

MASK AND ITS PERFORMANCE ANALYSIS WITH COMPUTATIONAL FLUID DYNAMIC (CFD) OF FILTERING SARS-COV-2 PARTICLES IN CONFINED SPACE

(Pelitup Muka dan Analisis Prestasinya terhadap Penapisan Zarah SARS-Cov-2 dalam Ruangan Terkurung dengan menggunakan Pengkomputeran Dinamik Bendalir (CFD))

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Abstract

SARS-CoV-2 virus can be transmitted through the air to another person via travelling water droplets. The use of facial masks has been strongly recommended to prevent the transmission of this highly infectious disease. Latest recommendation suggested that double mask configuration of surgical and reusable masks perform comparably well to surgical and N95 masks, however its efficiency has not been documented yet. In this paper, the effectiveness of double masks configuration to filter particles travelling through the air was investigated using particle tracing simulation study in the computational fluid dynamic (CFD) simulation. The movement of droplets at size range between 1 μm to 100 μm through the facial masks in a closed room between two people during talking and sneezing was simulated using particle tracing. The total number of particles filtered, and filtration efficiency of each mask were calculated. Our findings indicate that the configuration of N95-reusable mask had the lowest amount of particle escape, resulting in the best droplet filtering of all cases. For the case of the movement of the droplets, it shows that 30 μm and 37 μm droplets that escaped from a surgical mask and a N95 mask may reach 960 m and 631 m, respectively. These results can enhance future prediction of the duration and efficacy of measures required to manage COVID-19 and other outbreaks of a similar kind.

Keywords: airborne transmission, double mask, SARS-CoV-2, filtration efficiency

Abstrak

Virus SARS-Cov-2 boleh berjangkit melalui udara kepada orang lain melalui titisan air yang bergerak. Penggunaan pelitup muka sangat disyorkan untuk mencegah penularan penyakit yang sangat berjangkit ini. Pengesyoran terkini mencadangkan bahawa konfigurasi pelitup muka berganda bagi pelitup pembedahan dan pelitup guna semula berprestasi setanding dengan pelitup pembedahan dan N95, namun kecekapannya belum didokumenkan lagi. Dalam makalah ini, keberkesanan konfigurasi pelitup muka berganda untuk menapis zarah yang bergerak melalui udara telah disiasat menggunakan kajian simulasi pengesanan zarah

dalam simulasi dinamik bendalir pengiraan (CFD). Pergerakan titisan pada julat saiz antara 1 μm hingga 100 μm melalui topeng muka dalam bilik tertutup antara dua orang semasa bercakap dan bersin telah disimulasikan menggunakan pengesanan zarah. Jumlah bilangan zarah yang ditapis, dan kecekapan penapisan setiap topeng telah dikira. Penemuan kami menunjukkan bahawa konfigurasi pelitup muka N95-guna semula mempunyai jumlah lepas zarah terendah, menghasilkan penapisan titisan terbaik bagi semua kes. Bagi kes pergerakan titisan, ia menunjukkan bahawa titisan 30 μm dan 37 μm yang terlepas daripada pelitup pembedahan dan pelitup N95 masing-masing boleh mencapai 960 m dan 631 m. Keputusan ini boleh meningkatkan ramalan masa hadapan tentang tempoh dan keberkesanan langkah yang diperlukan untuk mengurus COVID-19 dan wabak lain yang serupa.

Kata kunci: penghantaran bawaan udara, pelitup muka berganda, SARS-CoV-2, kecekapan penapisan

Introduction

SARS-CoV-2 is a new variant of coronavirus that has plunged the world into a pandemic state since late 2019. As of August 2021, World Health Organisation (WHO) estimated that around 221 million cases have been reported, with around 4.4 million cases resulting in death [1]. In Malaysia alone, over 18 thousand deaths have been reported from around 1.8 million reported cases [2]. The high transmissibility of the virus poses a huge problem in tackling this pandemic. He et al. estimated that around 44% of the infections were caused by pre-symptomatic and asymptomatic infections [3]. Hence, the non-appearance of the infection symptoms makes it challenging to identify the transmission chains which make infected people unknowingly spread the diseases. Therefore, to protect themselves, individuals exposed to numerous social contacts in daily activities are advised to follow safety protocols such as maintaining personal hygiene, keeping distance from other people known as 'social distancing' and wearing personal protective equipment (PPE) [4].

The measurement of social distances varies by country, based on WHO recommendation in general it is between the ranges of 1-2 meters [5,6]. Maintaining social distances is not always possible in certain situations, particularly in confined spaces. A confined space is interpreted as either an enclosed or partly enclosed space, that is not designed specifically for human occupancy and poses risk of insufficient oxygen level, toxic airborne contaminations, flammable air contaminations or engulfment by a free flowing solid or liquid [7,8]. Given the impracticality of social distancing in confined spaces, the use of PPE, particularly facial masks, becomes highly important.

There are various types of masks available on the market, with their effectiveness influenced by factors such as its properties and environment conditions [9]. Demand for surgical masks and respirators has increased dramatically in recent years, creating an international shortage of supply and raw materials. The Centre of Disease Control (CDC) suggested to use cloth mask to the public in April 2020, while for both high risk and symptomatic individuals is advisable to use surgical mask [10]. CDC also recommends using 'double mask' technique by wearing a disposable mask underneath a cloth mask to provide extra protection and mask fitment to reduce droplet loss from coughing, sneezing, talking, and breathing against COVID-19 transmission [10,11]. It is recommended by the World Health Organisation that fabric masks to have three layers with an inner layer made of hydrophilic materials to absorb moisture, a middle layer that serves as a filter, and an outer layer composed of hydrophobic materials to repel moisture [12].

Numerous research have been published on the efficacy of various single masks under the effects of coughing, sneezing, and breathing [9,13,14]. The aerosol's charging state has a significant effect on the filtering performance of the filtering face pieces (FFP), surgical and hygienic masks. The duration of use of the mask also has a significant effect on its filtration performance: whereas hygiene masks perform poorly from the start, one of the two FFP masks tested functioned well after 24 hours of usage, and the surgical mask performed well after 8 hours [15]. Recently, Arumuru and co-workers experimentally explored the effectiveness of single or double masks for breathability and minimising the leakage of droplets from flow visualisation. However, they are more focusing on the breathability aspect when using double

mask and limited information on the effectiveness of mask in blocking of droplets [16].

Computational Fluid Dynamics (CFD) is regarded as a significant technique for modelling the flow of exhaled contaminants and particles in the air [17]. As pathogens have sizes of less than 100 nm, unlike other particles, they travel under the effect of air particles, making it difficult to study their movement patterns. Over the years, breakthroughs in computer science have solved this problem by utilising CFD-based method [18]. The CFD formulation of nonlinear Navier–Stokes equations permits simulation of extremely complicated fluid flows under various circumstances and areas [19]. Previously, CFD study have been conducted to study dispersion of exhaled contaminants generated by human breathing in a room using two different ventilation strategies, displacement ventilation and mixing ventilation [20]. In one case, Ho investigated the spatial and temporal distribution of airborne pathogen concentrations using CFD during an apparent COVID-19 epidemic in a restaurant in Guangzhou, China, 2021. It was found that by increasing the fresh-air from 10 % to 100 % of the supply air to the ventilation system, it can reduce the pathogen concentrations in the room to 30 % and 80 % respectively for 73 min and infection probability from 10 % to 50 %, respectively [21]. To the best of author's knowledge, the experimental or simulation study on the effectiveness of double mask to filter droplets is still lacking in the literature.

Thus, in this study, the performance of double mask configuration, consisting of a surgical, reusable and N95 mask in filtering airborne particles was investigated via CFD simulation. Based on the common usage of masks around the world [22], the surgical, reusable, and N95 masks have been used as the face mask in this study. The movement of particles through the mask during sneezing and talking was tracked using particle tracing and the number of particles escaped, along with the distance travelled and settling time were determined. The performance of double mask will then be compared to single surgical mask, single reusable mask and to a N95 mask.

Materials and Methods

Geometry

The particle tracing simulation was carried out in a two-dimensional room shown in Figure 1. The room was 4 m high and 5.5 m wide, with no ventilation or fan. Two people were placed in the room at 1.6 m from the ground with 2 m distance between them [10]. The particles will be released from the lower quadrant of the circle, simulating particles escaping from a person's mouth. To represent the presence of a mask, a small layer will be added at the front of the quadrant and act as a barrier, which the particles pass through as they escaped the person's mouth. During the simulation, the particles will be released from the domain representing the mouth, where they will pass through and interact with the layer representing the mask on their way to reach the outlet boundary, which was set at the walls of the room.

The mesh discretised the geometries into smaller regions, and the interaction between the particles and the mesh properties is used to calculate the trajectories of the particles. For this simulation, an unstructured grid comprising of two-dimensional triangular mesh was applied. The physics-controlled mesh was automatically generated, with finer size applied surrounding the mask region, while bigger domain sizes were applied to the other areas.

Mask properties

Table 1 lists the types and specifications of masks used for the simulation. Three types of masks were used in this simulation, which were reusable mask, surgical mask and the N95 mask. The properties of these masks were taken from the earlier study by [9]. The double mask configuration was listed as follows: 1) N95 mask as the first layer (inner layer) and the reusable mask as the second layer (outer layer), 2) reusable mask type as the first layer (inner layer) and the reusable as the second layer (outer layer), 3) surgical mask type as the first layer (inner layer) and the reusable mask as the second layer (outer layer). Each mask will have different permeability and porosity. For this exercise, the thickness of each mask was kept at a constant, which were 0.3 mm.

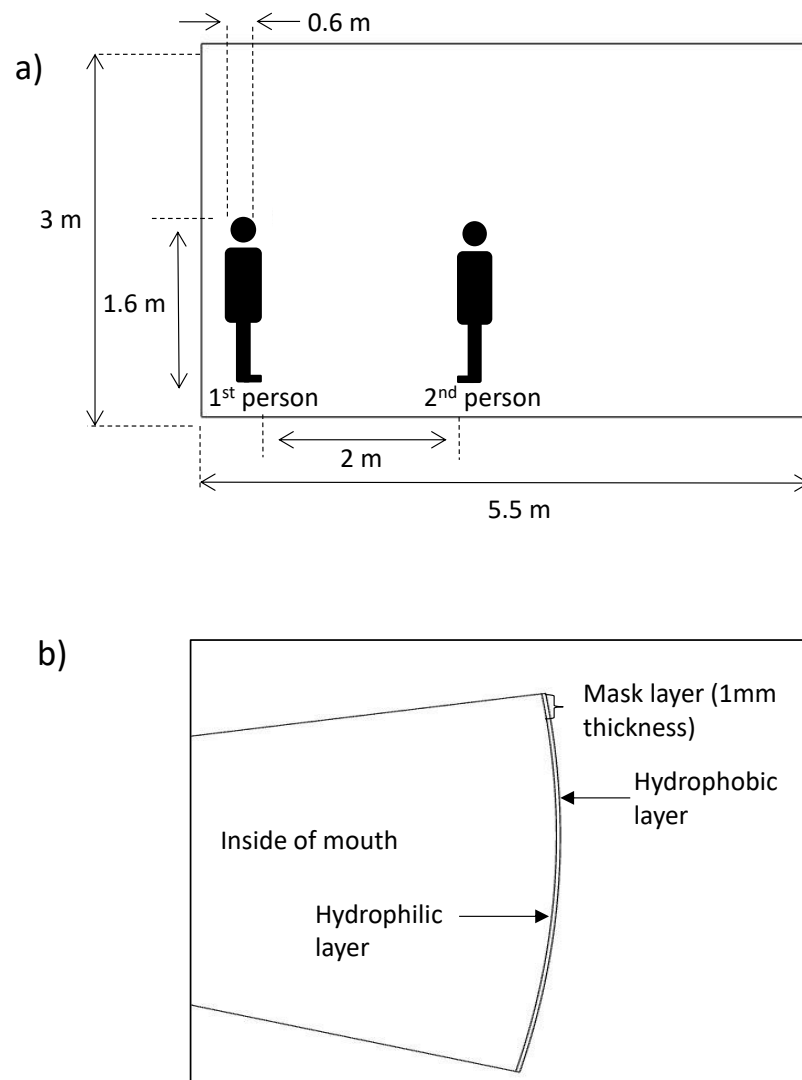


Figure 1. (a) Side view layout of a confined room with two people in a confined room and (b) Close up of the mask layer in the geometry.

Table 1. Parameters as for each respective mask

Mask	Porosity (μm)	Permeability (μm^2)
Reusable	0.82	0.37
Surgical	0.77	0.36
N95	0.65	0.26
Double mask (N95 as inner layer, reusable as outer layer)	N95: 0.65	0.26
	Surgical: 0.77	0.36
Double mask (reusable as inner layer, reusable as outer layer)	Reusable: 0.82	0.37
	Reusable: 0.82	0.37
Double mask (surgical as inner layer, reusable as outer layer)	Surgical: 0.77	0.26
	Reusable: 0.82	0.37

Particle properties and boundary conditions

To simulate the saliva properties, all particles were assumed to be water. Particle density was kept constant at 998 kg/m³ for all conditions, and their shape was kept similar at round shape with diameter of 10 µm. The diffusion coefficient of water particles in fiber and air was 1.3 x 10¹³ m²/s and 3.9 x 10⁻⁵ m²/s. The temperature and pressure of the entire simulation were conducted at a room temperature of 25 °C and pressure at 1 atm.

Experimental setup

The experimental setup of each simulation run is listed in Table 2. Two different conditions were simulated for each type of masks, which were sneezing and talking.

The calculation assumes that saliva droplets are randomly ejected from the mouth at 5 m/s for sneezing and 1 m/s for talking and stick to a wall surface when they hit it. Both sneezing and talking, number of particles were set to 500 particles, respectively.

Several parameters were observed during the simulation, namely the filtration efficiency of each mask. The filtration efficiency was calculated using Equation (1):

$$\text{Particle efficiency} = \frac{\text{Total particles} - \text{Escaped particles}}{\text{Total particles}} \quad (1)$$

Table 2. Simulation setup for particle tracing of water droplets through facial mask

Run	Condition	Mask
1	Sneezing	N95
2	Talking	N95
3	Sneezing	Reusable
4	Talking	Reusable
5	Sneezing	Surgical
6	Talking	Surgical
7	Sneezing	N95 (Inner) – Reusable (Outer)
8	Talking	N95 (Inner) – Reusable (Outer)
9	Sneezing	Reusable (Inner) – Reusable (Outer)
10	Talking	Reusable (Inner) – Reusable (Outer)
11	Sneezing	Surgical (Inner) – Reusable (Outer)
12	Talking	Surgical (Inner) – Reusable (Outer)

Result and Discussion

Figures 2 and 3 show the spread of droplets from the first-person mouth during talking and sneezing activity with condition of without mask and different types of single mask after 2.5 s and 10.0 s, respectively. According to published data, sneezing can produce up to 40 000 droplets with diameters ranging from 0.5 to 12 µm, which can be discharged at velocities of up to 100 m/s [9,23,24]. Droplets smaller than 100 µm in diameter would totally dry out in normal air conditions before falling about 2 m to the ground. Wearing a mask will create a physical barrier between the wearer's respiratory system such as nose and mouth with other person from splashes or sprays of fluids [25]. The result from talking activity shows that when the first person does not wear a mask, the particles immediately settle

down near to the first person after they are emitted while the droplets travel far from the first person after sneezing. However, wearing a mask significantly increased the time taken for the droplets to settle down to the ground as for both talking and sneezing as shown in Figure 2 (a-d) and Figure 3 (a-d). N95 and surgical mask demonstrated almost the same performance in preventing the droplets spread for both talking and sneezing compared to the surgical mask. This is due to the presence of multilayer of non-woven fibrous materials in N95 and surgical mask. Surgical masks are typically made up of three layers and N95 mask contains additional middle layer for added support and fit [26]. The results obtained is also coherent with previous study showing that surgical masks are as efficient against viral infections as N95 masks [25].

However, it can also be seen from the figure above that N95 had slightly better filtration efficiency than surgical mask. This is because N95 properly fitted and donned, so minimal leakage occurs around edges of the

respirator when user inhales. The efficiency of cloth mask preventing droplets spread is much lower than N95 and surgical mask due to the presence of two layers in the cloth mask.

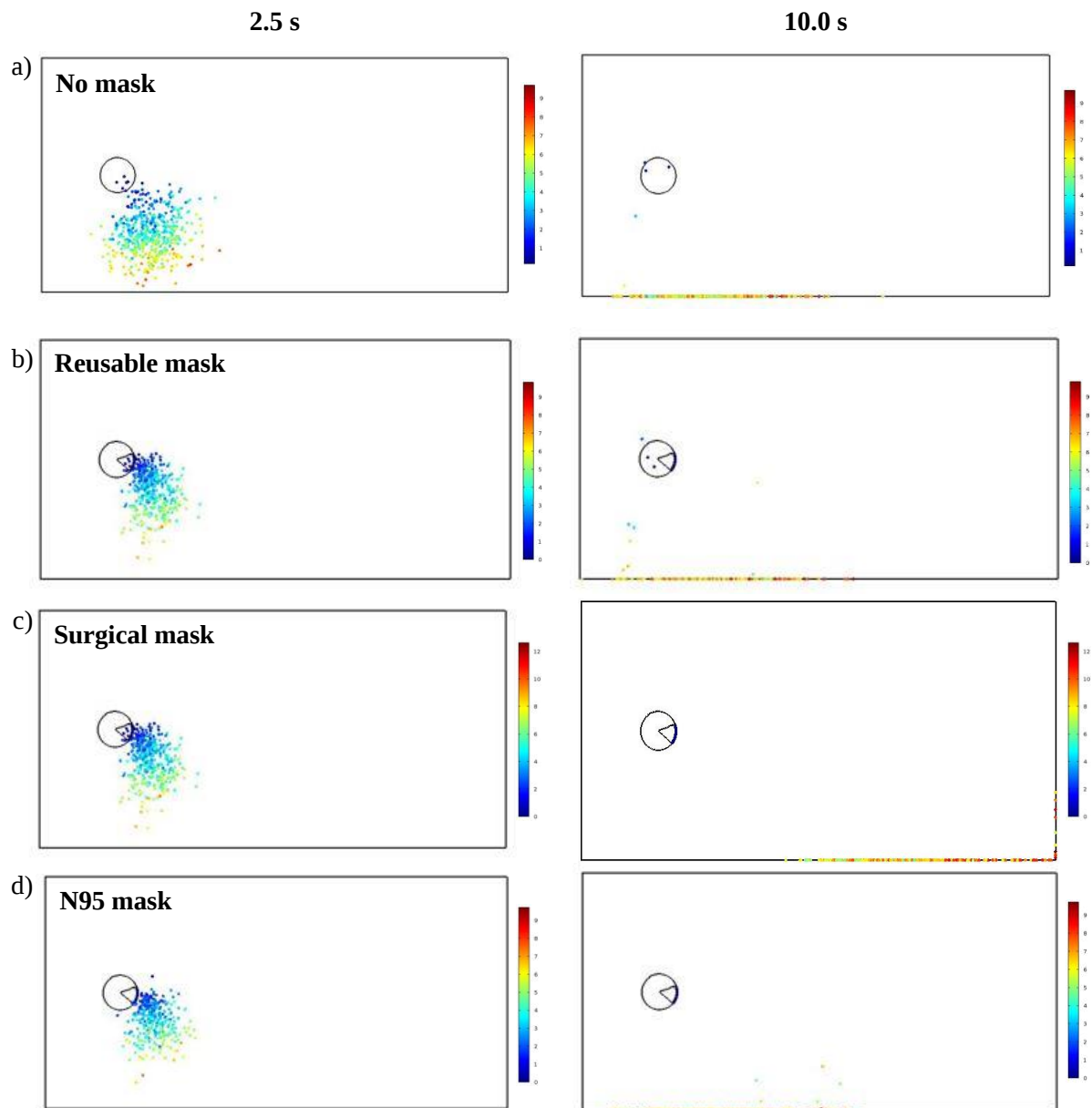


Figure 2. Particle contour from 1st person to 2nd person after 2.5 s and 10.0 s time with the condition of talking for (a) no mask, (b) N95 mask, (c) reusable mask and (d) surgical mask respectively.

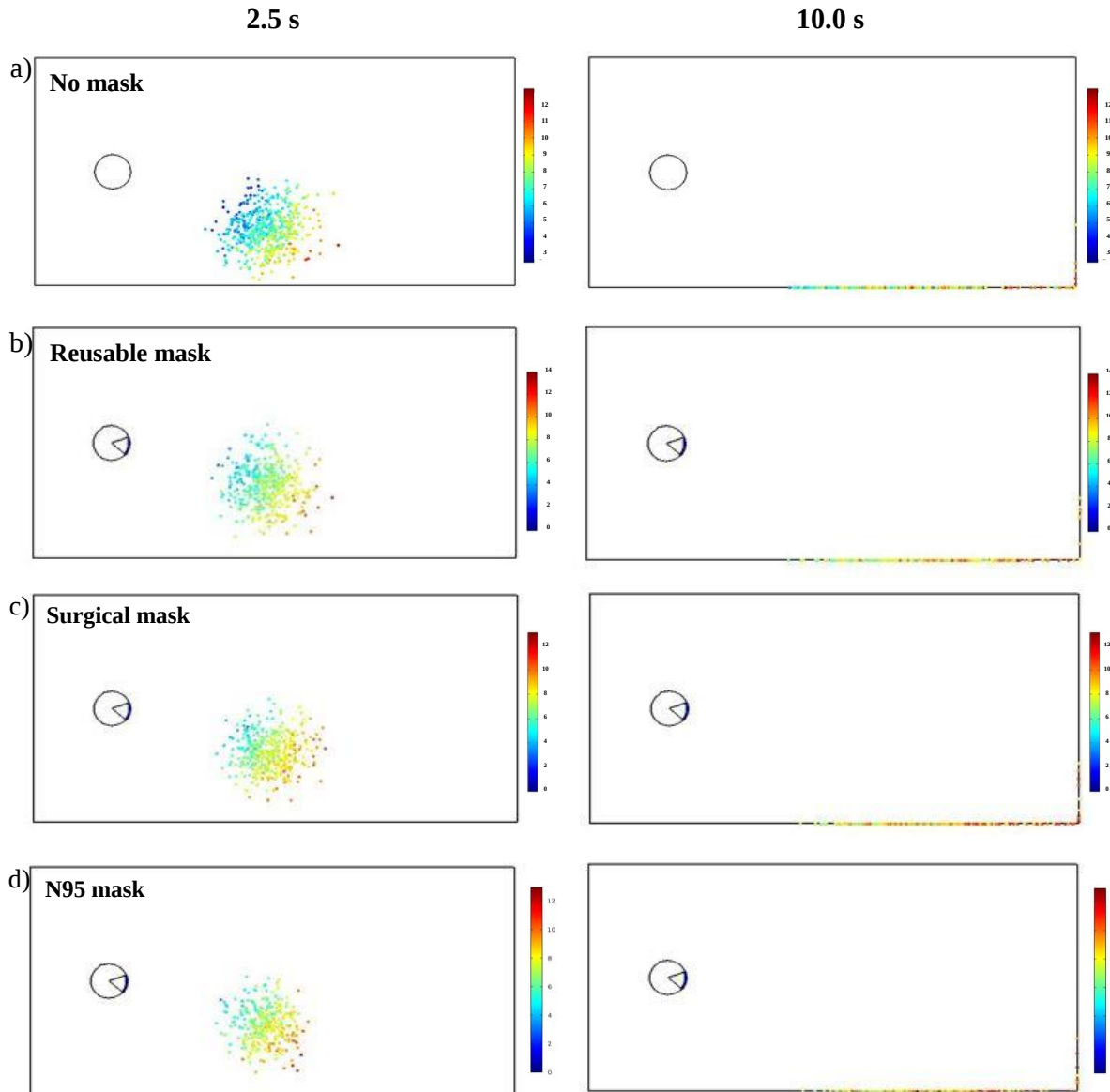


Figure 3. Particle contour from 1st person to 2nd person after 2.5 s and 10.0 s time with the condition of sneezing for (a) no mask, (b) N95 mask, (c) reusable mask and (d) surgical mask respectively.

The droplets contour at the early period of ejection from a human talking and sneezing activity are illustrated in Figure 4 and Figure 5 respectively with different combinations of double mask. The use of double mask such as N95 (inner layer)-reusable (outer layer), reusable (inner layer)-reusable (outer layer), surgical (inner layer)-reusable (outer layer) shows different efficiency in preventing droplets spread. The combination of N95 (inner layer)-reusable (outer layer)

or reusable (inner layer)-reusable (outer layer) showed the same performance where the droplets travelled near to the first person during talking. However, the droplets travelled to the 2 meters distance where the second person was located during sneezing. The combination of surgical (inner layer)-reusable (outer layer) improved the performance of preventing droplet size where the droplet only settled down near to the first person after they were emitted.

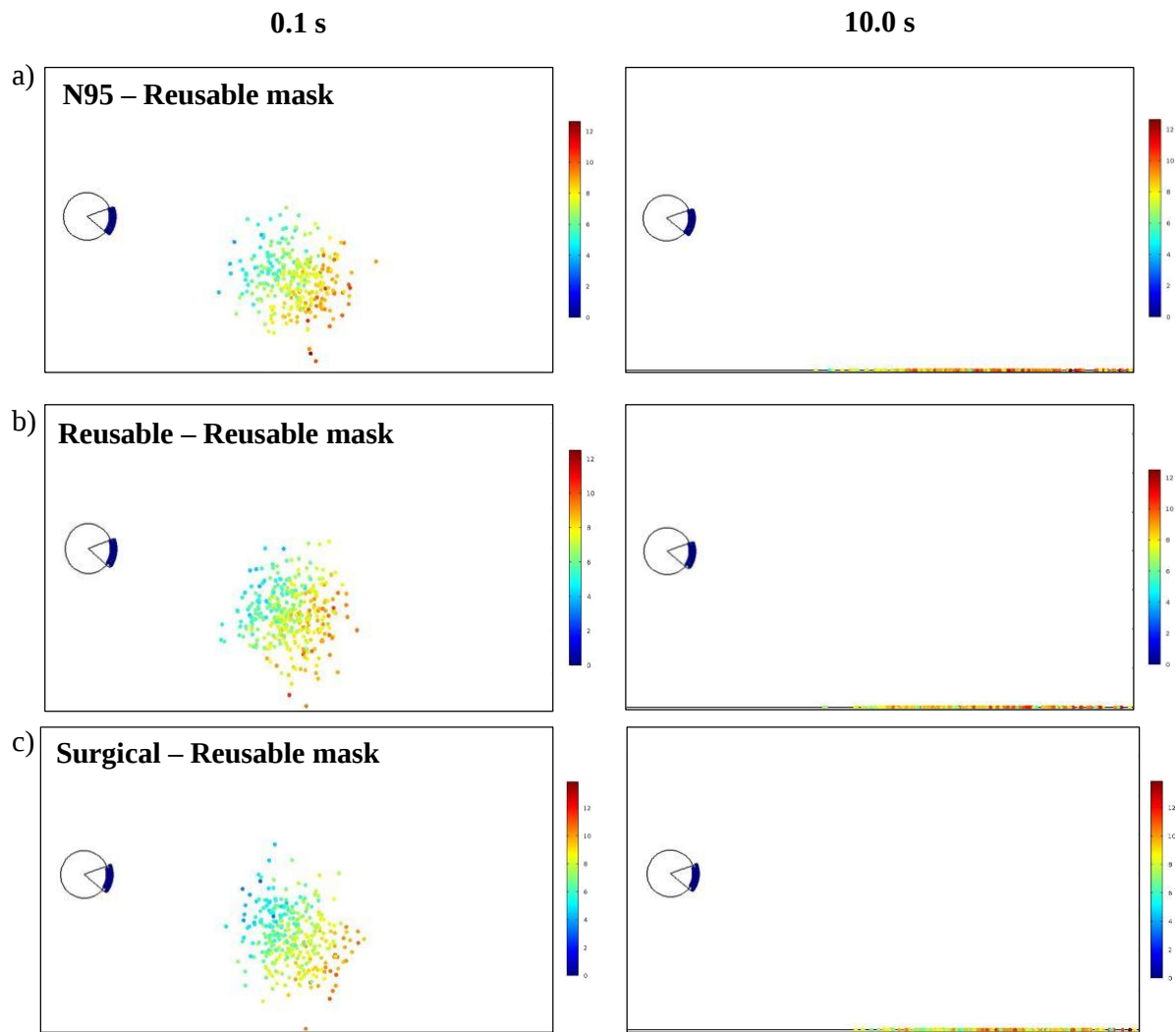


Figure 4. Particle contour from 1st person to 2nd person after 0.1 s and 10.0 s time with the condition of talking for double mask condition (a) N95 (inner layer)-reusable (outer layer), (b) reusable (inner layer)-reusable (outer layer), c) surgical (inner layer)-reusable (outer layer) respectively.

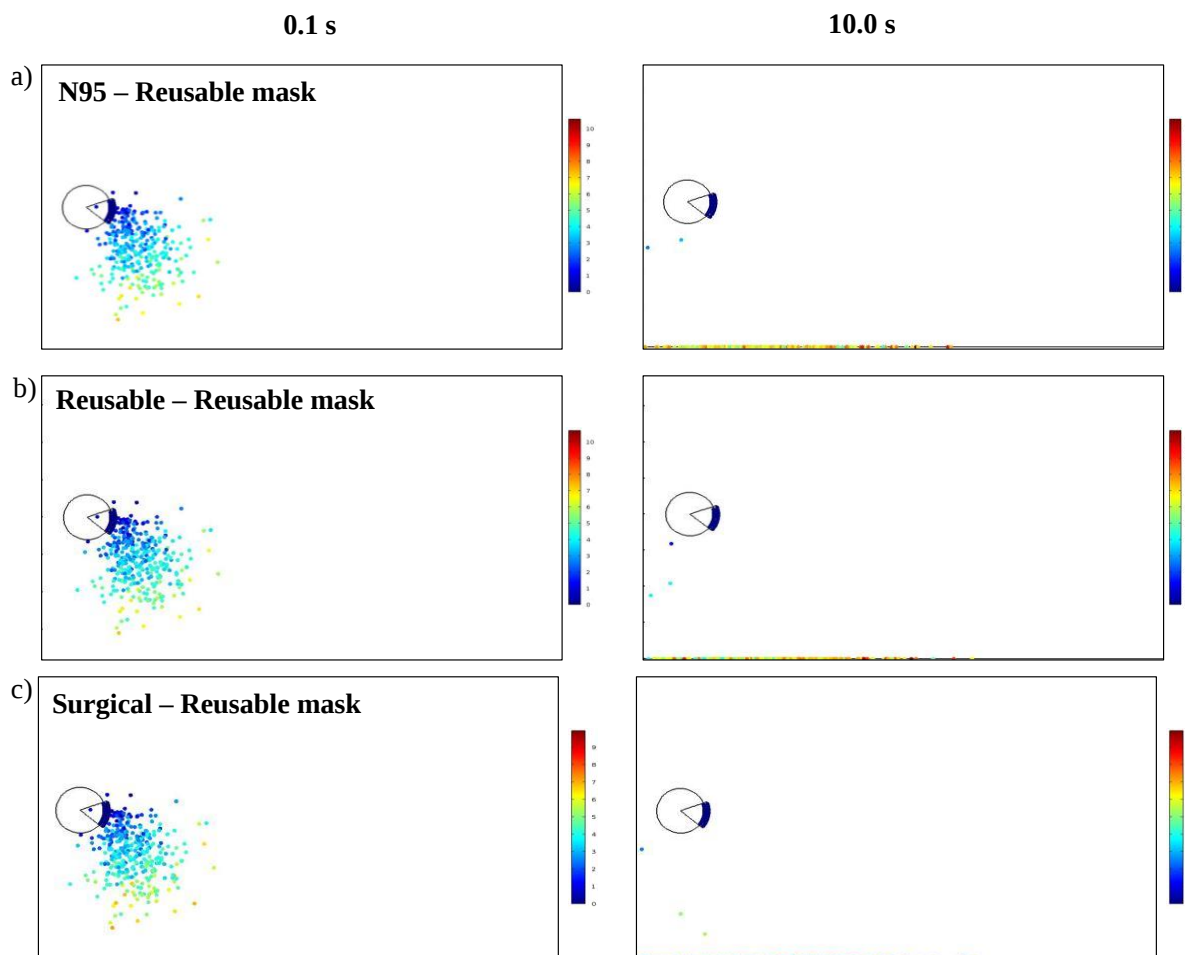


Figure 5. Particle contour from 1st person to 2nd person after 0.1 s and 10.0 s time with the condition of sneezing for double mask condition (a) N95 (inner layer)-reusable (outer layer), (b) reusable (inner layer)-reusable (outer layer), c) surgical (inner layer)-reusable (outer layer) respectively.

Figures 6 and 7 display the number of particles escape from the single mask or double mask configuration. Based on these results (Figure 6 and 7), each mask possesses different porosities which affect to the filtration efficiency. From the simulation results, all particles (500 particles) with the size ranging from 1 μm to 100 μm were released to the environment when a person does not wear a mask. However, the use of N95 and surgical mask can reduce the number of particles escape from the mouth during talking or sneezing to 133 and 151 particles, respectively. The same number of particle escapes from N95, and surgical mask were attributed by almost the same porosity diameter of both masks with the difference of only 0.12 μm . The reusable mask can filter only half of the particles released from the mouth due to its large porosity properties which is 0.82 μm . Although surgical mask

showed almost similar performance with the N95, there was significant difference in terms of particle's size filtered and escaped from the mask. Figure 6 shows that narrow particle size distribution ranging from 1 μm to 30 μm was obtained for N95 mask while wide particle size distribution from 1 μm to 44 μm was observed for surgical and reusable mask. $\frac{1}{4}$ of particles that escaped from surgical mask were 10, 15 and 30 μm in size causing formation of bimodal distribution. The use of different combinations of double mask was effective to reduce the number of particles escaped from the mask. The combination of N95-Reusable showed the lowest amount of particle escape as displayed in Figure 7. The Reusable-Reusable and Surgical-Reusable mask also showed significantly decrease in number of particles escaped from the single mask condition. The results above proved that Surgical-Reusable mask can be used

as alternative if the supply of N95 mask is limited. The information of particle sizes that escaped from the mask is important because the behaviour of the particle such as particle settling time and distanced travelled can be predicted as shown in Figures 8 (a) and (b), respectively. Generally, large particle size will settle both at a short time and distance, and vice versa. When a person sneezing or talking without wearing a mask, large particle droplet with size ranging from 1 μm to 100 μm can travel until 864 km and need the longest time up to 12 h to settle. From Figures 6 and 7, masks can prevent the spread of droplets over large area by reducing the velocity of the droplets thus protecting

others from the wearer's expelled respiratory droplets [25]. The larger droplet size of 30 μm and 37 μm escaped from surgical mask and N95 mask can travel to 960 m and 631 m, respectively. Meanwhile, particles with size of 47 μm that successfully pass through the reusable mask will need 19 s to settle at 391 m. The droplets tend to travel between 86 m to 960 m for sneezing activity and will travel at short distance from 25 m to 288 m if talking activity occurs. The different travelled distance obtained from the sneezing and talking activity was attributed by the different velocity of droplets produced from both activities [27].

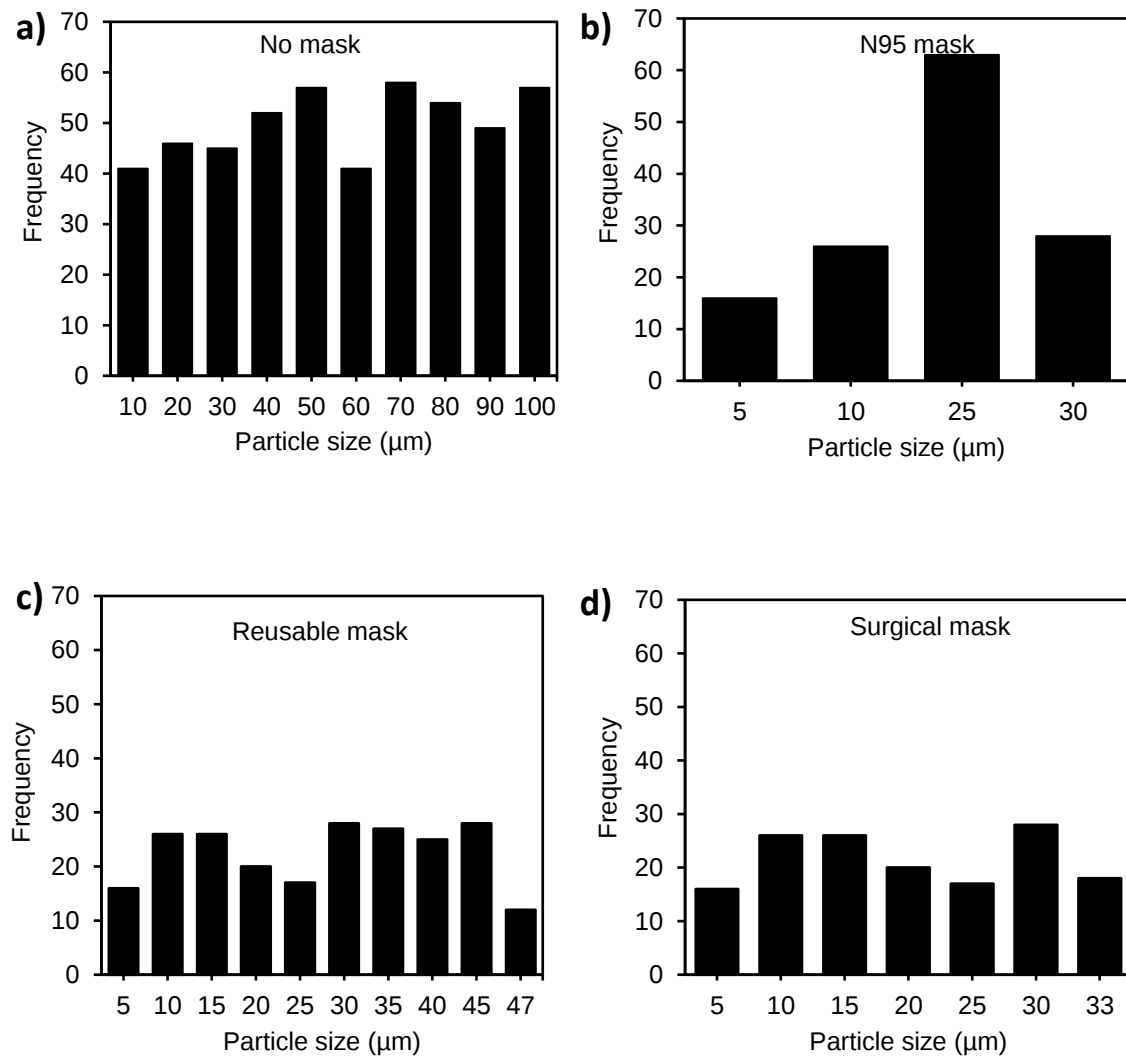


Figure 6. Range of particle size escape for condition (a) no mask, (b) N95 mask, (c) reusable mask and (d) surgical mask respectively.

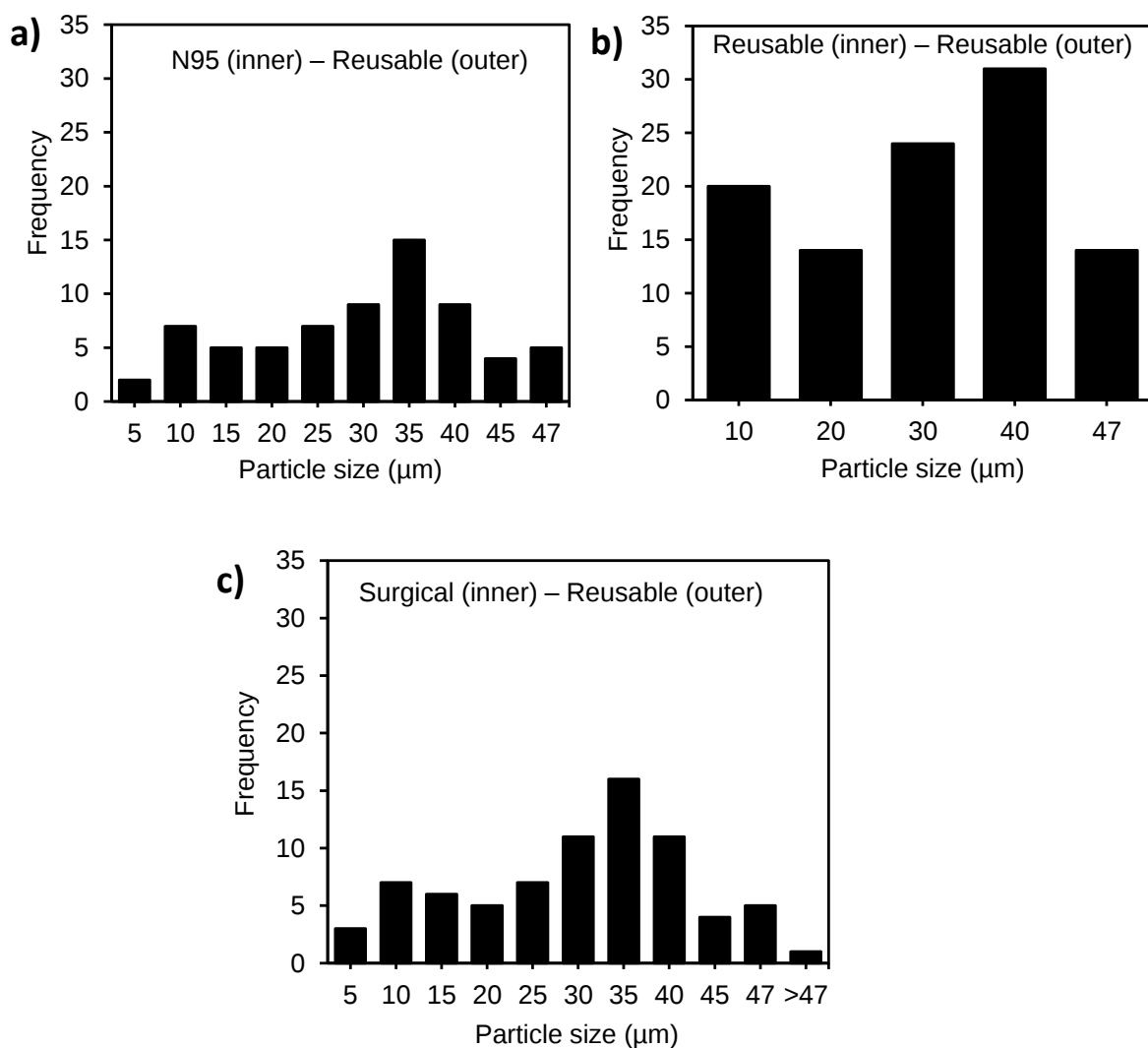


Figure 7. Range of particle size escape for double mask configuration (a) N95 (inner layer)-reusable (outer layer), (b) reusable (inner layer)-reusable (outer layer), c) surgical (inner layer)-reusable (outer layer) respectively.

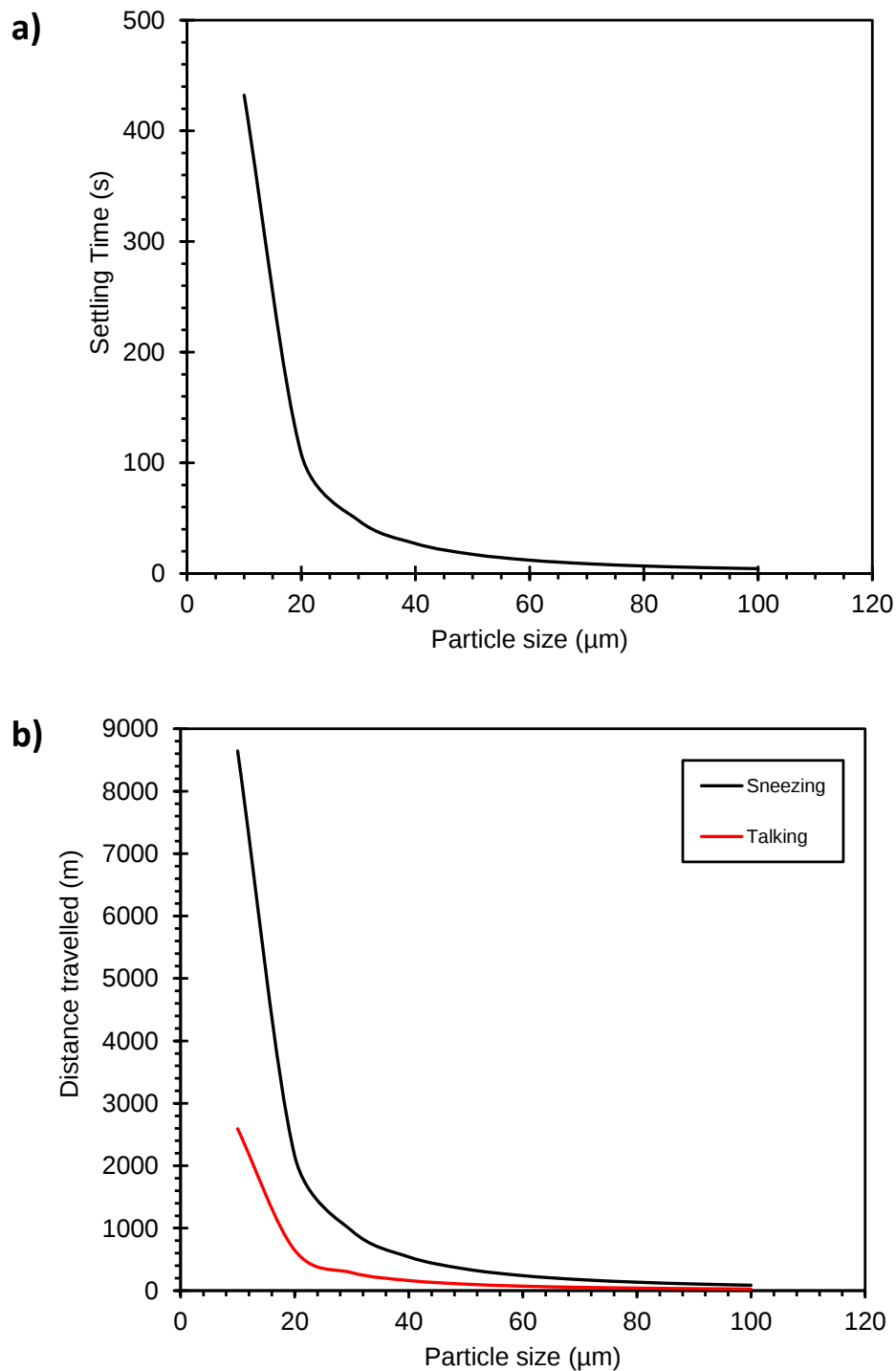


Figure 8. Graph of settling time vs various particle size and (b) distance travelled by different particles size for talking and sneezing activity.

The environment contains a wide range of contaminating particles with various sizes. Different sizes of particle droplets will affect the mechanism

filtration of the different types of masks. The four-mechanism involved for removing particles or micro-organism by masks were inertial impaction,

interception, diffusion, and electrostatic attraction as shown in Figure 9. The gravity sedimentation will occur to the droplet size from 1 μm to 100 μm due to the gravity force while droplets with smallest size can easily pass through the mask [28].

Inertial impact occurs when the particles deviate from the streamline flow due to the inertia, impact on the fibre and can adhere to them. This mechanism successfully removing particles with sizes greater than 1 μm . Brownian (random) motion of the particles causes them to come into contact with the fibre during diffusion. When a particle is captured on the fabric, another particle rushes to the empty space to be captured. A high microfiber concentration is required to increase the likelihood of this occurrence occurring. The probability of catching a particle increases as the

period of exposure to particles in the capture zone is prolonged [26]. Interception occurs when a particle follows the major streamline, allowing interaction between the particle and the filter media to occur within one particle width of the surface of the fibre. This approach is effective for collecting particles as small as 0.6 microns [14]. According to random Brownian motion, it is particularly effective for trapping particles less than 0.2 micrometre in size. Diffusion occurs when Brownian (random) motion contacts the fibre. When a particle is caught on the fabric, another particle seeks to fill the void. A larger microfiber concentration is required to increase the likelihood of this event. The likelihood of catching particles increases with exposure time in the capture zone [14].

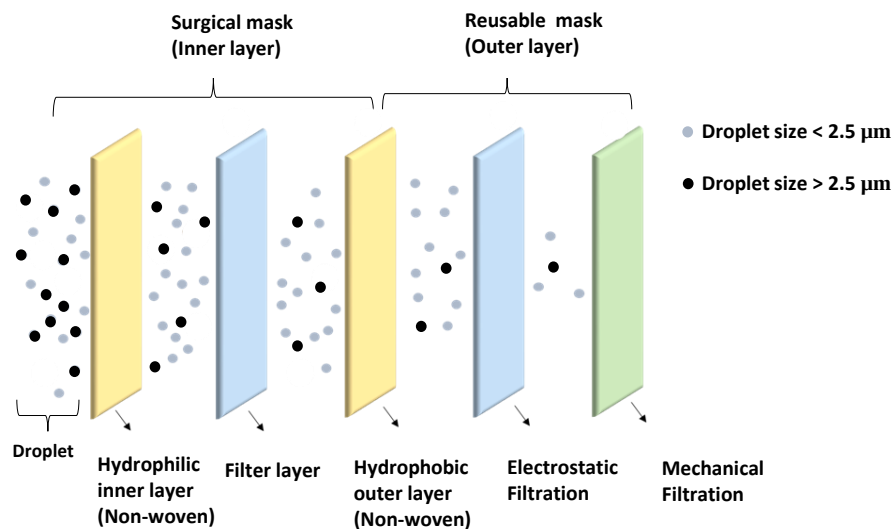


Figure 9. Mechanism of particle movement through double masks (surgical mask and reusable mask).

Conclusion

Filtration efficiency of three types of facial masks (Reusable, surgical and N95) has been measured as a function of particle size. It has been pointed out that for aerosols in the range of 1 μm –10 μm , gravity sedimentation plays an essential rule because ballistic energy or gravity forces have an early effect on the large, exhaled droplets. The CFD analysis of the proposed mask allowed us to visualise and quantify the movement of air inside confined space in a three-dimensional way. The filtration performance of N95

was within reasonable expectations and gave efficiencies above 80% for the whole particles studied. While the performance of the surgical mask was acceptable in confined space. We also believe that use of double facial masks can significantly decrease the momentum of the ejected droplets.

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