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# MATHEMATICAL MODELING OF SARS-COV-2 PARTICLES' PROPAGATION DURING HUMAN REFLEXES

**Abstract.** An unknown virus, which was detected in Wuhan city in 2019, had changed fate of the world immediately causing an economic loss, decrease in total population and etc. A penetration of coronavirus contaminated particles to a human cell is able to cause an overproduction of cytokines and antibodies. This process gives a rise to fatal cases. Hence, because of SARS-CoV-2's pathogenicity, severity and unexpectedness, effective safety measures should be implemented. Along with safe social distancing and wearing a mask, a presence of air conditioning, ventilation system and open windows can reduce the coronavirus propagation in enclosed spaces. The present article focuses on the modeling of coronavirus particles' propagation during human respiratory reflexes within a constructed three-dimensional confined space with inlet and outlet boundary conditions. Momentum and continuity equations, k-ε turbulence model and Lagrangian dispersion model were utilized to solve the problem. SIMPLE is a main method to solve all governing equations. The primary objectives of this work are to demonstrate the efficiency of air conditioning and open windows in preventing the spread of viruses and to examine particle behavior in the computational domain.

**Key words:** SARS-CoV-2, SARS-CoV-2 particles' transmission, coronavirus particles and aerosols, CFD (computational fluid dynamics), modeling, office room, air conditioning, open window.

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# АДАМ РЕФЛЕКСТЕРІ КЕЗІНДЕГІ SARS-COV-2 БӨЛШЕКТЕРІНІҢ ТАРАЛУЫН МАТЕМАТИКАЛЫҚ МОДЕЛЬДЕУ

**Аңдатпа.** 2019 жылы Ухань қаласында анықталған белгісіз вирус әлемнің тағдырын бірден өзгертіп, экономикалық шығынға, жалпы халық санының азаюына және т.б. тудырды. Коронавируспен ластанған бөлшектердің адам жасушасына енуі цитокиндер мен антиденелердің шамадан тыс өндірісін тудырады. Бұл процесс өлімге дейін апарады. Демек, SARS-CoV-2-нің патогенділігіне, ауырлығына және тосындығына байланысты тиімді қауіпсіздік шараларын қолданылуы қажет. Қауіпсіз әлеуметтік қашықтық пен бетперде киюмен қатар, ауаны тазарту, желдету жүйесі және ашық терезелердің болуы жабық кеңістіктерде коронавирустың таралуын едәуір тоқтауы мүмкін. Бұл мақала кіріс және шығыс шекаралары бар үш өлшемді жабық кеңістікте адамның тыныс алу жүйесіндегі рефлекстері кезінде коронавирус бөлшектерінің таралуын модельдеуге бағытталған. Есепті шешу үшін импульс және үздіксіздік теңдеулері, k-ε турбуленттік моделі және Лагранж дисперсиялық моделі қолданылды. SIMPLE әдісі – процессті сипаттайтын барлық теңдеулерді шешудің негізгі әдісі. Бұл жұмыстың негізгі мақсаты вирустардың таралуын шектеу үшін ауаны кондиционерлеудің және ашық терезелердің тиімділігін көрсету және есептеу аймағындағы бөлшектердің қозғалысын зерттеу болып табылады.

**Тірек сөздер:** SARS-CoV-2, SARS-CoV-2 бөлшектерінің таралуы, коронавирус бөлшектері мен аэрозольдар, есептеу гидродинамикасы, модельдеу, кеңсе бөлмесі, ауаны кондициялау, ашық терезе.

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# МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ РАСПРОСТРАНЕНИЯ ЧАСТИЦ SARS-COV-2 ПРИ РЕФЛЕКСАХ ЧЕЛОВЕКА

**Аннотация.** Неизвестный вирус, обнаруженный в городе Ухань в 2019 г., изменил судьбу мира, вызвав экономический ущерб, сокращение общей численности населения и т.д. Проникновение зараженных коронавирусом частиц в клетку человека способно вызвать перепроизводство цитокинов и антител. Этот процесс приводит к летальному исходу. Следовательно, из-за патогенности, серьезности и неожиданности SARS-CoV-2 необходимо принять эффективные меры безопасности. Наряду с безопасным социальным дистанцированием и ношением маски наличие кондиционера, системы вентиляции и открытых окон может снизить распространение коронавируса в закрытых помещениях. Данная статья посвящена моделированию распространения частиц коронавируса при дыхательных рефлексах человека в трехмерном ограниченном пространстве с входными и выходными граничными условиями. Для решения задачи использовались уравнения импульса и неразрывности, k-ε модель турбулентности и модель дисперсии Лагранжа. SIMPLE – это основной метод решения всех основных уравнений. Основные цели этой работы – продемонстрировать эффективность кондиционирования воздуха и открытых окон в предотвращении распространения вирусов и изучить движение частиц в вычислительной области.

**Ключевые слова:** SARS-CoV-2, распространение частиц SARS-CoV-2, частицы и аэрозоли коронавируса, вычислительная гидродинамика, моделирование, офисное помещение, кондиционирование воздуха, открытое окно.

## Introduction

In the world's history, one of the phenomena, which caused enormous damage to various aspects of life, including the economy, number of total populations etc., was coronavirus or SARS-CoV-2. Because of coronavirus's pathogenicity, severeness and unexpectedness various important mitigation strategies, which can stop its propagation, are still carrying out. Numerous preventive measures, including quarantine, lockdown, wearing medical masks and gloves, avoiding close contact with infected people, mouthwash, hand hygiene, and others, were researched and realized to stop and limit the spread of the disease.

Despite of some uncertainties, it is investigated, coronavirus particles can propagate through air via sneezing, coughing, talking and even by breathing [1]. Additionally, asymptomatic individuals tend to contaminate an environment with virus particles, which gives a rise to spread of coronavirus. Virus aerosols are prone to linger in the air for a long time and move to long-term distances [2]. It was detected that SARS-CoV-1 and SARS-CoV-2 drops and droplets linger in air and are exposed to intrabuilding movement. V. Stadnytskyi, C.E. Bax, A. Bax and P. Anfinrud utilized a laser-light scattering technique to identify the time, in which virus contaminated aerosols suspend in air [3]. These aerosols can remain in air longer than ten minutes. Vuorinen *et al.* defined the difference between aerosols, droplet nuclei and droplets [4]. Researchers indicated, aerosols and droplet nuclei can be accepted as residuals from a water evaporation, which contain coronavirus. They suspend in air for hours and spread through air. Small droplets are able to turn into aerosols and droplet nuclei. In addition, diameters for large droplets can be more than 200 μm. Aerosols, tiny particles and droplet nuclei have sizes less than 10 μm [7]. Medium diameter sizes for drops and droplets are in an interval of 10–100 μm. According to an investigation, a man exhales 100 to 1000 particles when coughing and 1000 to 10,000 particles when sneezing within 1 s [5].

One of the vast measures can be a fixed ventilation system in enclosed spaces, where an infection is detected. Many researchers observed a propagation of virus's particles within different spaces. Majority of observations showed that the ventilation system plays significant role in controlling of coronavirus's distribution. The authors of one of these studies are Armand and Tache [5]. Current work focuses on the particle distribution after the events such as continuous breathing and coughing. The model of a carriage, that contains three partitions, was utilized. In model, passengers occupied the first and the third parts, and the second part connects two divisions. An airflow comes from outside the first and third divisions and escapes from the top of the train. In this study, an airflow and trajectory of particles were simulated via a turbulent k-ε model and two dispersion models (Eulerian and Lagrangian), respectively. The results for simulation of particles' distribution are the same for both approaches. Results show, due to the continuity of breathing droplets tend to capture whole carriage. Initially, contaminated droplets reach passengers sitting next to an infected person, and then they continue to move to opposite side of an infected passenger.

In the study of Mariam *et al.* diluted particle propagation is examined in a standard office room for events such as sneezing, coughing etc. [6]. In the physical model, two human models, one of them is an infected person and another one is a healthy receiver, keep recommended distance for prevention from catching infection. Authors considered two cases of human models' positions, namely, sitting and standing opposite to each other positions. In each case two different locations of inlet-outlet boundary conditions were under the observation. In the first arrangement of inlet-outlet boundary conditions, inlet and one of the two outlets are at a ceiling and another outlet is placed at wall, while the second one offers inlet and outlets to be at the ceiling. The airflow was simulated using turbulent k-ε model. The received results show that the most optimal location for inlet and outlets should be as in the first arrangement. Because of the barrier generated by the airflow emitted particles cannot cross the barrier and the receiver. However, there were detected particles of both small and large sizes near the receiver in coughing and loud talking events. Authors deduced, keeping recommended distance as safety measures cannot prevent from infection fully. On the other hand, their study indicates that the ventilation system is one of the effective ways to control virus's dissemination. Precise location of inlet-outlet boundary conditions for venting system can enhance air purification from contaminated droplets.

Mirzaie *et al*. observed coronavirus particles' spread inside a class, where an infected teacher stands in front of the class [7]. CFD simulation was implemented for airflow generated by venting system and Lagrangian dispersion model was applied for motion of particles emitted by teacher's coughing. There were suggested two versions of the physical model. The first case consists of the standard classroom with ventilation system and student desks, while in the second one there are supplementary barriers for each desk. The results conclude that airflow from venting system can expel contaminated particles completely at precise velocity and time. Moreover, constructed barriers for each desk can be considered as one of the effective and supplementary precautionary measures. Another observation about modeling of virus propagation inside the classroom with air conditioning was conducted by Abuhegazy *et al.* [8]. It was studied that particles of small sizes, namely less than 15 μm, tend to float in the air for some time and then exit the classroom, while large, diluted drops settle on the surfaces. In addition, particle percentage was examined for each student desk after ejection. Researchers concluded that appropriate positions for healthy students can protect them from infection. They also deduced, presence of open windows as outlets reduces coronavirus contamination. Narayanan and Yang investigated an airflow generated by air purifiers and transmission of coronavirus particles in a music class [9]. Several scenarios of simulation were under observation, when a student is exhaling contaminated particles by playing on brass instrument and piano, the student is wearing a mask for safety measurements. Received result indicates, determined location for air purifier can effectively cut the number of particles. Ahmadzadeh *et al.* studied an efficiency of a ventilation system and open windows as outlet during virus propagation during talking and coughing [10]. Ventilation system and open windows can essentially manage the transmission of contaminants. It was concluded, a right location for the ventilation is close to the infected individual. In the work of Liu *et al.*, a real documented case of COVID-19 infection in one of the restaurants in China is described [11]. Authors studied the dissemination of coronavirus particles exhaled by an asymptomatic individual. Advanced CFD solver was implemented. It was concluded, a temperature of human body and environment can change direction of airflow produced by air conditioning and create vortexes that worthen the situation.

In the study of Mathai *et al.*, an indoor environment and injected coronavirus transmission inside a moving vehicle were examined [12]. Researchers studied two scenarios of virus emitter. In first case, emitter is a driver, in second one, a passenger infects the interior of the car. The best findings indicate that the concentration of particles is reduced when all windows are open. In contrast, particles capture interior of the automobile with closed windows and supplied air conditioning. Jayaweera, Perera, Gunawardana and Manatunge analyzed the virus propagation in several confined spaces [13]. Particle movement inside an aircraft was simulated considering precise environmental conditions such as humidity, temperature and air exchange rate. Low temperature and humidity increase the lingering time of aerosols in the air. An observation conducted by Issakhov *et al.* consists of the simulation of virus dissemination in an enclosed space during different respiratory events [14]. They concluded, a distance travelled by particles during breathing is much shorter than the case of sneezing and coughing. It was suggested, keeping a safety distance at 5 m during human reflexes reduces infection cases. Authors deduced that a recommended distance of 2 m by World Health Organization (WHO) is not sufficient when the infected person coughs or sneezes. Busco *et al.* considered a sneezing with upward head movement in a precise angle [15]. A real-life experiment was conducted to find out duration of sneeze and the angle, in which head moves in upward direction during respiratory reflex. Authors studied behavior of virus-diluted particles in high temperature and found high sedimentation tendency of particles on surfaces. Mortazavi *et al.* modeled the propagation of coronavirus droplets within a respiratory system and analyzed the most contaminated zones by virus in the system [16]. They considered virus droplets with diameter of 1 μm, 5 μm and 10 μm. For each dimension, three flow rates were considered. Researchers identified that lungs can easily become contaminated with aerosols, while larger particles deposit instantly in an oral cavity. Another observation of coronavirus particle propagation was studied by Guan, Ramesh and Memarzadeh [17]. Their research focuses on the transmission of particles during human movement. Several cases of human's speed and particle diameter were examined. The findings show that despite of the human's speed magnitude particles tend to distribute identically in all observed zones. Additionally, there were identified particles at the back of human model after its movement at precise time. Wang, Li, Liu and Cao conducted a CFD simulation to observe virus contaminated particles transmission from a urinal flushing [18]. Authors indicated, coronavirus aerosols released from flushing can reach up to a height of human model's knees. Based on the results, researchers emphasized the importance of preventive measures, namely wearing safety masks, in crowded public restrooms to control coronavirus transmission.

Based on the mentioned observations, the venting system, air conditioning, presence of open windows can substantially control the transmission of coronavirus aerosols and droplets in enclosed spaces. The goal of this study is to model an airflow generated by ventilation system in an office room, where infected person emits coronavirus's particles.

**Main provisions**

The main objective of this work is to simulate the particle injection from an infected person in an enclosed space during sneezing and coughing, and analyze the behavior of exhaled aerosols, droplets and drops. Additionally, this work considers a supplied air conditioning system and open window as one of the key preventive measures to control COVID-19 propagation. In addition to it, a safety distance of over two meters were examined in order to investigate its effectiveness.

Figure 1 demonstrates a geometry of the main problem, where there are three constructed human models, namely, one standing and two sitting human models. The standing human model was assumed to be the infected individual, who emits aerosols and particles with diameters in a range of 1.5–100 μm during expiratory events (sneezing and coughing).

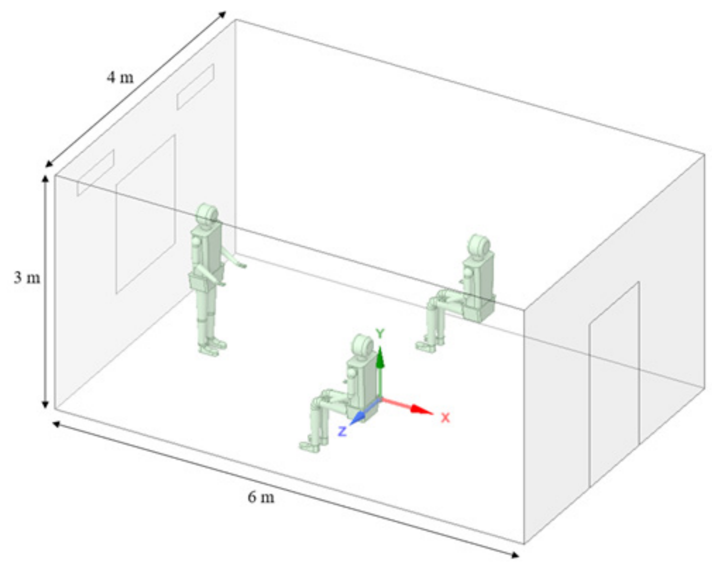



Figure 1 – Three-dimensional office room

All geometries were constructed in Ansys SpaceClaim. The confined space has dimensions of 6×4×3 m (L×W×H). A height of standing human model is approximately 1.85 m. Two inlets for air conditioning have 0.8×0.2 $m^2$ of area equally, while the dimension of window is 1.3×1.4 $m^2$. The area of outlet is 1.1×2.1 $m^2$.

Figure 2 shows the human model and the mouth. The mouth has a 0.0012 $m^2$ surface area. Inlet-outlet boundary conditions for this problem are displayed in Figure 3. A grid for above geometry was created using Ansys Fluent Meshing. Minimum and maximum cell sizes are chosen to be 0.002 m and 0.036 m, respectively. A local sizing was implemented near the model's mouth with cell size of 0.002 m. The grid of the computational domain is illustrated in Figure 4. A total number of cells is 3886310.

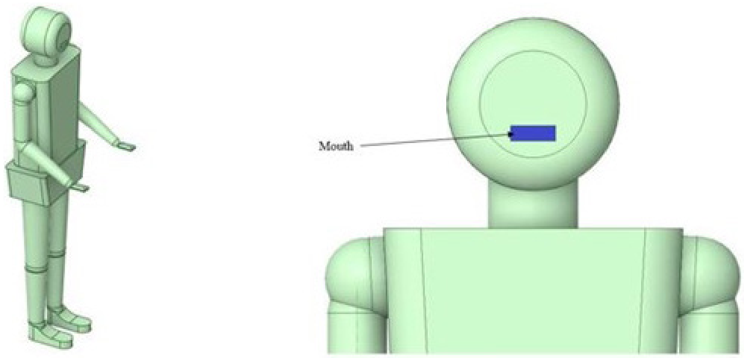
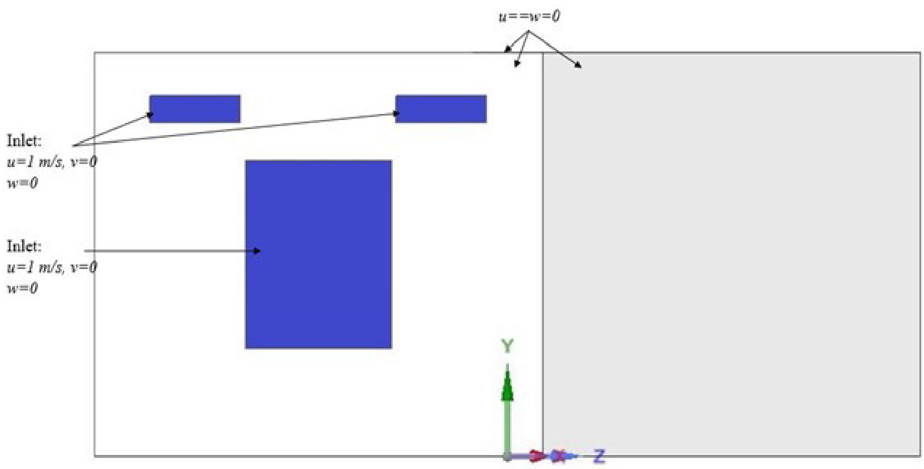
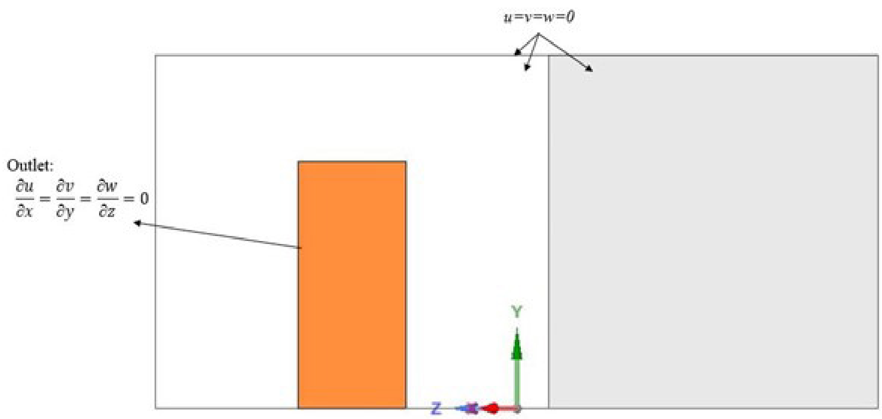



Figure 2 – Three-dimensional human model




a)




b)
Figure 3 – a) Inlet and b) outlet boundary conditions

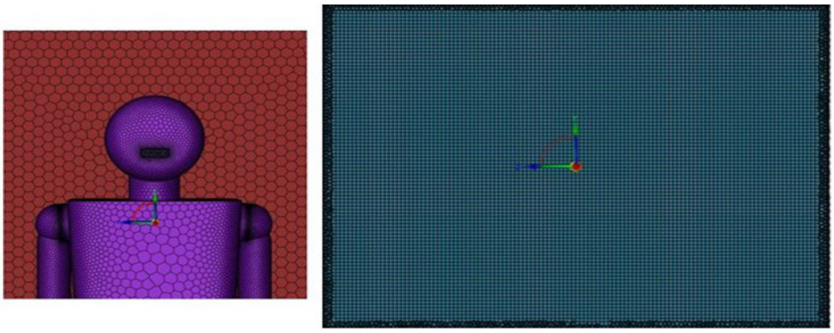


Figure 4 – The grid of the geometry

**Materials and Methods**

For the airflow from air conditioning system and window k-ε turbulence model was utilized [5]. Additionally, the mathematical model contains Reynolds Averaged Navier-Stokes equations. The system of equations is as follows:

$$\begin{cases} \rho\left(\frac{\partial \bar{u}_i}{\partial t}+\frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j}+\frac{\partial \overline{u_i' u_j'}}{\partial x_j}\right)=-\frac{\partial \bar{p}}{\partial x_i}+\mu\frac{\partial^2 \bar{u}_i}{\partial x_j^2} \\ \frac{\partial \bar{u}_j}{\partial x_j}=0 \end{cases}$$

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon)+\frac{\partial}{\partial x_i}(\rho \varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}, \tag{3}$$

where $\bar{u}_i$ is the averaged velocities for velocity components ($u$, $v$ and $w$) and $\overline{u_i' u_j'}$ stands for the Reynolds stress. $\rho$, $p$, $\mu$ represent the density, pressure and viscosity, respectively. In turbulence model, k is the turbulent kinetic energy, $\varepsilon$ is the dissipation rate. $\mu_T$ represents the turbulent viscosity, $G_k$ and $G_b$ are the turbulent kinetic energy produced from mean gradients of velocities and buoyancy, respectively. $\sigma_\varepsilon$ and $\sigma_k$ are the Prandtl numbers; $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{1\varepsilon}$ are constants.

The Lagrangian approach was applied for particle tracking [7]:

$$\frac{dV_d}{dt}=\frac{18\mu}{d^2\rho_d C_C}(\vec{V}-\vec{V_d})+\frac{\vec{g}(\rho_d-\rho)}{\rho_d}+F_L+F_B, \tag{4}$$

where $V_d$ is a particle velocity, $F_L$ represents a lift force of Saffman and $F_B$ is a Brownian force. $C_c$ is a Cunningham coefficient:

$$C_C=1+\frac{2K}{d}\left(1.257+0.4e^{-\left(\frac{1.1d}{2K}\right)}\right), \tag{5}$$

where $d$ is a particle diameter and $K$ is an average molecular distance.

In the present study, Discrete Phase Model (DPM) was applied to consider the particle injection from the infected individual. Ansys software suggests phase coupled SIMPLE method to solve the mathematical model. In addition to it, SIMPLE method solves the momentum equations, continuity equation and the turbulent model for the airflow produced by air conditioning (or ventilation system) and open window.

Semi-Implicit Method for Pressure Linked Equations, or SIMPLE, was developed in 1972 by Patankar and Spalding [19]. The algorithm for SIMPLE method is as follows:

1) Pressure $p^*$ is guessed;

2) By substituting $p^*$ into momentum equations, $u^*$, $v^*$ and $w^*$ are found. The correction equations for $u'$, $v'$ and $w'$ can be identified by subtracting momentum equations for $u^*$, $v^*$ and $w^*$ from equations for $u$, $v$ and $w$, respectively;

3) By using FVM and substituting velocity corrections, $p'$ is found;

4) Corrections are conducted for $p$, $u$, $v$ and $w$:

$$p = p^* + p',$$
$$u = u^* + u',$$
$$v = v^* + v',$$
$$w = w^* + w';$$

5) Solving other transport equations, for instance, for $k$ and $\varepsilon$.

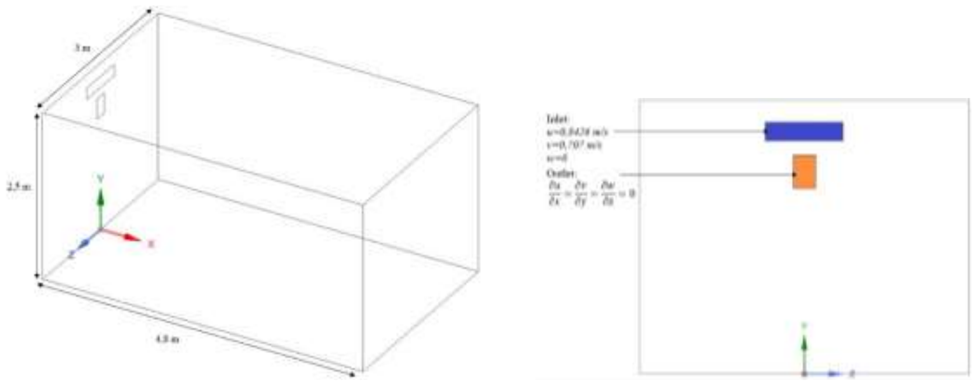
6) By setting $p^* = p$, $u^* = u$, $v^* = v$ and $w^* = w$, go to the 1st step and solve the equations until the convergence.

**Results and Discussion**

An observation of Deng, Wang, Tang and Gao was taken as the testing problem [20]. Authors simulated an airflow, which comes from a diffuser, within a three-dimensional confined space. The inlet-outlet of the geometry and geometry itself are demonstrated in Figure 5.

The velocity of 1.1 m/s and angle of 40˚ are used to drive the airflow upward. The data was taken from the literature. The areas of the inlet and outlet are 0.1207 $m^2$ and 0.06 $m^2$, respectively. Using two different step sizes in the $x$ direction of the first cell next to the diffuser, researchers compared the findings of total-flux and convective-flux approaches. It was identified, the optimal size of the first cell is in the interval of 0.005-0.02 m. In this work, $\Delta x$ = 0.01 m was taken as the size of the first cell near to the diffuser. Figure 6 shows a grid for geometry.

The mathematical model of testing problem consists of the momentum and continuity equations. Additionally, a standard k-ε turbulence model was applied to describe turbulence of the airflow inside the computational domain. The comparison of the findings from the aforementioned research with the current investigation is shown in Figures 7–9. It is shown, the results of this study are consistent with results of the study of Deng, Wang, Tang and Gao. Received results for the velocity repeat the tendency of experimental velocity profiles. Authors conducted the simulation of the airflow using two approaches such as total-flux and convective-flux methods. For each method they utilized two different step sizes in $x$ direction to minimize the error and compared received results. The findings for both methods considering two different very first cell sizes close to the inlet were deduced to be acceptable by researchers. However, they emphasized that a combination of $\Delta x$=0.0005 m and total-flux method had given desirable outcomes and conform to the experimental data, while using $\Delta x$=0.005 m cell size resulted in big difference with research findings.




a) b)

Figure 5 – a) Diffuser geometry and b) boundary conditions

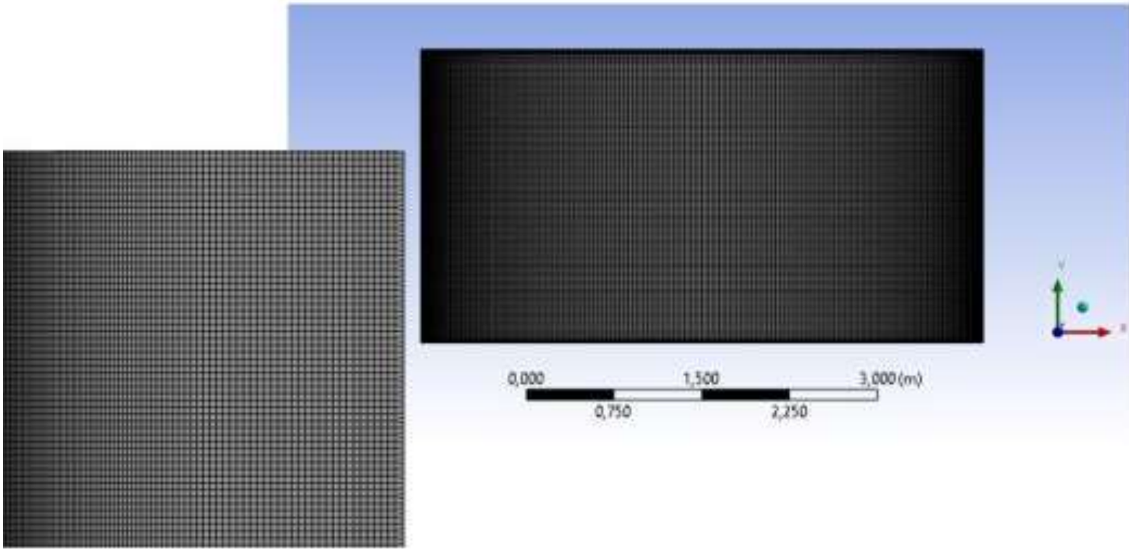



Figure 6 – Grid of the three-dimensional confined space

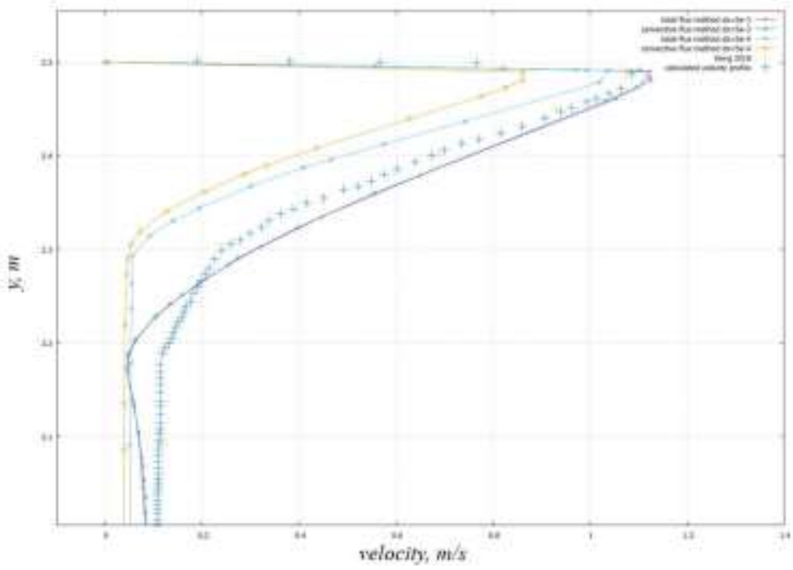



Figure 7 –Velocity at $x$=1 and $z$=0

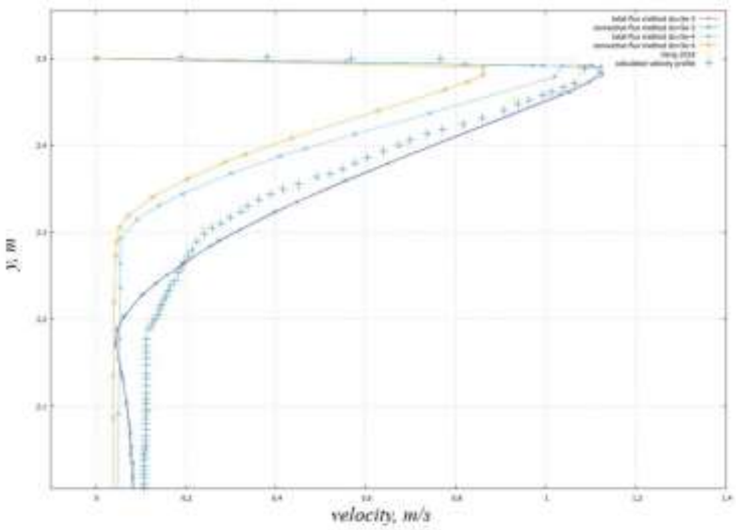



Figure 8 – Velocity at $x$=1 and $z$=0.5

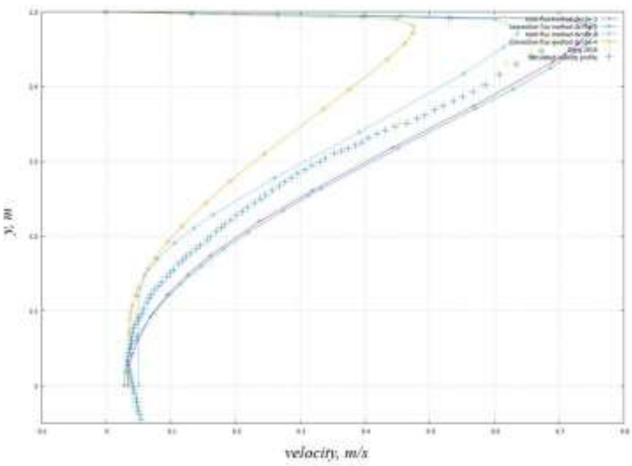



Figure 9 – Velocity at $x$=2.2 and $z$=0

In this study, the airflow established by two air conditioning systems and window, the motion and transmission of SARS-CoV-2 containing particles and aerosols, and their behavior in the computational domain were examined.

The supply air's velocity is between 2.54 m/s and 7.62 m/s, referring to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [7]. The velocity of 1 m/s was under the observation for venting systems and window in given study. The airstream enters and flows within the domain. Figures 10-12 demonstrate the airflow from the first and second inlets for venting system and open window, respectively. The airstream flows for 30 seconds for both cases of respiratory events. As it is shown, recirculation zones created by air conditions can be seen in the font and at the back of two sitting human models. At the same time, the airstream from window flows around the standing human model and tends to remove the aerosols at precise time, however, there is a recirculation zone between the infected person and the outlet. This recirculation zone enables medium and large particles to move back towards the emitter.

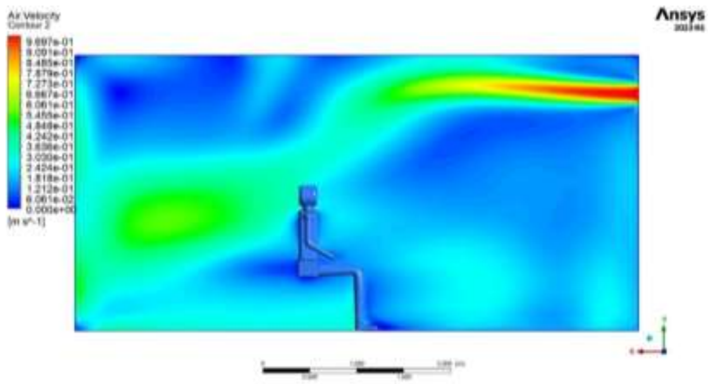



Figure 10 – Airstream from inlet 1

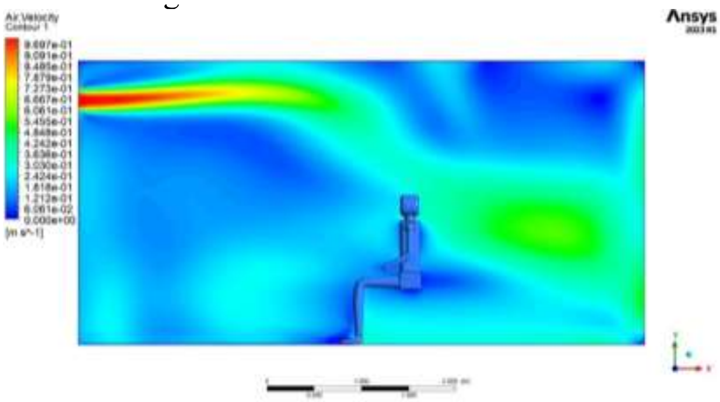



Figure 11 – Airstream from inlet 2

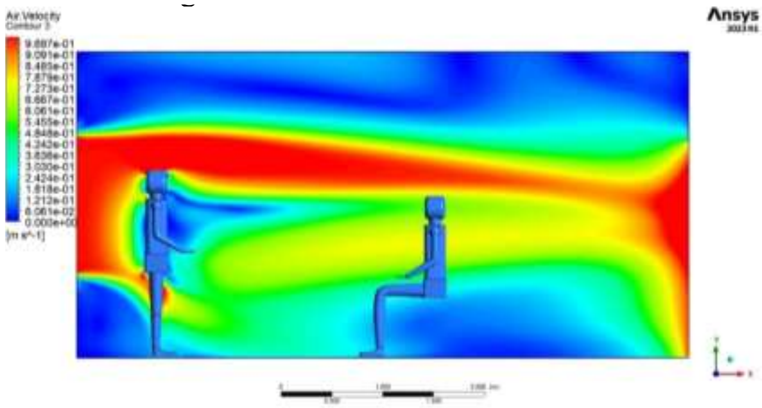



Figure 12 – Airstream from open window

Initially, the coronavirus contaminated particles' transmission during a sneeze was observed. Exhaled particles have diameters in the interval of 1.5–100 μm. In the simulation, the infected person is assumed to sneeze from 0 s to 0.5 s of flow time. An initial ejection starts at 0$^{th}$ second and a final one happens at 0.4$^{th}$ second, which means that there is no ejection at 0.5$^{th}$ second. In addition to emitted particles, an airflow from the human model's mouth was studied at the same time of emission. Table 1 shows a detailed information about particle injection when sneezing.

Table 1 – Data for particle injection during the sneeze

| | |
|---|---|
| Injection type | Group |
| Number of particles | 4940 |
| Velocity of particles | 30 m/s |
| Start time | 0 |
| Stop time | 0.5 |
| Minimum diameter | 1.5e-6 |
| Maximum diameter | 0.0001 |
| Mean diameter | 3.53e-5 |

As it is displayed, group injection type was chosen to model the dissemination of coronavirus. The precise number of contaminants is 4940. The velocity of particles is 30 m/s. To accomplish the simulation of the airstream from the mouth, a time dependent user defined function (UDF) was utilized. Figure 13 shows the airstream from mouth at 0.1-0.5 s.

Figure 14 illustrates the dissemination of coronavirus diluted particles. These visualizations show particle's behaviour at different times. Figure 14a shows overall exhaled aerosols, drops and droplets, having different diameter size in the interval of 1.5-95 μm, after the emission process or, namely, at 0.5 s. Large and medium contaminants flow more than 2 m within 3 s, whereas aerosols are able to travel approximately 2.65 m at the same period of time (Figure 14b). Figure 14c displays that particles with diameter of 95 μm fall on the ground at 6.1 s leaving over 2 m behind, while tiny particles tend to follow the airflow produced by open window and air conditioning. It is shown from Figure 14d, aerosols in the range of 1.5-10 μm commence to leave the computational domain at 8.9 s and traverse more than 5.02 m maintaining the height at about 1.68 m, at which emission happened. After two seconds, a small fraction of particles with diameter sizes of 30-60 μm starts to leave the office room (Figure 14e). Close to the end of total flow time, larger contaminants, which have dimensions of 40-95 μm, move back towards the infected person due to the recirculation zone created by the airstream, while particles with size of 7 μm start to go up, which means that they might follow the airflow and also leave the domain (Figure 14f).

A change of total number of tracked particles within 28.5 s is displayed in Figure 15. Initial number of tracked particles is 4940. Then number of drops and droplets starts to decrease substantially from 8.9 s to 10.8 s containing 3413 particles in the office room. Another sharp decline can be seen in the time interval of 14.2-17.1 s. At this period, number of contaminants reduces from 2989 to 1984. Finally, a gradual decrease happens at 17.2 s until the end of total flow time. A remained number of particles is 1656. With the help of air conditioning system and open window, total number of particles was cut by approximately three times.

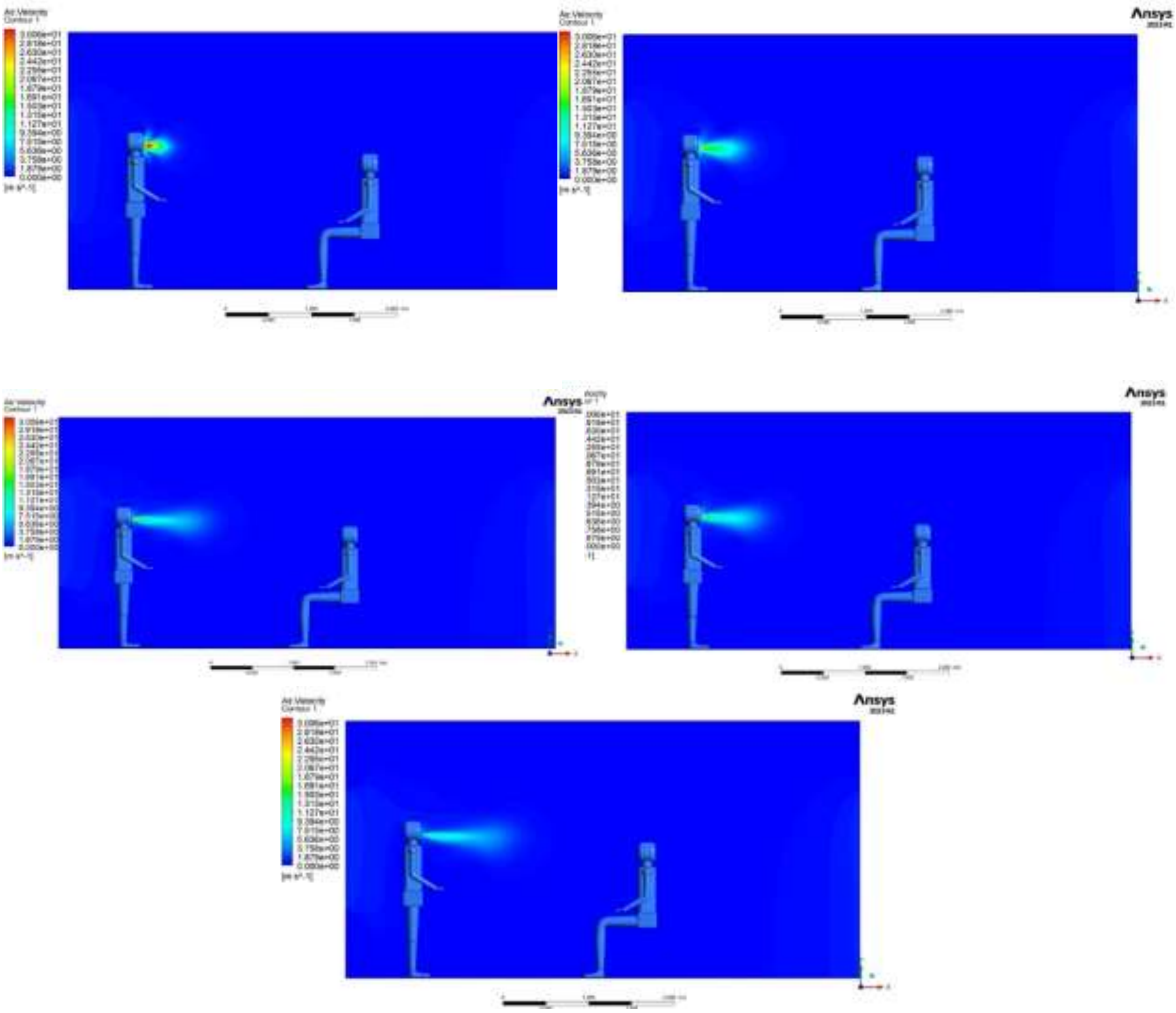
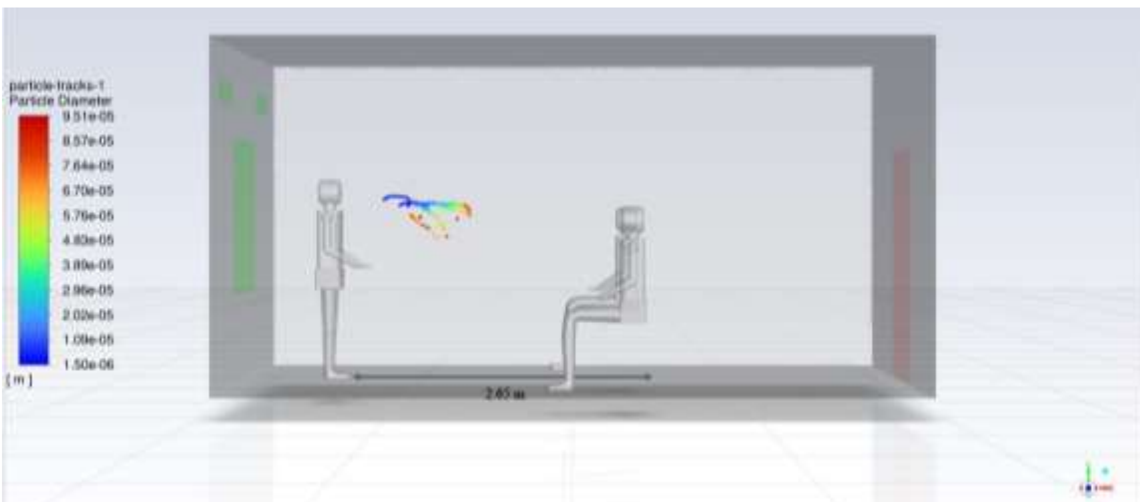
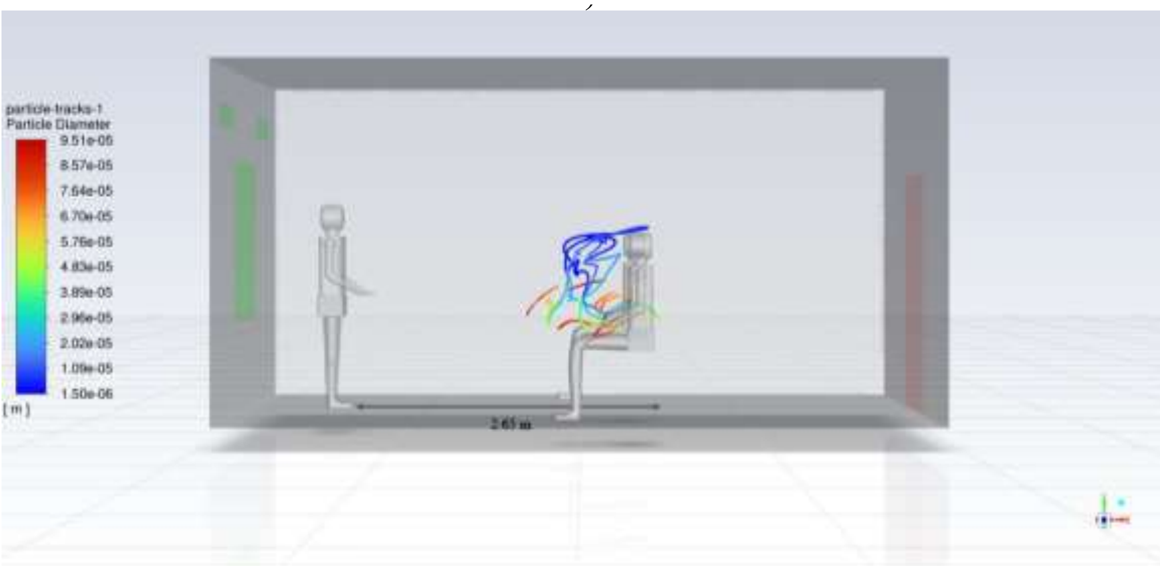


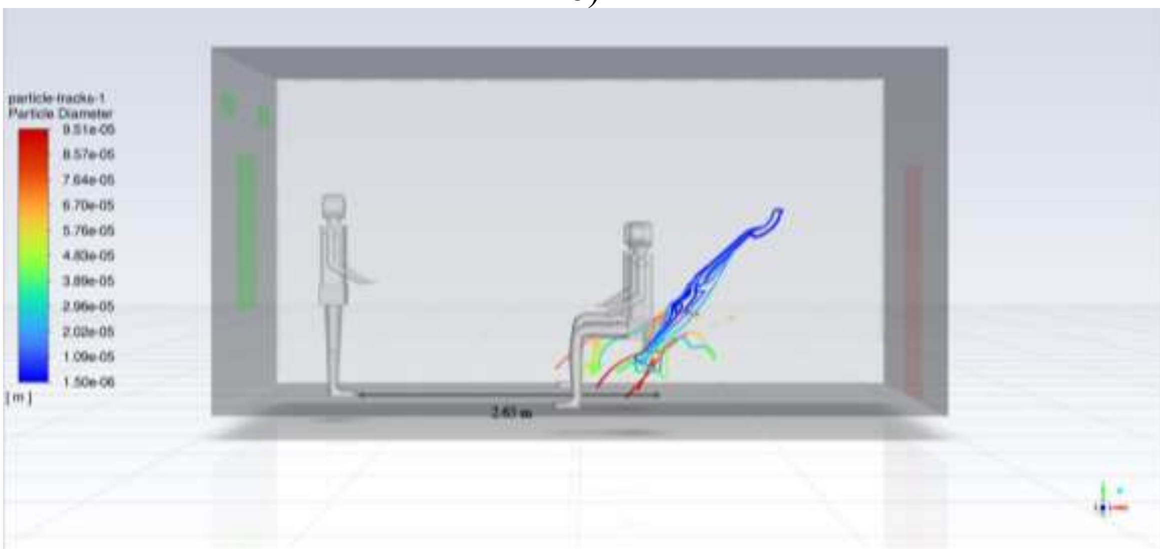

Figure 13 – Airflow from mouth at a) 0.1 s, b) 0.2 s, c) 0.3 s, d) 0.4 s and e) 0.5s




a)


particle-tracks-1
Particle Diameter
9.51e-05
8.57e-05
7.64e-05
6.70e-05
5.76e-05
4.83e-05
3.89e-05
2.96e-05
2.02e-05
1.09e-05
1.50e-06
[m]
2.65 m

b)


particle-tracks-1
Particle Diameter
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8.57e-05
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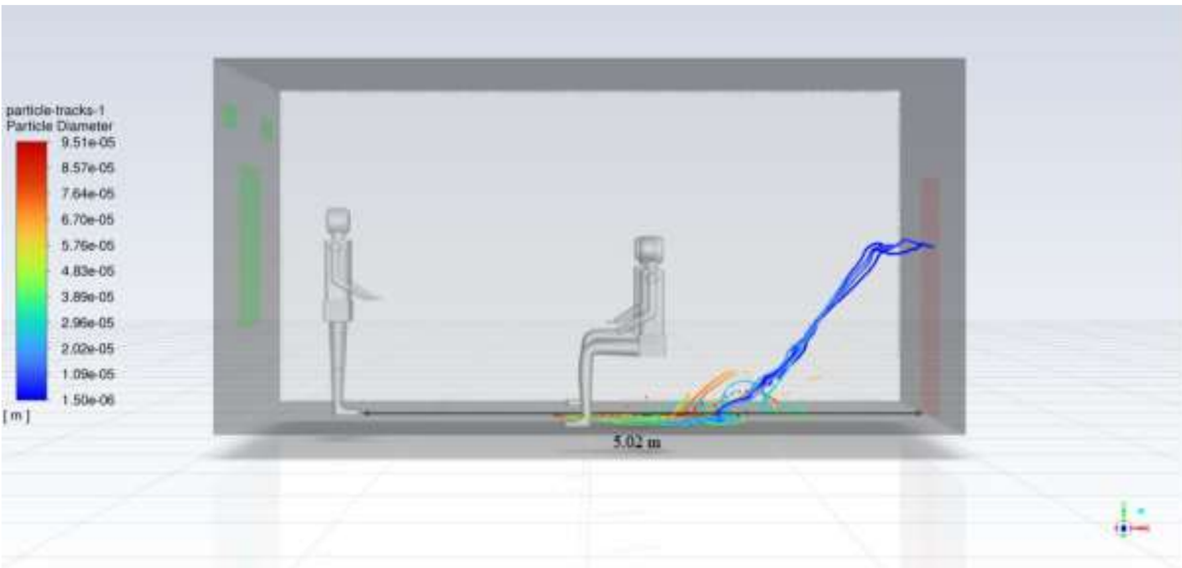
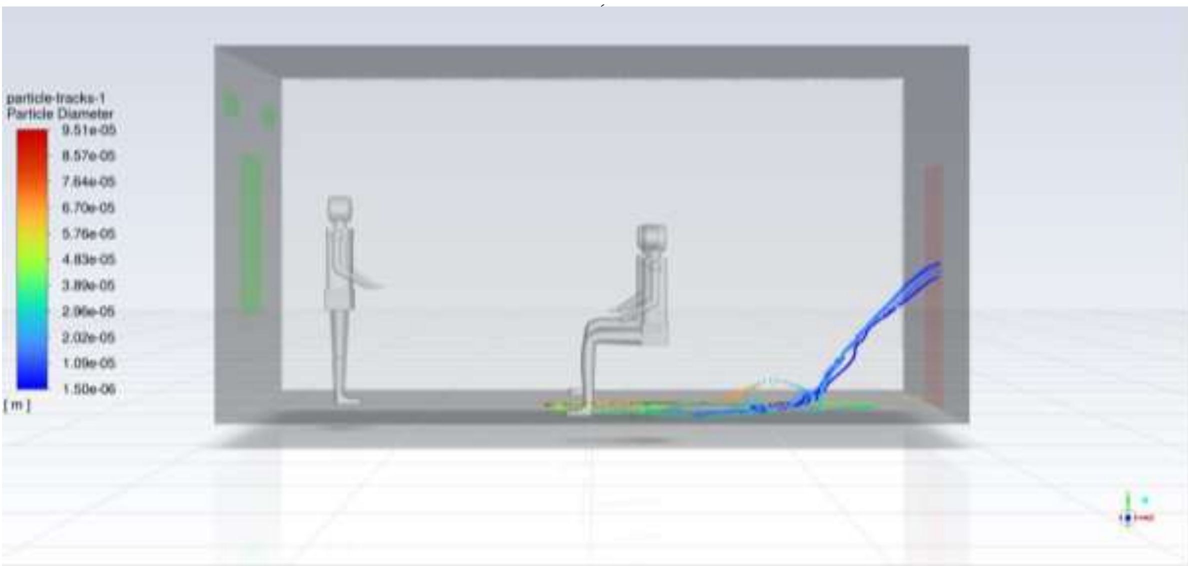
6.70e-05
5.76e-05
4.83e-05
3.89e-05
2.96e-05
2.02e-05
1.09e-05
1.50e-06
[m]
2.65 m

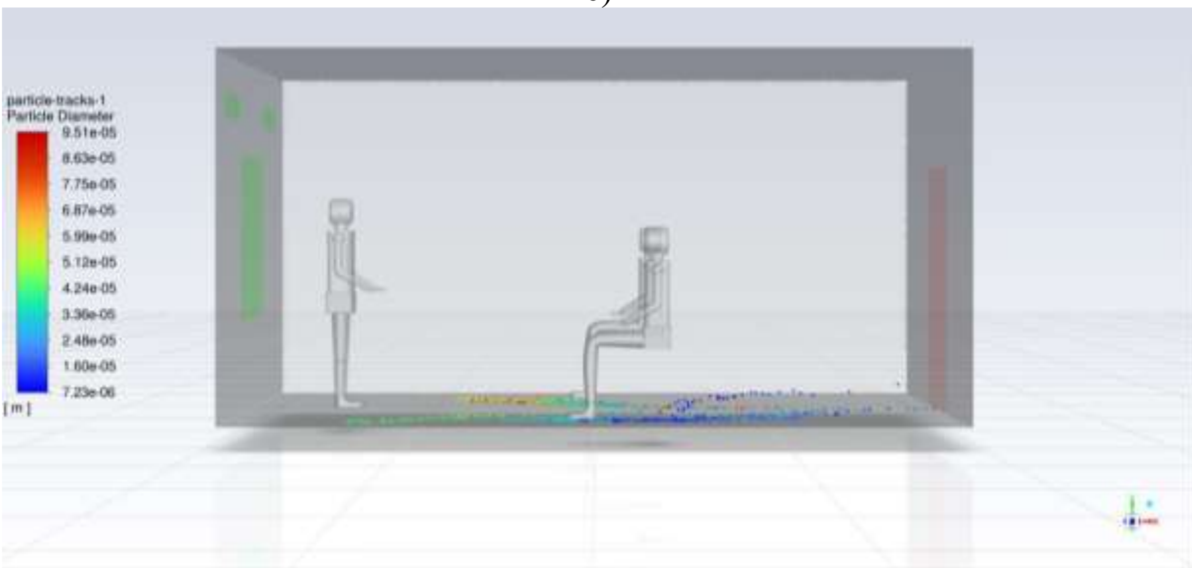
c)


particle-tracks-1
Particle Diameter
9.51e-05
8.57e-05
7.64e-05
6.70e-05
5.76e-05
4.83e-05
3.89e-05
2.96e-05
2.02e-05
1.09e-05
1.50e-06
[m]
5.02 m

d)




e)




f)

Figure 14 – Particle propagation at a) 0.5 s, b) 3.6 s, c) 6.1 s, d) 8.9 s, e) 10.9 s and f) 28.4 s

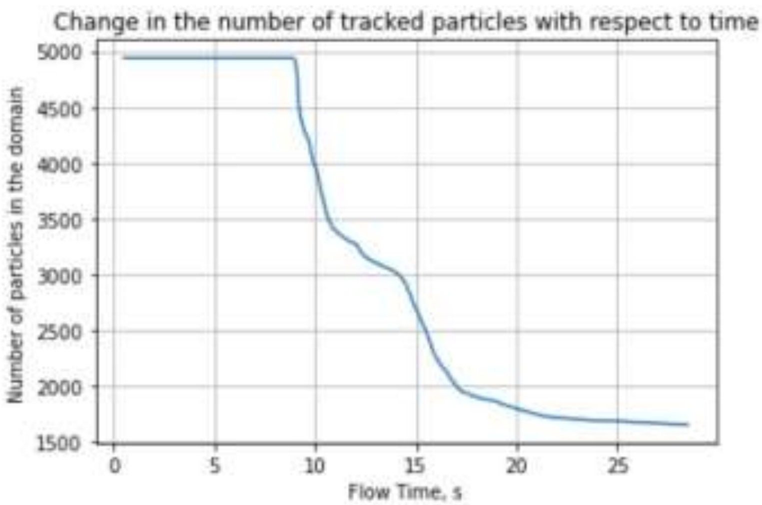



Figure 15 – Decline in the number of particles with respect to time (sneezing case)

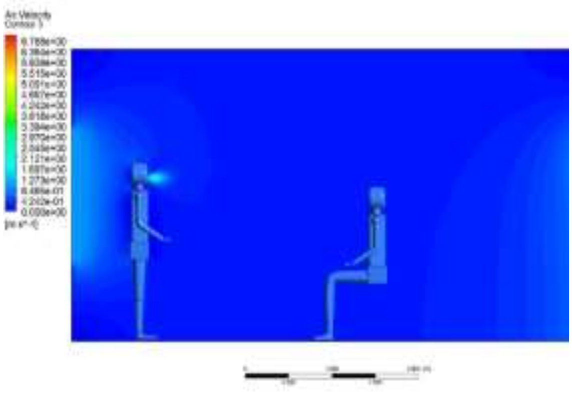
After the observation of sneezing event, which is the one of the main ways of coronavirus propagation, a coughing event was also examined as human reflex. In the simulation, the infected individual exhales contaminated aerosols, drops and droplets from 0 s to 0.5 s of flow time. Table 2 illustrates a detailed data about ejection of particles during a cough.

Table 2 – Data for particle ejection during the coughing

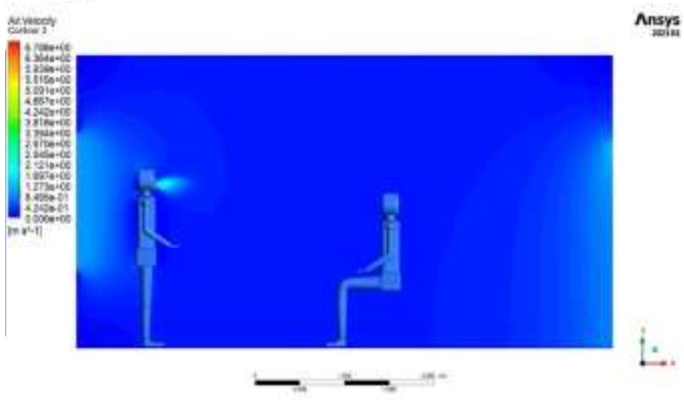
| Ejection type | Group |
|---|---|
| Number of particles | 990 |
| Velocity of particles | 7 |
| Start time | 0 |
| Stop time | 0.5 |
| Minimum diameter | 1.5e-6 |
| Maximum diameter | 0.0001 |
| Mean diameter | 3.53e-5 |

Total number of particles tracked in the enclosed space is 990. Minimum and maximum diameters of contaminants are in the range of 1.5-100 µm and a mean diameter is 35 µm. A velocity for coughing case is set to 7 m/s. Moreover, to simulate the airflow from the mouth time dependent UDF was applied. Figure 16 shows the airflow produced via coughing at 0.1-0.5 s. Figure 17 demonstrates the dissemination and the behavior of coronavirus contained particles during the cough. Figure 17a shows emitted particles after the emission at 0.5 s. It is seen that after the coughing large particles start to fall immediately, while aerosols and tiny droplets can traverse for more than 2 m within 5.3 s (Figure 17b). Therefore, contaminated drops with diameter of 95 µm settle on the floor at 5.8 s. Moreover, a part of particles with dimensions of 40-50 µm falls to the ground at 7 s, whereas aerosols in the interval of 1.5-10 µm leave 2.65 behind (Figure 17c). It is worth noting that light particles start to approach the floor after 7 s of flow time traveling 5.02 m. It is illustrated in Figure 17d, due to the recirculation zone close to the infected individual a fraction of medium drops (58-60 µm) is prone to go up and follow the airflow in *x* direction. At the same period, aerosols commence to escape the confined space. Figure 17e demonstrates the fraction of droplets with diameters of 58-60 µm leaving the computational domain at 20.5 s. In the end of flow time, particles with dimensions of 11-95 µm direct towards the emitter because of the recirculation and settle on the floor (Figure 17f).

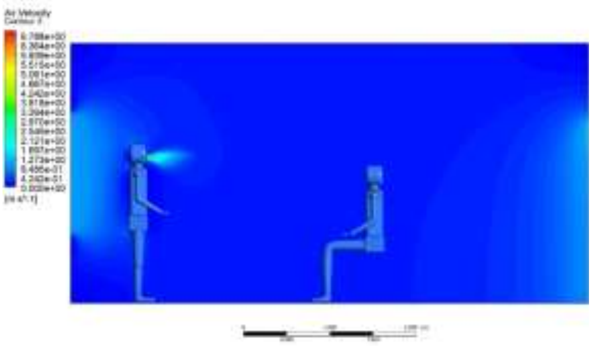
Figure 18 demonstrates a decline in the number of particles within 30 s during the coughing. Total number of contaminants remains the same from 0.5 s to 14.2 s. Further, there happens a dramatic decrease in the number of tracked particles. Namely, number of droplets is reduced from 990 to 598 in the period of 14.3-17 s. Finally, a progressive reduction of contaminated particles can be examined from 17.1 s to 30 s. 450 coronavirus contained droplets settle on the floor of office room. It is worth to note that the supplied airflow from ventilation system and open window can control coronavirus transmission reducing number of particles by two times.



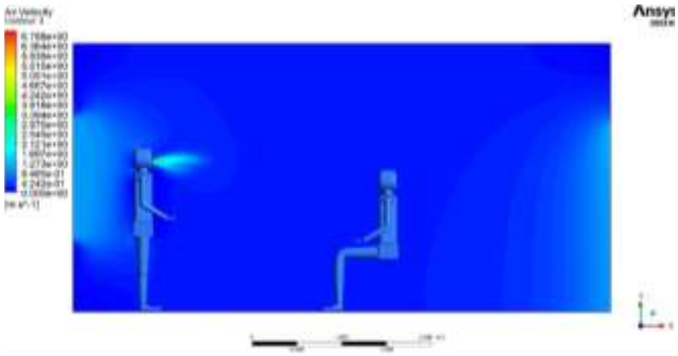
a)



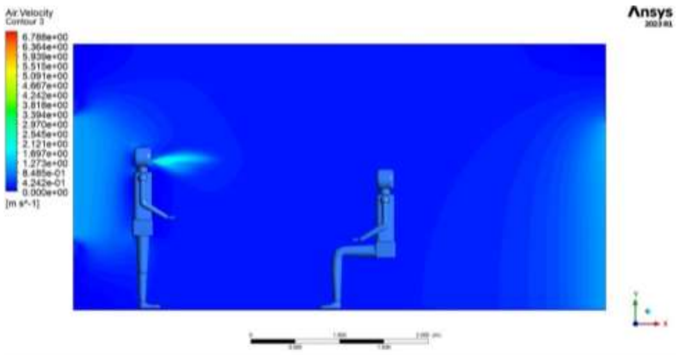
b)



c)

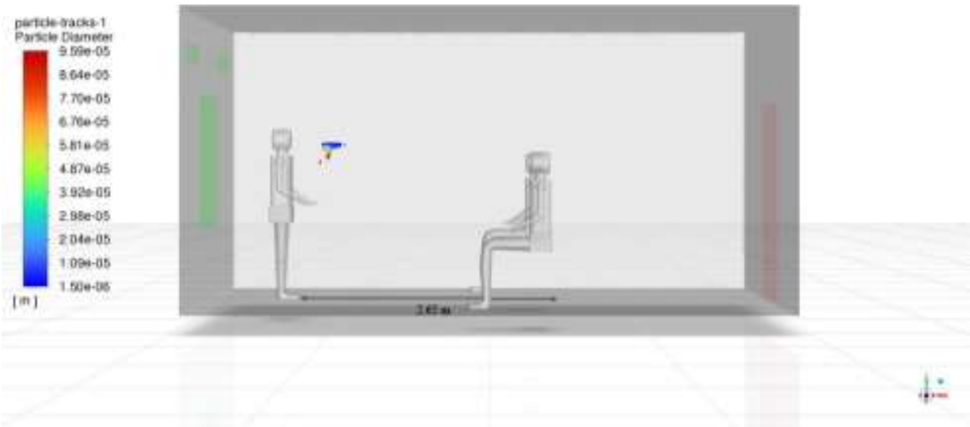


d)



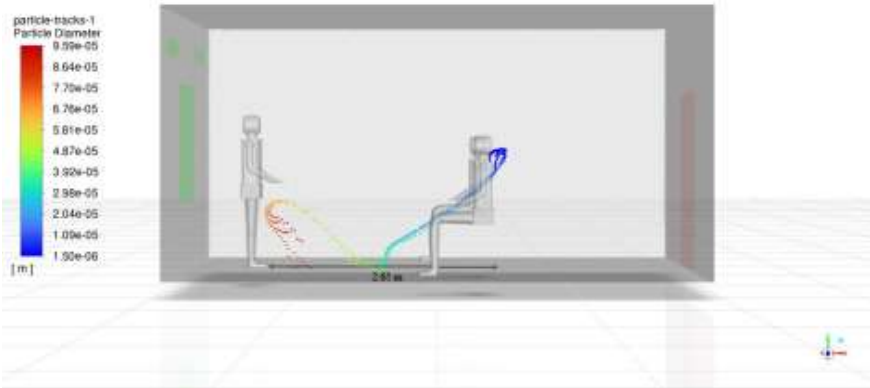
e)

Figure 16 – Airstream coming from the mouth at a) 0.1 s, b) 0.2 s, c) 0.3 s, d) 0.4 s and e) 0.5 s

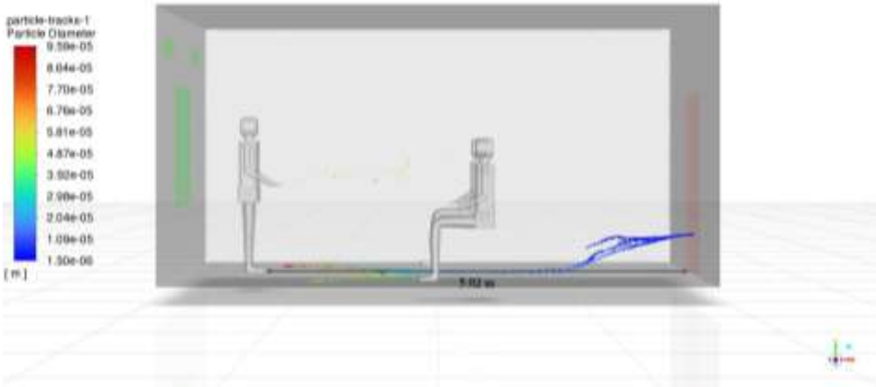



a)

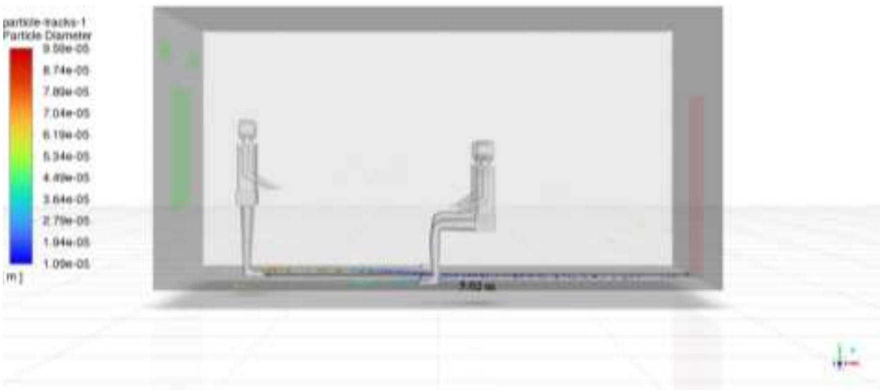

b)



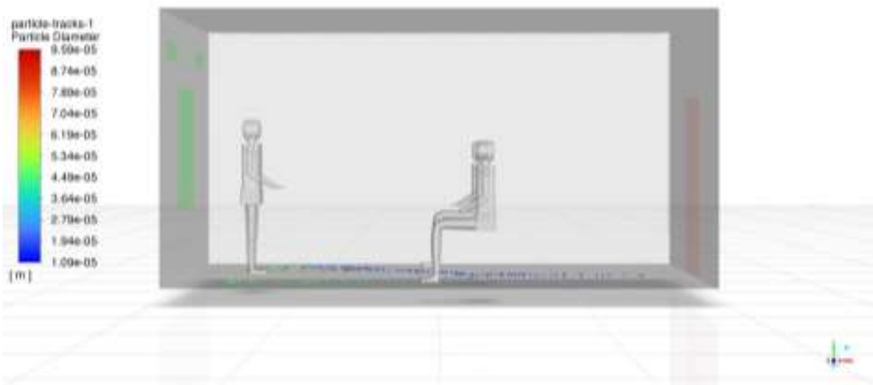

c)




d)




e)




f)

Figure 17 – Particle propagation at a) 0.5 s, b) 5.8 s, c) 7 s, d) 14.3 s, e) 20.5 s and f) 30 s

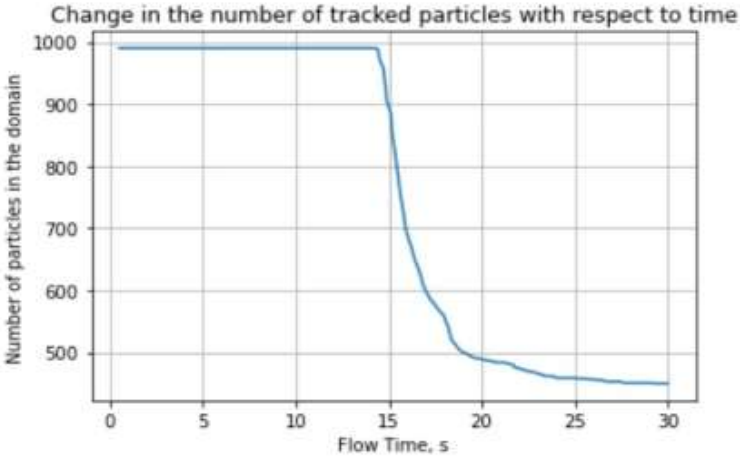



Figure 18 – Change in the number of particles with respect to time (coughing case)

**Conclusion**

COVID-19 pandemic, which was initially detected in Wuhan city in 2019, caused harmful consequences globally including the economic loss, total population, etc. To stop and control its propagation a myriad of preventive measures was investigated and implemented such as quarantine, lockdown, wearing medical masks and gloves, social distancing, mouthwash, hand hygiene and so on. In addition, many researchers studied the effectiveness of ventilation system and open windows. The findings showed that the airstream produced by air conditioning and a presence of open window as inlet or outlet can significantly manage virus transmission in enclosed spaces. Therefore, the main objectives of this work consist of the simulation of SARS-CoV-2 diluted particles' transmission in the confined space, observing the behavior of exhaled aerosols, drops and droplets and examining the efficiency of air conditioning and open window.

Two human reflexes were under the observation such as sneezing and coughing. As it was mentioned, viruses are prone to transmit airborne via breathing, talking, singing, sneezing and coughing. Propagation of virus particles depends on the diameter size and ejection velocity. It was examined in given study, after sneezing emitted particles can traverse for more than 5 m. To be precise, aerosols (1.5-10 μm) maintain the height of 1.68 m travelling more than 5 m and start to leave the computational domain at 8.9 s. Large particles commence to settle on the floor at 6.1 s of flow time leaving about 2.65 m behind.

In coughing case, light particles (1.5-10 μm) also travel more than 5 m, however, comparing to the sneezing event, the height maintained by particles gradually declines within 13.8 seconds. After the reflex, large contaminants (95 μm) are prone to settle on the floor immediately next to the infected individual.

In both cases, there is a tendency for tiny particles to traverse for more than 5 m, but it can be seen in coughing event, they approach the floor of the office room close to the outlet. After sneezing, aerosols escape the domain at 8.9 s; while in coughing case, tiny contaminants leave at 14.3 s. Further fate of particles in the domain for each case can be deduced as follows: due to the recirculation created by venting system and window large and medium sized droplets tend to direct towards the standing human model and settle on the ground. On the other hand, the effectiveness of the airstream generated by air conditioning system and open window is noticeable. The airflow allows aerosols with dimensions of 1.5-10 μm to leave at 8.9 s and 14.3 s for sneezing and coughing cases, respectively. The analysis of tracked particles during whole flow time shows that total number of coronavirus particles is cut by almost three times in sneezing case, while amount of tracked particles is reduced by two times in coughing case. Therefore, it is essential to have air conditioning system and open window as inlet for airflow in confined spaces during an epidemic or pandemic since they are able to manage virus transmission. Based on the findings of current paper, along with presence of ventilation system and open window, wearing medical masks and gloves, hand hygiene should be considered to avoid the cases of infection.

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