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Research Article

CFD modeling of influenza virus diffusion during coughing and breathing in a ventilated room

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ABSTRACT

The virus diffusion in a ventilated room with the droplets produced by coughing and breathing are presented by the Lagrangian model. When the human body is located in the middle of the room with two locations of AC, in front of and behind the human body, three angles of Air Conditioning (AC) gate are applied 0°, 30°, and 60° to show droplet particle diffusion in the room in these cases. Three types of coughing velocity profiles were selected, real human coughing, sinusoidal cough, and cough jet with one velocity profile of breathing as a step function to cover the inhaling and exhaling cycle. The simulation results show that the uncovered standing in the middle of the room, are more susceptible to infection for the bouncy and forced flow around the human body. Droplet particle moves in the room as a random diffusion and it is very sensitive to the thermal load inside the room, generally depends on the bouncy force and pressure force due to convection heat transfer. when the AC location at the opposite direction of coughing flow, the droplet travels a distance of about 3 m, 2.85 m, and 2.75 m for real cough, sinusoidal cough, and cough jet respectively. While the droplet travel distance is about 3.1 m, 3.2 m, and 2.9 m when the AC location is at the same direction of coughing flow. Finally, the adopted CFD modeling was also used to show the effects of different AC locations on coughing, breathing particle droplets distribution in different indoor spaces, such as buildings, hospitals, and public transports, Also, showed good visual demonstration and representation of the real physical processes.

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INTRODUCTION

In general, people are more susceptible to respiratory infectious diseases when they spent much more time in the closed space. The popular respiratory infectious diseases are influenza where it causes considerable economic losses and threatens human health. Recently with the outbreak of COVID-19 disease, a lot of researches about the droplets of breathing, sneezing, and coughing has been done. Previous literature is used two methods for

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this research area experiment and numerical simulation CFD to follow the transmission of airborne virus infection between person to person in indoor and outdoor environments. Moreover, issues are highlighted in this field of research which should take into account like droplet size and velocity, human gender, human activities like walking, running, and setting even indoor or outdoor. The experimental methods contain physical measurement of the concentration field in breathing zones and imaging visualization of expiratory flows. This method mainly used different apparatus for measuring the particle size, particle velocity, and particle movements, like as Interformatic Mie imaging, PIV, and Shadowgraph imaging [1, 2, 3] as shown in Table 1.

Numerical studies of particle-fluid flows, consist of three methods which can be used depending on the aim of the study i.e., fluid phases and particle movements: Eulerian-Eulerian methods, Lagrangian-Lagrangian methods, and Eulerian-Lagrangian methods as shown in Table 2. Some of numerical studies are presented by [4, 5, 6, 7, 8, 9, 10]. In the case of continuous interactions between particle phase and fluid phase, the Eulerian-Eulerian method can apply. For the particle tracking phase, the Discrete Phase Model (DPM) in Lagrangian form can implement this movement, and at the same time the Eulerian frame used for continuous phase. The third method treats the acting of the lift force, viscous drag, and buoyancy force on Lagrangian particles along their paths are taken into account and a stochastic behaviour of the surround turbulent flow [11]. CFD modelling utilizing numerical thermal manikins and well-founded different models for the transport of airborne particles can give a high accuracy of flow domain and concentration data [12, 13, 14]. The turbulence effect of the previous studies presented as LES model, DNS model, and RANS model, where the RANS model founded is more viable to simulate inner airflow (indoor) [6]. Airborne transmission in the indoor air sciences has become an important research topic [15, 16, 17]. The size distribution of droplets generated by human speaking, coughing, and sneezing in an isolated room, air-conditioned room, conference room in such different methods of ventilation, and supplying air have been covered in kinds of literature [4, 5, 6, 7, 8, 18, 19]. The expelled droplets size might be distributed from 0.1 μm to 1000 μm [1, 18, 20], which is broad enough to cause infections [18]. A human respiration activity generates tens of thousands of droplets by breathing, speaking, coughing, and sneezing [1, 21, 22]. The diffusion of droplet infection between occupants inside a space (indoor) is robustly affected by complicated interactions of AC flow, human thermal flow, and coughing flow [12, 23]. Ventilation flow type is one of the most important influential engineering methods the controls of airborne transmission indoors [24, 25, 26]. Zhu et al. [27] measured the velocity of coughing droplet by PIV experimentally, it's ranged between 6 m/s to 22 m/s, while Soon-Bark Kwon et al. [2] studied the effect of the initial velocity distribution of exhaled air from coughing and speaking of 17 males and 7 females. The PIV experimental data conducted that the average coughing velocity for males and females were 15.3 m/s and 10.6 m/s respectively, while speaking velocities were 4.07 m/s and 2.31 m/s respectively. Table 2 shows summery the headlines of previous studies with specific conditions.

Current study dealing with transport characteristics of virus droplets produced by coughing and breathing in a ventilated room. The aims of this work are to study the effect of change the AC setting as AC location and gate angle in the room, cough and breathing velocity profiles, as a real, sinusoidal, and jet form on thermal load distribution in the room. In order to predict the transient particle transport in airflow in the room at each time step, Lagrangian approach method was used in this study. Also, to analyze the coughing and breathing flow interaction with the mixed convection flow around human body.

METHODS AND MATERIALS

Method methodology

In CFD modeling of current study, there are two phases, air as a carrier phase and cough, breath droplets as a discrete phase. Finite volume method was used to solve the general governing equations by ANSYS CFX software.

Table 1. Sample of droplet size and velocity generated by coughing and speaking in previous studies

Authors	Case Study	Human activity	Results	Experiment test section
C. Chao et al. [1]	air jets and droplet size	Coughing and Speaking	dp=13.5 μm dp=16 μm	Interformatic mie imaging +PIV
Kwon et al. [2]	Exhaled air	Coughing and Speaking	Cough speak (m/s) 15.3, 10.6 M 4.07, 2,3 F	PIV
Tang et al. [3]	Airflow of human jet	Sneezing and Breathing	Nasal: 1.4 m/s Mouth: 1.3 m/s	Shadowgraph imaging

dp= droplet particle diameter

Boussinesq approximation and Second-order upwind schemes are selected for this purpose. Three-dimensional transient study with turbulent flow selected for modelling in this case. The general equation becomes as bellow [28].

$$\partial(\rho\phi)/\partial t + \nabla.(\rho\phi V) = \nabla.(\Gamma_{\phi}\nabla\phi) + S_{\phi} \quad (1)$$

Where ρ = density, V = velocity, ϕ = variables, Γ_{ϕ} = diffusion term, and S_{ϕ} = source term

Generally, the particle volume fraction is low for particle modeling in an enclosed environment. As a result, particles have little effect on turbulent flow and the interaction between the carrier air and the particles can be thought of as one-way coupling. Flow to particles, not the other way around. Furthermore, particle size is the most significant factor to consider. In this study, Lagrangian method was used to solve particle motion, tracking time and gets trajectory [5]. Where this process calculates individual trajectory after solving the particle momentum equation. when using the external forces with particle inertia. Lagrangian particle tracking model advantage and disadvantage as shown in Table 3.

the momentum equation will become as:

$$du_{pi}/dt = f_D/\tau_p \,.\, (u_i - u_{pi}) + F_{pi} + F_a \quad (2)$$

Where u_i = air velocity, u_{pi} = particle velocity, f_D = Stoke's drag as define in [29]:

F_{pi} = gravitational acceleration, F_a additional forces it can be expressed by the sum of force, thermophoretic force and Saffman's lift force [30, 31]. The mass transfer coefficient estimated with correlation at the air-water interface [32]. Where the floating droplets moves due to gravity, drag and Brownian forces according to Tian [33]. The following settings and assumptions were implemented in this simulation as shown in Table 4.

The solver running time according to the Computer Model hp Z820 workstation desktop Intel(R) Xeon(R)

Table 2. Sample of numerical studies refer to particle flow treatment

Authors	Numerical solution	Case Study	Human activity	Droplet size µm	Space of study
Jinliang et al. [4]	Eulerian model	Influence of human walking on droplets	Stationary and walking human	0.5-20	Isolation room
Gouhui Feng et al. [5]	Lagrangian And Eulerian	Respiratory aerosol transportation	Student talking un a room	5	Classroom
Zhigiang kang et al. [6]	Lagrangian model	Cough droplets	Coughing	10	AC room
Yixian zhang et al [7]	Lagrangian model	Cough droplets	Coughing	5	Conference room
Yihuan Yan et al. [8]	Lagrangian model	Effect of thermal human body on cough droplets	Coughing	≤20 ≥50	Enclosed chamber
B. Blocken et al. [9]	Lagrangian-Eulerian model	Social distance of droplet exhaled	Walking and running		Outdoor (tunnel)
J.M. Villafruela et al. [12]	3-D transient CFD model	predict the risk of airborne cross-infection in a room.	Breathing and standing people		Displacement ventilated room
Caiqing Yang et al. [13]	Lagrangian model	the droplets cross transmission between two manikins	Coughing and Breathing	100 µm, 10 µm	Isolation room

Table 3. Lagrangian particle tracking model advantage and disadvantage

Advantage	Disadvantage
• To obtain complete information about the behaviour and residence time of the particle. • Cheaper for a wide range of particle sizes. • Mass and heat transfer. • For flow when the different particle sizes result in different particle velocities.	• Large number of particles, it is very computational heavy. • The model is very expensive when turbulence is required. • It is restricted to low volume fraction. • Only possible as a post process for a large number of particles.

CPU E5-2690 0 @ 2.90 GHz (32 CPUs), RAM: 128 GB, and System type: 64-bit Operation System. For steady state solution (initial condition for transient solution without coughing and breathing cycles was 3 days), while for transient solution needs about 2 weeks to finish three cycles of coughing and one cycle of breathing.

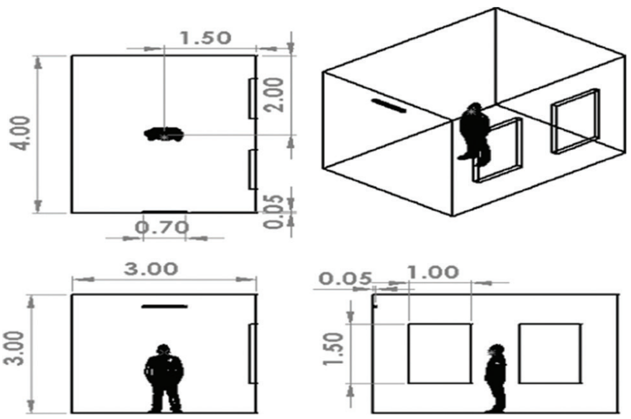

Figure 1. Presents the geometric room model, AC, and human body location.

Geometry model and mesh generation

Figure 1 describes the geometry model of the room case study with one human body (Man) stand in the middle of the room. The room dimensions are (4m, 3m, 3m), with two windows each one has dimensions (1.5 m x 1 m), which are located in the external wall. The full body computational model of 170 cm height and 75 kg weight with a realistic human head geometry containing full facial features was employed, the size of mouth is (0.02m×0.01m), and each nose hole has 0.01m diameter. There are two different models of room depending on the AC location (in front of or behind the human body). AC dimension is (0.7 m, 0.05m, 0.05m) with three gate angles (0^{o}, 30^{o}, and 60^{o}) with vertical wall.

Due to the complex geometry model, unstructured grids (Tetrahedral and hexahedral elements) are used around the human body, as shown in Figure 2. The unstructured mesh was chosen for volume domain with refined mesh in front of the human body to predict high cough resolution. The high concentration of the gradient, vector and scalar variables needs a very fine local grid; therefore, the cell size of less than 0.5 mm is significantly refined at the human body's nose and mouth besides, the cell size of AC inlet, AC

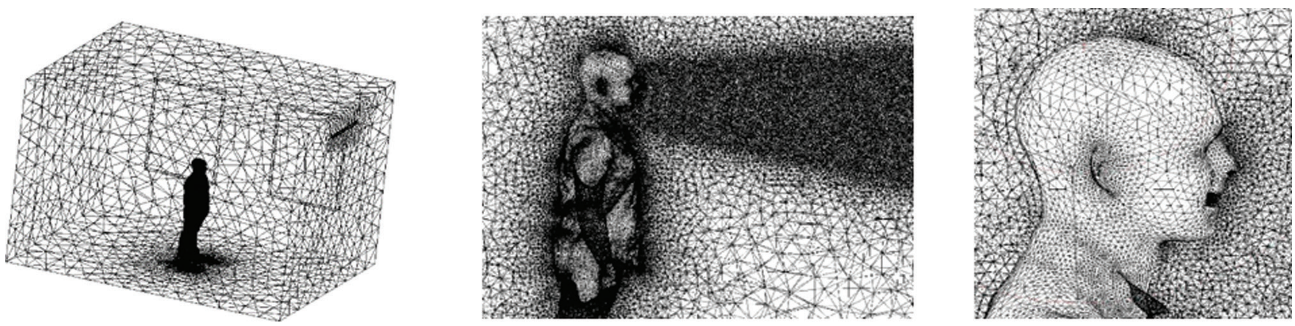

Figure 2. Mesh generation of the computational domain.

Table 4. Simulation setup

Analysis type	Steady state solution for initial condition to next step of transient solution
Advection scheme	High resolution
Transient scheme	Second order backward Euler
Turbulence model	k-ε model with scalable wall function
Convergence criteria	Residual target 10^{-6} + Courant number less than 10 (Adaptive time step. Nearly, time step equal 0.001 s)
Practical movement model	Lagrangian model
Drag force	Schiller and Naumann model [34]
Practical heat transfer	Ranz Masrshal model [32]
Practical diameter distribution	Rosin Rammler model [35]
Rosin Rammler size	10 micron
Rosin Rammler power	3
Practical mass flow rate	$2.4e0^{-9}$ kg/s

outlet and human body surface. Mesh quality and statistics: Total number of elements were 2757452 with curvature size function, target skewness about 0.98 and smoothing medium type. Inflation option was used around the human head body with 10 layers and growth size 1.2.

Implemented boundary condition

Three types of coughed velocity profiles are investigated as a real human cough profile [36], sinusoidal cough profile and jet airflow profile as shown in Figure 3. Cough profile cycle is repeated three times during each case to show the droplet movement in the room clearly. Also, the figure shows velocity profile of nose breathing as exhaling and inhaling during transient case. Working fluid taken as an air and caught droplet as water.

Near the human body surface, a log-law wall function was applied to capture the generated forces on the wall, moreover to predict the convective heat transfer for extended study. Boundary conditions are presented as shown in Table 5.

Numerical solution and validation test

The equations (1, and 2) are discretized into algebraic equations, and solved by SIMPLE algorithm. The second-order central difference is implemented respectively for the convection and diffusion terms. All settings were presented

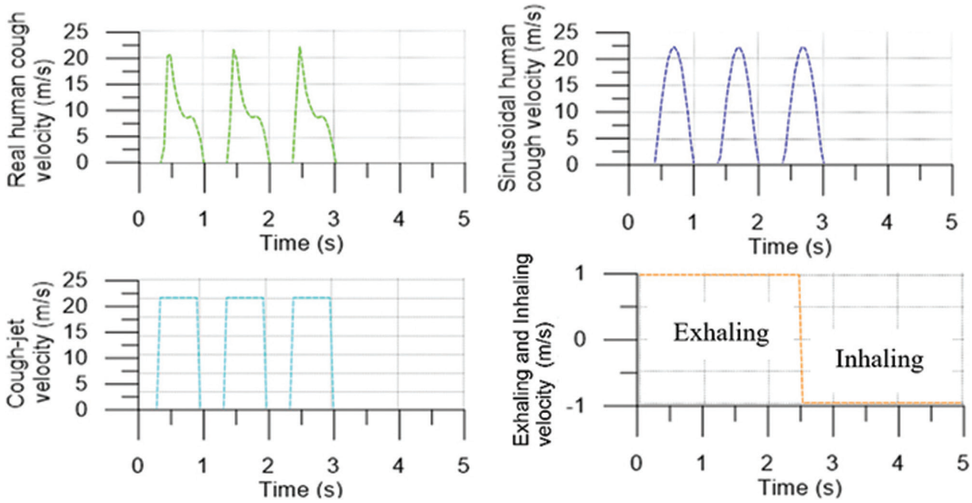

Figure 3. Types of cough human body and exhaling, inhaling velocity profile.

Table 5. Implemented boundary conditions

Items	Descriptions
Room walls	
External wall	Isothermal 31 □
Internal wall	Isothermal 25 □
Front wall	Adiabatic
Back wall	Adiabatic
Bottom wall (floor)	Adiabatic
Top wall (ceiling)	Adiabatic
Mouth	
Cough profile	Velocity profile (Figure 3), turbulence intensity 10%, 35 □
Cough droplet	Water
Temperature	35 □ [6]
Human body surface	Heat dissipation 22.8 W/m^2 [37, 38]
Nose	Velocity profile (Figure 3), turbulence intensity 10%, 35 □
AC Inlet	2 m/s, turbulence intensity 5%, 22 □, with different β (Figure 4)
AC Outlet	Air change per hour (ACH)=5, mass flow rate= 0.059 (kg/s)
Particle injection region	Cone injection with angle 25^o, 35 □

in Table 4 and 5. The single cough duration is assumed to be 0.6 s [11], in this study three cycles of coughing with one cycle of breathing during simulation applied.

Due to case study complexity, the first step was finding the temperature and velocity distribution in the room when Air conditioning worked with bouncy force effect according to the boundary conditions under absence coughing and breathing cycles. This case will be as an initial condition for the next step of the transient simulation. In this way, the solution convergence criteria will be satisfied. Therefore, the validation case applied to the public previous studies in this field like references [39, 40, 41] to capture the thermal load in the room without coughing and breathing cycles.

The results show a good agreement against the experimental and numerical published data as shown in Figure 5. The figure presents the measured location points inside the room, and compare results with previous studies.

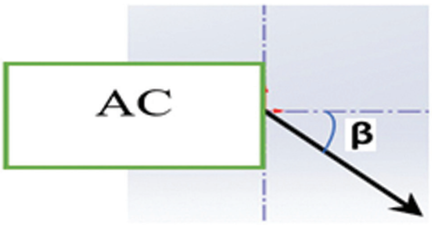

Figure 4. AC inlet gate angle.

RESULTS AND DISCUSSION

Particle diffusion in the room

Figure 6 shows the influenza viruses diffusion in the room due to coughing and breathing cycles of human body during transient condition for real human cough type, and β=30°. For visualization procedure each case in the figure included cumulative droplet particle from t=0 to current time step. The particles size scaled to clear the particle streamlines path in the room. The results show random diffusion of droplet particle in the room and it is very sensitive to the thermal load inside the room, generally depends on the bouncy force and pressure force due to

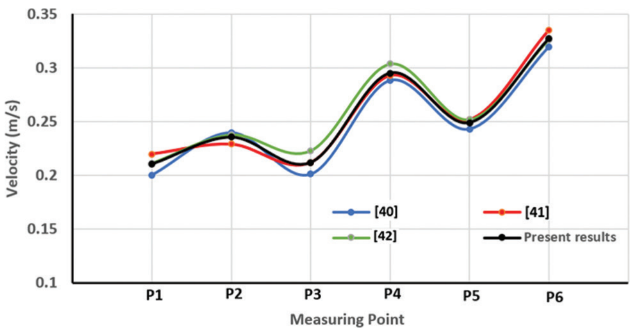

Figure 5. Case study for validation test with measured location points inside the room, and comparison results with previous studied (inlet velocity = 1.36 m/s).

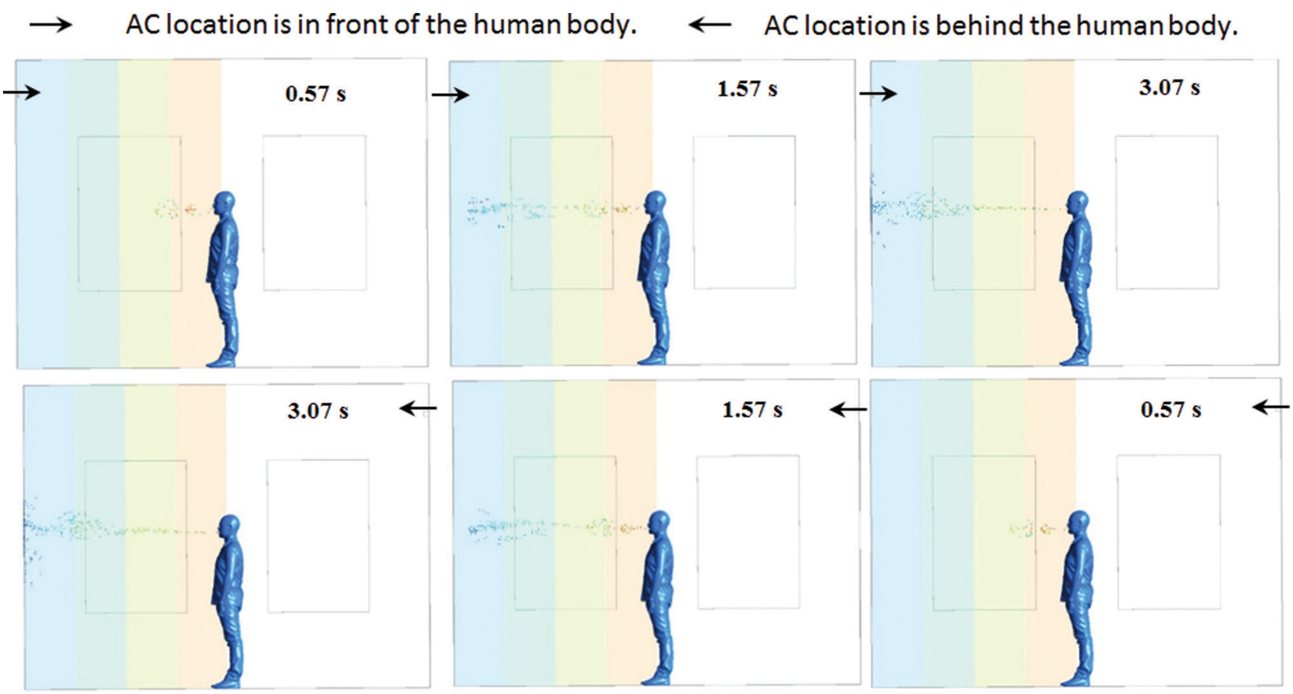

Figure 6. Particles diffusion during cumulative time step for real human cough at β=30° and two AC locations (particle size for visualization).

convection heat transfer. In order to clarify the results, the colors were added to the figure, as each color represents a distance of 0.5 m of distance to know and track the particle movement in the room. It is clear that, the particle needs 2s to moves about 2m, where it collided with the wall and reflect in random directions. AC location in the room and inlet AC gate angle are effective on flow streamlines and particle diffusion. When it is located behind human body leads to thrust of coughing strength and increase of particle diffusion area.

Airflow pattern and isotherms contour

Normalized flow velocity in the room during coughing and breathing cycles with temperature contours, for real human cough type at β=30° and AC location in front of the human body is presented in Figure 7. The results noted that, there is a strong vortex of isotherms contour over the human body head due to heat dissipation from the body and thermal load where its moves gradually to the front. Also, there is a collect region in front of the body between coughing flow and the convection flow in the room. It was

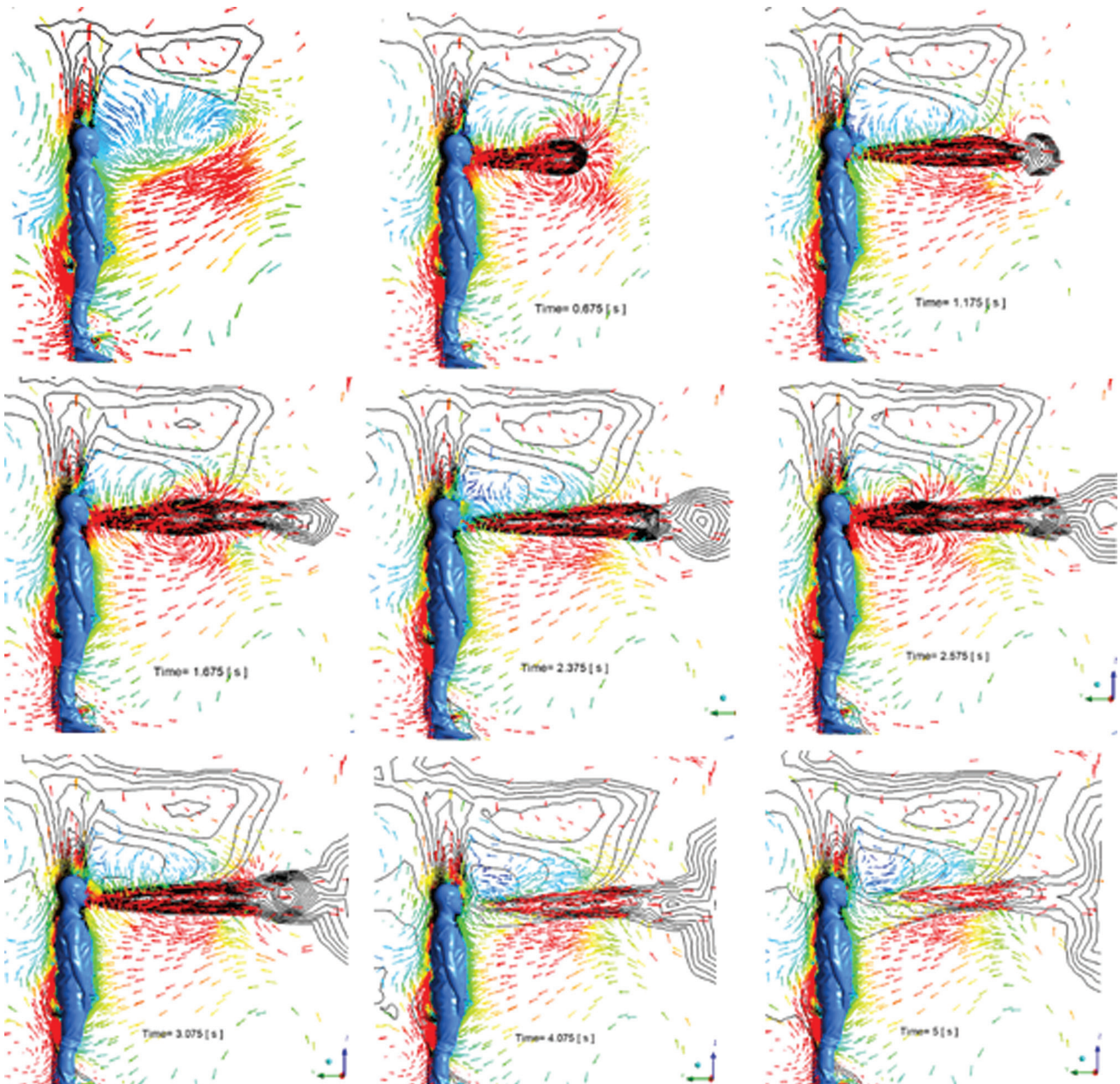

Figure 7. Normalized flow velocity in the room during coughing and breathing cycles with temperature contours for real human cough, β=30° and AC location in front of the human body.

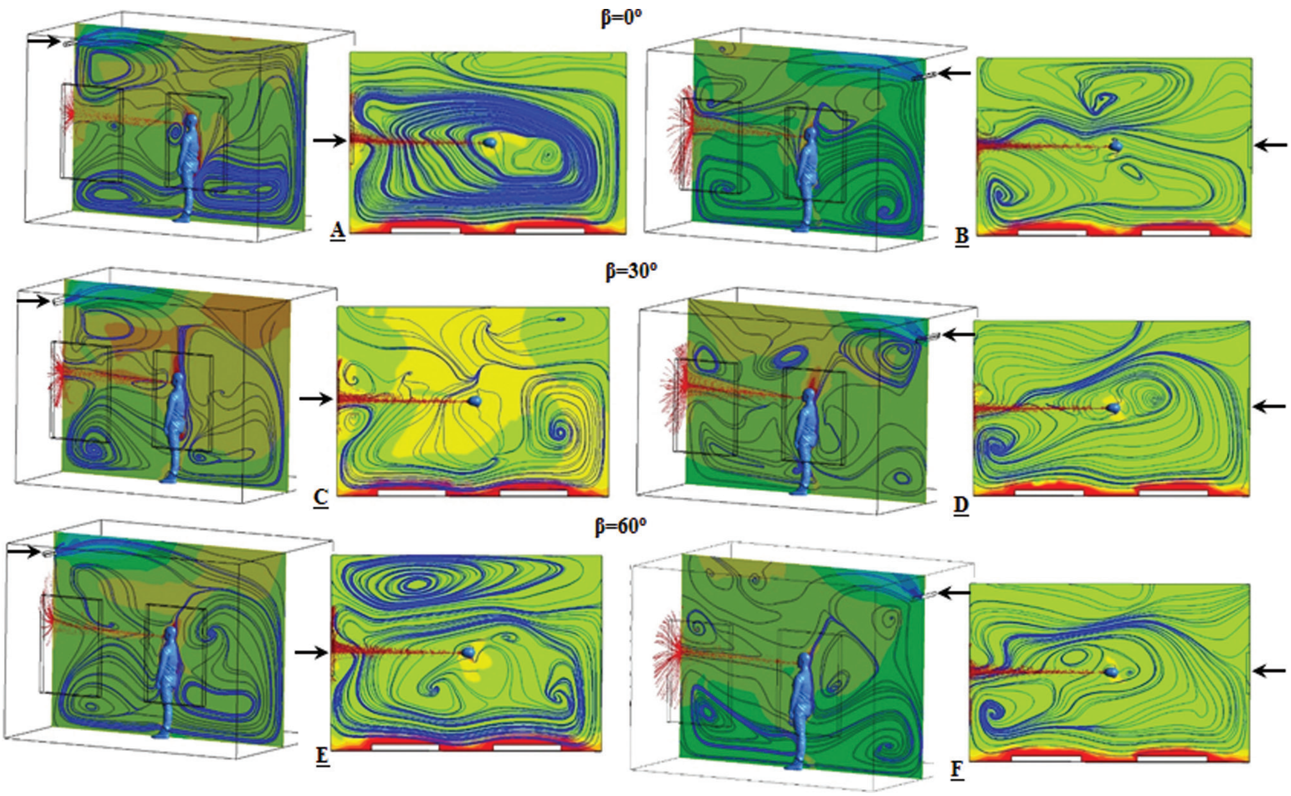

Figure 8. Particles diffusion, streamlines and temperature contours in the room for real human coughing at different inlet gate angles.

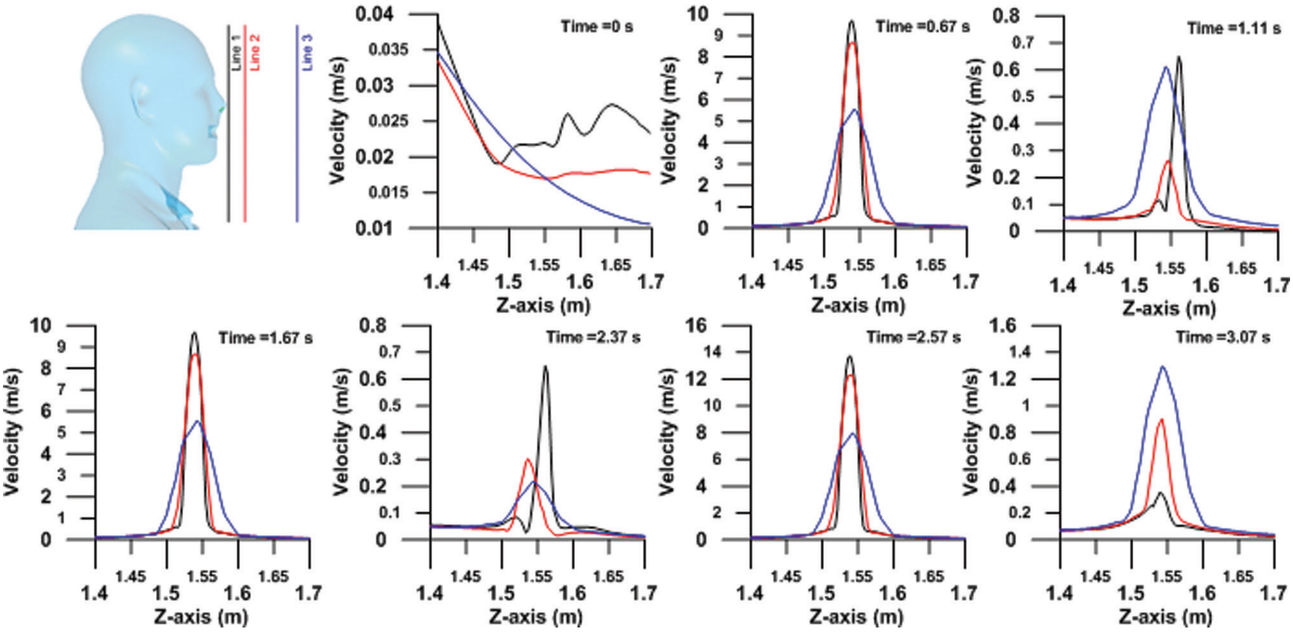

Figure 9. Transient flow velocity distribution along lines 1, 2, and 3 in in front of the human head for real human cough and β=30°.

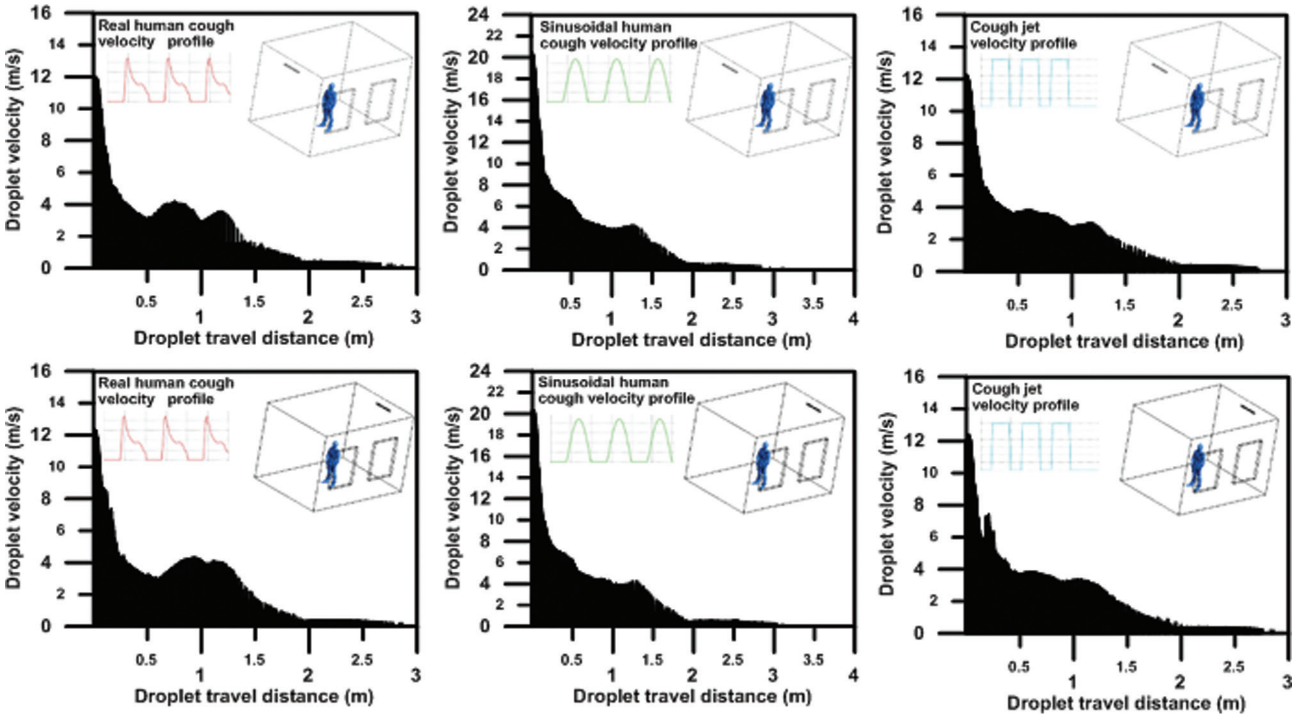

Figure 10. Droplet velocity vs droplet travel distance for different cough velocity profile in the room for β=30°.

noted that the stagnation region in the room was located far from AC and the human body head. where the buoyancy force dominates in this region and droplet particles will stay a long time. while the other region will be more effective on particle diffusion in space.

Figure 8 presents particle diffusion, streamlines, and temperature contours in the room for real human coughing at different inlet gate angles. The results for β=0° show that there are two circulation vortices with different strength around the human body close to the floor, and one located between the AC inlet flow and the zone of the droplet collect the front wall as shown in case β=0°, where the gate inlet angle equal zero and AC flow is in the opposite direction of coughing flow, generally the stagnation point with circulation zone can be seen behind the human body and the streamlines move gradually towards the internal wall of the room due to coughing flow, bouncy force, and convection flow effects. When the AC inlet flow direction changes as shown in case β=30°, the streamlines take another behavior, with three vortices in the plane are exist, and two vortices around the human body with unsymmetrical strength and location.

Increasing the AC inlet gate angle to β=30° leads to another flow distribution in the room with weak vortices generated behind the body, also coughing flow divided the vortex in front of human body into two vortices around it as shown in case β=60°.

Transient flow velocity distribution along different lines 1, 2, and 3 in front of the human head for real human cough are illustrated in Figure 9. The lines 1, 2, and 3 locations are 1.5, 4, and 12 cm from the mouth respectively. Firstly, the flow velocity effect with flow strength in the room due to bouncy force and AC flowrate and location. Where flow velocity more changed in line one due to nearest from the coughing velocity and heat dissipation from the body, then the effect will be decreased in line 2 and line 3 during time period.

Figure 10 Shows the droplet velocity distribution with droplet travel distance for different cough velocity profile in the room for β=30°. when the AC flowrate at opposite direction of coughing flow rate, the droplet travel distance about 3 m, 2.85 m, and 2.75 m for real cough, sinusoidal cough, and cough jet respectively. While the droplet travel distance about 3.1 m, 3.2 m, and 2.9 m when the AC flowrate at same direction of coughing flow rate.

CONCLUSION

In this study, transient cough and breath flow from the human body standing in the middle of the room with thermal load effect were investigated. The effects of cough velocity profile, AC location in the room and AC gate angle were presented, while the influenza virus diffusion in flow field and transient cough and breath cycle types were carefully simulated. Due to the convection current in the room, the coughing and breathing modes can directly influence the microenvironment in the space. Where The aerodynamic data obtained through the use of CFD tools improved our understanding of the mechanisms involved in disease transmission by air. The droplet particle diffusion could strongly break up the ascending thermal plume of the thermal load in the room, even though the thermal plume became more robust in some zones due to united heat, especially near the external wall. Also, the droplet flow has significant effects on the period of cough contaminants by activating the contaminants traveling longer in the space.

Droplet particle moves in the room as a random diffusion and it is very sensitive to the thermal load inside the room, generally depends on the bouncy force and pressure force due to convection heat transfer. when the AC location at the opposite direction of coughing flow, the droplet travels a distance of about 3 m, 2.85 m, and 2.75 m for real cough, sinusoidal cough, and cough jet respectively. While the droplet travel distance is about 3.1 m, 3.2 m, and 2.9m when the AC location is at the same direction of coughing flow.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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