

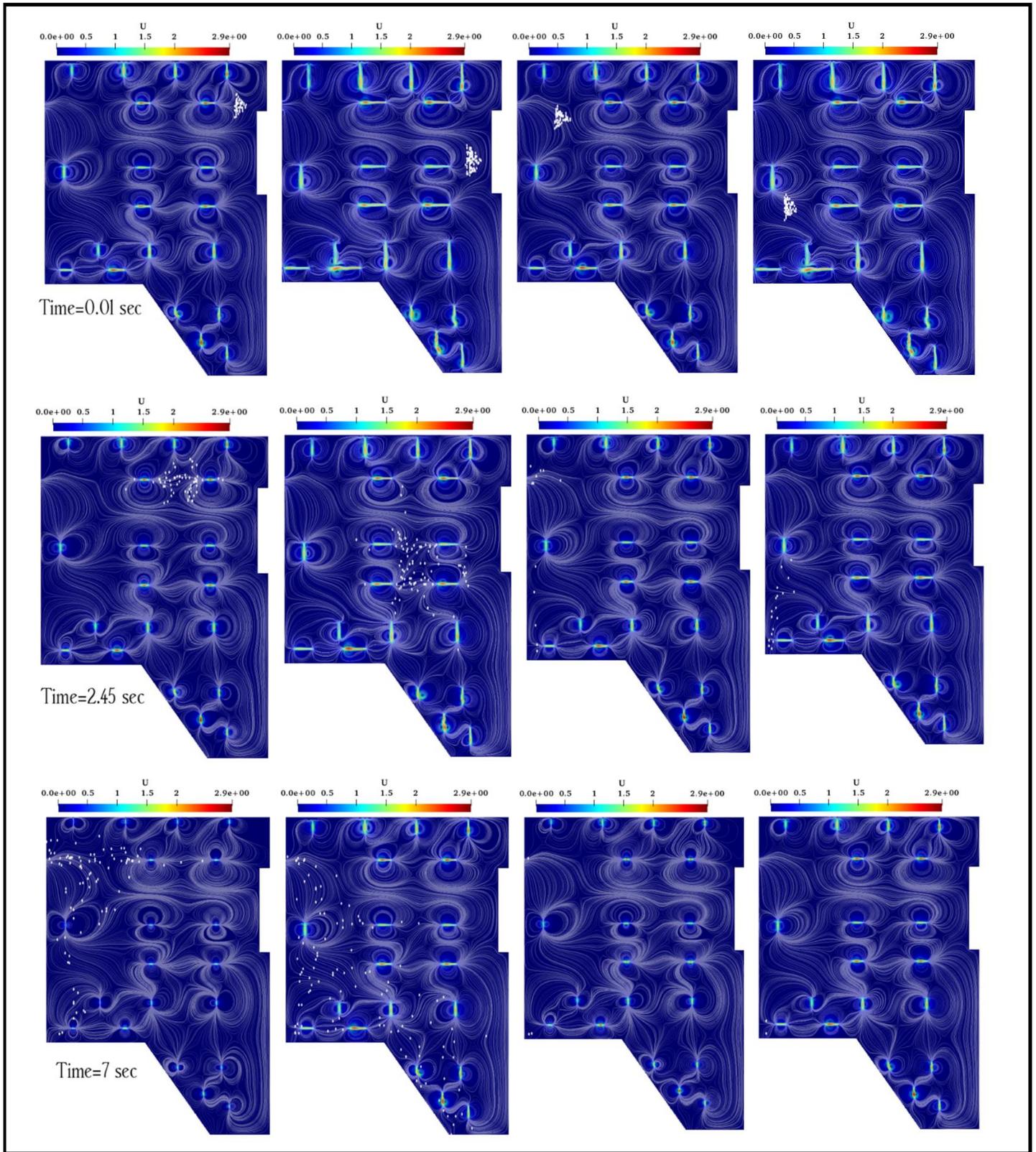


Figure 5. Comparison of the velocity distribution of saliva droplets within the underground car parks for sneeze sources 1 (left most column), 2 (middle left column), 3 (middle right column), and 4 (right most column).

As demonstrated in **Figure 6**, we determined hazard and safety zones based on the concentration of respiratory droplets/particles upon the sneeze (as the source of infection). To decrease viral infection (in this regard COVID-19) transmission, susceptible individuals in underground car parks should try to move in safety zones as demonstrated in **Figure 7**. In the following, we have provided learning tips for traffic within the underground car parks which are ventilated by the jet fans system:

- to wear a mask.
- to move far away from the core of jet fan flow.
- to leave the hazard zone to the safety zone
- not to enter the hazard zone for a long time.
- to traffic on lines in the mid-distance of jet fans and parallel to their axis
- to find the shortest pathway to exit

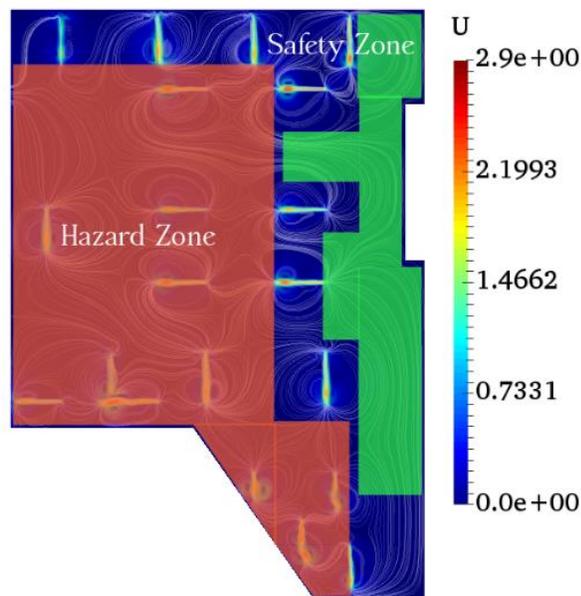


Figure 6. Safety (green) and hazard (red) zones within the underground car park (case study).

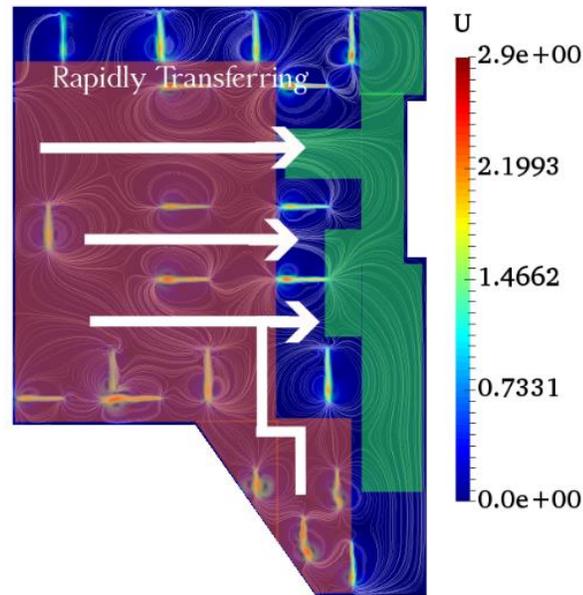


Figure 7. Recommendation on rapidly transferring from the safety zone to the hazard zone within the underground car park.

7. CONCLUSIONS

In this article, we computationally investigated the effects of jet fans on the spreading of viruses (e.g. SARS-CoV-2) inside the underground car parks. We assumed four different locations as the sneeze sources inside the underground car parks. The mechanisms of the viruses spreading in a low-speed stream of jet fan air were investigated using the OpenFOAM C++ libraries. After validating the numerical results using the experimental data, several recommendations were offered as follows:

1. By determining safety ways inside the underground car parks, it will provide greater protection to the viral transmission. Due to the jet fans flows directions, these safety ways should be close to the fresh air ducts.
2. By equipping ultraviolet light emitters and HEPA filters inside the jet fans, it will also eliminate the viruses.
3. Usages of face masks are strongly encouraged by authors, to prevent the spread of respiratory droplets and aerosols within the underground car parks.

8. ACKNOWLEDGMENTS

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9. DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

10. CONFLICT OF INTEREST STATEMENT

All Authors declare that there is no potential conflict of interest.

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Figures

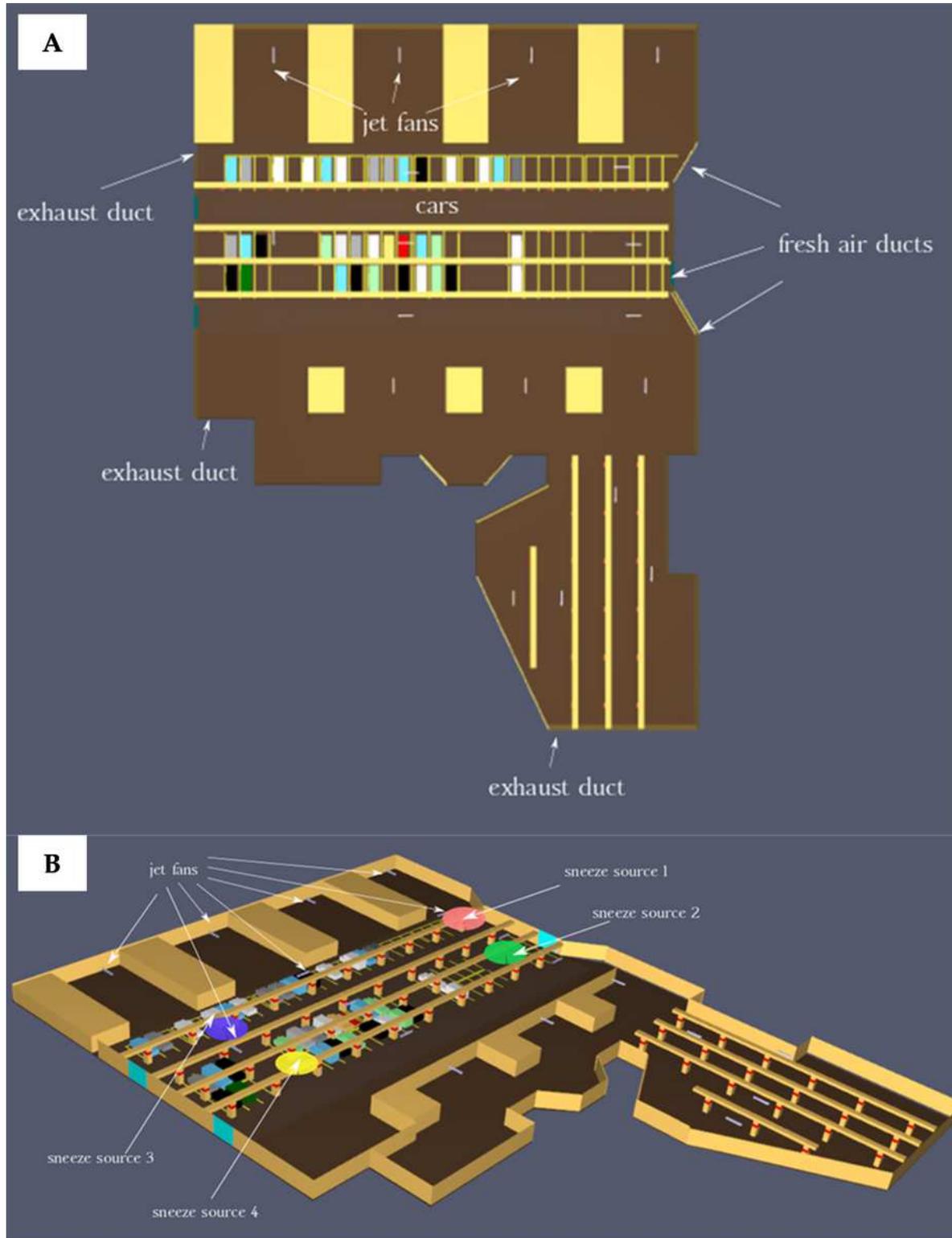


Figure 1

Schematic view of the underground car parks containing fresh air ducts, exhaust ducts, jet fans, and cars (A) and locations of the sneeze sources (B).

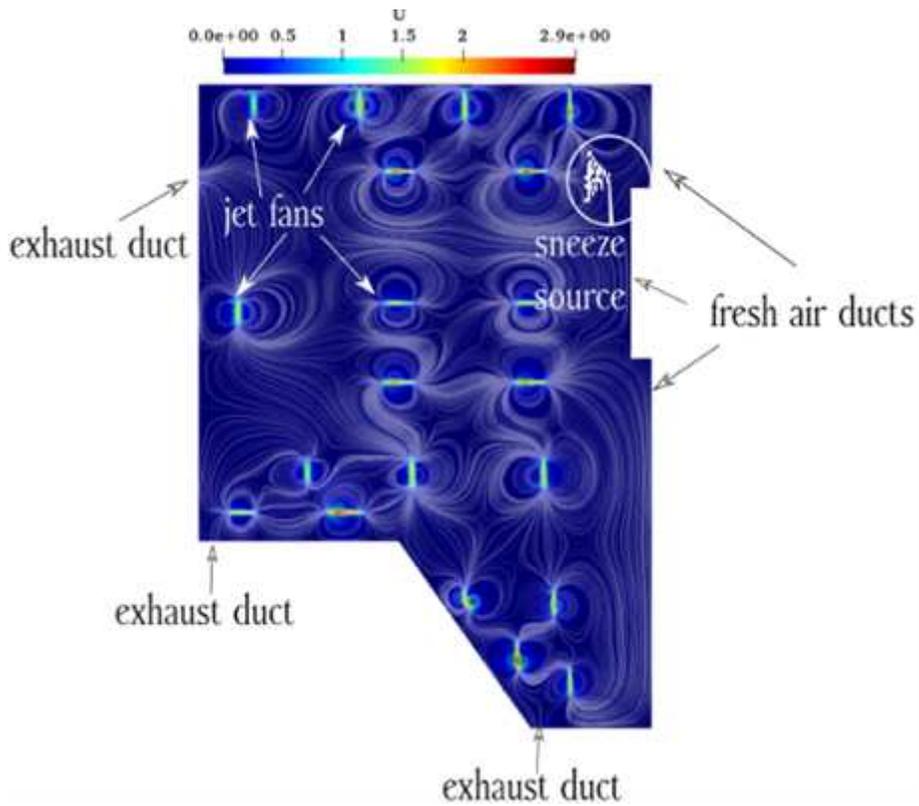


Figure 2

Schematic view of the created streamline due to the continuous jet fan air flows and sneeze sources.

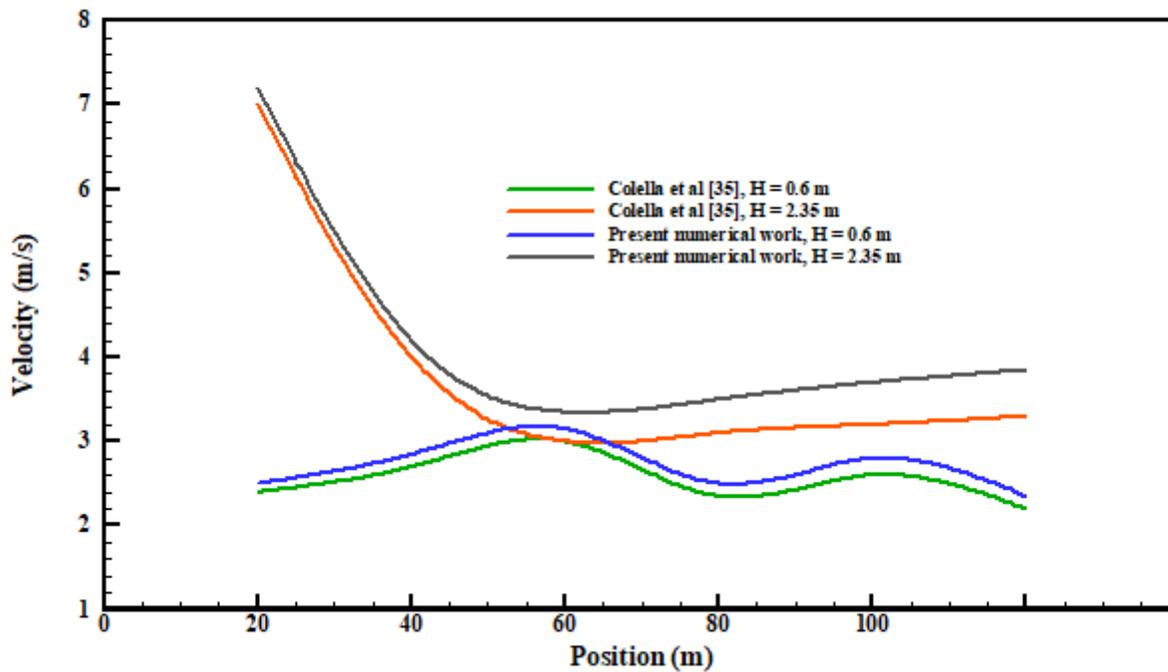


Figure 3

Comparison of the jet fan discharged velocity with the results of Collela et al.'s study.

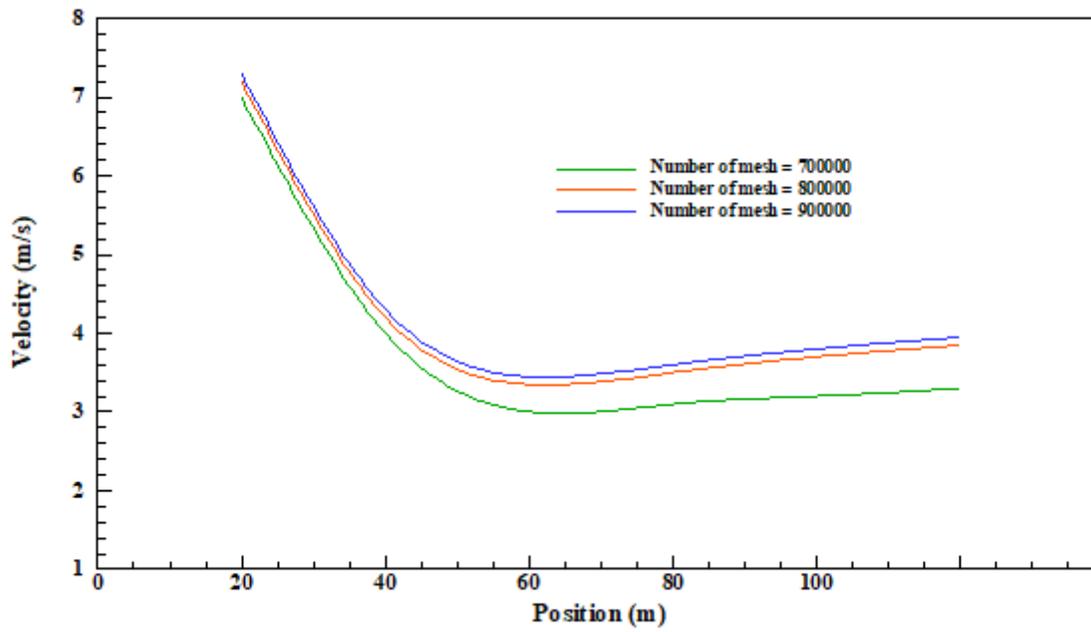


Figure 4

Jet fan discharged velocity obtained using coarse mesh 700000, fine mesh 800000, and finest mesh 900000.

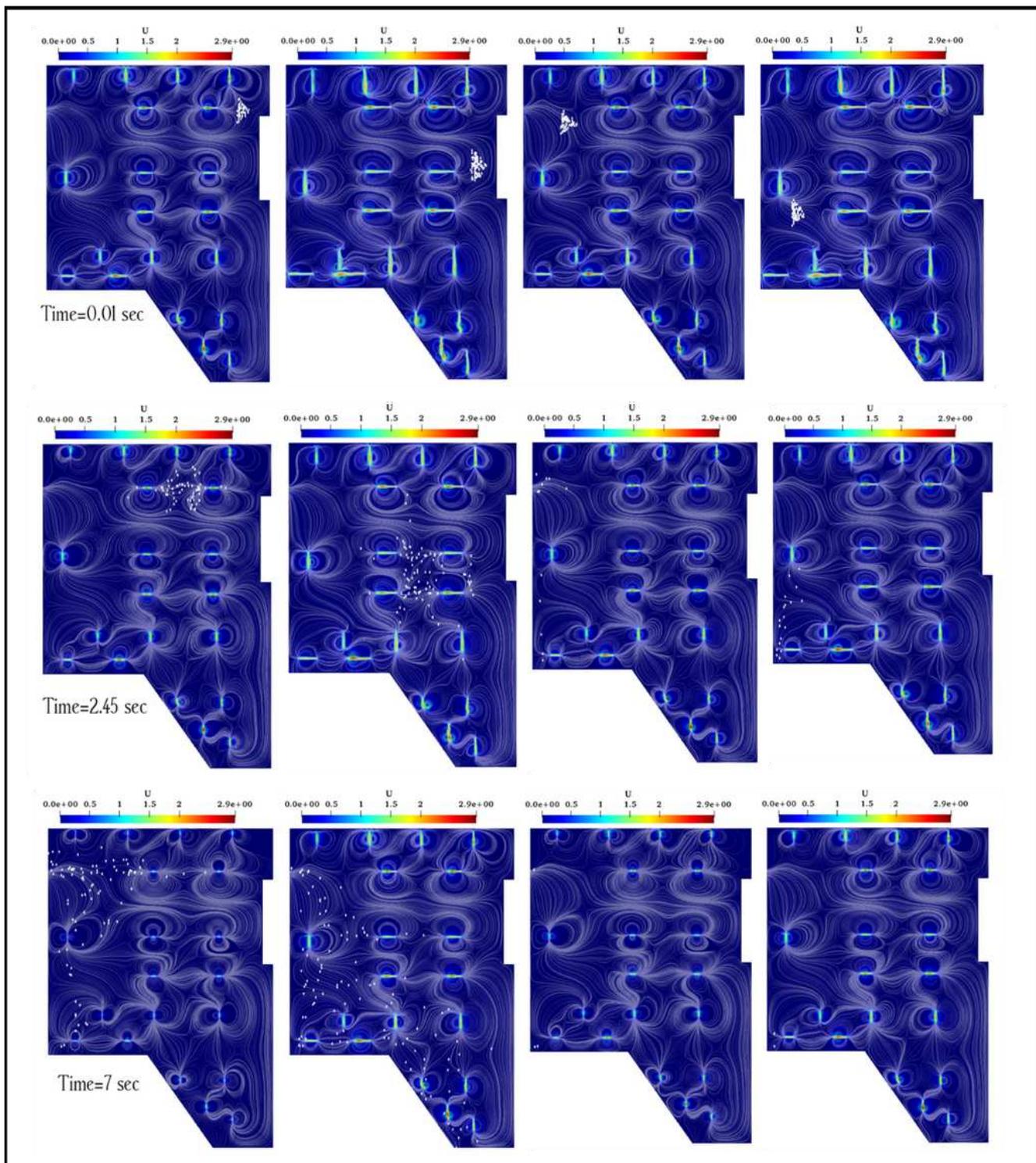


Figure 5

Comparison of the velocity distribution of saliva droplets within the underground car parks for sneeze sources 1 (left most column), 2 (middle left column), 3 (middle right column), and 4 (right most column).

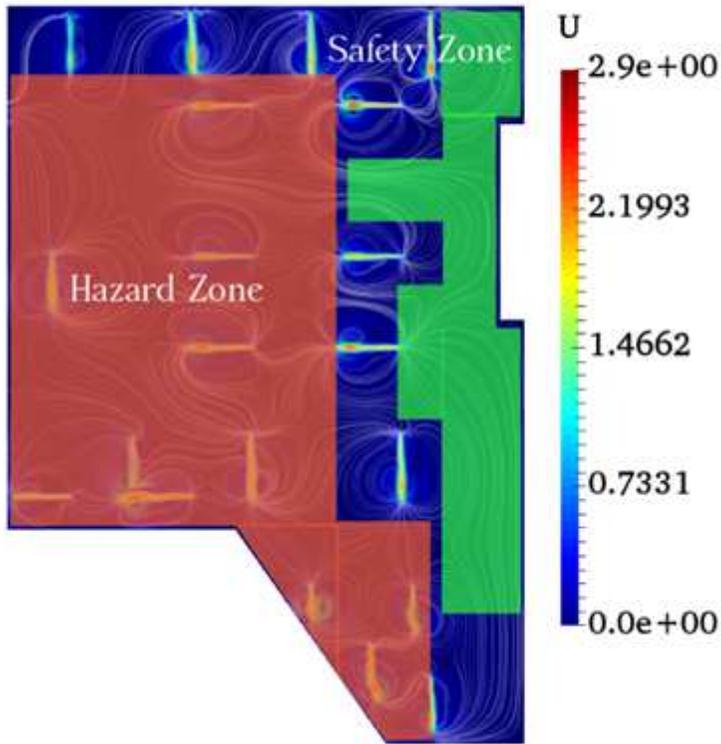


Figure 6

Safety (green) and hazard (red) zones within the underground car park (case study).

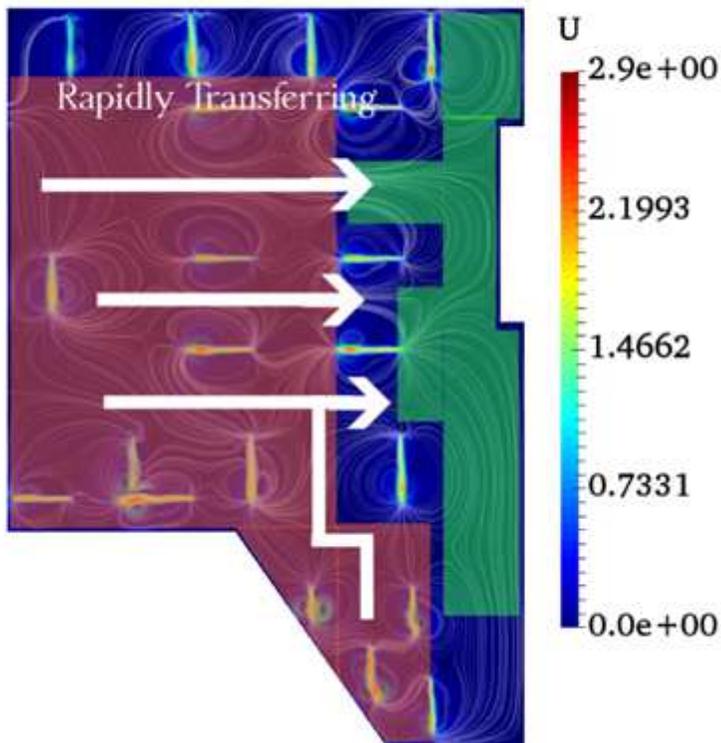


Figure 7

Recommendation on rapidly transferring from the safety zone to the hazard zone within the underground car park.