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Finding the proper position of supply and return registers of air conditioning system in a conference hall in term of COVID-19 virus spread

Détermination de la position correcte des registres d’air extrait et d’air soufflé du système de conditionnement d’air d’une salle de conférence en termes de propagation du virus COVID-19

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ARTICLE INFO

Keywords:
COVID-19
Dispersion
Computational fluid dynamic (CFD)
Cough droplets
Discrete phase model (DPM)

Mots clés:
COVID-19
Dispersion
Mécanique numérique des fluids (CFD)
Gouttelettes projetées par la toux
Modèle de phase discrète (DPM)

ABSTRACT

The outbreak of the COVID-19 has affected all aspects of people’s lives around the world. As air transmits the viruses, air-conditioning systems in buildings, surrounded environments, and public transport have a significant role in restricting the transmission of airborne pathogens. In this paper, a computational fluid dynamic (CFD) model is deployed to simulate the dispersion of the COVID-19 virus due to the coughing of a patient in a conference hall, and the effect of displacement of supply and return registers of the air conditioning system is investigated. A validated Eulerian-Lagrangian CFD model is used to simulate the airflow in the conference hall. The particles created by coughing are droplets of the patient’s saliva that contain the virus. Three cases with different positions of supply and return registers have been compared. The simulation results show that case 1 has the best performance; since after 80 s in case 1 that the inlet registers are in the longitudinal wall, the whole particles are removed from space. However, in other cases, some particles are still in space.

1. Introduction

Most of viruses are transmitted through the secretions caused by sneezing and coughing and through the air (Sun et al., 2022). On the other hand, humans spend 85% of their time in closed environments such as homes, workplaces, offices, cinemas, conference halls, transportation vehicles, etc. (Rodriguez-Criado et al., 2022). The combination of these issues has caused the issue of indoor air quality to be considered by architects and building HVAC’s specialists in recent years. Due to the efficiency of CFD in multi-phase flow analysis, this tool has been used to analyze the spread of various viruses.

Some researchers investigated the dispersion of viruses in closed spaces. Li et al. (Li et al., 2018) modeled the diffusion of cough droplets in the quiescent air. They examined the effect of ambient temperature, droplet mass, and air humidity on droplet diffusion. Zhu et al. (Zhu et al., 2006) experimentally measured the initial velocity of coughed droplets in the quiescent air. They represented that the initial velocity ranges of droplets due to coughing are between 6 m/s to 22 m/s. Aliyu et al. (Aliyu et al., 2021) compared the number of respiratory droplet transfers with and without facemasks in the ventilated rooms by a mathematical model. Portarapillo et al. (Portarapillo and Di Benedetto, 2021) proposed a methodology to perform a risk analysis of the virus spread. Mirzaie et al. (Mirzaie et al., 2021) investigated the distribution of COVID-19 particles in a classroom with and without partition. They placed some transparent barriers in front of the seats and measured the concentration of infectious particles in any partitioned space. Trytyakow et al. (Trytyakow et al., 2021) developed a model to quantitatively evaluate the effect of the face shield on decreasing the airborne transmission risk of the coronavirus SARS-CoV-2 using the computational

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### Nomenclature

| Symbol | Definition                                      |
|--------|-------------------------------------------------|
| P      | Pressure (Pa)                                    |
| t      | Time (s)                                         |
| T      | Temperature (K)                                  |
| u, v, w| Velocity components (m/s)                        |
| x, y, z| Cartesian direction                              |
| n      | Number of particles                              |
| FD     | Drag force                                       |
| r      | Particle radius                                  |
| G      | Gravitational acceleration components (m/s²)     |
| F      | Force (N)                                        |
| V      | Velocity vector (m/s)                            |
| m      | Mass (kg)                                        |
| c_p    | Specific heat capacity (J/kg K)                  |
| N     | Total non-dimensional numbers of droplets        |
| D      | Droplet diameter (m)                             |
| K      | Fluid thermal conductivity (W/m K)               |
| C      | Concentration (Microgram/m³)                     |
| PRT    | Particles resident time                          |
| Q      | Heating load of coil                             |
| C_f    | Rate of air flow (ft³/s)                         |
| C_c    | Cunningham coefficient                           |
| d      | Particle's diameter (m)                          |
| k      | Turbulent kinetic energy (J)                     |
| S      | Source term                                      |
| A      | Area number                                      |
| m      | Mass flow rate of particles (kg/s)               |

### Greek symbols

| Symbol | Definition                                      |
|--------|-------------------------------------------------|
| ε      | Dissipation rate of the turbulent energy        |
| ρ      | Density (Microgram/m³)                          |
| μ      | Dynamic viscosity (m²/s)                        |
| α      | Thermal diffusivity (m²/s)                      |

### Subscripts

| Symbol | Definition                                      |
|--------|-------------------------------------------------|
| d      | Droplet                                         |
| p      | Particle                                        |
| x, y, z| Cartesian directions                            |
| tot   | Total                                           |
| avg   | Average                                         |
| db - e| Entering dry bulb air temperature               |
| db-sa | Supply dry bulb air temperature                 |

**Fig. 1.** Schematic of a) conference hall with three layout of registers b) the space that has been zoned into 20 regions (top view).
fluid dynamics (CFD) technique. Guan et al. (Don Guan et al., 2014) investigated the effect of a moving patient on the transmission characteristics of cough particles by dynamic mesh and Lagrangian particle tracking method.

Many studies evaluated the effect of ventilation systems on the distribution of pathogens in closed spaces due to coughing, sneezing, etc.

Zhang et al. (Zhang et al., 2020) investigated the distribution of cough droplets using CFD in a conference room. They did it in four different positions of the air-conditioning inlet and outlet registers. They changed the position of the air-conditioning inlet and outlet registers to evaluate its effect on the dispersion of particles. Their goal was to identify the best form of particle distribution in terms of the distribution of pathogenic particles. They found that when the supply register is at the bottom, and the return register is at the top, it is the best form to reduce the concentration of pathogenic particles. Motamedi et al. (Motamedi et al., 2022) proposed a framework to assess the infection probability under different ventilation strategies. Kotb et al. (Kotb and Khalil, 2020) studied how the virus spreads through coughing and sneezing in an airplane cabin and concluded that sneezing is more contagious than coughing, because sneezing droplets travel longer distances. Their results also showed a direct relationship between the speed of a passenger moving inside an aircraft and the distance traveled by the virus. They investigated the effect of patient’s movement on particles dispersion.

Feng et al. (Feng et al., 2020) investigated the influence of wind and relative humidity on the social distancing effectiveness to prevent COVID-19 airborne transmission. Srivastava et al. (Srivastava et al., 2021) investigated the infection risk with the spatial distribution of SARS-CoV-2 in an office building in the presence of an Ultraviolet-C (UV-C) disinfection device. Li et al. (Li et al., 2021) experimentally
and numerically studied the steady-state aerosol transmission characteristics in a full-size room using a dedicated outdoor air system coupled with ceiling fans. Liu et al. (Liu et al., 2020) studied the dispersion of COVID-19 in an elevator during the movement of the elevator from the ground to the 35th floor, during the movement from the ground floor to the 35th floor. During this time, a patient spreads the virus particles inside the elevator by breathing. Yan et al. (Yan et al., 2020) investigated the cough flow and its time-dependent jet effects on the transport of contaminants in a three-row Boeing 737 cabin. Cao et al. (Cao et al., 2022) investigated the impact of the turbulence model, ventilation system, geometry simplification, particle simulation method, and boundary condition assignment on the airflow and particles distribution in airliner cabins with various ventilation systems. Ahmadzadeh et al. (Ahmadzadeh and Farokhi, 2021) studied the impact of mechanical and natural ventilation on the distribution, transmission, and shelf life of COVID-19 particles inside a classroom due to coughing and speaking. Ren et al. (Ren et al., 2021) investigated the effect of barrier heights on the dispersion of particles in an open office space with a well-designed ventilation mode and inlet air rate. Ren et al. (Ren et al., 2021) conducted a comparative study of three typical ventilation strategies using computational fluid dynamics in a prefabricated Coronavirus disease double-patient ward. Ahmadzadeh et al. (Ahmadzadeh and Shams, 2021) investigated the spread of droplets inside the cabin of a train. The innovation of their work was the investigation of the influence of the infected passenger’s motion while talking. They changed the outflow location and the infected passenger’s position and studied their effects. An attempt was made by Mesgarpour et al. (Mesgarpour et al., 2021) to provide a novel approach to the prediction of droplet distributions set by sneezing of an infected person inside a bus. Taheri et al. (Taheria et al.,

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**Table 3**

| No. | Number of meshes | $V_{avg}$ (m/s) | $P_{avg}$ (Pa) |
|-----|------------------|-----------------|----------------|
| 1   | 498000           | 0.5775          | 19.9705        |
| 2   | 1157000          | 0.5511          | 20.0727        |
| 3   | 2085000          | 0.5449          | 21.2561        |
| 4   | 2694000          | 0.5441          | 21.2569        |

**Table 4**

| NO. | Time step | $V_{d,avg}$ (m/s) | $D_d$ (m) | $C_{avg}$ (kg/m³) |
|-----|-----------|-------------------|-----------|-------------------|
| 1   | 0.001     | 1.9563 e^{-05}    | 3.8735 e^{-09} | 1.8557 e^{-08}   |
| 2   | 0.0008    | 1.9385 e^{-05}    | 4.0070 e^{-09} | 1.7156 e^{-08}   |
| 3   | 0.0006    | 1.6437 e^{-05}    | 4.5438 e^{-09} | 1.6355 e^{-08}   |
| 4   | 0.0005    | 1.6038 e^{-05}    | 4.6173 e^{-09} | 1.5190 e^{-08}   |
| 5   | 0.0004    | 1.6001 e^{-05}    | 4.6170 e^{-09} | 1.5155 e^{-08}   |

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**Fig. 6.** Comparison of airflow pattern in the centerline plane (width = 1.5 m) (a) present study (b) done by Lu et al. (Lu et al., 1996).
Zou et al. (Zou et al., 2022) investigated the effects of fan-coil airflow direction on the indoor air quality in a room. They did this work by vertical, 60° inclined, 30° inclined, and horizontal discharge fan-coils. Zou et al. (Zou et al., 2022) studied the flow in a cross-flow fan that worked in an Air-conditioner Indoor Unit. They proposed a structure optimization strategy for the cross-flow fan, which effectively improves the aerodynamic and acoustic characteristics of the cross-flow fan. Dai et.al (Dai and Zhao, 2022) proposed a simple model to investigate the effect of the indoor position of portable air cleaner on reducing the airborne infection risk of COVID-19. Zhao et al. (Praeger et al., 2021) investigated the effect of increasing the ACH and returning the air volume in contaminant concentration in occupied zone and unoccupied zone in a Class 10,000 cleanroom. Prager et al. (Zhao et al., 2021) evaluated the influence of bin stacking arrangements and fan position on the airflow in an industrial apple storage room. They found that locating the fan above the gaps was more efficient for bin ventilation than directly above the bins.

According to the above report, it can be found that most of the methods proposed by other researchers to decrease the exposure time use additional equipment such as fan or cause to increase the energy consumption such as raising the ventilation velocity. The main objective of this research is to find a passive method to control the COVID-19 viruses expelled by the coughing of an infective person, which is inexpensive and low energy loss. The way that has been investigated in this study is the displacement of ventilation registers and its effect on the exposure time. Three cases are considered for the layout of ventilation registers. The performance of ventilation system in removing the COVID-19 particles from the environment has been compared. A parameter called discharge performance has been defined, which is considered as a criterion of the performance of the air conditioning system in removing contaminants.

### 2. Problem description

Many aspects of life and work have been affected by the emergence of the Coronavirus in recent years. Because the work environment of many businesses, especially office jobs, is a closed space, it is necessary for architectural and HVAC engineers to make changes in the design of spaces and air conditioning systems. So that in addition to providing thermal comfort conditions for residents, better conditions are provided in terms of non-transmission of airborne diseases. So far, several methods such as setting an extra fan to remove pathogens, increasing the speed of the ventilation system, opening doors and windows, setting the air curtains, partitioning the spaces, etc. have been suggested to encounter pathogens. Some of these methods require a system independent of the air conditioning system, and some cause energy loss and consequently increase the costs. The authors of this paper are looking for a method that is not independent of the air conditioning system and is cheaper to implement. Some of these methods require a system independent of the air conditioning system, and some waste the energy and consequently increase the costs. Also, a method is needed that, first, is not independent of the air conditioning system and is implemented at a lower price. Secondly, it does not cause energy loss. Therefore, it is suggested to replace the supply and return air registers. The purpose of this study is to obtain the proper position of the register to create adequate air turbulence to remove viruses and pathogens faster. In the conventional air condition systems design, the position of the registers is considered only from the aspect of uniform temperature distribution in the whole space. It is not considered in terms of creating proper turbulence to remove pathogen particles.
3. Equations and solution method

3.1. Equations

In Eulerian Lagrangian’s view, the fluid phase is considered a continuous environment. To solve the flow field, the Navier-Stokes equations are solved, while the discrete phase is solved by tracking a large number of particles, bubbles, or droplets in the calculated field.

Continuous phase

Governing equations for Steady Incompressible Eulerian model (continuous phase) include continuity, momentum, and energy conservation equations as the following.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{1}
\]

\[
\rho \left( \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla P + \mu \nabla^2 \mathbf{V} + \mathbf{S} \tag{2}
\]

\[
\rho \frac{\partial T}{\partial t} + \rho \nabla \cdot (T \mathbf{V}) = \nabla \cdot \left( \frac{K}{C_p} \nabla T \right) + S_T \tag{3}
\]

Fig. 9. Particles (0.150, 1, 10, 50, 100, and 150 μm according to Table 2) dispersion for different times for cases 1, 2, and 3.
k-ε RNG is used to consider the effect of turbulence on the simulation of fluid flow. The corresponding equations are given as follows:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho u_i k) = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k \tag{4}
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho u_i \varepsilon) = \frac{\partial}{\partial x_j} \left( \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_1 \varepsilon \varepsilon k (G_k + C_3 G_b) - C_2 \rho \varepsilon^2 \varepsilon - R_\varepsilon + S_\varepsilon \tag{5}
\]

In these equations, \(G_b\) is the production of turbulence kinetic energy due to buoyancy. \(G_k\) is the production of turbulence kinetic energy due to the mean velocity gradient. \(Y_M\) is the contribution of compressibility in turbulence. \(\alpha_k\) and \(\alpha_\varepsilon\) are turbulence Prandtl numbers. \(S_k\) and \(S_\varepsilon\) are source terms specified by the user. \(C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}\) are constants.

Discrete phase

The Lagrangian model is applied to model the trajectory and distribution of the discrete respiratory droplets exhaled from the patient’s mouth. The particle position is \(x_p\) achieved from:

\[
\frac{dx_p}{dt} = u_p \tag{6}
\]

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

\[
m_p \frac{du_p}{dt} = \sum F_p \tag{7}
\]

Where \(m_p\) is the particle mass and \(\Sigma F_p\) is the forces applied on the particle that is calculated from:

\[
\sum F_p = F_{\text{gravity}} + F_{\text{drag}} + F_{\text{other}} \tag{8}
\]

Where \(F_{\text{other}}\) is other extra forces applied on the particle, including the pressure gradient, the Brownian motion effect, the thermophoresis, the Saffman lift force, and the Magnus. Because the particles are small enough and there are no intense temperature changes, only the Brownian motion effect and pressure gradient force are considered. To investigate the effect of the drag force, the Stokes-Cunningham drag model is used. Consequently, the total force on the particle is:
In equation (9), the terms on the right-hand side are gravity/buoyancy force, the Stokes drag force, Saffman lift force, Brownian force, and pressure gradient force, respectively.

\[
m \frac{d \rho_c}{dt} = F_{\text{gravity}} + F_{\text{drag}} + F_{\text{saff}} + F_{\text{brownian}} + F_{\text{pressure}}
\]  

(9)

\[
F_{\text{drag}} = \frac{18 \mu f \rho_p d_p^2 C_c}{\rho_p d_p^2 C_c} (u_f - u_p)
\]  

(10)

\[
C_c = 1 + \frac{2 \lambda d_p}{\rho_p} \left( 1.257 + 0.4 \epsilon \left( \frac{11}{12} \right) \right)
\]  

(11)

Fig. 12. The distribution of cough droplets presence in different areas of the conference hall in different times.
Fig. 13. Average droplet concentration on the virtual plane at different times in three cases.
\[ m_p = \rho_p V = \rho_p \left( \frac{\pi d_p^2}{6} \right) \]  

(12)

\[ F_{\text{eff}} = 1.615 \rho_p u_p^6 d_p^2 \left( u_y - u_p \right) \left( \frac{d_n}{d_p} \right) \left( \frac{\rho_{\text{air}}}{\rho_p} \right) \]  

(13)

\[ F_{\text{pressure}} = -\frac{dp}{dx} \left( \frac{d_n}{d_p} \right)^2 \]  

(14)

\[ F_{\text{gravity}} = -\left( \rho_p - \rho_{\text{air}} \right) V \]  

(15)

\[ F_{\text{Brownian}} = m_p G \sqrt{\frac{2k_B T_{\text{in}}}{m_p}} \]  

(16)

where \( C_p \) is the Cunningham coefficient (Zhang et al., 2019), and \( G \) represents zero-mean, unit-variance, independent Gaussian random numbers, and

\[ S_{\text{in}} = \frac{216k_B T_{\text{in}}}{\pi \rho_{\text{air}} d_p^2 \left( \frac{\rho_{\text{air}}}{\rho_p} \right)} k_{\text{Boltzman}} = 1.380645 \times 10^{-23} \text{ J}/\text{k} \]  

(17)

The mass flow rate of particles is presented as:

\[ \dot{m} = \frac{4\pi d_p^2 \rho_p n}{t} \]  

(18)

where \( \rho \) and \( n \) are the density and number of particles, respectively.

By considering the total non-dimensional number of droplets at any time (Mirzaie et al., 2021), \( N_{n_{\text{in}}} \), as:

\[ N_{n_{\text{in}}} = \frac{n_{\text{in}}}{n_{\text{tot}}} \times 100 \]  

(19)

where \( n_{\text{in}} \) is the number of particles remaining in the environment and \( n_{\text{tot}} \) is the total number of particles injected into the environment, which according to Table 2 is 10,800 particles; the performance quality of the air conditioning system can be quantitatively compared in three cases.

3.2. Geometry

\[ Q = 1.08 \text{ cfm} \left( T_{\text{out}} - T_{\text{in}} \right) \]  

(20)

The space that is considered in this research is a conference hall with dimensions of 10 m \( \times \) 8 m \( \times \) 5 m (L \( \times \) W \( \times \) H), where 60 people are present. One of these people is considered a patient person (the source of the spread of the COVID-19 virus). The viruses are expelled from the mouth of the patient due to coughing. The cooling system considered for this conference hall is an air handling unit (AHU). Low-temperature air enters the space through the supply registers and after temperature exchange with the environment, it leaves the space and enters the AHU. After filtration and re-cooling, it is returned to space. To investigate the effect of changing the registers position on the spread of the virus, three cases have been considered for their layout. Fig. 1 shows the configuration of the conference hall in these cases. The return registers in all three cases are identical and are located one meter above the floor. Their dimensions are (60 cm \( \times \) 80 cm) and are located in longitudinal walls. In each wall, one return register is placed. The position of the supply registers is different in three cases. In case 1, four registers with dimensions of (40 cm \( \times \) 60 cm) are located in the longitudinal wall at 60 cm under the ceiling. In the second case, two (60 cm \( \times \) 80 cm) registers are placed on the ceiling, and, in the third case, two (60 cm \( \times \) 80 cm) registers are placed in the latitudinal walls and 60 cm on the ceiling. The injection location of particles (the patient’s position) is also shown in this image. Since in this research, the goal is only to investigate the effect of the movement of the registers on the distribution of viruses and to obtain the exposure time of the pathogens from the environment, so the energy consumption is considered the same in all three cases. Eq. 20 represents the consumed energy: where \( Q \) is the heating load of the AHU coil and is the function of cfm (the air flow rate entering the AHU coil), \( T_{\text{in}} \) is the temperature of the air entering the coil, and \( T_{\text{out}} \) is the temperature leaving the coil and entering the hall. In this equation, cfm or the flow rate of air entering the coil is obtained from the product of the velocity in the cross section of the registers. The speed of the inlet air, which is one of the boundary conditions of the problem, is the same in all cases. The cross-section of the registers is also the same in all three cases. In case 1, where the number of registers is more, instead, the registers have become smaller so that the cross-section of the air inlet is the same in all three cases.

3.3. Boundary conditions

According to ASHRAE, the supply air velocity is in the range of 500 ft/min (2.54 m/s) to 1500 ft/min (7.62 m/s). Supply air temperature is 55 °F (summer day). The air leaves the room through two return registers. In both registers, a pressure-outlet condition is imposed. Table 1 shows the boundary conditions used during simulation. Discrete phase boundary condition types that have been used are the trap condition in the solid walls and the escape condition for the inlet and outlet. The patient’s mouth has been modeled as a circle of diameter 0.04 m. Human exhalation contains droplets in the range of 0.01–500 μm (Gratton et al., 2011). In this research, six types of particles with different diameters have been injected. Gupta et al. (Gupta et al., 2009) measured the variation in flow rate at the mouth using a pneumotachograph-based spirometer to define the length of a cough or sneeze ejection flow. They showed that the period was approximately 0.3–0.8 s for a cough. In this study, 0.75 s has been selected for coughing duration. The particle’s density equals that of water (998.2 kg/m³) at 37 °C. Some experiments have counted the particles emitted per cough in various respiratory activities (Chao et al., 2009). The total number of droplets used was 10,800. The velocity of particles at the mouth is 10 m/s (Han et al., 2020), and their mass flow rates are calculated from equation (17). The complete specifications of droplets are given in Table 2.

4. Numerical model

4.1. Simulation

ANSYS-Fluent-20 is used to simulate the flow in this study, and the mesh type used is the poly-hex core mesh (Fig. 2). The Simple algorithm is employed for the velocity-pressure coupling. A high-resolution up-wind scheme is used to discrete the convection term. The RNG k-ε model obtained high reputation for predicting in-office airflow (Chen, 1995; Tsa-Hsing et al., 1995).

To cover the convergence condition, the residuals are plotted in any iteration and have to be decreased below the specified value (10⁻⁶). First, the continuous phase has been solved, and then the particles have been injected by keeping the continuous flow solution. The simulation has been done for (120 s) to investigate the dispersion of particles in the flow field. According to the experimental data of Gupta et al. (Gupta et al., 2009), a pulse air jet accompanied by droplets enters the space that is applied to the patient’s mouth. The pulse air jet has a time length of 0.5 s and a maximum flow rate of 4.2 L/s at t=0.08 s (Fig. 3), which makes the air velocity 13.4 m/s at the outlet. Droplets are injected into the space with the same velocity as the pulse air jet. Then a user-defined function (UDF) is used to apply the time dependent airflow of coughing at the patient mouth. Some assumptions have been used in this research which are: (1) cough emits only particles/droplets; (2) temperature differences are negligible; (3) droplet/particle sizes listed in Table 2 are those after evaporation of their water content, and there is no further evaporation; (4) no-slip conditions between phases is considered; (5) virus-infected droplets are treated as particles; (6) heat transfer from the human bodies is neglected (Mirzaie et al., 2021).
4.2. Validation

The present numerical solution is validated by comparison with Li et al. (Li et al., 2018), where droplets with 10 μm diameter at mass flow rates 5.24 × 10^{-11} kg/s and a humidity of 0% are used. Their model was a chamber with a dimension of (L \times H \times W = 4 m \times 3 m \times 2 m). No ventilation was deployed for creating a quiescent space. As shown in Fig. 4, the predicted droplets diameter (solid lines) due to coughing is compared with the Li et al. (Li et al., 2018) (dot points) result. A good agreement between them is achieved.

The second validation is performed for steady-state airflow i.e., continuous phase solution. The study conducted by Lu et al. (Lu et al., 1996) is used. The geometry studied in this study is a room shown in Fig. 5. The room is divided into two areas by a slightly thick wall. The supply and return registers with specific dimensions for the air inlet and exhaust, as much as ten times air change per hour, are installed in the latitudinal walls. In Fig. 6, the airflow velocity vector patterns are compared. All measurements have been done in a section of the room at (z = 1.5 m). As shown in Fig. 6, there is a good agreement between them.

4.3. Grid independence

In this study, to evaluate the mesh independency, four different grid sizes are investigated. The results of the grid independency analysis and the number of cells have been shown in Table 3. As can be seen, by increasing the number of meshes from 2085000 to 2694000, there is no noticeable change in the average velocity and pressure. Therefore, the solution is continued with 2085000 meshes.

4.4. Independence of time step

To examine the time step independence, the problem has been resolved for various time steps, and, then, the mean velocity, diameter, and concentration of particles were determined. Table 4 shows the results. As can be seen, by decreasing the time step from (0.0005 s) to (0.0004 s), there is no significant change in the mean velocity, mean diameter, and mean concentration. Therefore, a time step of 0.0005 is used to solve the time-dependent part.

5. Results and discussion

The simulation results are reported and discussed in this section. As mentioned earlier, the flow is first solved steadily without particle injection to obtain the continuous phase velocity and pressure field. The particles are then injected into the same field. Fig. 7 and Fig. 8 show the velocity contours and airflow streamlines in three cases under steady flow conditions. As can be seen, when the supply air enters the environment, an air jet is created, which then creates a circulating flow region. Then, by injecting the droplets, the distribution of droplets containing the pathogens (COVID-19 viruses) has been investigated. Fig. 9 illustrates how the particles distribute at various times (resident time) after injection in three cases. As shown in Fig. 9, in all three cases, up to (35 s) after the injection of the particles, the particles are almost scattered throughout the space, and contamination is possible in all parts of the space. The turbulence due to the air conditioning system causes droplet scattering throughout the space. There is almost no secure location for attendees in the conference hall, and it is possible to get infected everywhere. After (35 s), the air conditioning system starts removing particles from the environment. In (80 s) later, there are no particles in the environment in case 1; in contrast, in the other two cases, there are still some particles in the environment, which indicates the better performance of the air conditioning system in expelling the infectious particles in case 1, compared to other cases. In Fig. 10, performance of the air conditioning system in all cases has been compared. In this figure, N_{p} in three cases is obtained via equation (19) and is plotted at different times. As shown in Fig. 10, case 1 has the best performance, because it takes less time (80 s) to remove all droplets from space. Fig. 11 shows a bar chart of the number of particles that remained in the environment at different times after injection. As can be seen, while in cases 2 and 3, still 179 and 151 particles are, respectively, present in space, in case 1, there is no particle in environment, and all of the particles are either trapped or removed from space by the air condition system. Fig. 12 shows the percentage of cough droplets distribution in different zones of the conference hall at different times. The zoning of the conference hall space is shown in Fig. 1b. As can be seen, (1.5 s) after coughing in all cases, 100% of droplets are in zone A14. In (12 s) later, droplets have been dispersed in space and 60 % of them in case 1 posed in zone A8. The rest of them have been posed in zones A14, A13, and A9. In case 2, most of the droplets (60%) have been posed in zone A14, and the rest are in A19, A15. In case 3, droplets have been dispersed in more regions: A9, A10, A18, A14, A15, and A17. Droplet average concentration in different zones at different times in three cases has been shown in Fig. 13. Measurement location is a virtual plane that is in 1.2 m height. For example, droplet average concentration in A10 at (75 s) for case 1 is 0 while for case 2 are 0.7 Microgram/m³ and for case 3 is 2.5 Microgram /m³.

6. Conclusion

Another way to encounter with the Corona virus, in addition to medical measures, is not being exposed to this virus. In closed spaces, the ventilation system can remove these viruses from the environment. In this research, an inexpensive method is proposed and investigated to remove the COVID-19 virus. The effect of the ventilation registers displacement on air flow is studied, and a proper layout of ventilation register to decrease the exposure time is proposed. The studied environment is a conference hall that is cooled by an Air Handling Unit. It is assumed that viruses are trapped in a filter after passing through the return channel, and the returned air is clean and virus-free. A validated CFD code was used and the simulation was performed in two steady and unsteady stages, using the k-ε turbulence model. Three different cases were considered for the layout of the registers. The simulation was performed in all three cases and the number of viruses that remained in the environment was measured at specified times after particle injection. It cleared that changing the position of the register changes the air flow turbulence pattern, which this issue caused to change the exposure time. Specifically, in this research, in case 1, where the supply registers are located in the side walls, it has the best performance in terms of the viruses removing time. Of course, it is clear that the optimal layout of the registers depends on the air speed, the dimensions of the space, etc., and it differs from one space to another. In addition, how viruses are distributed throughout the space before they completely leave the environment has been shown to identify high-risk zones in terms of possible infection due to the presence of high virus numbers. This study can be a starting point for HVAC designers to pay attention to the last- ingness of pathogens in the space in addition to the uniformity of temperature distribution in the design of registers layout and to choose the best layout of register based on both of these factors.

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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