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Impact of Cough Dynamics and Mask Usage on Covid-19 Particle Dispersion in Open Air: A CFD Analysis

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ABSTRACT

The COVID-19 pandemic underscores the crucial need for effective safety measures and guidelines to reduce viral transmission during gatherings. This study aimed to assess the flow characteristics and necessary safety distances in a model simulating coughing in public settings. To accomplish this, various velocities were tested to visualise and analyse the fluid spread dynamics. Previous research has indicated that the average coughing velocity of an adult ranges from 10.6 m/s to 15.3 m/s. Consequently, this study examined three velocity groups: 11 m/s, 13 m/s, and 15 m/s. In the model, the mouth served as the inlet, whereas the surrounding air acted as the pressure outlet. The results suggest that a safe distance of at least 2 m is recommended to mitigate the risk from an unmasked individual. However, this does not rule out the possibility of droplets travelling further. This study acknowledges certain limitations, including the interaction of physical factors such as wind direction and speed with biological factors such as infectious dose, which collectively influence the risk of transmission in open-air environments.

1. Introduction

Currently, the world is facing one of its biggest and most challenging threats: the coronavirus disease (COVID-19) [1]. According to the COVID-19 statistics in Malaysia, the total number of cases has reached 2,541,147, which represents approximately 1/16 of the Malaysian population, indicating that COVID-19 is classified as a dangerous threat to human beings [2,3]. The main concern with this coronavirus disease is its high contagiousness and potential lethality, as it can spread from person to person through viruses present in an individual's oral and nasal secretions [4,5]. As previously mentioned, the medical department in Malaysia suggests preventing transmission by avoiding physical contact such as handshakes and hugging [6]. Nevertheless, coronavirus can still spread through an individual's cough in the open air [7,8]. Viral particles can disperse in open air and

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potentially infect other individuals, even without physical contact [9]. Researchers are still studying and examining the appropriate distance between healthy and infected individuals to prevent disease transmission [10,11]. This type of distance research, known as social distancing, should not exceed the second level [12].

In this study, which focused on the dispersion of COVID-19 through coughing in open air, fluid dynamics played a crucial role [13,14]. To simulate the spread of COVID-19 through coughing, an RNG k-epsilon model was implemented using ANSYS Fluent software [15-17]. The geometry consists of a person standing in a cube, with the person acting as the velocity inlet and the cube representing the fluid domain of the open air. As mentioned in the Abstract, three velocity groups were tested. The simulation will help visualise the spread of virus particles in open air in terms of flow characteristics and potential infection at various distances from the source [18]. Consequently, the concept of "social distancing" mentioned earlier is still being studied, and simulations using Computational Fluid Dynamics (CFD) can help calculate the appropriate and suitable distance between infected and healthy individuals to avoid infections by analysing flow characteristics such as velocity and pressure. [19].

2. Methodology

2.1 Geometry

The present 3-D model was designed using the Design Modeller. The model geometry consisted of a human figure with a height of 1.8 m standing in the centre, positioned within a defined computational space containing airflow, as shown in Figure 1. The space surrounding the human figure is represented by a rectangular cube measuring 5m x 3m x 3m, which simulates a portion of the open air around the person's body. This free space was intended to study the distribution of wet viral particles released from the mouth. The surface of the person's mouth was designated with an inlet-mouth boundary condition, as this surface was assumed to be the source of virus release in this model.

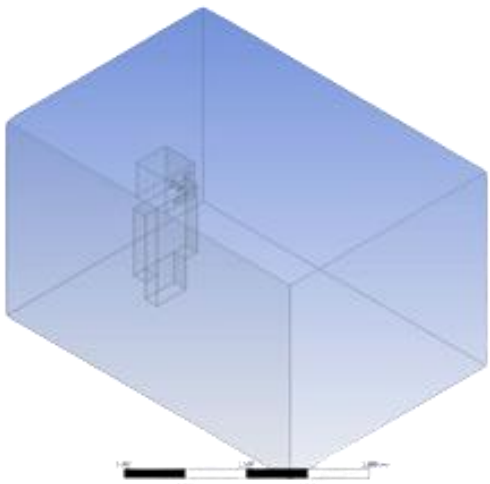

Fig. 1. Geometry of a man standing in the open air

2.2 Meshing

The meshing of the model was performed using ANSYS Meshing software, employing an unstructured tetrahedral mesh type, as illustrated in Figure 2. The mesh accuracy was higher in areas close to the patient's mouth than in the other regions. The model consisted of 361,283 nodes and 2,067,327 elements, with an element size of 0.06m. A patch-conforming method was used during meshing (Figure 3).

Fig. 2. The meshing geometry of domain open air

Details of "Patch Conforming Method" - Method	
Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Method	Tetrahedrons
Algorithm	Patch Conforming
Element Midside Nodes	Use Global Setting

Fig. 3. Patch conforming method

2.3 Governing Equation

One of the assumptions used in this study is that the fluid is incompressible. For an incompressible fluid, the density remains constant, and the continuity equation is reduced to the following condition [20]:

$$\nabla.\vec{v} = 0 \tag{1}$$

The momentum equation is a mathematical formulation of the law of conservation of momentum. It states that the rate of change in the linear momentum of a volume moving with a fluid is equal to the sum of the surface and body forces acting on the fluid. Conservation form:

X direction

$$\rho\frac{Du}{Dt}+\nabla.(\rho uV)=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}+\rho f_x \quad (2)$$

Y direction

$$\rho\frac{Dv}{Dt}+\nabla.(\rho vV)=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+\rho f_y \quad (3)$$

Z direction

$$\rho\frac{Dw}{Dt}+\nabla.(\rho wV)=-\frac{\partial p}{\partial z}+\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}+\rho f_z \quad (4)$$

2.4 Boundary Conditions

The boundary conditions applied in the simulation were as follows: the floor and the man's body were both considered stationary walls with no heat flux, meaning that their heat flux was set to 0 W/m². The area surrounding the simulation space was designated as the pressure outlet. At the inlet mouth, the gauge pressure was set to 0 Pa, with initial velocities varying across cases: 11, 1, 13 m/s for Case 2, and 15 m/s for Case 3. The temperature of the inlet mouth was maintained at 310 K. These conditions are essential for accurately simulating coughing dynamics and the subsequent dispersion of particles in an open-air environment. The boundary conditions for the simulations are listed in Table 1.

Table 1
Boundary conditions

Boundary conditions		
Floor	Condition	Wall
	Wall motion	Stationary wall
	Heat flux	0 $W.m^{-2}$
Around		Pressure outlet
Inlet mouth	Gauge pressure	0 Pascal
		Velocity inlet
	Velocity	Case 1: 11 m/s
		Case 2: 13 m/s
		Case 3: 15 m/s
	Temperature	310 K
Man body		Wall
	Wall motion	Stationary wall
	Heat flux	0 $W.m^{-2}$

2.5 Parameter Assumptions

Several key assumptions were made to simulate the present model effectively. A pressure-based solver was employed for the simulation, which was conducted under steady state conditions. The effect of gravity was incorporated with a value of -9.81 m/s² along the z-axis. The setup conditions used in the simulations are presented in Table 2.

Table 2
Condition setup

Setup		
Model	Viscous	k-epsilon, RNG
	Energy equation	On
Pressure-velocity coupling		Coupled
	Pressure	Second order
	Momentum	Second order upwind
	H2O	Second order upwind
	O2	Second order upwind
	Energy	Second order upwind
Initialize		Hybrid

3. Results

3.1 Velocity Magnitude

This study examined the velocity distribution of coughing particles at three different initial velocities, 11, 13, and 15 m/s, as shown in Table 1. Figure 4 illustrates the velocity charts for Cases 1, 2, and 3. In Case 1, the particle velocity increased sharply from 0 m/s to 11 m/s immediately after the cough. It then dropped to 2 m/s at a distance of 0.4 meters and gradually decreased to 0 m/s between 0.4 m and 1.6 m, remaining at 0 m/s beyond this distance. This parabolic curve indicates that the velocity decreased as the particles moved further from the source.

In case 2, the initial velocity surged to 13 m/s before decreasing to 2.5 m/s at 0.4 m, then gradually fell to 0 m/s at 1.7 m, again forming a parabolic curve similar to case 1. For Case 3, the particle velocity initially peaked at 15 m/s and then decreased to 3 m/s at 0.4 m. The velocity then gradually diminished to 0 m/s at 1.9 m. This pattern also mirrored the parabolic trends observed in previous cases. The velocity contour charts confirm that the velocity of the particles decreases consistently within a 2 m distance. Red areas in the charts indicate high velocity, whereas blue areas denote low velocity. All cases showed similar contour patterns; therefore, only one representative chart is provided, as shown in Figure 5.

This study successfully simulated the complex phenomena of coughing dynamics by accounting for turbulent buoyant cloud formation and propagation, particle size distribution, particle-fluid interaction, particle coalescence or breakup, multi-component droplet evaporation, and relative humidity. The numerical results were validated using experimental data and analytical models from literature.

The transient coughing velocity profile was generated using different mouth opening areas and flow rates for males and females. The highest velocity for males was approximately 13 m/s, whereas that for females was approximately 10 m/s. The velocity gradually decreases to nearly zero. The overall trends for both females and males were the same. This trend was similar to that obtained in this study, thereby proving the accuracy of the results.

Wearing a cloth mask was found to reduce the average contamination range by approximately two-thirds compared with the no-mask case. Additionally, less than 1% of the particles in the mask cases reached distances beyond 2 m, in contrast to more than 70% of the particles in the no-mask cases. However, the results also indicate that aerosolised particles could reach further distances and remain suspended for longer periods.

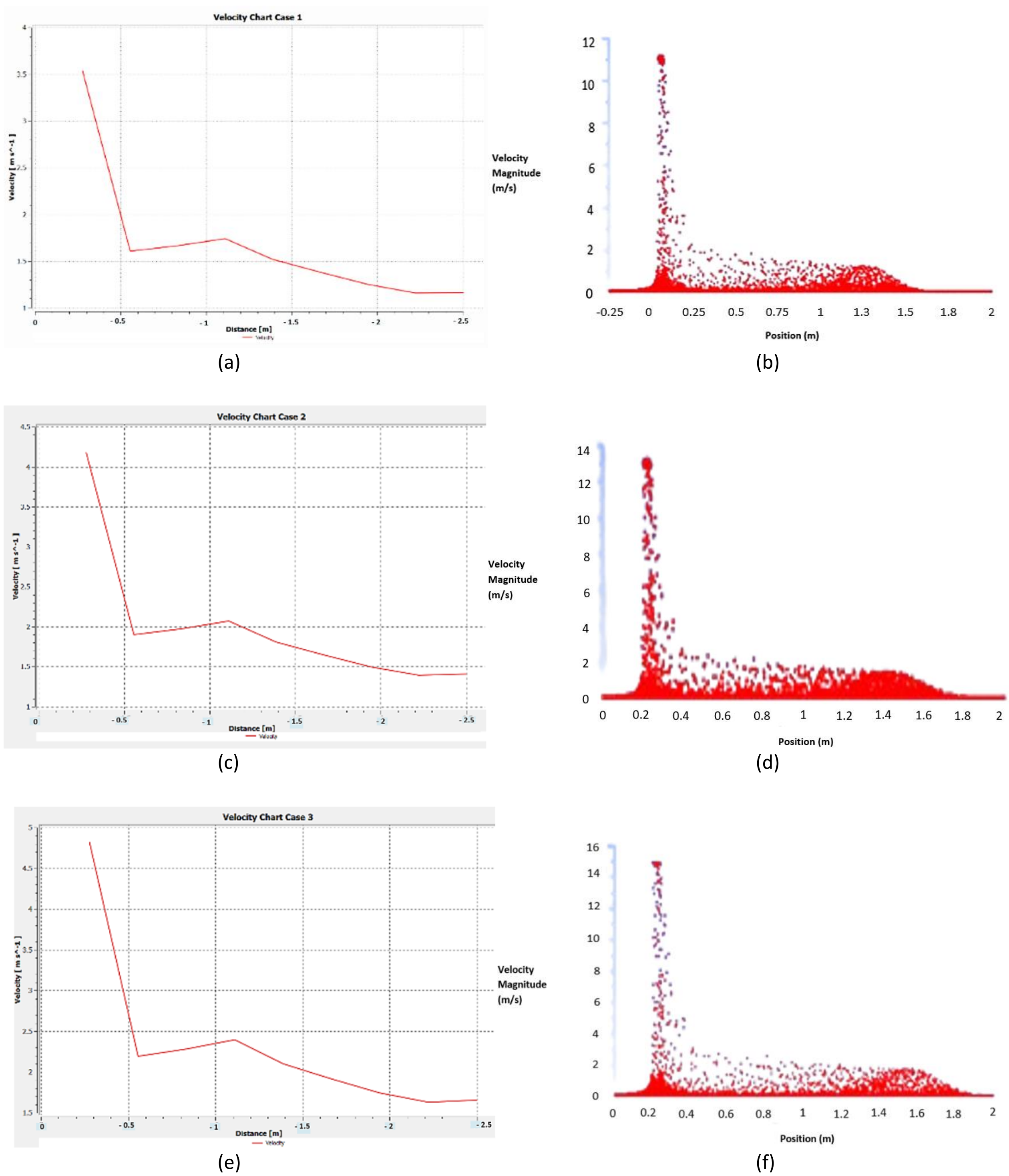

Fig. 4. Case 1: velocity at 11 m/s (a) Velocity against distance (b) Velocity against position. Case 2: velocity at 13 m/s (c) Velocity against distance (d) Velocity against position. Case 3: velocity at 15 m/s (e) Velocity against distance (f) Velocity against position

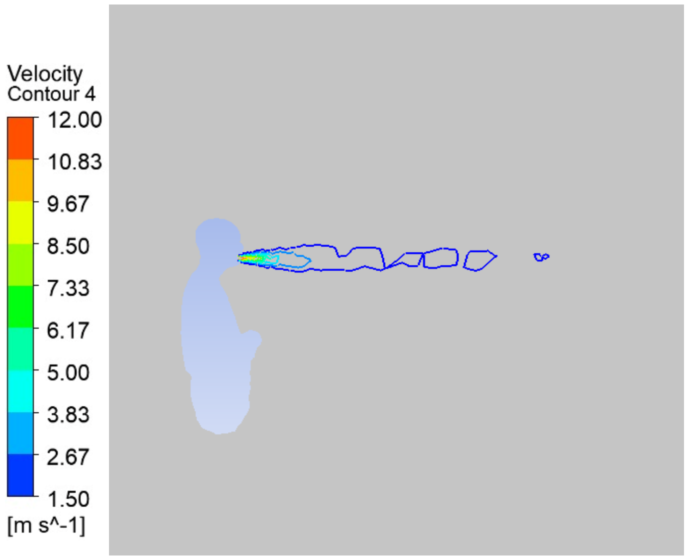

Fig. 5. Velocity contour chart

3.1.1 Pressure distributions

The pressure distribution was also analysed for the three cases, as illustrated in Figure 6. For Case 1, the pressure increased from near 0 Pa to a maximum of 80 Pa immediately after the cough, then dropped to 10 Pa at 0.4 m, and continued to decrease gradually as the distance increased. In Case 2, the pressure followed a similar pattern, peaking at 110 Pa and decreasing to 17 Pa at 0.4 meters before gradually decreasing to near 0 Pascal. Case 3 exhibited the highest pressure reading of 150 Pa, which gradually decreased along the distance, similar to other cases.

From the data analysis in the previous section, it can be observed that the maximum travel distance for coughing particles is 1.9 m at the highest coughing velocity of 15 m/s. It should be noted that the travel distance here is defined as the longest distance at which both the velocity and pressure no longer change. Thus, in our study, the maximum value was necessarily at 1.9 m, but this does not imply that these droplets cannot travel further. This is due to the fact that the study was conducted in open air, where numerous factors could influence the particle travel distance.

In summary, the results indicate that the closer an individual is to the source of the cough, the higher the risk of exposure to COVID-19, particularly within a distance of less than 0.5 m. Given that the maximum travel distance simulated in CFD was 1.9 m, it is recommended that individuals maintain a minimum distance of 2 m from a coughing person. The data were compared with results from journals and research papers to validate our findings. From this comparison, it can be concluded that the CFD simulation results were accurate.

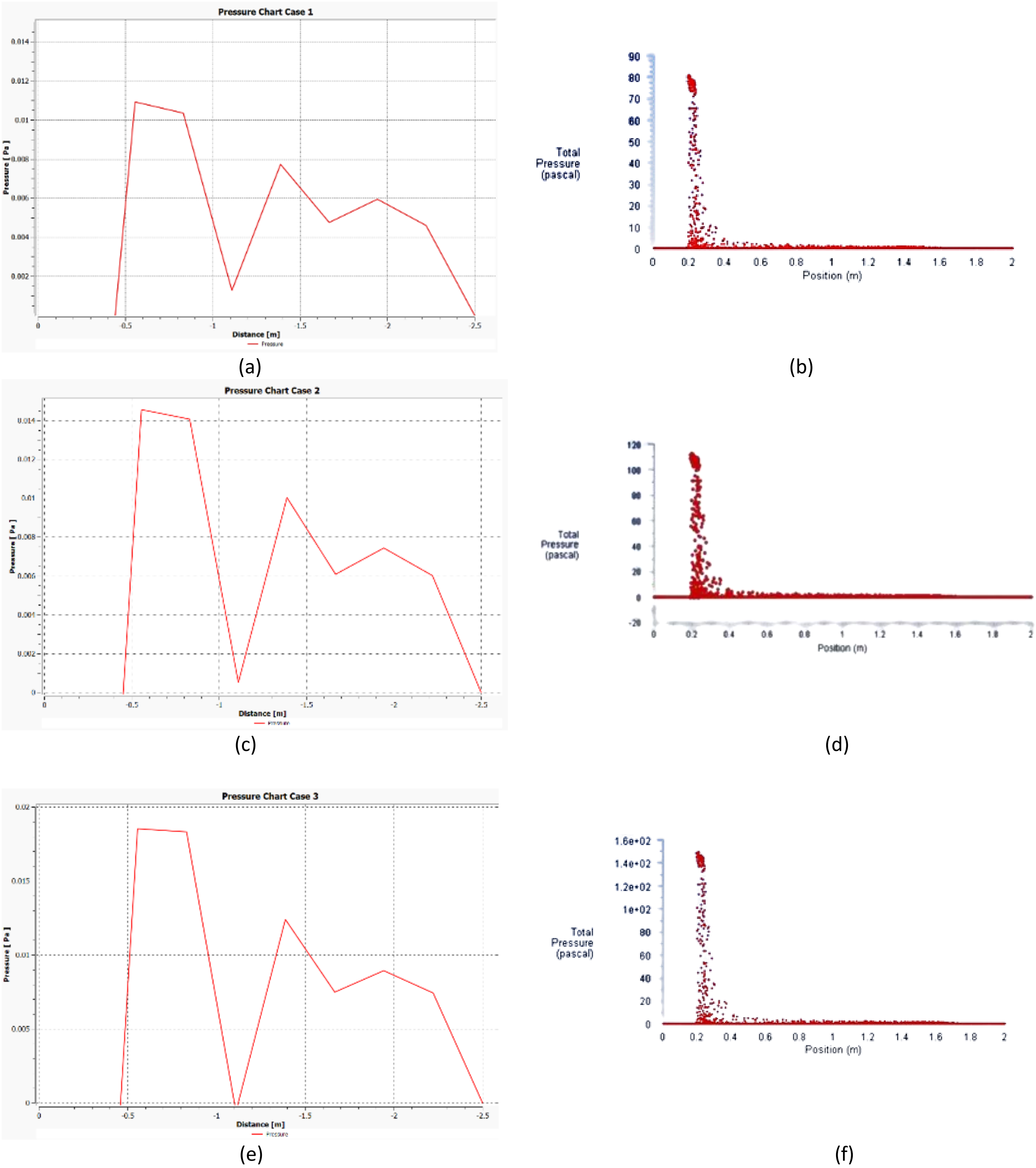

Fig. 6. Case 1: Velocity at 11 $\mathrm{m/s}$ (a) Pressure against distance (b) Pressure against position. Case 2: Velocity at 13 $\mathrm{m/s}$ (c) Pressure against distance (d) Pressure against position. Case 3: Velocity at 15 $\mathrm{m/s}$ (e) Pressure against distance (f) Pressure against position

4. Conclusions

In conclusion, the spread of coronavirus due to coughing in open air was successfully analysed. Our model provides an appropriate and accurate simulation to describe the behaviour of human cough airflow. From the data above, it is evident that the velocity, pressure, and exposure risk are very high at distances less than 0.4 m or immediately after a person coughs. Subsequently, these characteristics decrease as the horizontal distance increases. Among the three velocity cases examined (11, 13, and 15 m/s), the longest distance simulated for the particles to stop was 1.9 m. These findings have important implications when COVID-19 management experience is translated into a valuable tool for the future.

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