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RESEARCH ARTICLE

# Assessment of airborne transmission from coughing processes with thermal plume adjacent to body and radiators on effectiveness of social distancing

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## Abstract

The new coronavirus disease COVID-19 has caused a worldwide pandemic to be declared in a very short period of time. The complexity of the infection lies in asymptomatic carriers that can inadvertently transmit the virus through airborne droplets. This kind of viral disease can infect the human body with tiny particles that carry various bacteria that are generated by the respiratory system of infected patients. In this study, numerical results are proposed that demonstrate the effect of human body temperature and temperature from radiators in a room on the spread of the smallest droplets and particles in an enclosed space. The numerical model proposed in this work takes into account the sedimentation of particles and droplets under the action of gravitational sedimentation and transport in a closed room during the processes of breathing, sneezing or coughing. Various cases were considered, taking into account normal human breathing, coughing or sneezing, as well as three different values of the rate of emission of particles from the human mouth. The heat plume, which affects the concentration of particles in the breathing zone, spreads the particle up to a distance of 4.29 m in the direction of the air flow. It can also be seen from the results obtained that the presence of radiators strongly affects the propagation of particles of various sizes in a closed room. From the obtained results, it should be noted that in order to recommend the optimal social distance, it is necessary to take into account many factors, especially momentum, gravity, human body temperature, as well as the process of natural convection, which greatly affect the propagation of particles in a closed room. The conclusions drawn from the results of this work show that, given the environmental conditions, the social distance of 2 m may not be enough.


**Keywords** Airborne transmission · Thermal effects from radiators · Particle dispersion · Indoor

## Introduction

Coronaviruses are a family of viruses that predominantly infect animals but in some cases can be transmitted to humans. This is a well-known and studied group of viruses; however, like many others, these viruses mutate rather quickly, changing some properties.

Usually, diseases caused by coronaviruses proceed as usual acute respiratory viral infections in a mild form, without causing severe symptoms. However, there are also severe forms such as Middle East Respiratory Syndrome (MERS) and Severe Acute Respiratory Syndrome (SARS).

COVID-19 is a disease caused by a new coronavirus called SARS-CoV-2. WHO first became aware of this new virus on December 31, 2019, when a cluster of cases of "viral pneumonia" were reported in Wuhan, People's Republic of China. It took the viral disease only a couple of months to spread to every part of the planet. Due to the serious danger that has arisen, SARS-CoV-2 is being actively studied in many articles (Zhou et al. 2020a, b; Wu et al. 2020).

Based on scientific evidence from a variety of studies (Liu et al. 2020; Chan et al. 2020; Huang et al. 2020; Burke et al. 2020) on transmission, it was concluded that mainly the respiratory virus COVID-19 is transmitted in two ways: airborne droplets and by contact.

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One of the most serious problems in a pandemic is to prevent the spread of an infectious disease and continuously keep it under control, since the disease has caused the death of many people around the world (Shah et al. 2021; Li et al. 2020a, b). In March 2020, the governments of most countries took immediate measures to contain the spread of a dangerous infection. Thus, unhindered international movement between major countries was terminated in early spring 2020. The free movement of citizens within countries was also restricted. Compliance with mandatory social distancing (2 m) and sanitary and epidemiological rules and regulations, hygienic standards, wearing face masks in confined spaces and prohibiting large numbers of people from gathering in public places have become an integral part of the life of the world's population (Vuorinen et al. 2020; Elegant, 2020). It was found that, unlike younger people, older people are at greatest risk of infection (Zhou et al. 2020a, b), whose stay at home was strongly recommended (Alwan et al. 2020). Most of those infected with the SARS-CoV-2 virus are considered so-called asymptomatic carriers, which despite the absence of pronounced symptoms of the disease, they are nevertheless capable of infecting others with infection (Prompetchara et al. 2020). The consequences of the imposed quarantine, namely the closure of small and medium-sized businesses, bans on the free movement of citizens and travel, turned out to be disastrous for the global economy, and the unemployment rate in the countries also rose sharply (Long and Van Dam, 2020; Elmashae et al. 2017).

Mathematical modeling can be used to predict the spread of COVID-19 and generally achieve the best results in providing an assessment of infection behavior (Goel et al. 1971; Bogoch et al. 2020). The popularity of mathematical modeling is explained by its low resource consumption and the ability to consider various options for the outcome of events using the mathematical language. In a number of research works, the authors have demonstrated the developed mathematical models (Hui et al. 2020; Zhao et al. 2020; Li et al. 2020a, b; Djordjevic et al. 2018; Rachah and Torres, 2018; Wei and Li, 2017; Chen, 2020).

Life-threatening viral diseases are transmitted by airborne droplets during the process of coughing or sneezing by a person. Aerosol-borne infectious diseases are transmitted through ejected particles or aerosols, which are deposited on the surface due to their size. For example, infectious pathogens COVID-19 have been found in the ventilation systems of hospital rooms of infected patients in hospitals in China (Ong et al. 2020). Noxious aerosols can also be transmitted from person to person if the distance between people is less than 1 m and even further in the case of a working ventilation system or continuous movement of people (Tang et al. 2006). Thus, the results of a numerical study (Xie et al., 2007) made it possible to conclude that large aerosols with a diameter > 60 μm can spread over a distance exceeding 6 m. Bourouiba et al. (2014) demonstrated that aerosols with a diameter of 30 μm in the process of coughing are scattered horizontally over a distance of approximately 2.5 m. Therefore, it is extremely important to maintain social distance, because after ejection from the mouth or nose, most of the microdroplets settle (Olsen et al. 2003; D'Alessandroa et al. 2021). The dispersion of microdroplets is also influenced by other factors: human walking (Wang and Chow, 2011), aerosol size (Morawska, 2006; Gao and Niu, 2007), their speed, the temperature of a closed room and the human body. It is known that the rate of air flow exhaled when sneezing is higher than, for example, when coughing or inhaling. Therefore, large microdroplets, evaporating, turn into smaller ones and at the moment of sneezing move a very large distance, thereby increasing the risk of infection (Gupta et al. 2009; Zhao et al. 2005; Chen and Zhao, 2010; Parienta et al. 2011; Guan et al., 2014; Bourouiba, 2020). In the paper, Xie et al. (2009) estimate the mass and size of inhaled microdroplets when talking and coughing around the source, since their size and gravitational force play the main role in the settling of particles. Even in the course of ordinary speech, a considerable number of respiratory particles are distributed by a person and, therefore, their number will increase even more when vocalizing or increasing the volume of a person's voice. For example, a 10-min conversation at medium volume creates a cloud of a total of 6000 aerosol particles that are difficult to see with the naked eye.

Studies show that it is extremely difficult to determine the exact size of microdroplets (Xie et al., 2009; Dbouk and Drikakis, 2020). Drops with a diameter > 5–10 μm are usually called respiratory, and those with a diameter < 5–10 μm are called droplet nuclei (Yan et al. 2018; Dhillon et al. 2021). Tiny particles with a diameter of less than 100 nm can have a harmful effect on human health up to respiratory and cardiovascular diseases through their transmission from an infected person to a healthy person (Buonanno et al. 2019; Ragde et al., 2016; Romano et al., 2017; Brüske-Hohlfeld et al. 2008), whereas larger droplets, dissolving, turn into microdroplets and can remain in the air for a long time (Massarotti et al. 2020; Ai et al. 2020). In a study (Sen, 2021), a three-dimensional numerical Euler–Lagrange model was developed to simulate the dispersion of 1 μm aerosols formed by one person or a group of people in an elevator.

Another factor that significantly affects the nature of the spread of viral microdroplets is taking into account the temperature of a closed room and the human body. This is due to the fact that the temperature allows aerosol droplets to contract and evaporate, which changes the trajectory of movement and the nature of dispersion of aerosols. From the point of view of the authors of the work (Mao et al. 2016), in a room with a certain temperature, the process of formation of a heat plume around the human body takes place. Such a heat plume has a certain effect on the speed of microdroplet propagation: it reaches approximately 0.2–0.3 m/s (Craven and Settles, 2006) and can even increase the total number of infectious pathogens in the room (Salmanzadeh et al. 2012; Rim and Novoselac, 2009). The results of a study (Shadloo-Jahromi et al. 2020) showed that with an increase in the temperature value in a closed room, the frequency of collision of microdroplets with environmental molecules increases significantly. The authors of the work investigated the nature of the vertical dispersion of droplets of various sizes and three different values of the temperature of the surrounding atmosphere.

In this study, in order to approximate a real case, the spread of an infectious disease in a closed room was considered, taking into account the heterogeneous body temperature and taking into account radiators of various sizes. For a more accurate forecast, the human body was built as close to reality as possible. To reduce computational costs, mesh refinements were used, which were described in Issakhov et al. (2021). From the obtained numerical results, it can be seen that the influence of the temperature plume from the human body and radiators is significant for the development of the local flow, the trajectory of the transfer of particles of various sizes, as well as such characteristics as the propagation distance of particles, the direction and velocity of particles.

## Mathematical model

In order to construct a mathematical model of the air flow, the Navier–Stokes system of equations is used, which is numerically implemented by ANSYS Fluent. Incompressible Navier–Stokes equations are used to model the flow field. The continuity, momentum and temperature transfer equations used in the model are defined as follows: (Eqs 1, 2 and 3)

$$\frac{\partial u_j}{\partial u_j} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = f_i \frac{1}{p} \frac{\partial p}{\partial x_i} + v \frac{\partial^2 u_i}{\partial x_j \partial x_j} \tag{2}$$

$$\frac{\partial T}{\partial t} + \frac{\partial p u_j T}{\partial x_j} = \frac{\partial}{\partial x_j}(D_{\text{eff}} \frac{\partial T}{\partial x_j}) \tag{3}$$

Where $\mu_{eff}$ —the effective viscosity, $D_{eff}$—the effective diffusion coefficient, $p$— the pressure, $\mu_{eff} = \mu + \mu_t$, where $\mu_t$ —the turbulence viscosity, $D_{eff} = D + D_t$, where $\mu_t$ —the turbulence diffusion coefficient. The external force of the body considered is gravity, so that $f = pg$, where $g$ is the acceleration due to gravity, $p$ —the density.

The kinematic relationship between the position of the particles and the speed of the particles is (Eqs 4 and 5)

$$\frac{dx}{dt} = u_p \tag{4}$$

$$m_p \frac{du_p}{dt} = F_D + F_G \tag{5}$$

Where $x_p$ —the particle location, $F_G$—is the gravity force, $F_D$—the drag force, $u_p$—the velocity of particles, $u_f$—the velocity of fluids,$m_p$ —the mass of particles and $F_D$—calculated as follows:

$$F_D = \frac{1}{2} P_f \frac{\pi d_p^2}{4} C_D (u_f - u_p) \left| u_f - u_p \right| \tag{6}$$

where the drag coefficient (Eqs 6 and 7)

$$C_D = \begin{cases} \frac{24}{Re};(Re < 1) \\ \frac{24}{Re}\left(1 = 0.15Re^{0.687}\right);(1 < Re < 1000) \end{cases} \tag{7}$$

These equations are approximated by the finite volume method. To numerically solve the system, the numerical algorithm SIMPLE (semi-explicit method for pressure-related equations) of Patankar and Spalding (Patankar, 1980) is used. This method is used in many works to solve various problems of hydrodynamics and heat transfer and served to create a whole class of numerical methods (Issakhov and Omarova, 2020; Issakhov and Borsikbayeva, 2021; Issakhov et al., 2022). All variables that were used in these calculations were taken in dimensional terms.

## Verification

To verify the constructed mathematical model and the used numerical algorithm, various test problems were solved, in which the obtained numerical solutions were compared with the experimental and numerical data of other authors. For the distribution of the velocity flow, verification was presented in Issakhov et al. (2021). Verification of the temperature plume distribution was presented in Issakhov et al. (2021), Issakhov and Omarova (2020), Issakhov et al. (2020a, b), Issakhov and Zhandaulet (2019) and Issakhov et al. (2020a, b). Particle propagation verification was presented in Issakhov and Omarova (2020) and Issakhov et al. 2019).

## Numerical simulations

In the present study, a human model was examined in a full-scale room with a radiator and used as an indoor environment installation. In the presented work, the influence of human body temperature and the effect of a radiator, which sets the room temperature on the spread of the smallest particles in the room, were investigated, taking into account various natural human reflexes: breathing, coughing and sneezing. In this case, the smallest particles were considered of different sizes, and in addition to this, different values of the particle emission rates (breathing, coughing and sneezing) were considered. The total size of the room was $X \times Y \times Z = 8 \times 3 \times 3$ m, the height of a person inside a closed room is 1.8 m and the dimensions of the two types of radiator were $580 \times 520$ mm and $580 \times 1040$ mm, respectively. The human mouth was located 1.65 m above the floor. A full description of the dimensions of the study area is presented in Fig. 1.

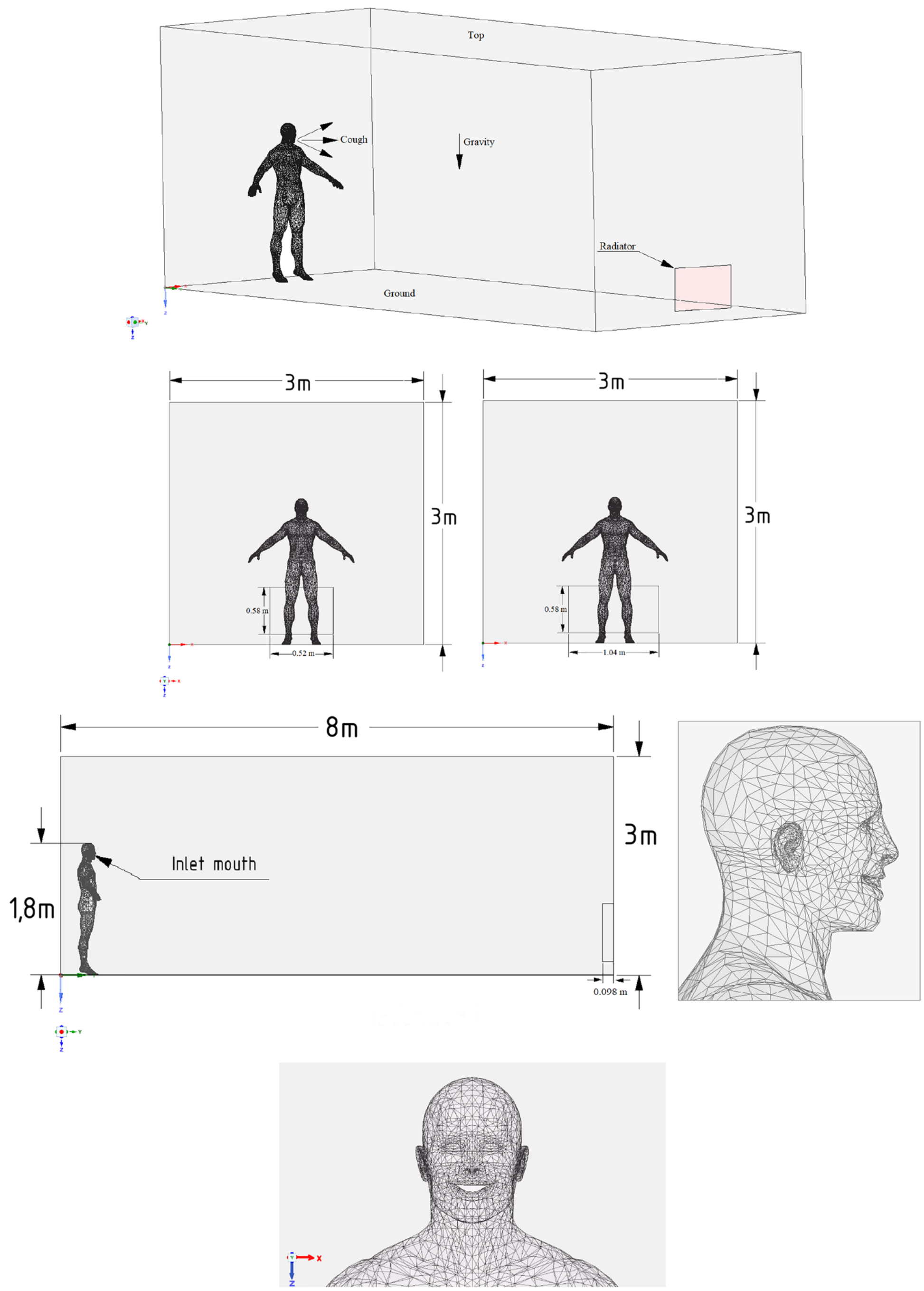



**Fig. 1** Geometry of the study area

Other studies show that the ejection rate of particles from the mouth of a person varies from 1 to 20 m/s when sneezing and coughing (Gao & Niu, 2006). Based on these data, in the presented work, the speed during the normal process of human breathing was set as periodic, and the speed during the process of coughing or sneezing—pulse. It should also be noted that in the process of sneezing, this cycle continues more than once, and the diameter of the particles and droplets changes depending on the reflex (breathing, coughing or sneezing). Particles and droplets with a diameter of about $10^{-4}$–$10^{-3}$ m in a short period of time can separate to an even smaller diameter: up to $10^{-6}$–$10^{-4}$ m.

Therefore, in this work, the particle diameter varied in the range of $10^{-6}$–$10^{-4}$ m, and the particle density is set as 600 kg/m$^3$ (Zhao et al. 2005). This choice of density is explained by the approximate density of particles or droplets of a mixture of water and air. It should be borne in mind that the use of different density values in general does not significantly affect the distribution and transport, since these particles are very small in size (Zhao et al. 2005).

It should also be noted the choice of the particle diameter range. In this work, the smallest value of the particle diameter is used as $10^{-6}$ m. However, it should be noted that in real cases the particle sizes can be even smaller. In this work, particles with smaller diameters than $10^{-6}$ m are not used, since in the work (Zhao et al. 2005) particles with smaller diameters were used and the obtained results did not show a significant difference between the results from each other. For this reason, in this work, only $10^{-6}$ m is used as the smallest particle diameters.

The ejection of particles from the mouth of a person is carried out in the period from 0.1 to 0.3 s since the sneezing process in time showed that it is approximately 0.1925s (Busco et al. 2020).

In this work, the following two cases are considered:

a) case 1, in this case, the calculations are carried out for the first 120 s, taking into account the temperature of the human body and taking into account the effect of temperature from a radiator with a dimension of 580 × 520 mm, while the emission of particles is carried out in a period of 120.1–120.3 s, and a further period of time up to 150 s a simple inhalation and exhalation of a person is carried out without the emission of particles.

b) case 2, in this case, the calculations are carried out for the first 120 s, taking into account the temperature of the human body and taking into account the effect of temperature from a radiator with a dimension of 580 × 1040 mm, while the emission of particles is carried out in a period of 120.1–120.3 s, and a further period of time up to 150 s a simple inhalation and exhalation of a person is carried out without the emission of particles.

In order that the calculations did not depend on the temperature distribution, the first 120 s was used without taking into account the propagation of particles. In both cases, already within the first 120 s, a change in temperature is observed, 120.1–120.3 s is accompanied by an ejection and then, up to the 150th second, a person's usual inhalation and exhalation without the ejection of particles. The radiator temperature was set in the form of a constant $T = 353$ K, and the human body temperature was taken not uniform and was distributed depending on the body parts with a minimum value of $T = 309.75$ K.

So in this work, in order to implement the procedure for the rate of emission of polluting particles from the mouth, the following formula is given:

$$\begin{cases} u = V, shifttime + 0.1 \le t \le shifttime + 0.3 \\ u = V\sin(2\pi t), shifttime + 0.3 \le t \le shifttime + 0.5 \\ u = V\sin(2\pi t), else \end{cases}$$

where *shiftime* is set as 120 s.

In order to realize the initial distribution of body temperature, it was taken into account that body temperature is not evenly distributed throughout the body (Psikuta et al., 2017). Since the maximum temperature is on the human head (310.75 K), and the minimum temperature is on the lower extremities (309.75 K). For this purpose, the initial approximation of body temperature is given by the following formula:

$$T_{body} = 303.75 + z/1.8$$

Where z—varies according to the height of the person.

All temperature scenarios for this problem are presented in Table 1.

To carry out numerical modeling, a computational grid with a dimension of more than 8 million computational nodes was built. Figure 2 shows a three-dimensional (3D) computational grid of the study area. By using a clustering of the computational grid around the mouth and radiator, the number of computational cells and computational costs for this complex geometry has been reduced. By clustering in certain areas, a more accurate result has been achieved in a short period. The boundary conditions were specified as inlet for the mouth, and all others as walls.

Figures 3, 4, 5, 6, 7, and 8 show the results of the velocity contours with temperature at different points in time.

**Table 1** Scenarios for numerical simulation

| Scenarios | Particle ejection velocity | Particle diameter [m] |
|---|---|---|
| Scenario 1 | $V_{em} = 1$ m/s | $1*10^{-6} - 1*10^{-4}$ |
| Scenario 2 | $V = 6$ m/s | $1*10^{-6} - 1*10^{-4}$ |
| Scenario 3 | $V = 20$ m/s | $1*10^{-6} - 1*10^{-4}$ |

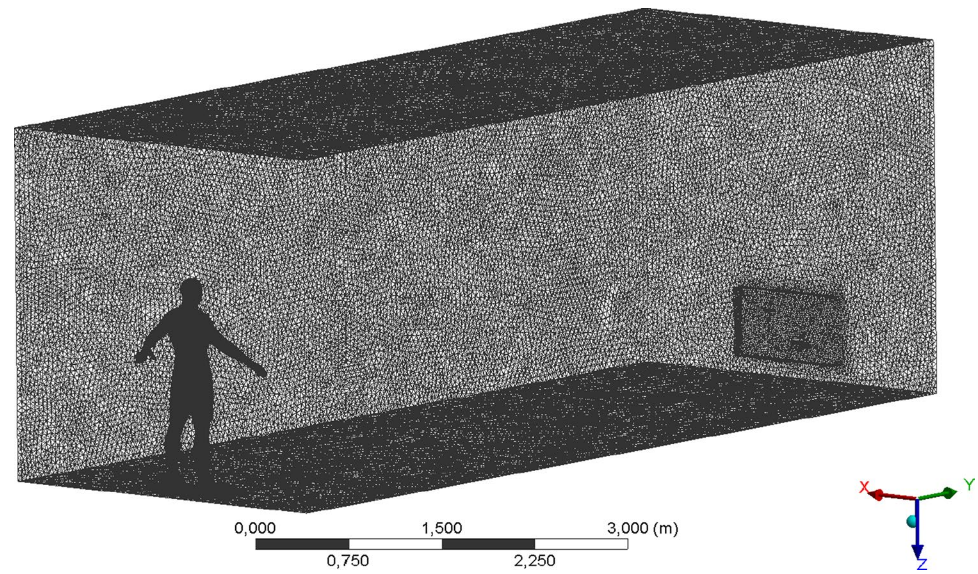



**Fig. 2** Computational grid of the study area

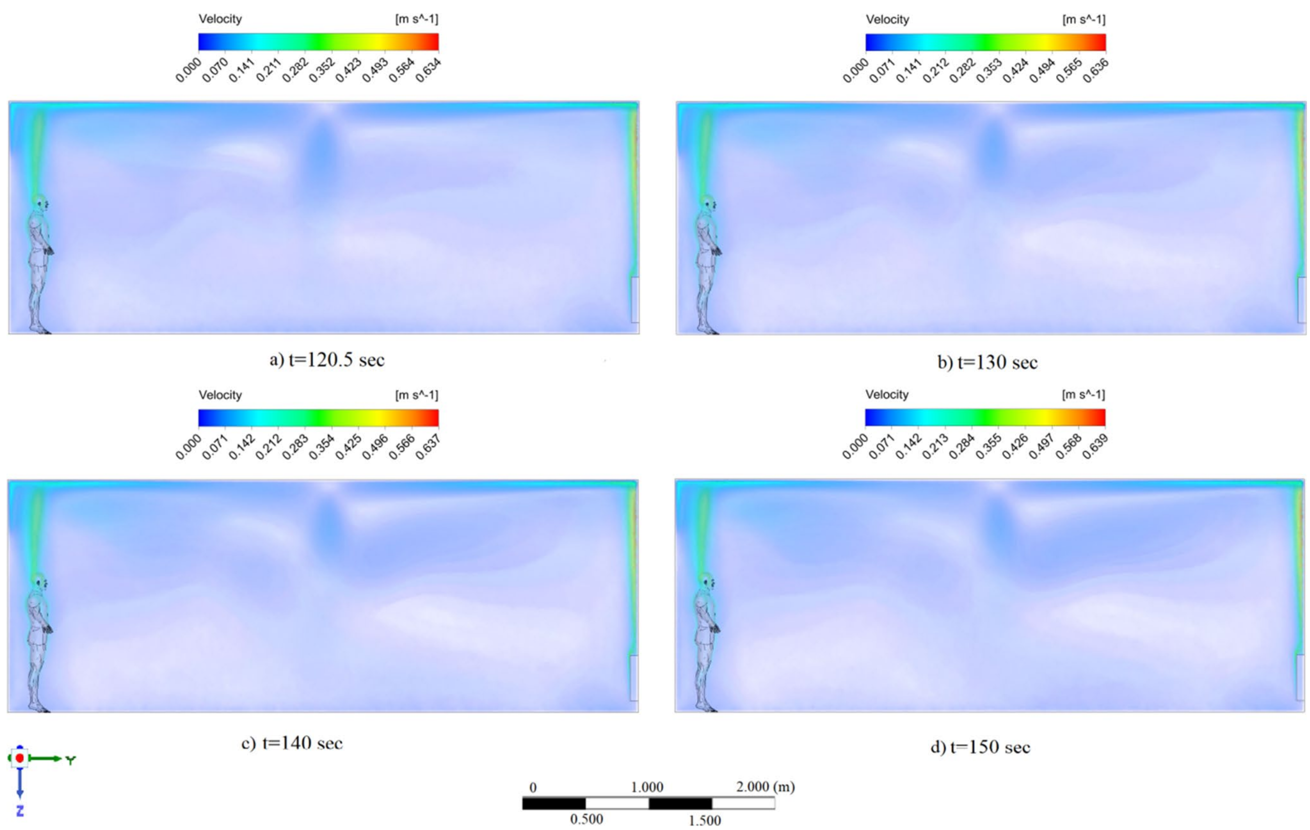



**Fig. 3** Contour velocity cough = 1 m/s with one radiator 120.5–150 s

The results show that increasing the velocity significantly affects the flow distance in the room. However, the range of propagation of particles can be influenced by other factors: friction force and gravity. This means that under such conditions, particles cannot be transported to even greater distances. Figures 9, 10, 11, 12, 13, and 14 show the effect of temperature on flow propagation. A strong change in the flow is noticed already at the 120th second. The results show that the heat plume around a person and the heat generated by the radiator affect the propagation velocity and diffusion of the particles.

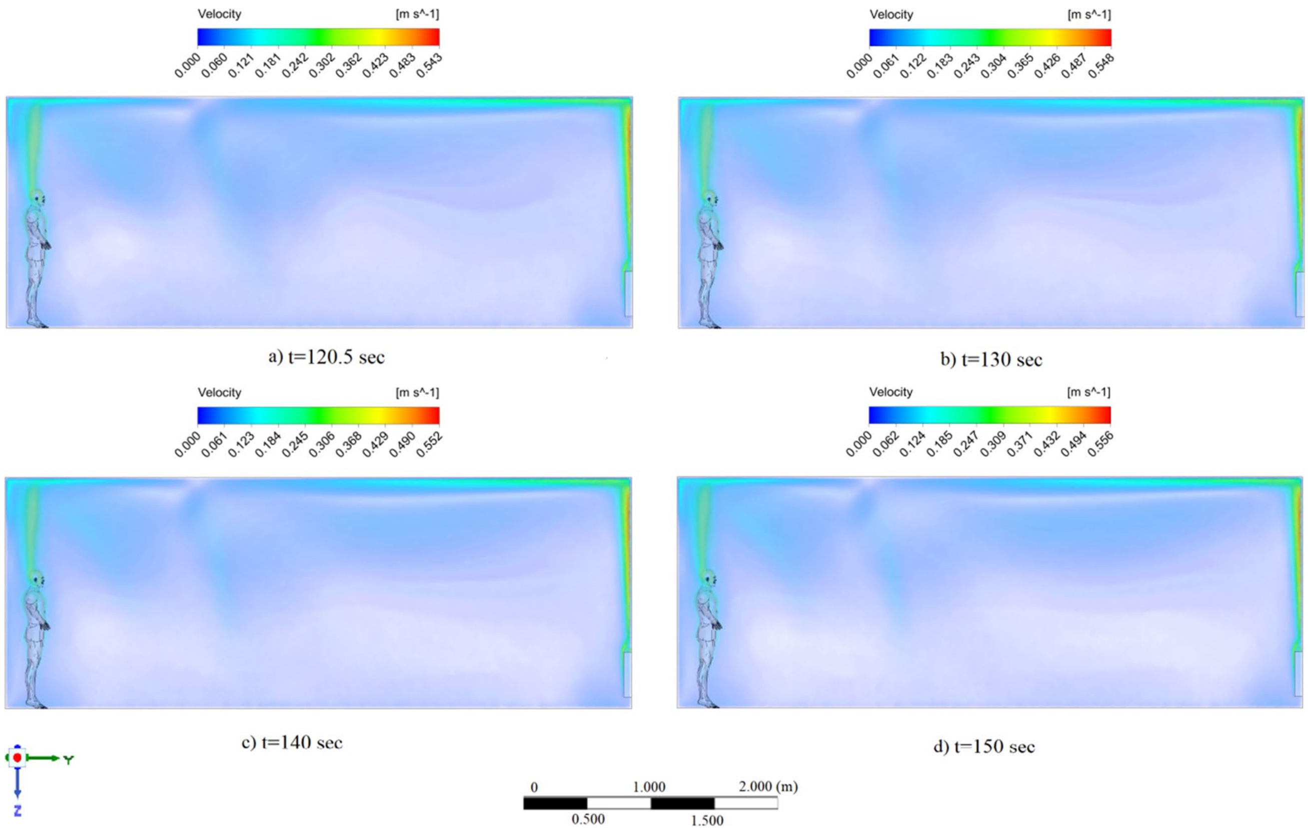



**Fig. 4** Contour velocity cough = 1 m/s with two radiators 120.5–150 s

From the obtained results, it can be seen that the size of the radiator strongly affects the velocity distribution and changes the distance of movement of particles and the concentration ejected from the mouth of a person. Small vortices, formed due to the heat plume, change the direction and distance of particle propagation. Consequently, taking into account the forces of friction and gravity, the distance of particle transfer also changes significantly. The value of the rate of emissions from the mouth leads to a change in the heat plume around the person. The heat generated by the radiator spreads throughout the room and affects the flow.

In Fig. 15, in the case of case 1 (a small radiator), it can be seen that due to temperature, the flow direction changes and particles with a small diameter rise upward. As it can be seen, the settling of particles, taking into account the force of gravity in scenario 1, is not particularly noticeable, despite the temperature and time.

In Figs. 15–16, the difference lies only in the dimensions of the radiators and, despite this, the nature of the propagation of particles is almost the same. However, the distribution of particles across the width of an enclosed space is significantly different. This can be explained by the fact that the effect of temperature changes the flow velocity in the room and strongly affects the range of particles. It should also be noted that the rate of release of particles from the mouth of a person and the temperature of the room play an important role in the spread of particles. The obtained results show that at a velocity of 1 m/s, both cases exceed the recommended social distance.

Figures 17 and 18 show the numerical results of case 1 (small radiator) and case 2 (large radiator) of particle propagation, where the coughing or sneezing speed is 6 m/s. From these results, it can be seen that at the same velocities and body temperature, the size of the radiator from which the temperature plume is released strongly affects the transfer of particles when coughing or sneezing. From the obtained Figs. 15 and 16, it can be noted that the heat plume has a very strong effect on particles with a small diameter, as for large particle diameters, the effect of the heat plume is minimal due to the fact that large particles are more sensitive to the force of gravity. At $t = 120.5$ s, the particles propagate over 0.47 m, at $t = 130$ s at 1.065 m and at $t = 150$ s, the propagation distance is 0.91 m. As can be seen from the obtained results, at 150 s, a decrease in the particle propagation distance is observed. This is because the transfer of particles is influenced by the heat flow around a person and heat plumes from the presence of radiators. It should also be noted that the distribution of particles across the width

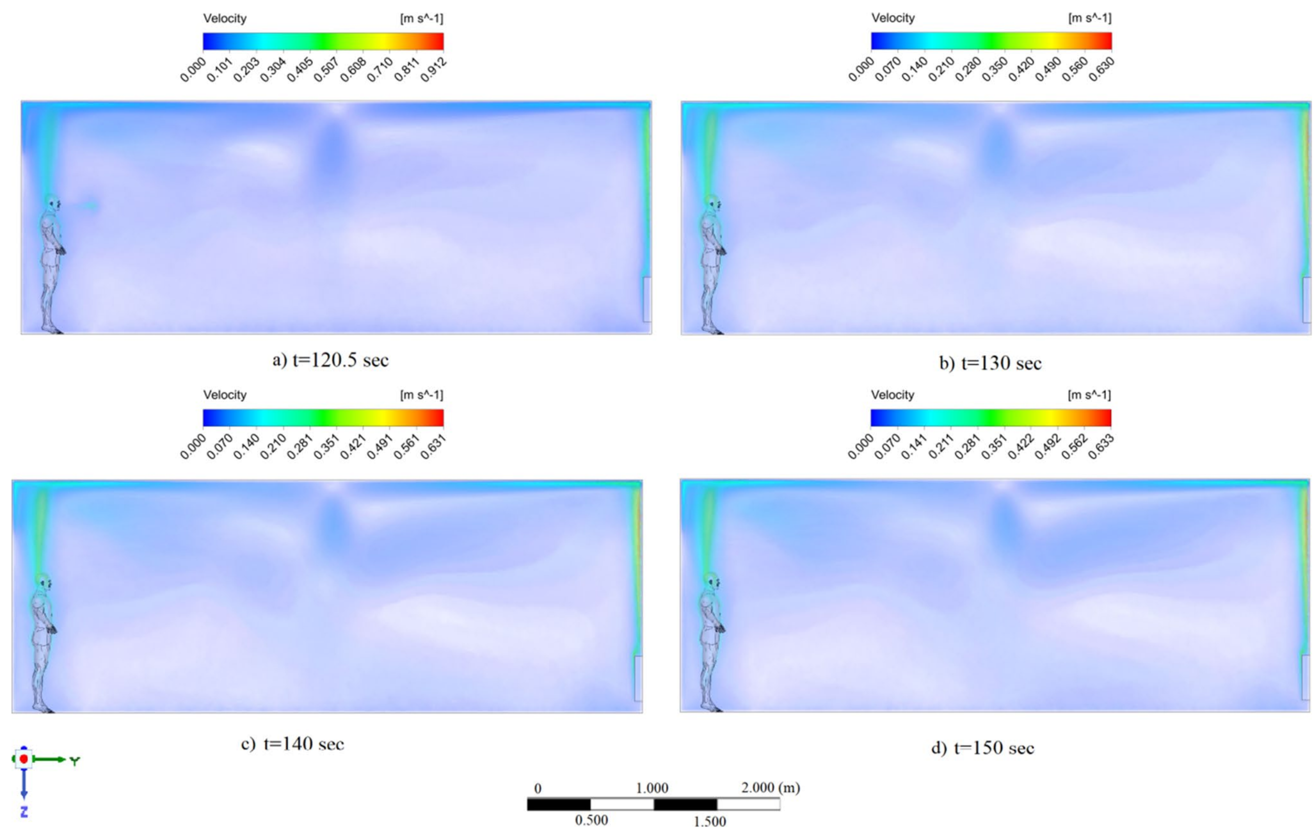



**Fig. 5** Contour velocity cough = 6 m/s with one radiator 120.5–150 s

of the room is more symmetrical on both sides with respect to the side walls.

The numerical results for the first case (small radiator) at a coughing velocity of 20 m/s, which are displayed in Fig. 19, show that in $t = 150$ s the particles settle to a height of 1.197 m, but are transported up to 3.46 m. As can be seen from the obtained results in the process of sneezing or coughing, the difference in results depends on the rate of emission of particles, and after a certain point in time, the characteristics of the particles change depending on the influence of temperature. After the process of sneezing or coughing, due to the relatively small volume of air flow during breathing, the processes of inhalation and exhalation have little effect on the structure of the air flow in the room; however, the presence of a temperature plume plays an important role in the formation of the structure of the air flow into the room.

Figure 20 shows the results of the 2nd case (large radiator) with a coughing velocity of 20 m/s. The particles have similar propagation characteristics to the numerical results shown in Fig. 19. However, after the sneezing process, the particle propagation is greatly affected by the heat plume from the large heat sink. Due to the large size of the radiator, more heat is generated; as a result of which the temperature begins to greatly affect the air flow, which in turn increases the particle propagation distance. So at $t = 150$ s, the range of propagation of particles is 4.29 m, and they fall to a height of 1.109 m. Now, the propagation of particles across the width of the room, on the contrary, differs depending on the speed.

The results presented in Fig. 21 show the trajectory of particles propagating in a room without the presence of radiators, as well as take into account temperature conditions for different radiator sizes. Different modes of particle emission significantly affect the transport of particles along the emission range. In the mode of ejection of particles with a velocity of 20 m/s, particles in 30 s can cover a distance 3 times greater than when ejection with a velocity of 1 m/s and a distance 2.5 times greater than with an ejection of 6 m/s without the presence of radiators. In this case, the settling of particles with large sizes for all modes of emission has approximately the same characteristics. It is also worth noting that when a particle is ejected, for the first 0.5 s, the effect on the trajectory of particle transfer, all velocity modes show almost the same distances. So, taking into account the temperature regime of the propagation of particles for a velocity of 20 m/s along the length and height, there is a tendency of linear dependence. Whereas for other modes, 1 m/s and 6 m/s have nonlinear distribution. This phenomenon is more due to the fact that these velocity regimes are more subject to natural convection. However, when using

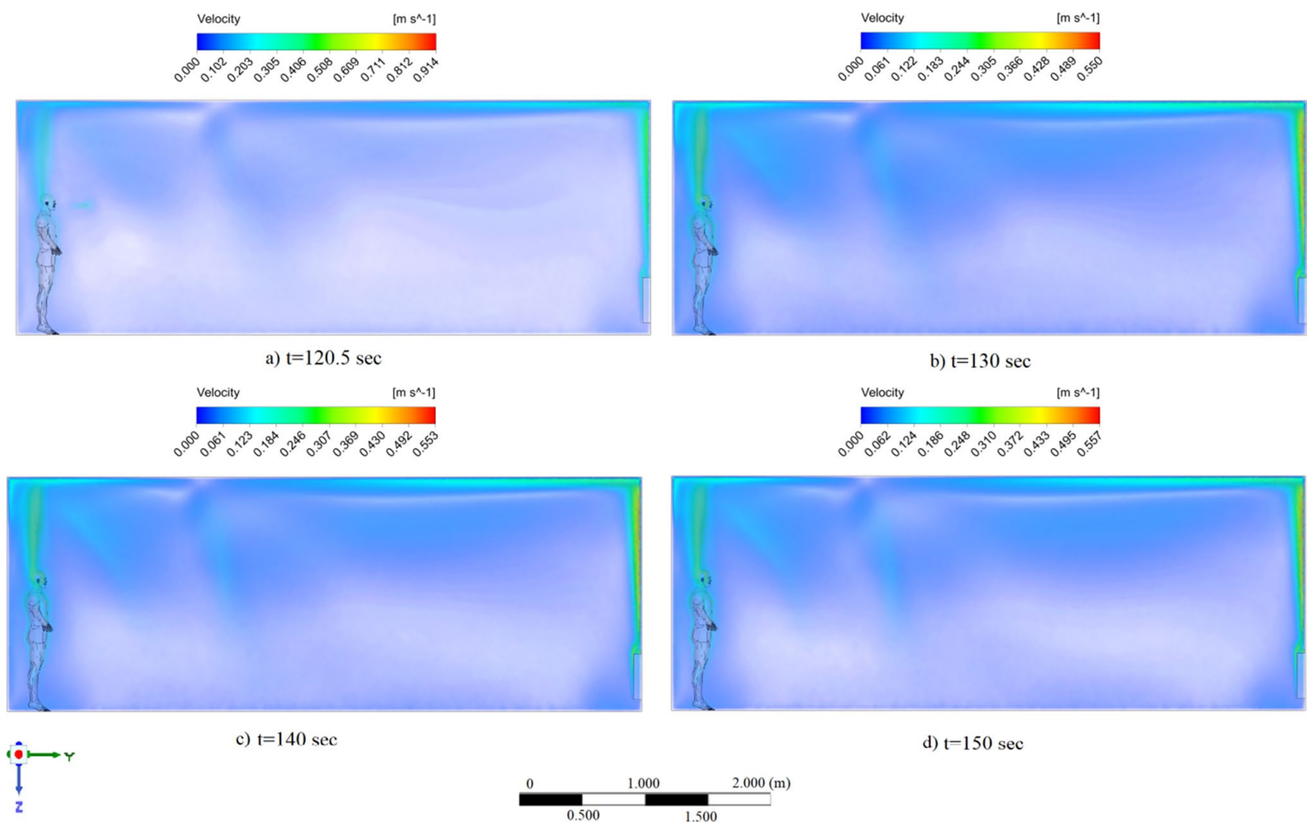



**Fig. 6** Contour velocity cough = 6 m/s with two radiators 120.5–150 s

radiators, as can be seen from the results of particle propagation, the initial moments for velocity modes of 6 m/s and 20 m/s differ little than without the presence of radiators. Since at the initial moments, the movement of particles is very strongly subject to pulse movements, while after the sneezing process, the propagation of particles is strongly susceptible to natural convection. But it should be noted that at a velocity of 1 m/s, both with and without a radiator, very strong differences in the obtained numerical results are noticeable. These differences can be explained by the fact that the generated velocities from natural convection have sufficient strength compared to the velocities obtained from coughing at a velocity of 1 m/s. It should be noted that the initial moment, the dimensions of the radiators differ little in the trajectory of particle propagation. However, after the coughing or sneezing process, there is a difference in the resulting particle paths for different radiator sizes. This can be explained by the fact that the larger the radiators are, the more buoyancy forces are created and the influence of these forces increases.

The obtained numerical results made it possible to conclude that the presence of body temperature in a person and in the presence of radiators of various sizes in a closed room changes the nature of the propagation of the air flow and particles. In the process of sneezing or coughing, depending on the velocity and taking into account the influence of temperature, the particles are transported to different distances, both in length and in width. For this purpose, in order to get as close as possible to the real case, it is necessary to take into account these external factors such as inhomogeneous body temperature and temperature emitted from radiators. At the same time, it should be noted that at the initial moment of coughing and sneezing (6 m/s and 20 m/s) for all variants, the obtained results show that the results differ little, whereas after this process the trajectories of particle propagation are very different. So for the sneezing option (20 m/s), it is noticeable that the presence of radiators increases the particle propagation distance, while for the coughing process (6 m/s), on the contrary, a decrease in the particle propagation distance is noted. This effect can be explained by the fact that in the presence of radiators, natural convection is created, which in turn creates additional vortex motions, which in turn have a positive or negative effect on the propagation of particles.

From the obtained data, it can be seen that taking into account the presence of radiators affects both positively and negatively on the propagation of particles. So for coughing and sneezing (velocities to 6 m/s), in general, it can be noted that these velocity modes have a positive effect, since they do not exceed the recommended social distance, if even

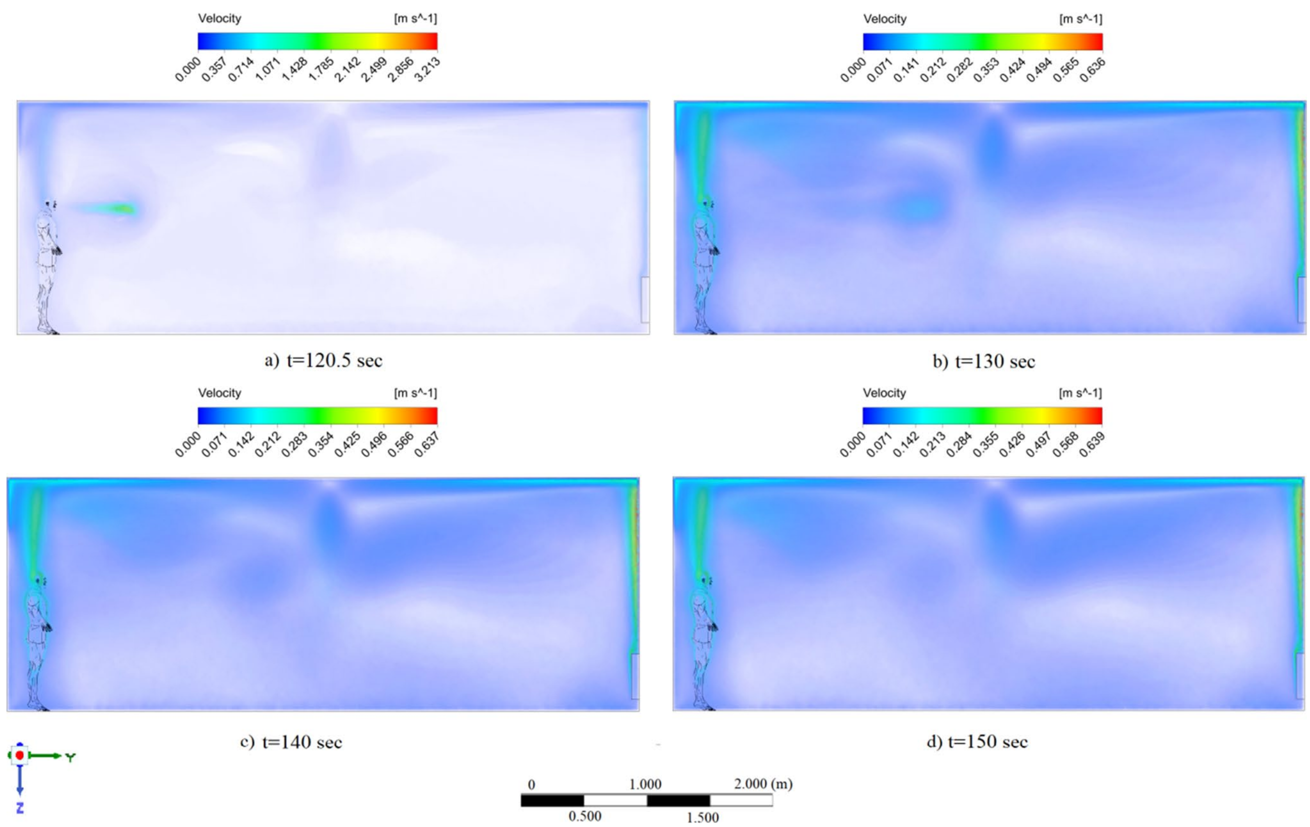



**Fig. 7** Contour velocity cough = 20 m/s with one radiator 120.5–150 s

generally exceeds, then the distribution of particles is higher than the average height of a person's growth. However, for coughing and sneezing (20 m/s), the presence of radiators has a negative effect and spreads much farther than without taking into account the radiator, so it should be noted that the excess is almost 2 times. For this work, 3 scenarios of different particle ejection rates and 2 cases of different radiator sizes were considered. Often, larger particles can carry smaller, harmful droplets and particles and, as a result, pose a greater hazard and risk in terms of airborne transmission of diseases from person to person. It can be seen from the obtained results that not only the velocity of particle propagation, but also the temperature of the human body and the presence of radiators affect the transfer of particles during the process of inhalation, coughing or sneezing.

The obtained numerical results show that droplets or particles formed during normal breathing are transported over relatively small distances, while droplets or particles formed during coughing or sneezing can move over much longer distances, which can negatively affect the protection of the human the body from the spread of infectious diseases. In many scenarios, the transport of particles exceeds the WHO recommended social distance (2 m). It should also be noted that different temperature regimes from radiators can strongly affect the spread of particles in an enclosed space. From the obtained results, it should be noted that making recommendations close to reality and choosing a social distance should take into account not only the modes of emission of polluting particles, but also external conditions, especially momentum, gravity, human body temperature, as well as the process of natural convection, which very strongly affect the propagation of particles in a confined room.

## Conclusion

This paper uses CFD to study the transport and scattering of particles generated by coughing or sneezing, taking into account the temperature of the human body and the temperature of the radiator of an enclosed space. Computational studies have been carried out on the emission of particles during normal human breathing, sneezing and coughing. The room model validation is in good agreement with the experimental data, which means that the entire mechanism can be efficiently modeled.

The obtained numerical results of the transfer and distribution of tiny particles and droplets formed during normal breathing, sneezing or coughing in a closed room, taking into account the temperature, lead to the following conclusions: during the normal breathing process, particles or

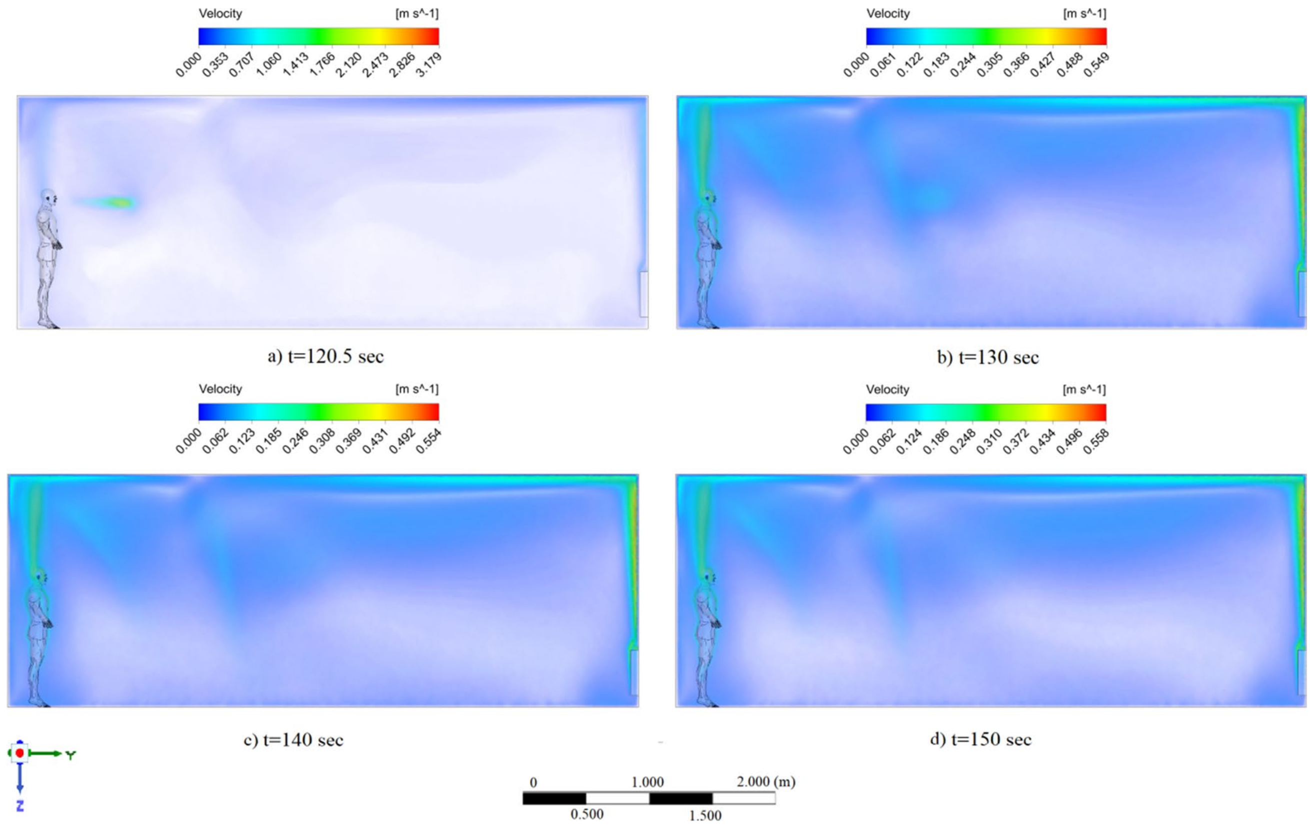



**Fig. 8** Contour velocity cough = 20 m/s with two radiators 120.5–150 s

droplets are mainly transferred only over short distances, and when sneezing or coughing this distance increases. The presence of body temperature in a person and in a room causes tiny particles or droplets to travel more than 4 m in 150 s. Analysis of the propagation of particles and droplets during sneezing showed a maximum propagation distance of 4.29 m, 1.109 m in height, 1.113 m and 1.173 m in lateral directions. This mode exceeds the social distance recommended by WHO (2 m) more than 2 times, which may lead to unfavorable consequences.

Based on the obtained numerical results, it can be seen that the influence of the temperature of the human body and radiators is significant for the development of the local air flow, the trajectory of transport of particles of various sizes, as well as such characteristics as the propagation distance of particles, the direction and speed of particles.

It should also be noted that the above results are based on simplified and ideal scenarios without considering many contributing factors such as ventilation, humidity, evaporation of droplets and particles, etc. For this reason, the obtained results must be used with caution. The results of the presented study can also be viewed as a new direction in understanding the complex phenomena of particle transport in enclosed spaces, taking into account temperature and, ultimately, in preventing the transmission of infectious diseases.

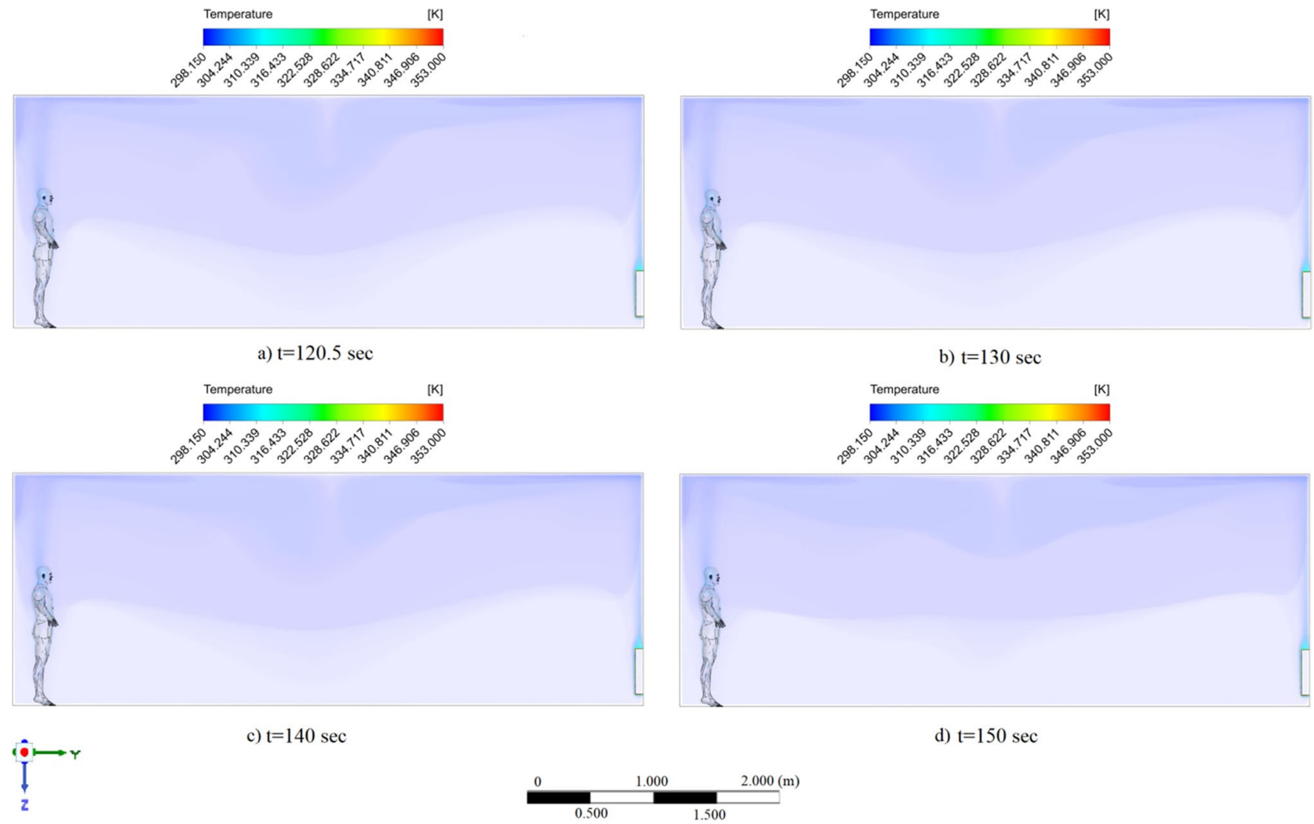



**Fig. 9** Contour temperature cough = 1 m/s with one radiator 120.5–150 s

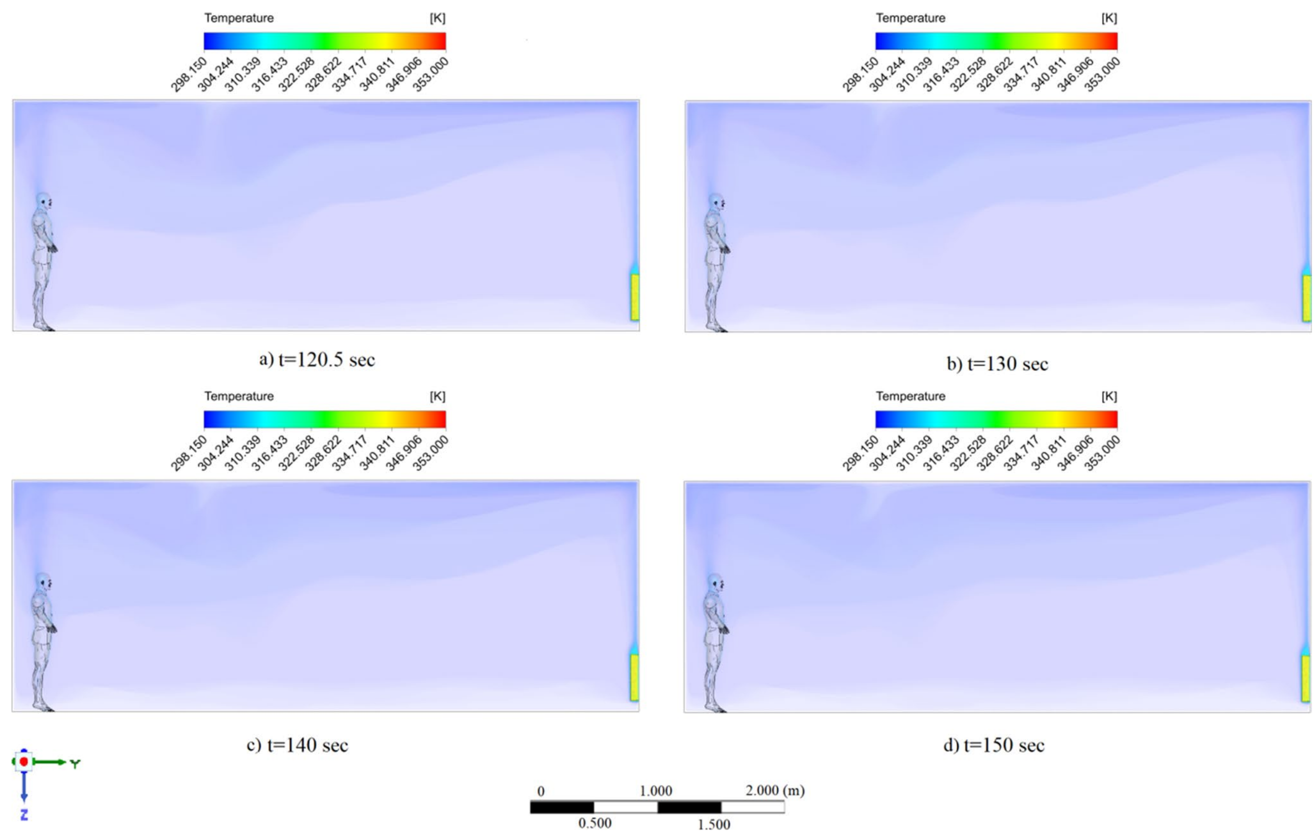



**Fig. 10** Contour temperature cough = 1 m/s with two radiators 120.5–150 s

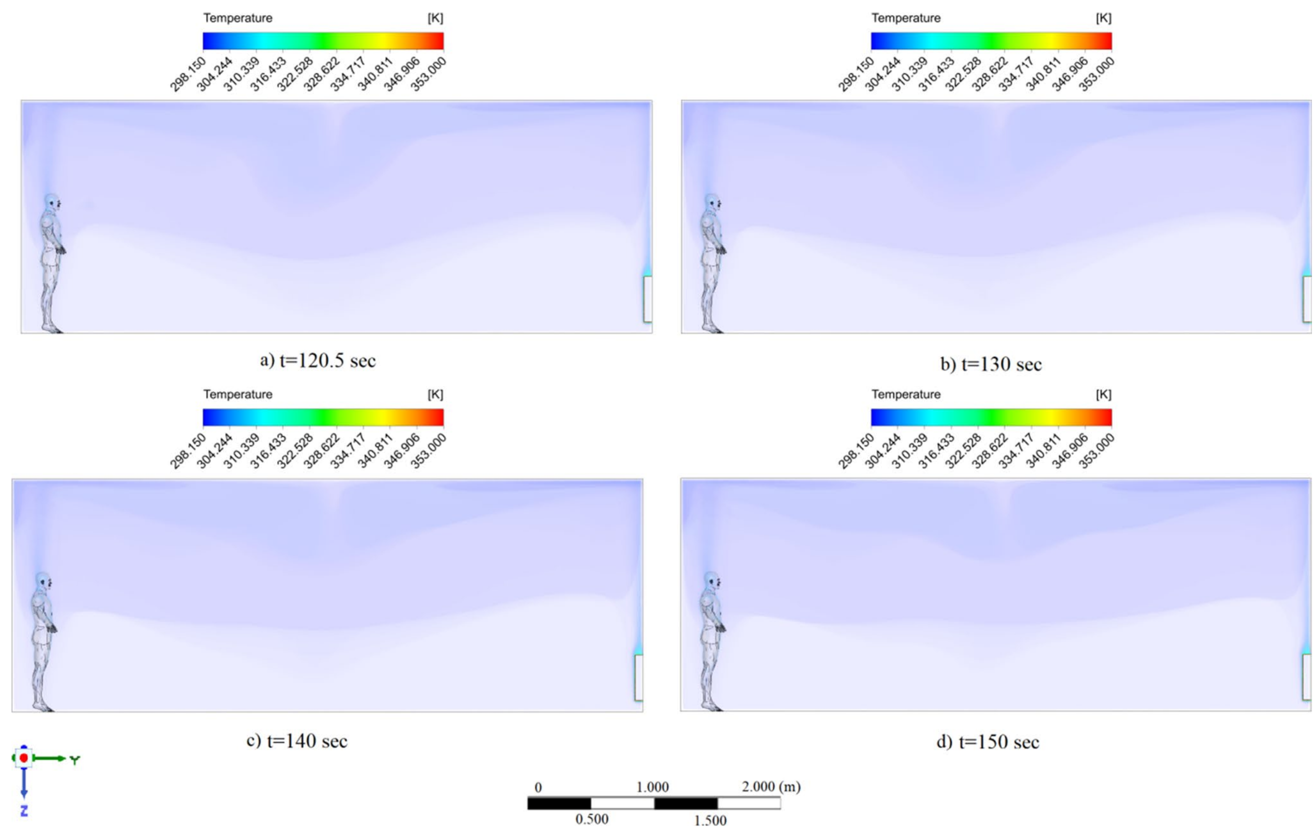



**Fig. 11** Contour temperature cough = 6 m/s with one radiator 120.5–150 s

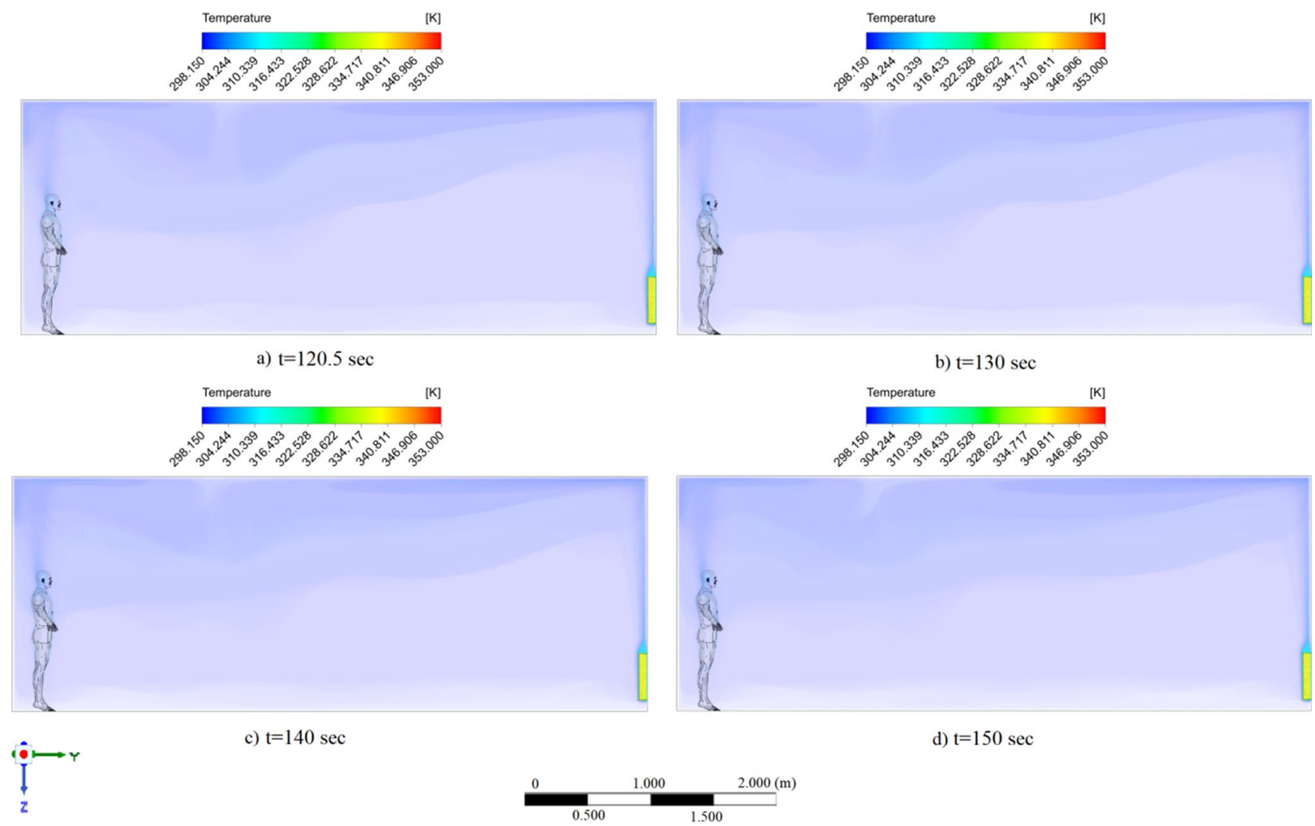



**Fig. 12** Contour temperature cough = 6 m/s with two radiators 120.5–150 s

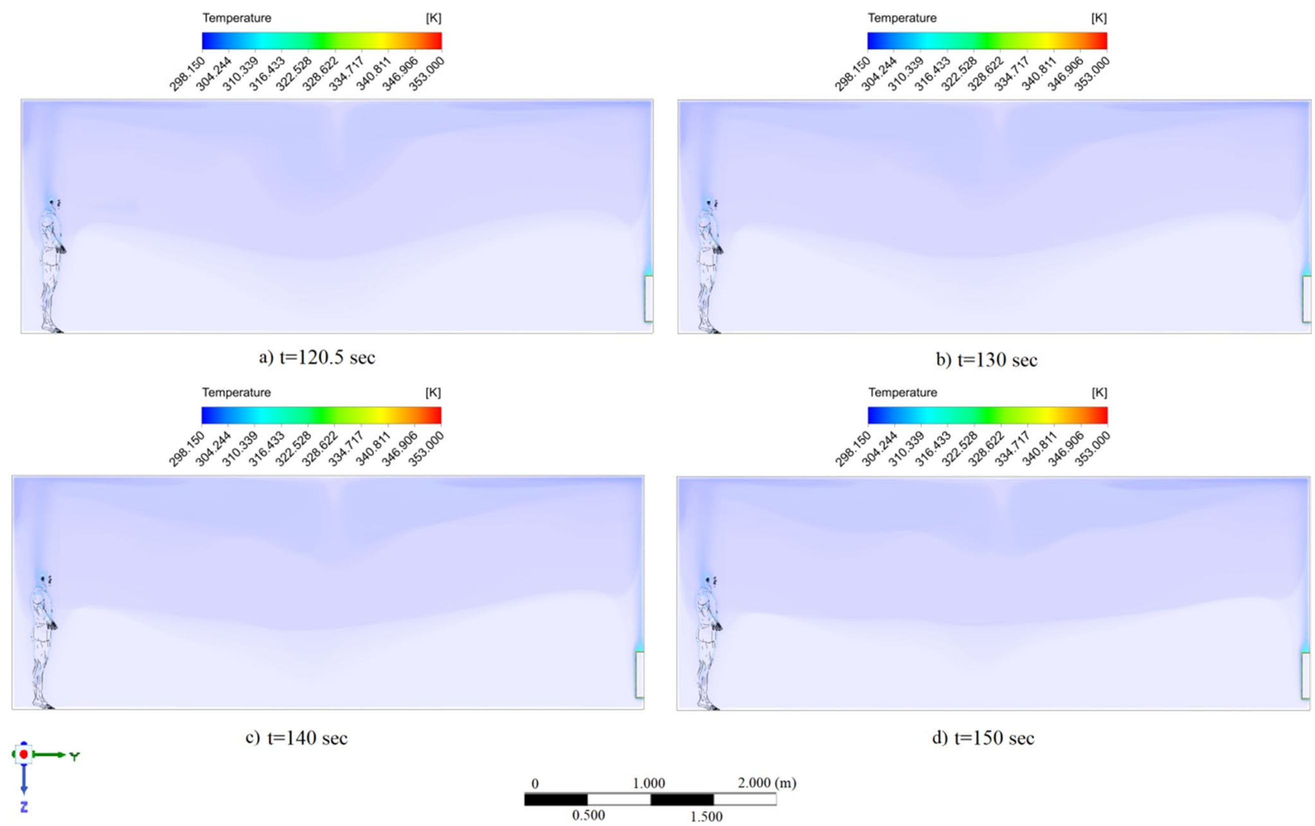



**Fig. 13** Contour temperature cough = 20 m/s with one radiator 120.5–150 s

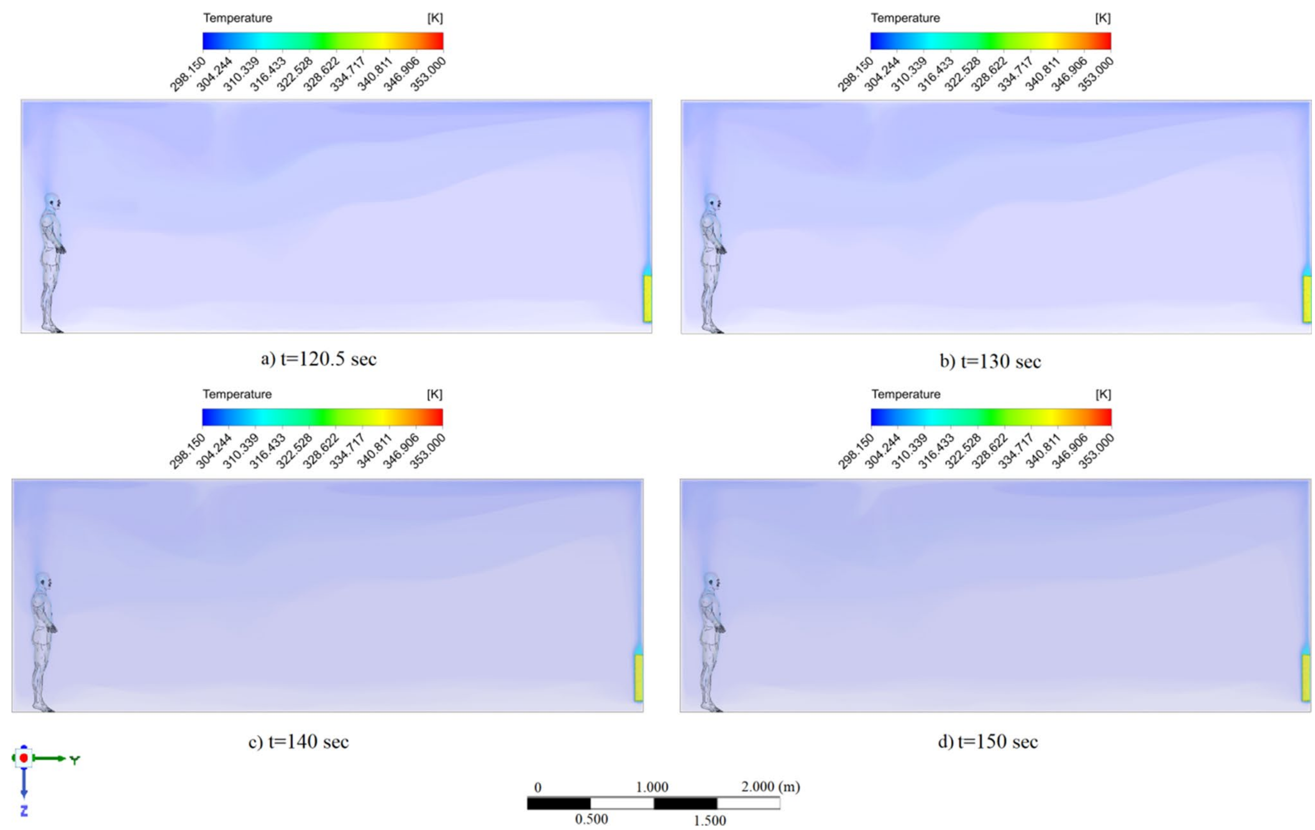



**Fig. 14** Contour temperature cough = 20 m/s with two radiators 120.5–150 s

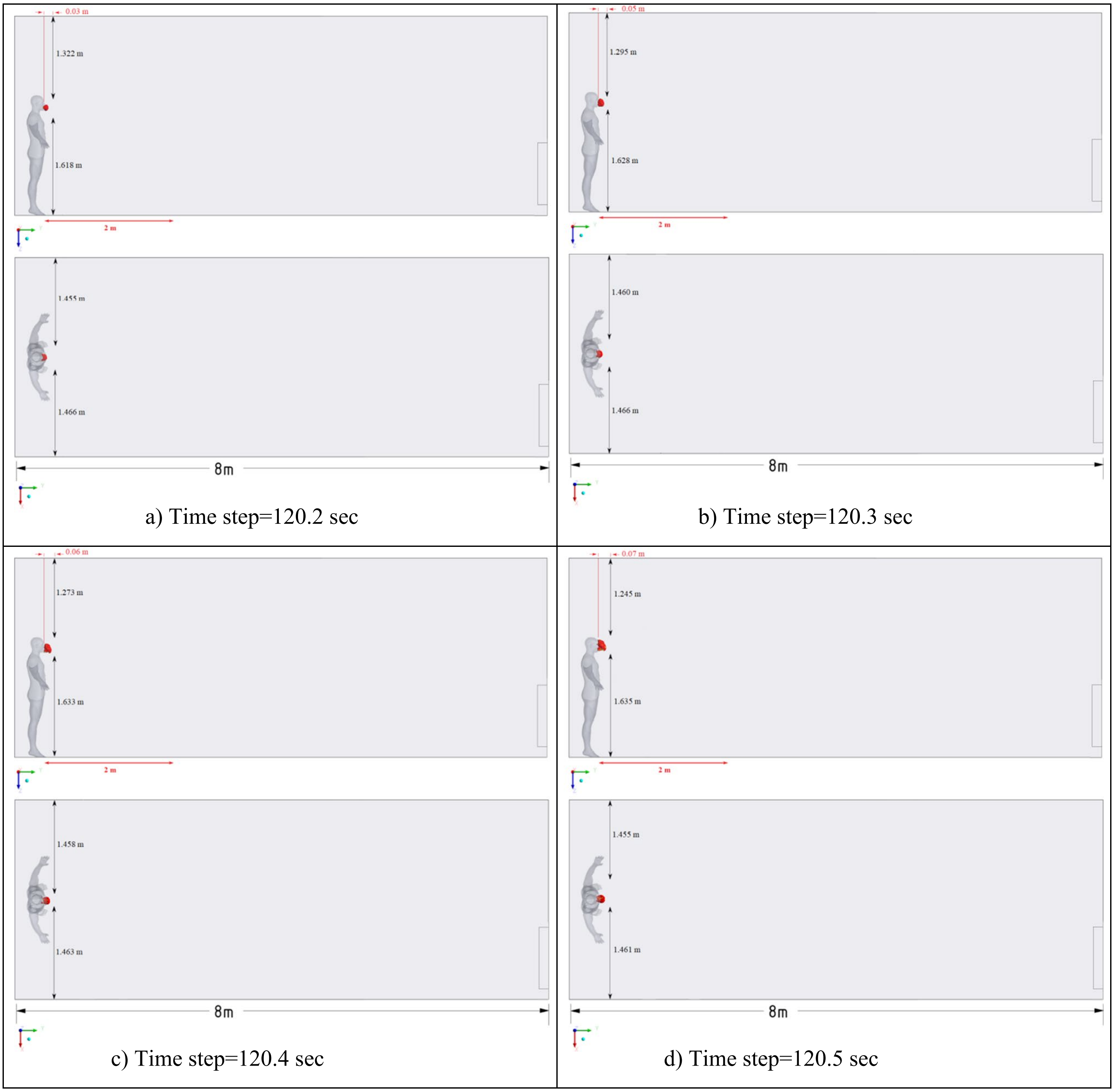
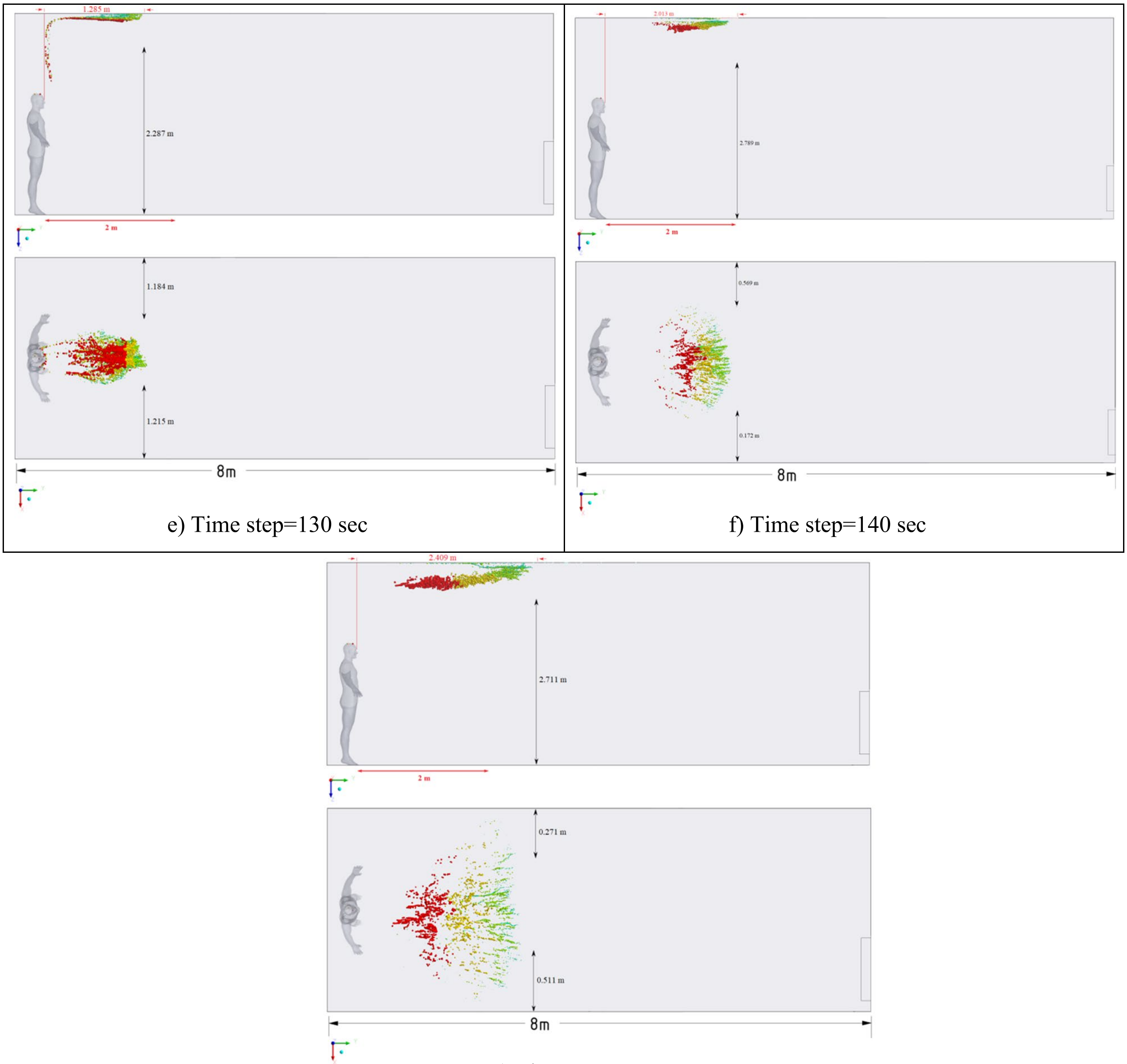



**Fig. 15** Particles, cough = 1 m/s with one radiator 150 s




e) Time step=130 sec

f) Time step=140 sec

g) Time step=150 sec

**Fig. 15** (continued)

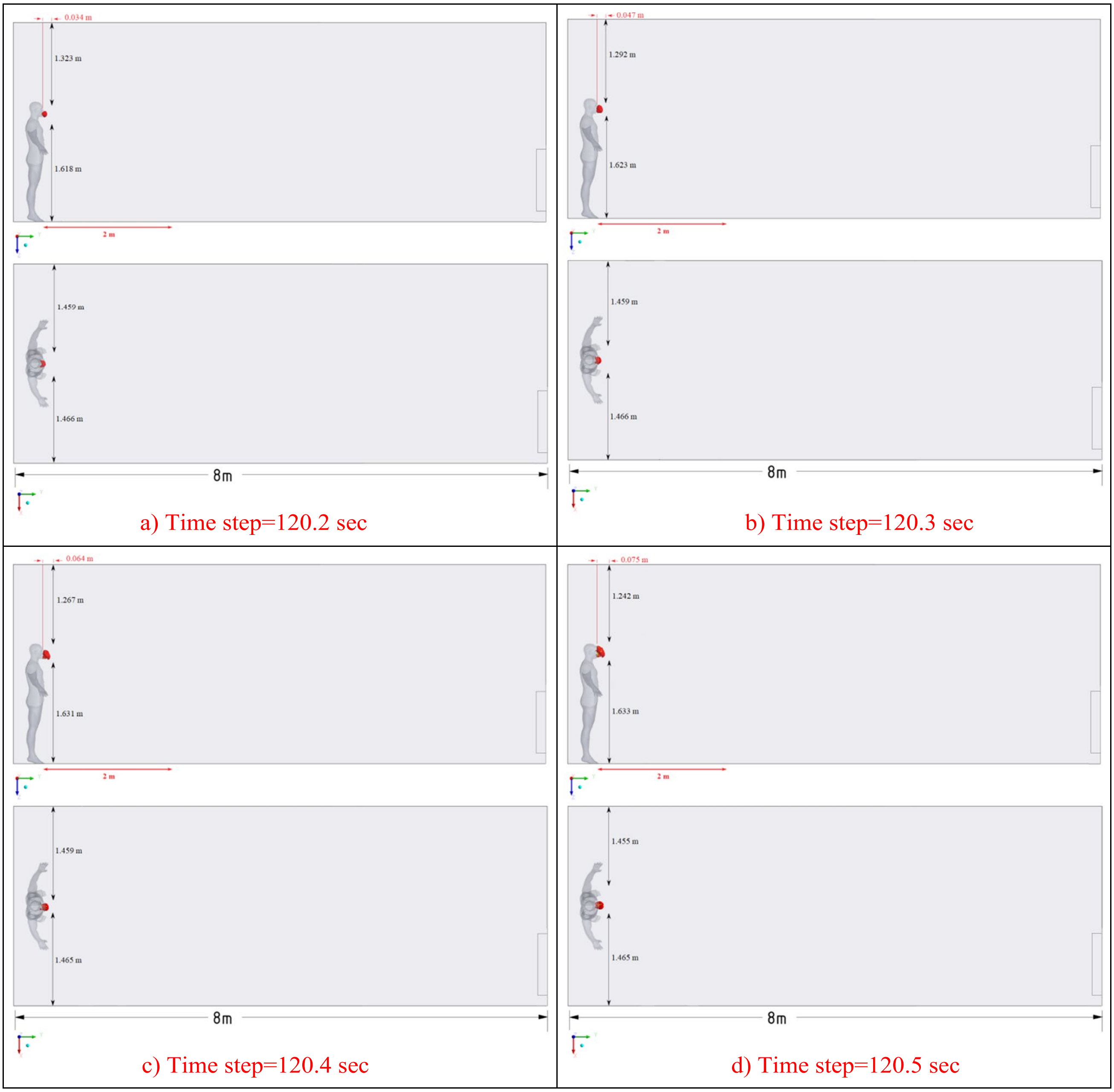



**Fig. 16** Particles, cough = 1 m/s with two radiators 150 s

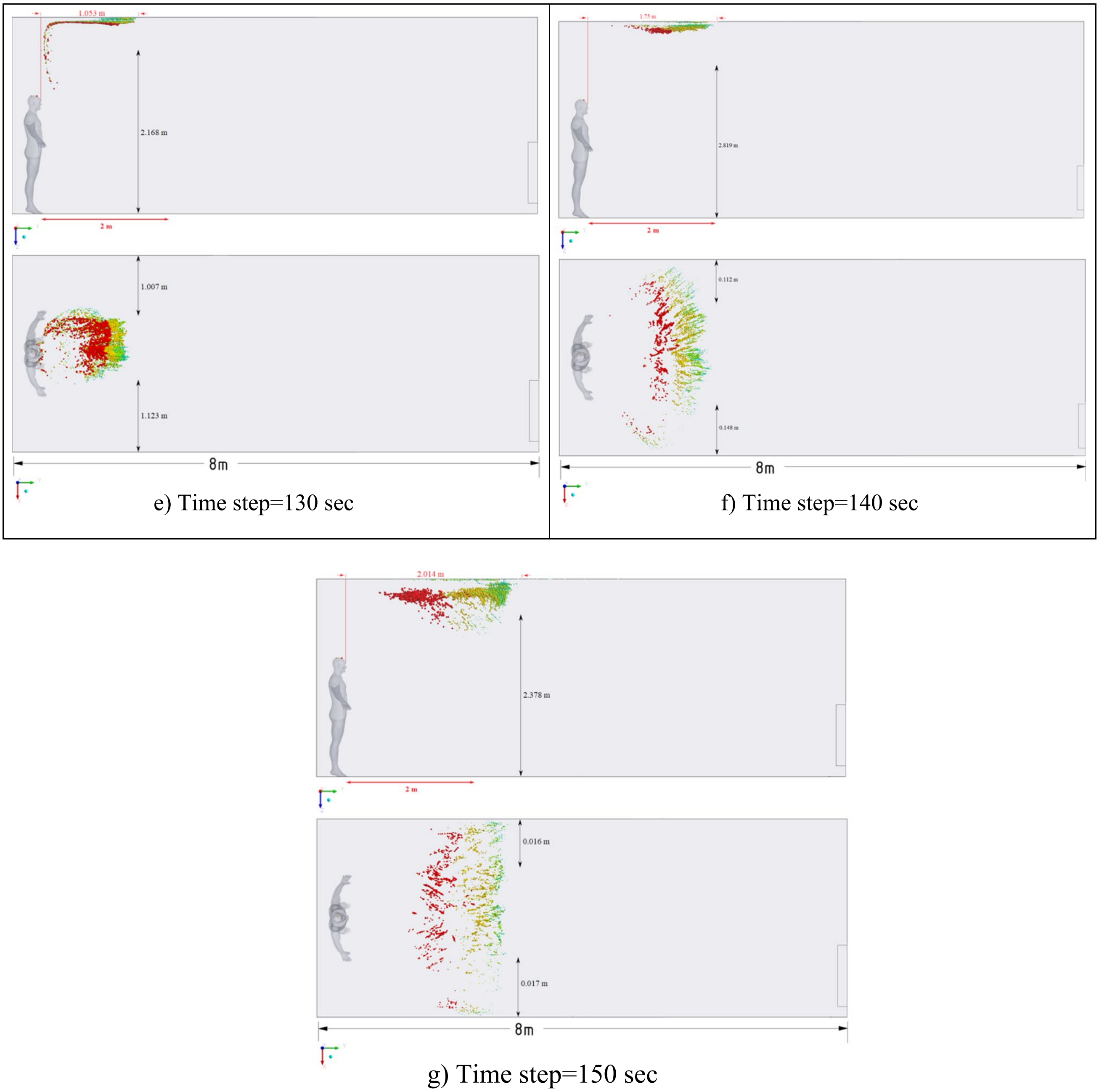



**Fig. 16** (continued)

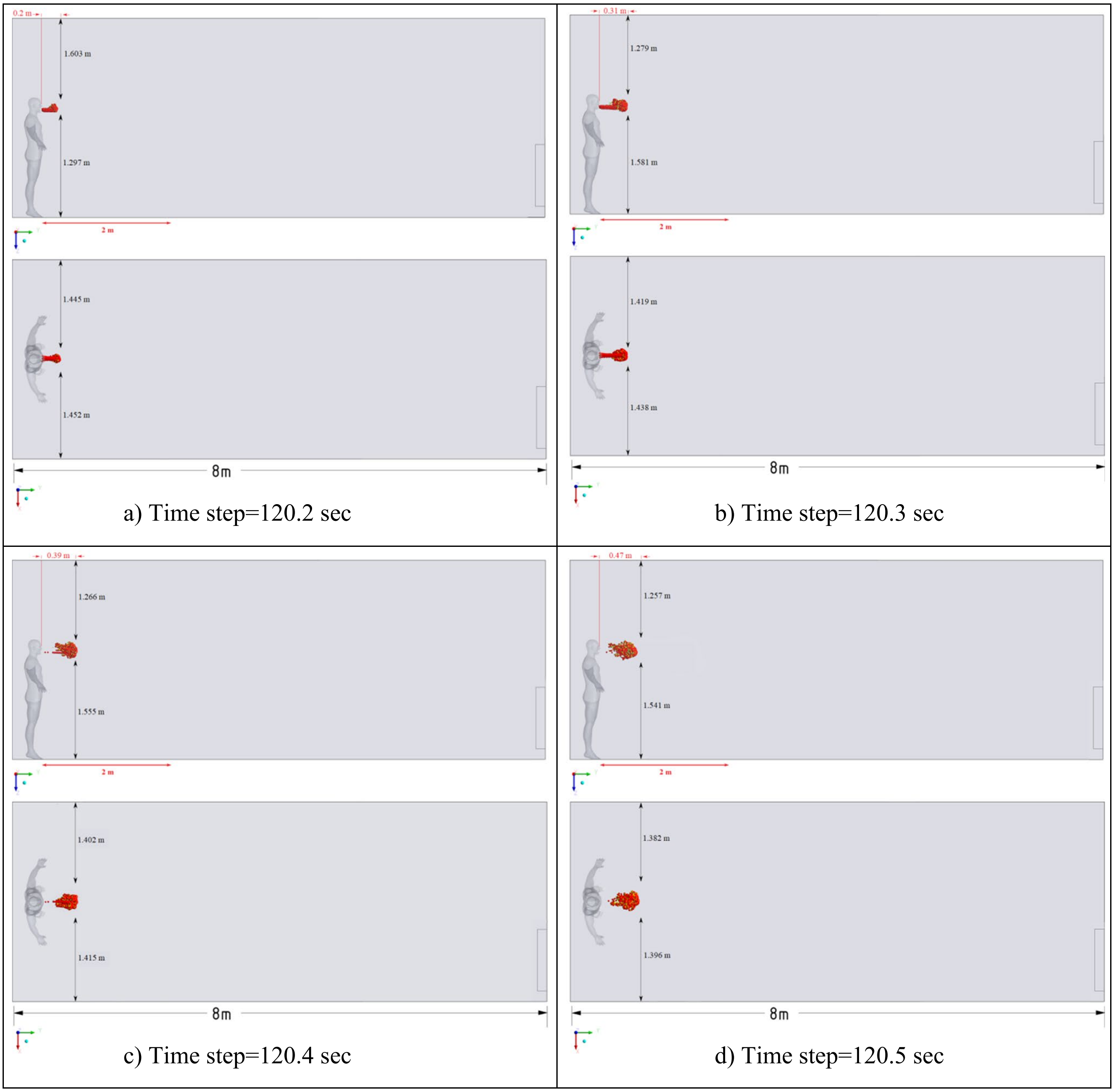



**Fig. 17** Particles, cough = 6 m/s with one radiator 150 s

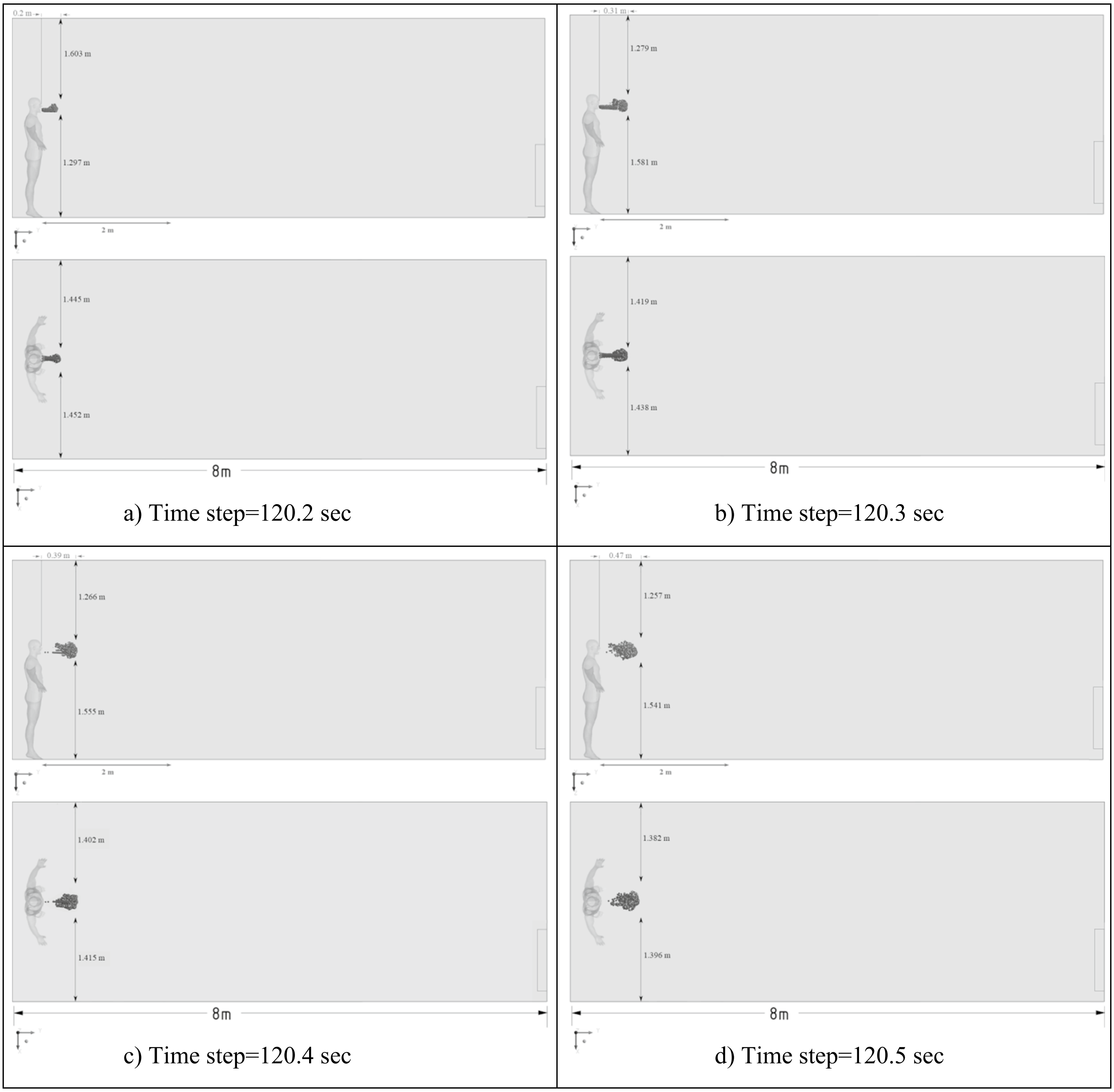



**Fig. 17** (continued)

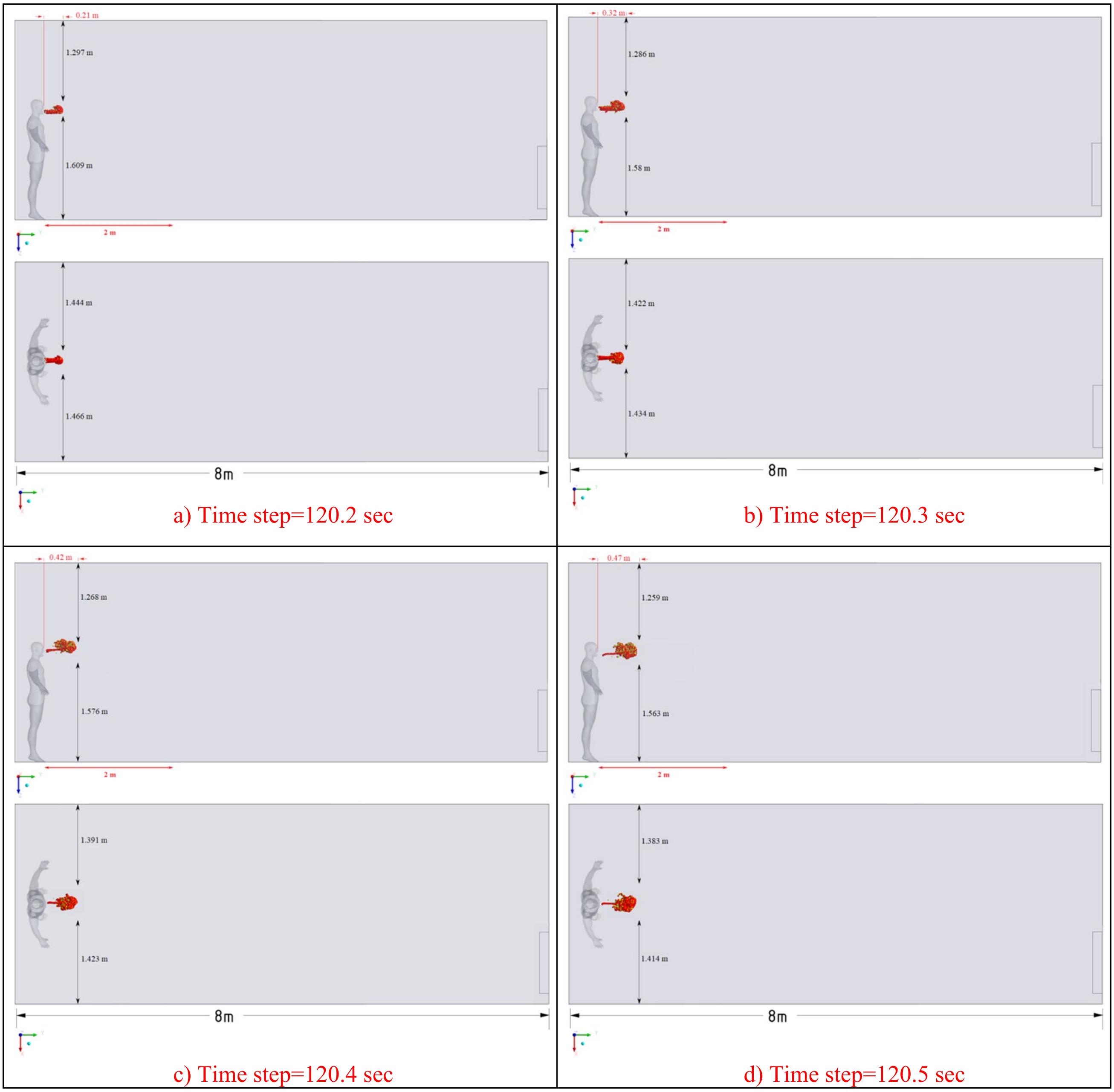



**Fig. 18** Particles, cough = 6 m/s with two radiators 150 s

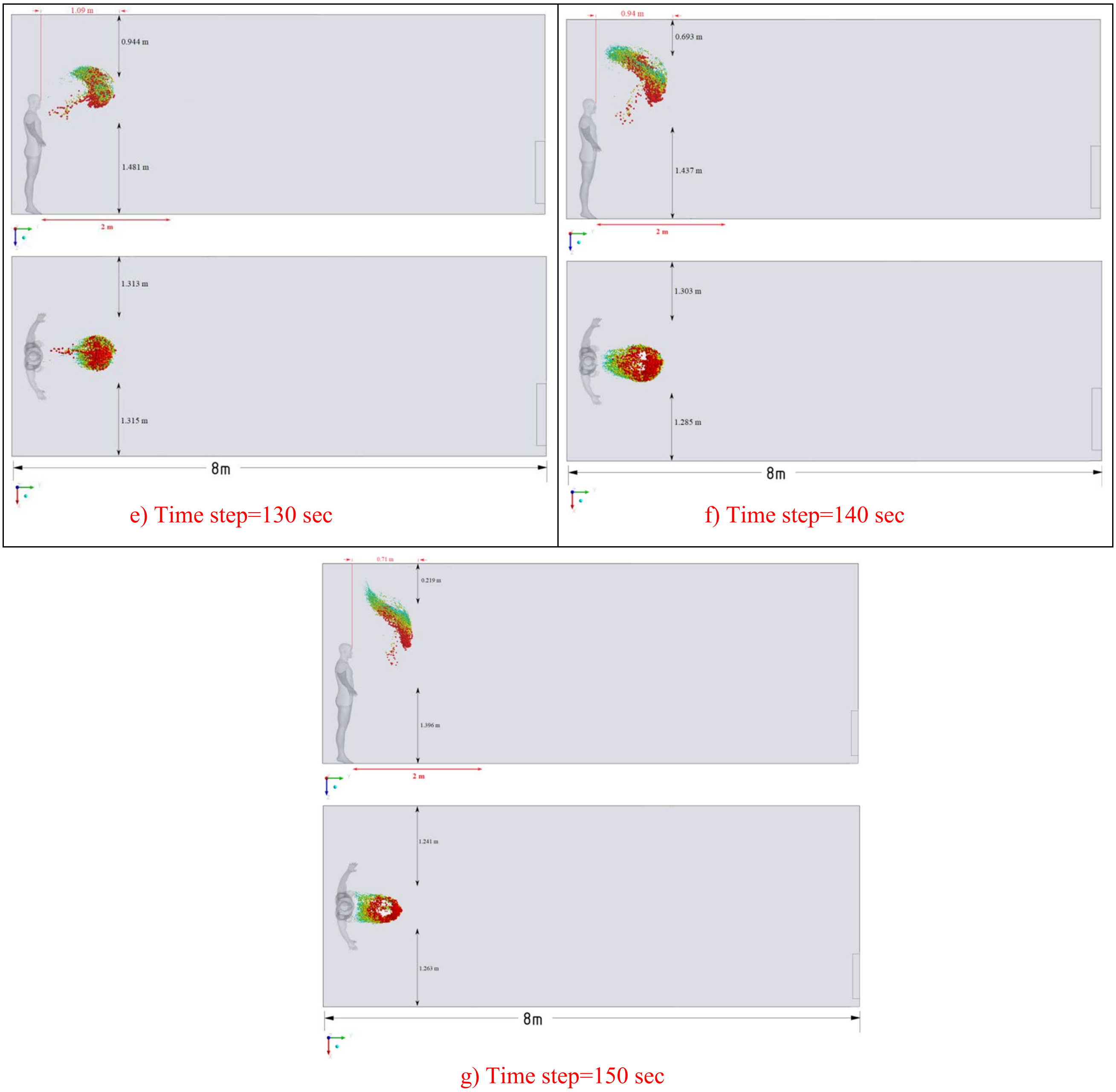



**Fig. 18** (continued)

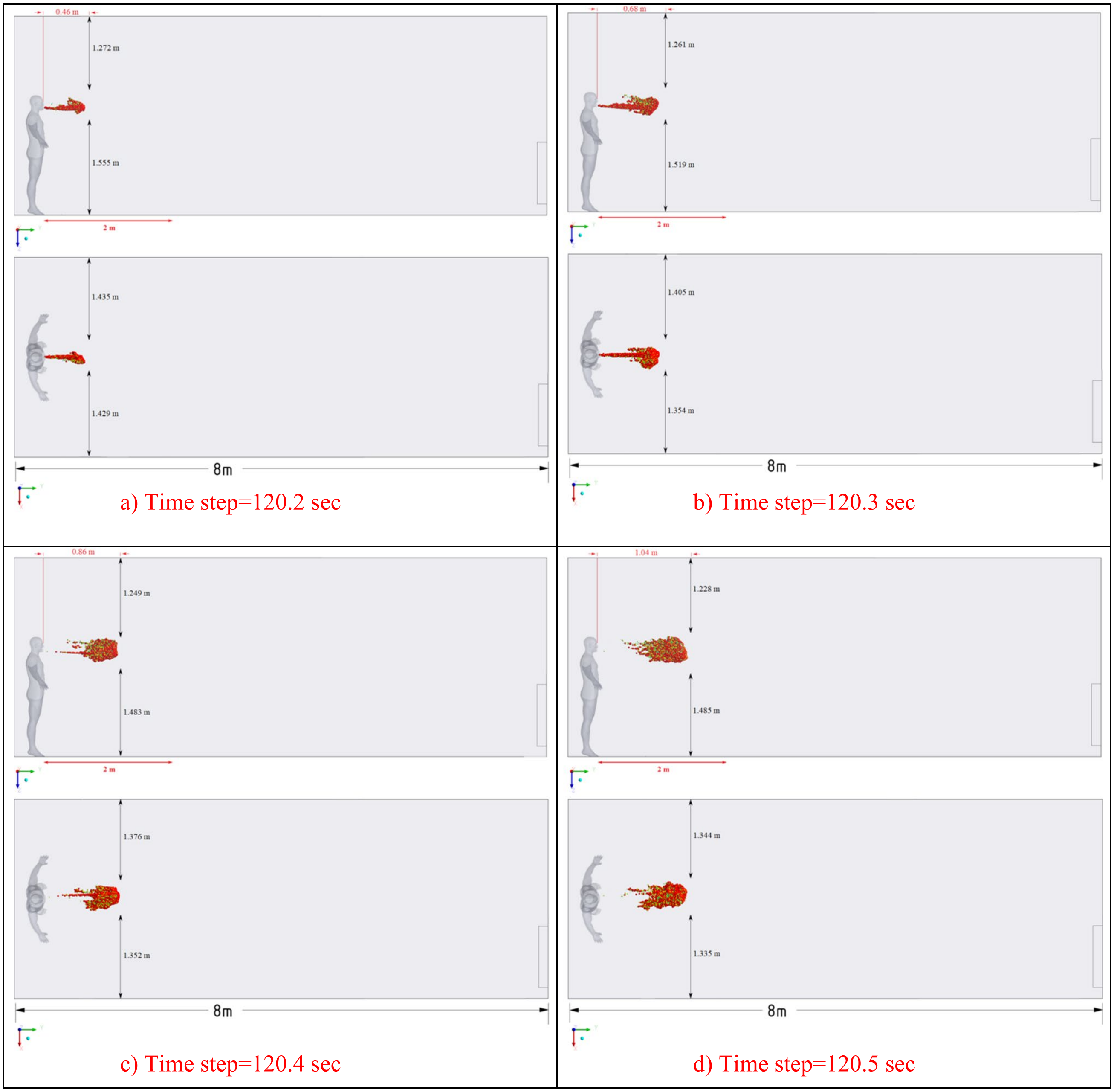



**Fig. 19** Particles, cough = 20 m/s one radiator 150 s

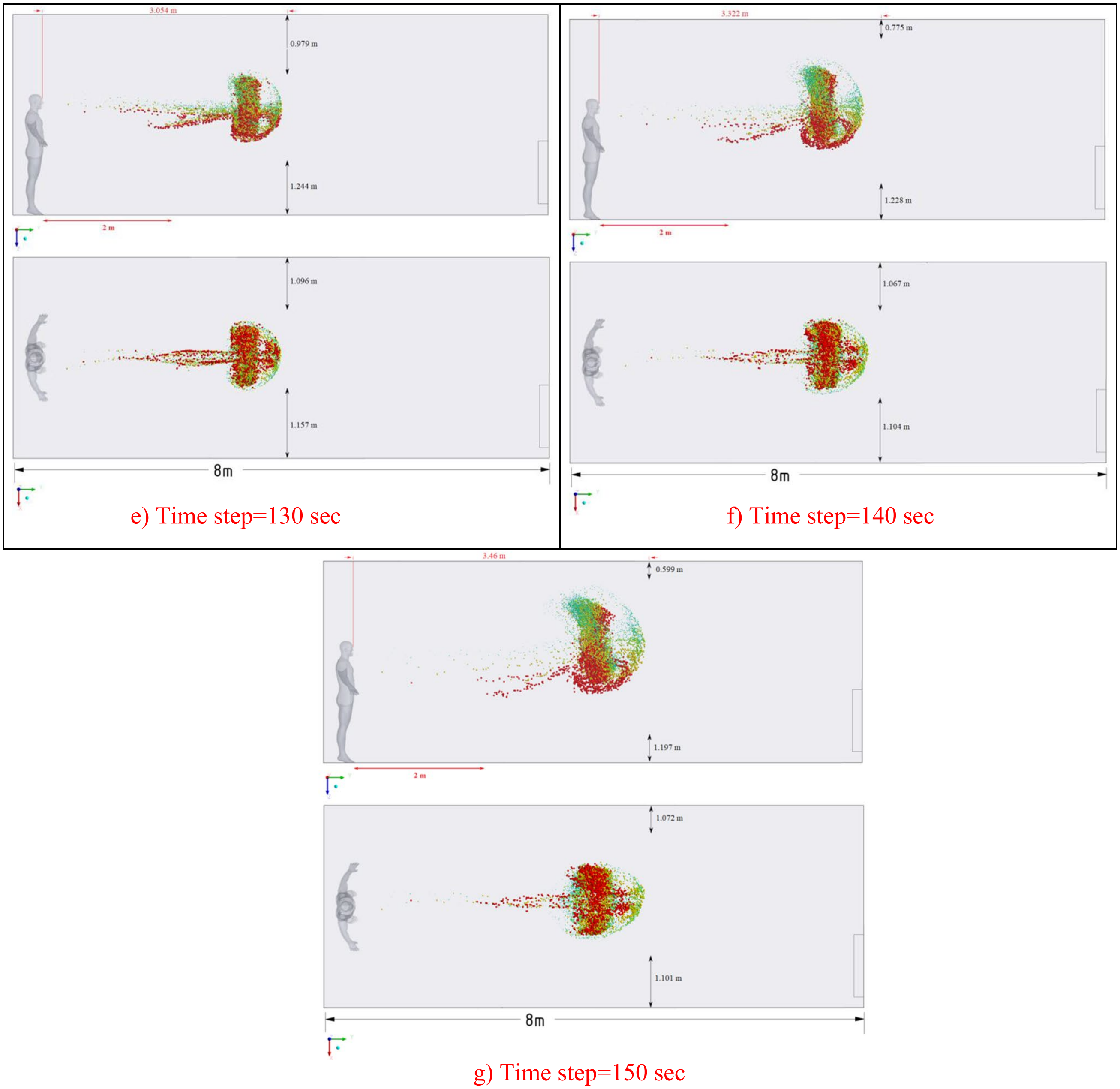



**Fig. 19** (continued)

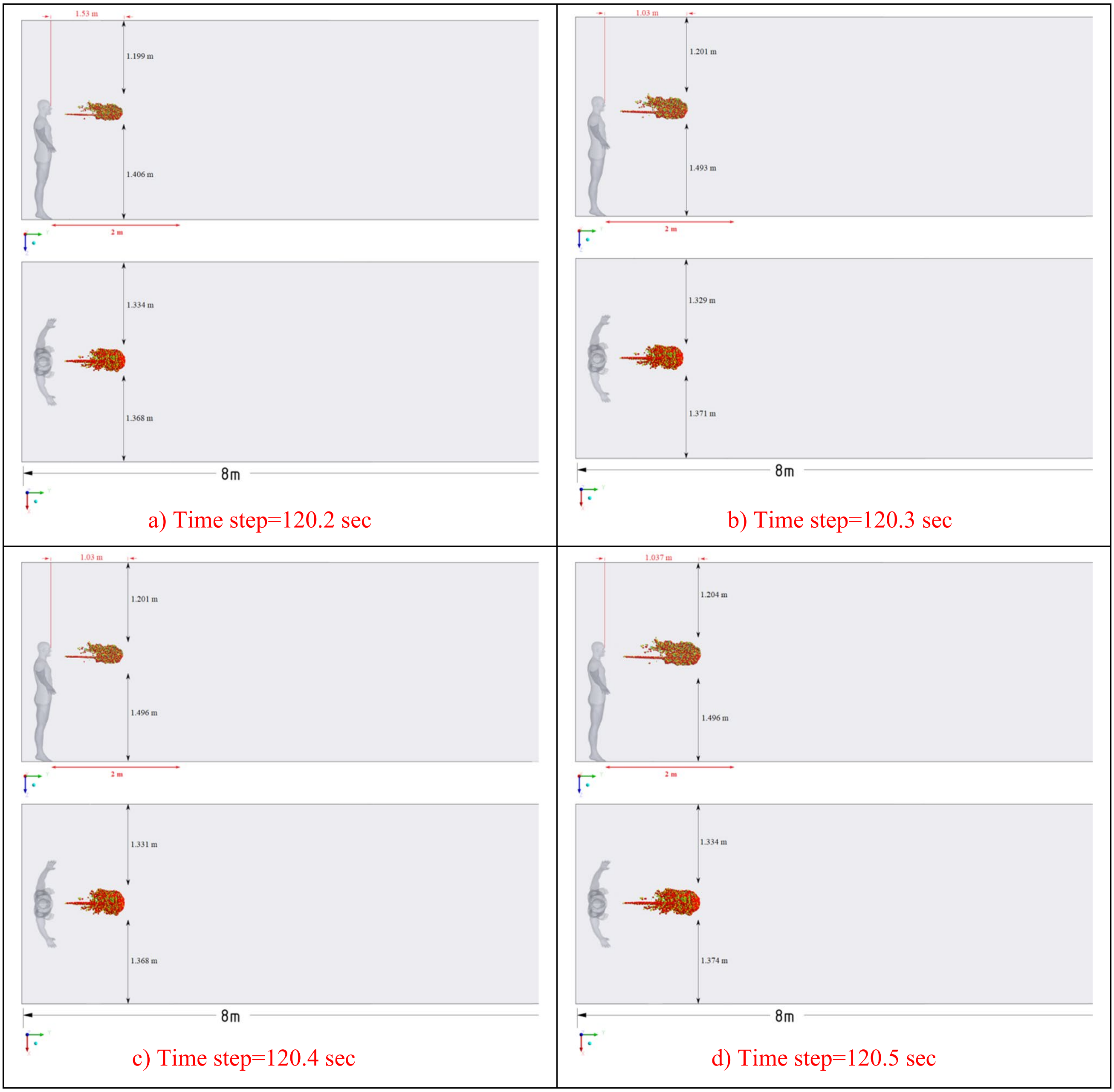



**Fig. 20** Particles, cough = 20 m/s with two radiators 150 s

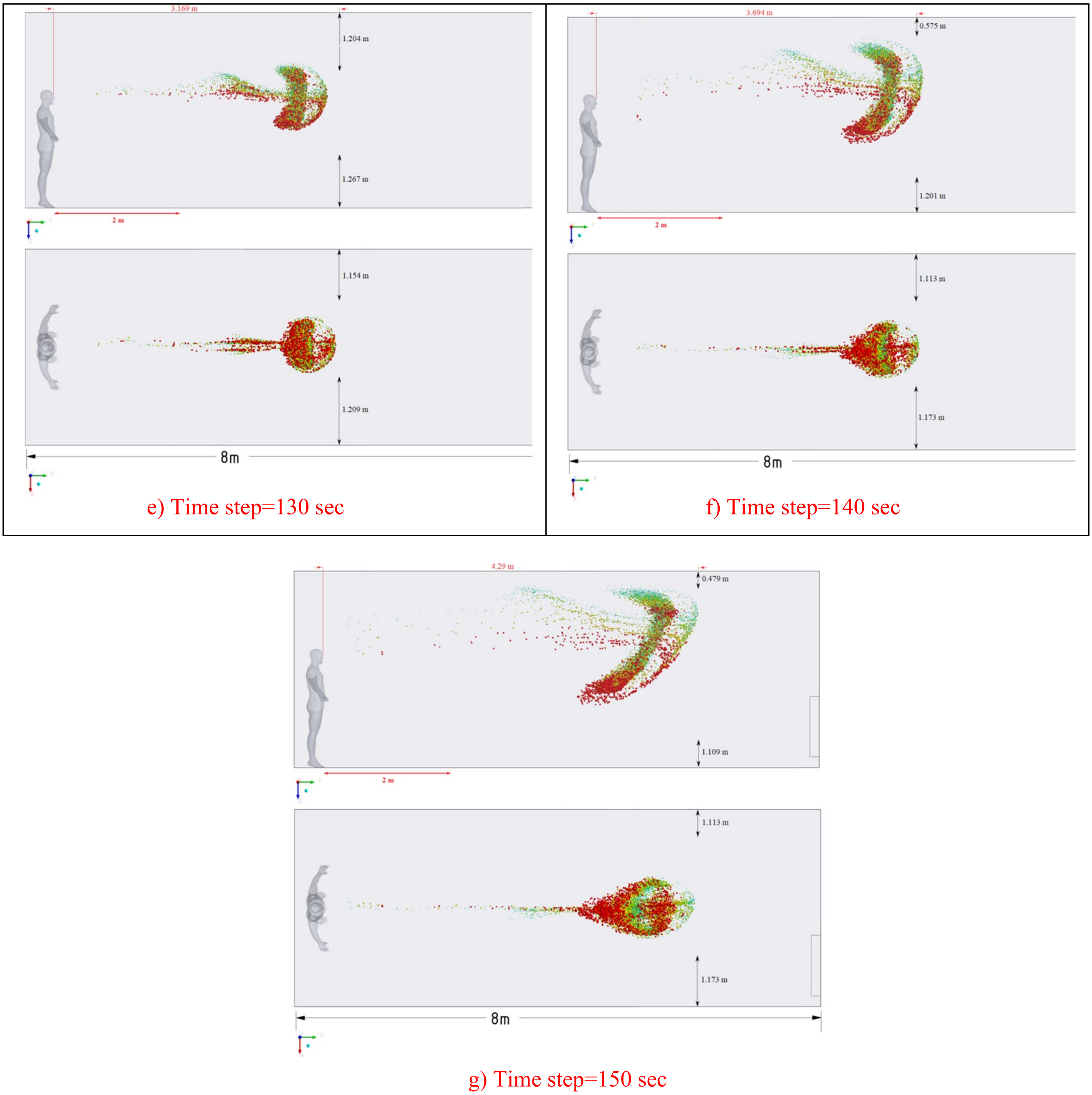
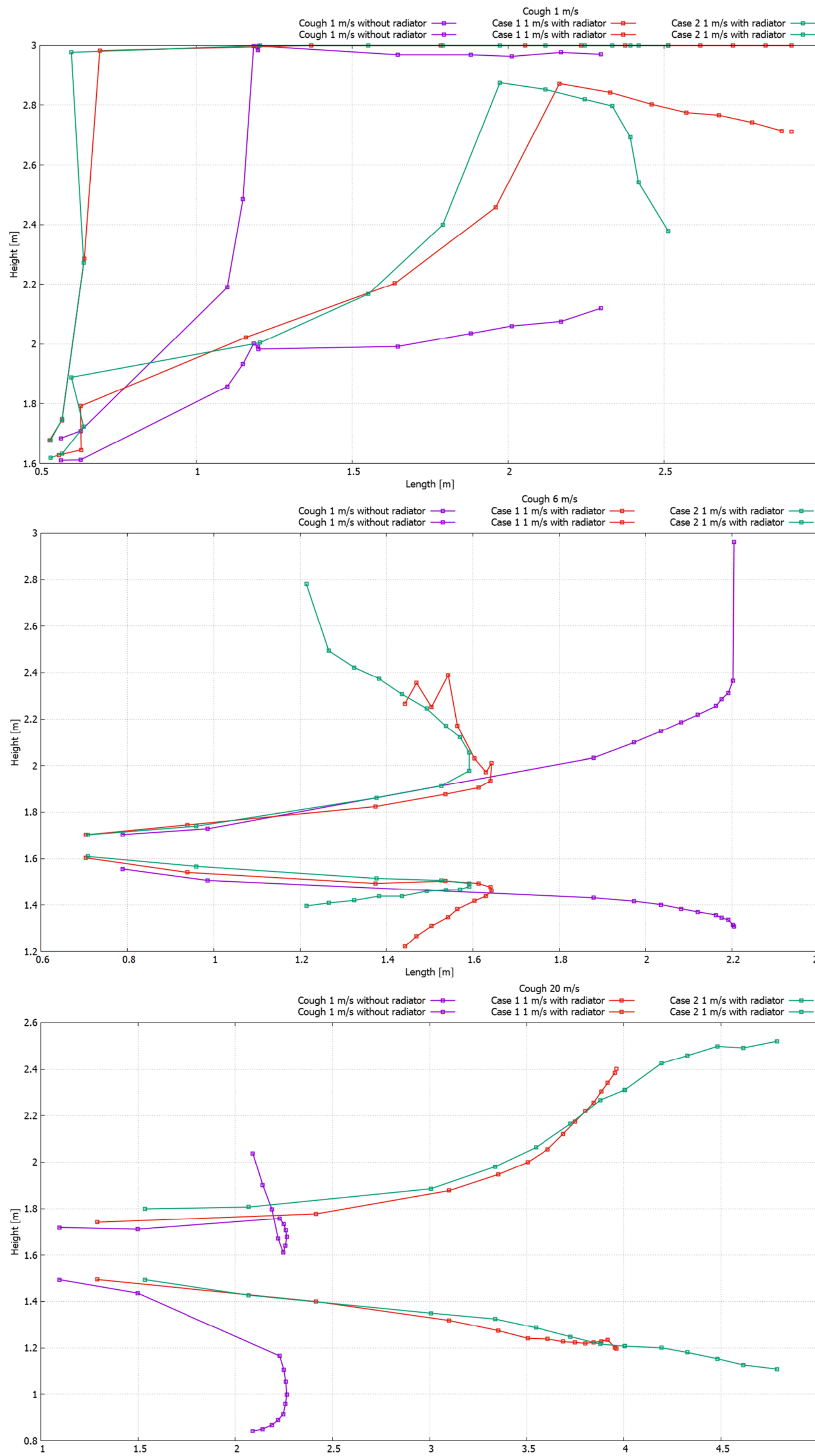



**Fig. 20** (continued)

**Fig. 21** Particle spread range case 1–2 (scenario 1–3)



**Author contribution** AI has made the conception, designs of the study, writing the manuscript and interpretation of data; PO and AB have made simulation, visualization, analysis and interpretation of data.

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**Availability of data and materials** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval** Compliance with ethical standards.

**Consent to participate** Not applicable.

**Consent for publication** All authors agree to publish.

**Conflict of interest** The authors declare no competing interests.

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