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Modelling of coughed droplets in a hospital ward

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SUMMARY

Coughing and its importance for spreading respiratory infectious diseases has been confirmed in many previous studies. The dispersion process of respiratory droplets released by the coughing of a patient in a hospital ward was studied using computational fluid dynamics simulation. Two relatively realistic three-dimensional thermal mannequins with a parallel bed arrangement simulated the patients. The maximum dispersion distances in time under ward ventilation conditions were studied. A velocity profile simulated a time-dependent cough with total duration of 0.4 s. The results indicated that the transport characteristic of droplets due to coughing is highly influenced by their size. Although the effects of gravity or inertia on small droplets (< 40 μm) are negligible and the indoor airflow mostly influences their transport, droplets of > 40 μm are significantly affected by gravity and soon fall as the strong coughing airflow field becomes weaker and the droplets separate from the general flow.

INTRODUCTION

Aerosol particles generated in the human respiratory passages leave the body by exhalation and predicting human respiratory activity is important to understand air quality and cross-infection. Exhalation airflow is highly influenced by activity levels, the micro-environment, and air distribution around the air passage (nose or mouth) [1]. Coughing, as one of the exhalation activities, is a defence mechanism to remove foreign material or mucus from the lungs and respiratory tract [2], and is one of the primary sources of airborne diseases as it has high velocity and large amount of droplets [3].

Transmission of infectious respiratory diseases in indoor environments has been a major public health concern for decades and has received attention from various disciplines. Respiratory droplets carrying infectious pathogens can be expelled by exhalation activities such as mouth and nose breathing, laughing, sneezing, coughing, and talking. The size distribution of such droplets ranges from sub-micrometre to super-micrometre and may influence the type of organisms that may be carried, as well as strategies for controlling

airborne infection [4]. However, experimental measurement has already confirmed that most coughed droplets fall within the range of 40-250 μm [5]. Depending on the airflow [6] and droplet size [7], the droplet nuclei may remain suspended in the air for a few hours and travel over a long distance or settle out. Larger droplets may rapidly settle out of the air and facilitate disease transmission in close proximity. Smaller droplets may remain suspended and contribute to disease transmission over larger distances [5]. Complications in collecting and measuring respiratory droplets are mainly due to their small sizes and rapid evaporation [5]. As the immune system is usually weak and ineffective in hospital wardrooms, such droplets can present complications, making infectious disease a far greater threat. Therefore, good understanding of cough flow dynamics can potentially help to control the airborne disease transmission.

This study, therefore, simulated the dispersion process of coughed droplets in a hospital two-bed wardroom by employing computational fluid dynamics (CFD).

METHODOLOGIES

Case study

Figure 1 shows a two-bed hospital wardroom measured 4.2 m × 3.6 m × 2.5 m. The room dimension is in accordance of the International Energy Agency Annex 20 work. Two beds, each with dimensions of 2.0 m × 0.8 m × 0.8 m (H), were placed in parallel with a gap distance of 1.4 m.

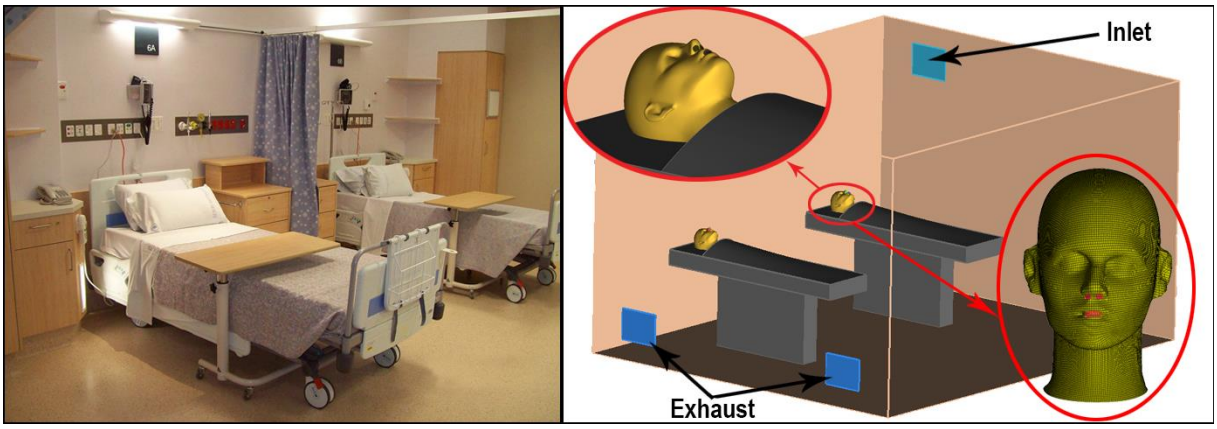

Fig. 1: Two-bed hospital ward (a) and its corresponding CFD model (b)

Detailed thermal mannequin CAD models that were equipped with realistic breathing mechanisms were considered.

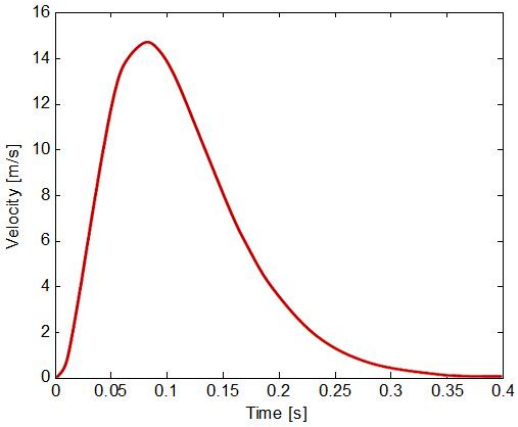

Figure 2: Time-dependent airflow velocity of a single cough model

A time-dependent airflow velocity of a single cough model was assigned to the mouth of each mannequin; see Figure 2 [8]. The heat load of each mannequin was set at 58 W/m^2, representing an adult person at rest [9]. Incoming air was supplied to the ward through a ceiling-level, rectangular inlet opening. The supplied air was evacuated through two exhaust grills at the bottom of the wardroom. Simulations were performed at a constant ventilation air exchange rate of 6 ACH and temperature of 20 °C to mimic a general hospital wardroom. To simulate coughing droplets, a source of airborne particles was emitted together with coughing exhalation air from the mannequin's mouth. Droplets were considered as pure water droplets and their concentration was normalized by the patient's mouth, resulting in a unit mouth concentration. Totally, four different droplet size (i.e., 40, 70, 150, and 250 μm) were considered is accordance to the measurement done by Xie et al. [5]. For each droplet size, a full coughing process cycle was transiently simulated until the released particles either settled or evacuated.

The airflow was simulated using the Realizable k-ε turbulence model and particle trajectories were stochastically tracked using the Lagrangian approach. The governing equations were solved using commercial CFD code, FLUENT 15.0. An independence test was conducted to evaluate the effects of grid sizes on the results. Three sets of mesh were generated using ICEM CFD software. Finally, a grid size of 1.2 million yielded very small changes during simulations and was thus selected. In addition, the transient simulation was subjected to time-step sensitivity analysis. Model validation in terms of airflow and particle movement were already carried out [10,12] and thus not repeated here.

RESULTS AND DISCUSSION

The jet velocity and its direction from the coughs is shown in Figure 3 four distinct time-steps representing a single coughing process.

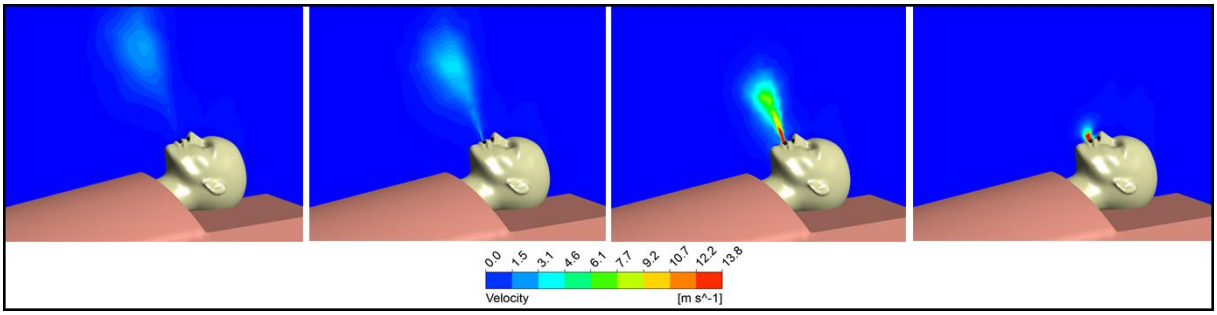

Figure 3: Coughing velocity contour plot for a single process

Very high velocity after only 0.1 sec from the start of the coughing process can be observed at the vicinity of the mouth area. However, air velocity soon moderated, as droplets traveled only 20 cm from the mouth.

The dispersion process after a single cough was derived by plotting the locations of all airborne droplets, as shown in Figure 4. The droplets were colored by the particle velocity and residence time.

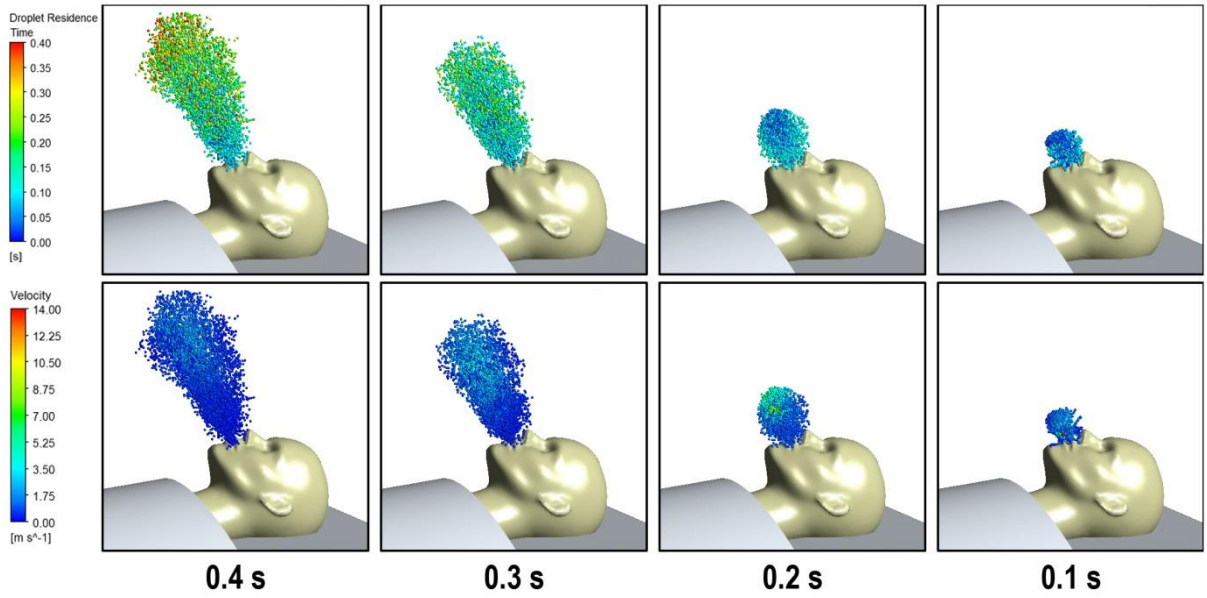

Figure 4: Predicted behavior of moving droplets for different time steps (Droplet size: 40 µm)

Fast penetration of droplets could be observed in the first 0.2 sec of the coughing process due to the high air jet velocity. In the next 0.2 sec, the coughing air velocity was reduced drastically and thus had moderate impact on the droplets' trajectories. Therefore, droplets movement was then dictated by both gravitational acceleration and overall airflow pattern of the indoor environment.

The droplet dispersion after a single cough for different droplets diameter was shown in figure 5. Droplets with diameter of 40 µm reach the breathing zone of the other person in the ward after only 25 sec; however, this time increased while the droplet diameter increased. Moreover, by increasing the droplets' diameter, the settling velocity increased and thus fewer particles can reach the neighbouring person.

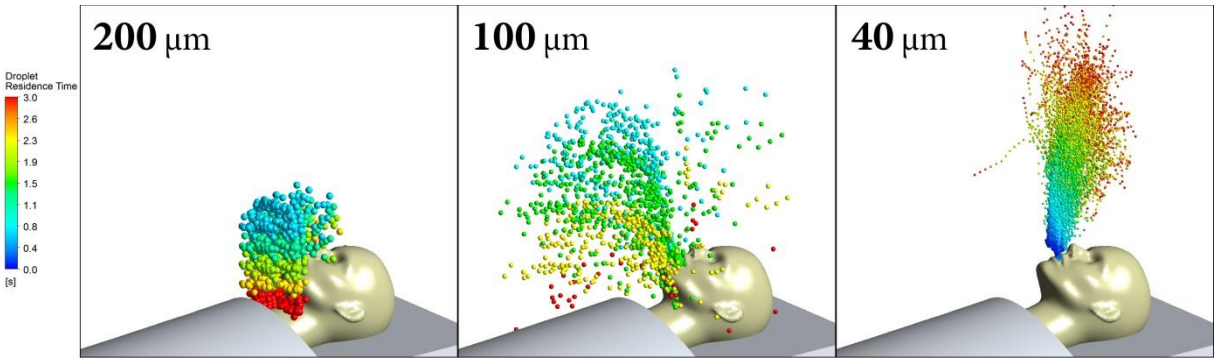

Figure 5: The droplet dispersion after a single cough for different droplets diameter

During the total coughing process time (0.4 s), the evaporation mechanism had negligible influence on the droplets' diameter and thus can be disregarded. This is according

to the results presented by Xie et al. [7] as shown in Figure 6. This figure shows how the diameter of a water droplet decreases with time for different droplets' initial sizes.

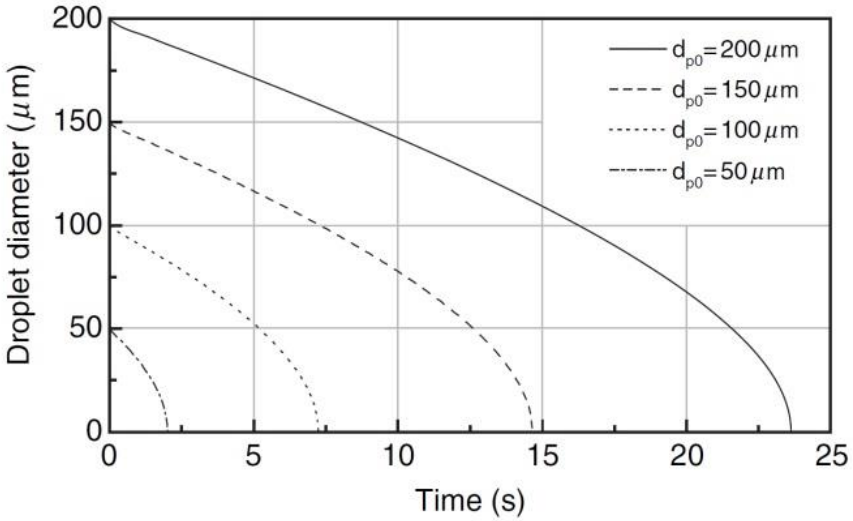

Figure 6: The droplet dispersion process after a single cough from Xie et al. [7]

It is clearly shown that smaller droplets evaporated faster compared to the large droplets. Assuming it is pure water, a 50-μm droplet evaporates completely at about 2.0 s, while a 200-μm evaporates at about 24 s.

CONCLUSION

Movement of droplets expelled due to coughing was analyzed using computational fluid dynamics. The effects of size and exhaled air velocity on droplet dispersion were examined for four different droplet sizes (40, 70, 150 and 250 μm). It was shown that small droplets could easily travel far from the source (mouth) and spread to the entire room; however, large droplets fall to the ground quickly due to gravitational acceleration. Droplets smaller than 70 μm (here, 40 μm and 70 μm) were reached the outlet openings, which confirm that droplets within this rage can spread to the entire environment. However, the particles above this size (here, 150 μm and 250 μm) settle down in a short distance from the releasing area. Current findings may be useful for developing engineering applications to limit and control cross-infections and disease transmission via large droplets or airborne routes within hospital wardrooms.

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