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An overview of filtration efficiency through the masks: Mechanisms of the aerosols penetration

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A B S T R A C T

The masks have always been mentioned as an effective tool against environmental threats. They are considered as protective equipment to preserve the respiratory system against the non-desirable air droplets and aerosols such as the viral or pollution particles. The aerosols can be pollution existence in the air, or the infectious airborne viruses initiated from the sneezing, coughing of the infected people. The filtration efficiency of the different masks against these aerosols are not the same, as the particles have different sizes, shapes, and properties. Therefore, the challenge is to fabricate the filtration masks with higher efficiency to decrease the penetration percentage at the nastiest conditions. To achieve this concept, knowledge about the mechanisms of the penetration of the aerosols through the masks at different effective environmental conditions is necessary. In this paper, the literature about the different kinds of face masks and respiratory masks, common cases of their application, and the advantages and disadvantages of them in this regard have been reviewed. Moreover, the related mechanisms of the penetration of the aerosols through the masks are discussed. The environmental conditions affecting the penetration as well as the quality of the fabrication are studied. Finally, special attention was given to the numerical simulation related to the different existing mechanisms.

1. Introduction

We are currently living in a time when covid-19 is already causing the infection of more than 2.5 million people and more than 300,000 deaths worldwide. In this situation to protect the population, an effective solution is individual containment, it is the use of a high-performance mask. In fact, the main purpose of using masks is to prevent inhalation and to trap the airborne particles (natural or man-made), and biological organisms (bacteria, viruses, prions, and fungi) [1–3]. Airborne particles of natural origin (volcanic eruptions, dust storms, naturally occurring fires) and man-made (such as industrial emissions) are on a nanometer scale. Several studies have shown the severe impact of the respiration of nanoparticles on the respiratory and cardiovascular diseases. Also, inhalation of these particles (particles smaller than 2.5 μm) resulted in an estimated 8.9 million deaths in 2015 [4]. In addition, to airborne nanoparticles, bio-aerosols are among the other health-threatening that have been the focus of many studies [5]. These microorganisms may cause a health risk; furthermore, protection against infectious microorganisms has been of great importance, and studies have always tried to improve protection against these microorganisms [2,4,6].

Achieving a mask with higher capacity, optimal comfort, as well as high efficiency in eliminating bio-aerosols and optimal filtration of airborne particles has always been one of the goals of studies conducted in this field [7]. For this purpose, the factors affecting the determination of the final mask quality have been focused on increasing and improving the efficiency of the mask in the center of attention. In general, the filtering ability of the mask is influenced by the specifications of the mask filter and external factors [8,9].

Mask filter specifications include the inherent properties of the materials used in the mask, such as the chemical composition of the filter, and characteristics such as the thickness and packing density of

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the fibers in the filter [6]. Also, studies have shown the importance of the external effect of factors such as face velocity or airflow, the steady or unsteady pattern of flow, the charge state of the particle, frequency of the respiration, relative humidity, and temperature, and loading time on the filtering efficiency of the mask [6,10–12].

Due to the significant and important effect of external factors on the performance of filtering, determining the mechanism of filtration has a high status. Only by clarifying and understanding these mechanisms it will be possible to increase and improve the design and filtration of the mask [13]. Examination of the mechanism and elucidation of how the particles entered has been one of the topics of interest in this term. Mask filtration is based on different mechanisms consist of gravity sedimentation, inertial impaction, interception, diffusion, and electrostatic attraction and thermal rebound [6]. The overall effectiveness of the filter is determined by adding efficiency to the influence of the individual filtration mechanisms. Therefore the role of individual particulate filtration mechanisms must be addressed as the first step [13].

On the other hand, modeling and clarifying the mechanism of bioaerosols penetration into the mask has high importance [2,14]. This becomes important when contaminated particles and microorganisms reach the outer surface of the mask. If the surface does not destroy the virus or microorganisms that have fallen on it, the contaminated particles can penetrate the mask by various mechanisms such as capillaries [15].

Furthermore, a mask often becomes a virus collector during repeated breathing activities, particularly when its outer surface is exposed to contaminated droplets [8,16]. Given that viruses and bacteria will stay on the surface and in the masks during wear for a considerably long period of time, it is obviously dangerous and undesirable if they can live safely and remain active in the warm and humid microenvironment in the masks. Due to the conditions of the mask and the high humidity and temperature created during the respiration cycle, it will lead to the formation of steam in the mask, and this process will accelerate the mechanism of penetration and faster spread of microorganisms to the inner parts of the mask. Simulations and numerical studies have considered this phenomenon as a physical process in heat transfer and mass transfer in porous materials [13].

To avoid such anomalies, it is vital to analyze the transmission mechanisms of the bio-particles and particles in the mask and to monitor the design and use of the mask in accordance with such mechanisms. This review was conducted with the aim of investigating the mechanisms of particle filtration by the mask and examining the parameters affecting such as face velocity or airflow, the steady or unsteady pattern of flow, the charge state of the particle, frequency of the respiration, relative humidity and temperature, and loading time the efficient mask filtration.

2. Different types of masks

In the following different kinds of masks are discussed, and the advantages and disadvantages of them are reported.

2.1. Face masks

These kinds of masks that cover the user's nose and mouth, are used as physical barriers for the fluids and particulate materials in a certain efficiency [17,18]. Face masks can be classified into three categories:

2.1.1. Basic cloth face mask

This type of mask is the simplest one which can be used during severe periods. During a pandemic respiratory because of the scarcity or availability of filtering facepiece respirators, some people may prefer to use cloth products for respiratory safety [19]. Fig. 1 represents the basic cloth masks.

In a study by Rengasamy et al. [17], they have studied the penetration of the aerosols in the five different types of clothes sweatshirts, T-shirts, towels, scarves, and cloth masks compared to the filtration of the N95 respirator filter masks. The tests have been conducted for different sizes of polydisperse and monodisperse aerosols around 20–1000 nm for the particles of NaCl at two different face velocities 5.5 and 16.5 cm s^{-1}. Further, they have concluded that the penetration of the particles in these types of material was much higher than that of the N95 respirator filter masks (shown in Fig. 2) [17]. One can note that the percent aerosol penetration (P) is defined as the ratio of the downstream aerosol concentration (C_{Down}) to the challenge aerosol concentration (C_{chal}):

Fig. 1. Representation of the basic cloth masks [20].

$$P(\%) = \frac{C_{Down}}{C_{Chal}} \times 100 \qquad \text{Eq. 1}$$

2.1.2. Surgical face mask

Surgical face mask (Fig. 3) is initially designed to shield the wearer from infectious droplets in clinical environments, but it does not help much to protect from spread of respiratory diseases [4,18,21]. While they are not an absolute method of protection, they have a shield that will protect the wearer from a stream of fluid, for example, sneezing, and capturing bacteria from the wearer's mouth and nose in liquid droplets and aerosols [22]. The commercial surgical face masks commonly had a three-layer structure. The middle layer is the filter media, whereas the inner layer is for absorbing moisture, and the outer layer repels water [23]. However, the planar mask has a lower protection level, and it is necessary to take careful consideration of comfort sensation and protection level when choosing a planar type mask in the polluted air [23].

In a study by Milton et al. [24], they have investigated the effects of using surgical masks in preventing the aerosols influenza transmission. The obtained results indicated that surgical masks had prevented the viral detection aerosols by 25-fold for the coarse aerosols, and 2.5-fold for the fine particles, hence, generally 3.4-fold reduction was reported for the exhaled aerosols. In consequence, the surgical masks can limit the release of the droplets larger than 5 μm. Therefore they are not sufficient for limiting the emission of the small droplets [24]. However, other studies on the effectiveness of the surgical masks and N95 masks (section 2.2.1) have been revealed that there is no significant difference between the surgical masks and N95 masks. Though the statistical methods were sufficiently comprehensive to provide moderate influence sizes [25,26]. In general, it is claimed that the lack of sufficient literature that can support the effectiveness of the surgical masks in reducing the risk of the infection [25,27].

2.1.3. Full-length face shield

It is the light weighted and low-cost masks that are composed of elastic headbands through the head and a transparent rigid polymeric full-length face shield. The transparent part is made in most cases by Polycarbonate (PC). It functions as a shield to protect the face parts from the direct contact of the liquid splashes from the Infectious when

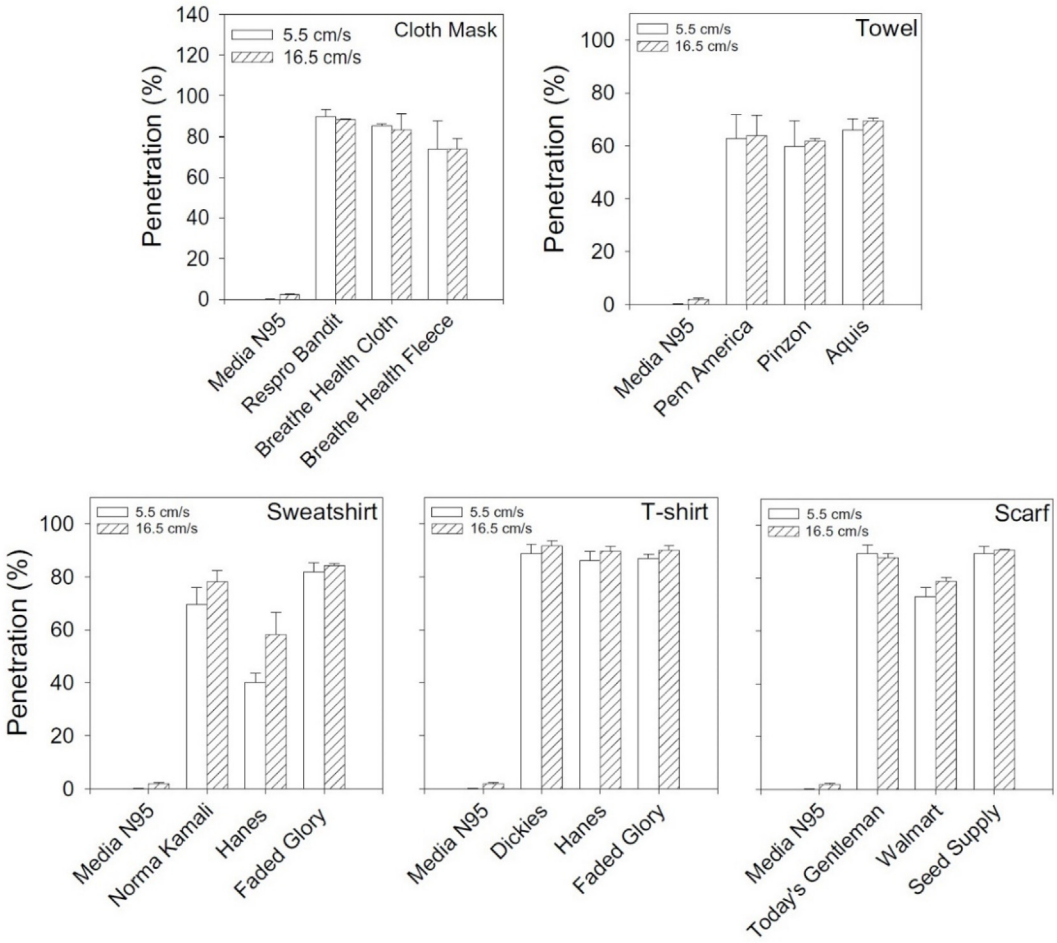

Fig. 2. Aerosol (NaCl polydisperse) penetration for levels of (a) cloth mask, (b) towel, (c) sweatshirt (d) T-shirt, and (e) scarves at two different face velocities compared with N95 mask. Error bars suggest a trust level of 95% [17].

Fig. 3. Surgical face mask [20].

speaking, sneezing, and coughing [28,29]. The schematic of full-length face shield is shown in Fig. 4.

Fig. 4. Schematic of Full-length face shield.

2.2. *Filtering facepiece respirator*

They are personal protectors that are worn on the face, which cover the nose and mouth against the airborne particles like dust, infectious agents, gases, or vapors [18,30]. It helps in air-purifying and therefore reduces the risk of the contamination of the wearer in the polluted area.

Most workplaces choose to filter facepiece respirators (FFRs), referring to the accessibility and low-cost disposable. Wherein various studies approved the acceptance level of the filtration of FFRs against the monodisperse and polydisperse aerosols, which are larger than 20 nm in size [10,31–33]. There are different types of FFRs, such as N95, P100, FFP2, FFP3, KN95, etc. Here, the two most known N95 and P100 respirator masks are presented.

2.2.1. *N95 respirator*

These types are a type of FFR masks, are non-oil resistant, also known as electrets filters. The word N95 is obtained from the fact that these types of masks can at least filter 95% of aerosols around 0.3 μm [34].

In a study by Balazy et al. [27], they have stated that N95

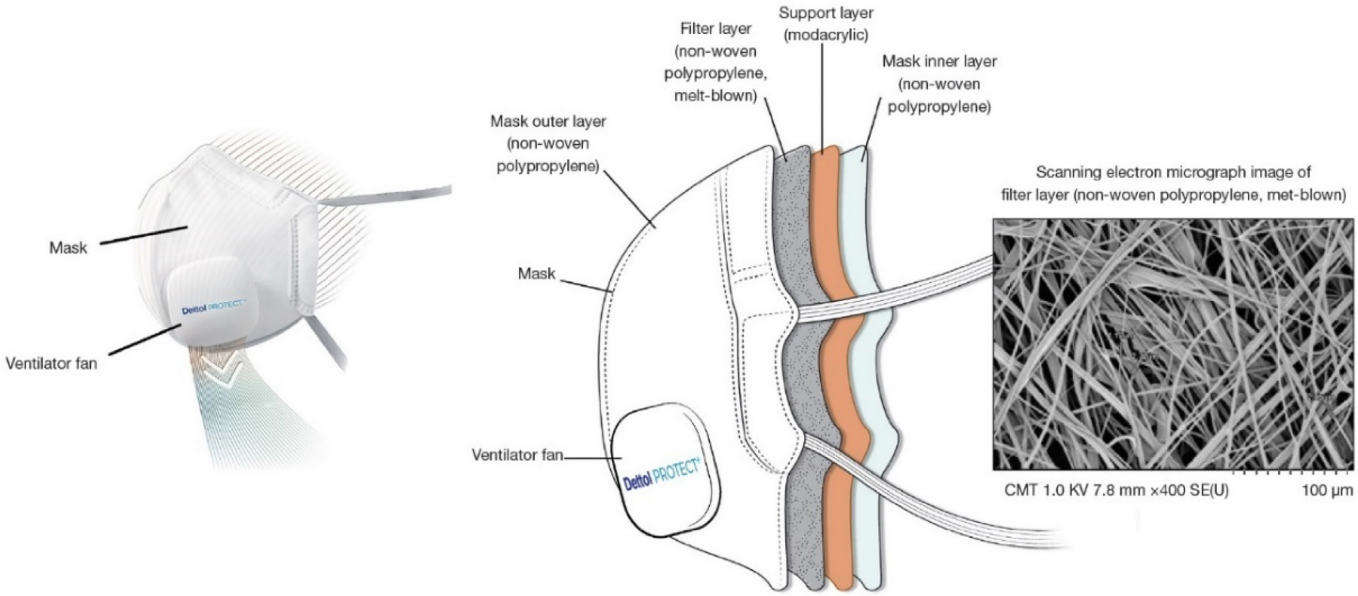

Fig. 5. Schematic representation of the N95 mask with various layers [35].

respirators may not always provide sufficient safety against the penetrating aerosols particles smaller than 300 nm. Therefore the protection offered by some N95 respirator masks can fall below 95%, particularly at the high inhalation flow rates [27]. It should be mention that N95 respirators of various companies have different performances depending on the size of the penetrating particles [31]. Fig. 5 shows the schematic of a N95 mask and its different layers.

N95 respirator also has different types, such as surgical N95 respirator, with higher efficiency of the standard N95. As can be seen from Fig. 5, the N95 respirator consists of four principal layers, which include inner layer, support layer, filter layer, and layer mask filter layer from inside to outside of it. Also, a ventilator fan is embedded on the outer layer of N95 to improve breathing.

2.2.2. *P100 respirator/gas mask*

This is a type of a FFRs are strongly resistant/oil-proof facepiece respirator filters that can filter around 99.97% of the aerosol particles. There exist several studies to compare the efficiency of the N95 and P100 respirators. The results for comparing these two types of masks before and after exercise were indicated that there was no major gap in the permeability values before exercise. Whereas the results after post-exercise were more convenient for P100, nevertheless, FFR N95 failed the post-exercise criteria. Additionally, due to the probable effects on the face seal, breathing resistance, and moisture retention during the exercise and hard work, there is the risk of reshaping the mask. In this regard, rigid FFRs like P100 could maintain their form in humid and high temperature compared to the N95 [36]. This efficiency is proved by several studies, where the experimental results on the high volumetric flow showed that the mean penetration for N95 and P100 are respectively, 2 and 0.03% [37].

2.2.3. *Self-contained breathing apparatus*

A self-contained breathing apparatus (SCBA) typically comprises of a facepiece that is attached to an air supply (liquid air, liquid oxygen, or oxygen-generating chemical) held by the user through a hose and a regulator. Only positive-pressure SCBAs are advised for the entrance into life and safety (IDLH) atmospheres that are instantly unsafe. Self-contained breathing apparatus (SCBA) are generally used for personal firefighting protective. Therefore, this kind of masks should provide safety for the user in the smoky atmosphere. SCBAs offer defense against certain forms of airborne pollutants and their rates. However, air supply length is a significant preparation consideration for the use of SCBA that is constrained by the volume of air shipped and their usage rate [38].

Entry-and-escape SCBA respirators provide employees to move in all aspects of the worksite, but hinder worker mobility, especially in restricted spaces, due both to the unit's bulk and weight. Its usage is particularly advised when working with unspecified and unquantified airborne pollutants. These types of masks can efficiently prevent the entrance of any toxic and harmful particles from the outside atmosphere [39,40].

2.2.4. *Full face respirator*

A full-face respirator mask is made up of a stiff plastic that has a transparent part for observing, and a central port part below the view part. These kinds of masks are destined for the treatment of breathing problems and sleep troubles (e.g., apnea) by supplying or supporting patient respiration with a spray of breathable air. The segment which is contacted with the face is a soft, adaptable elastomeric material that goes well to cover the different forms of the face. Straps typically secure the mask to the wearer's head. The straps are designed to hold the mask with enough force against the face to create a gas-tight seal between the mask and the wearer's face. Nonetheless, this configuration of the masks may arise with a problem when the wearer rolls in the sleeping mood. In this case, the mask will be dislodged, and in this manner, the sealing between the mask and face of the wearer will be broken. In the cases of respiratory problems such as apnea, this leakage will decrease the pressure necessary to the treatment and therefore decrease the effectiveness of the therapy [41].

2.3. *Comparison of different masks*

As discussed in the section of cloth masks, Rengasamy et al. [17] indicated that the penetration of cloth masks is more than N95, and it means that wearing cloth masks will not have much effect. Qian et al. [31] mentioned that N95 respirators have better performance in comparison of dust/mist (DM) and dust/fume/mist (DFM) respirators and noncertified surgical masks. The results for comparing N95 and P100 respirators before exercise was the same.

On the other hand, the results after post-exercise were more acceptable for P100 respirator compare to the N95 respirator [35]. Balazy et al. [27], mentioned that N95 respirators may not always provide

Table 1
Comparison of different kinds of masks.

Mask type	Affordable	Efficiency	Sealing and fitting	Light weight	Comfortable	Respiratory filter	Reusable	Mobility	Durability	Difficult to breath	Eye protection
Basic cloth face mask	High	Low	Low	High	High	No	Yes	High	Moderate	Moderate	No
Surgical face mask	High	Moderate	Low	High	High	No	No	high	Low	Moderate	No
Full-length face shield	High	Moderate, low for indirect aerosols	Low	high	Moderate	No	Yes	High	Moderate	Low	Yes
N95	High-Moderate	High	Moderate	High	High	Yes	No (not suitable for washing)	High	Low	High	No
P100 respirator	Low	High	High	Moderate	Moderate	Yes	Yes	Low	High	Low	Yes/No
Self-contained breathing apparatus	Low	Excellent	Excellent	Low	Moderate	Yes	Yes	Low	High	Low	Yes
Full face respirator	Low	Excellent	Excellent	Low	Low	Yes	Yes	Low	High	Low	Yes

sufficient safety against the penetrating aerosols particles smaller than 300 nm. It has been concluded that N95s and surgical masks against airborne are equally valid, as was reported in some cases [20,42]. Li et al. [43] represented that N95 respirators had a lower air-water vapor permeability than surgical masks, but it is not comfortable like surgical masks. Long et al. [44] reported that using the N95 respirator compared with the surgical mask is not safer against the risk of laboratory-confirmed influenza. Besides, N95 respirators are not recommended for the public and nonhigh-risk medical staff who are not in close contact with influenza patients or suspected patients. It has been indicated that surgical masks and facemasks by taking advantage of electrothermal layers can be more effective than N95s or typical surgical masks for pediatric [42] Kang et al. [45] reported that the specially designed PP mask with a synthetic adhesive at the edge of the mask is more effective than the standard surgical mask, and N-95 respirator. To sum up; Table 1 shows comparison of important parameters and their performance on different masks.

3. Polymers used in masks

Some polymers are usually utilized for fibers of facemasks like polypropylene, polyethylene, polyesters, polyamides, polycarbonates, polyphenylene oxide. Some fluorinated polymers are also used in this case, such as tri-fluoro-chloro-ethylene.

One can note that the nonabsorbent, slippery feeling hydrophobic thermoplastic polymers are more favorable to apply [46]. Polypropylene fiber is utilized due to nonabsorbent properties for the basic medical masks, and it does not absorb the humidity [47]. Huang et al. [48] also mention that one kind of polymers that are used to improve the efficiency of the mask is polypropylene (PP) fibers that were treated with dimethyl-dioctadecyl-ammonium bromide to import a positive electrical charge that is able to attract bacteria [45]. Two different of masks that have been produced by polypropylene and polypropylene-insulated surgical mask are illustrated in Fig. 6.

It should be mention that the fluffed PP is used to produce a PP mask and to edge standard surgical and N-95 respirators to avoid leakage. As a result, the PP edging seal decreased bacterial leakage of standard masks adequately, and it is better to adhesive paper tape edging in decreasing respiratory resistance. It has been claimed that the specially designed PP mask with a synthetic adhesive at the edge of the mask can be more impressive than the standard surgical mask, and N-95 respirator.

Madsen et al. [49] used a testing method for disposable surgical masks to simulates the actual in viva conditions of the surgeon in the operating room to evaluate the efficiency of four commonly masks: a polypropylene fiber mask, a polyester rayon fiber mask, a glass fiber mask, and a cellulose fiber mask.

There is no crucial difference between the performance of the polypropylene fiber mask and polyester rayon fiber mask, although both of them are notably better than glass fiber mask. It has been reported that the efficiency of these four masks is organized in descending order by considering the corresponding efficiency: polypropylene fibers, polyester-rayon fibers, glass fibers, and paper.

Konda et al. [42] evaluated the filtration efficiency of different materials, and some of them consist of polyester like chiffon (90% polyester and 10% Spandex), flannel (65% cotton and 35% polyester), synthetic silk (100% polyester), satin (97% polyester and 3% Spandex). The results showed that protection of chiffon is above 50% in the entire 10 nm to 6.0 μm range, and in general, chiffon and flannel provide appropriate filtration across both nanoscale (< 300 nm) and micron-scale (300 nm–6 μm). It should be noted that satin and synthetic silk were considered to be inefficient for filtration (< 30%).

3.1. Role of nanofibers in mask

Skaria et al. [50] described that the incorporation of nanofiber filter

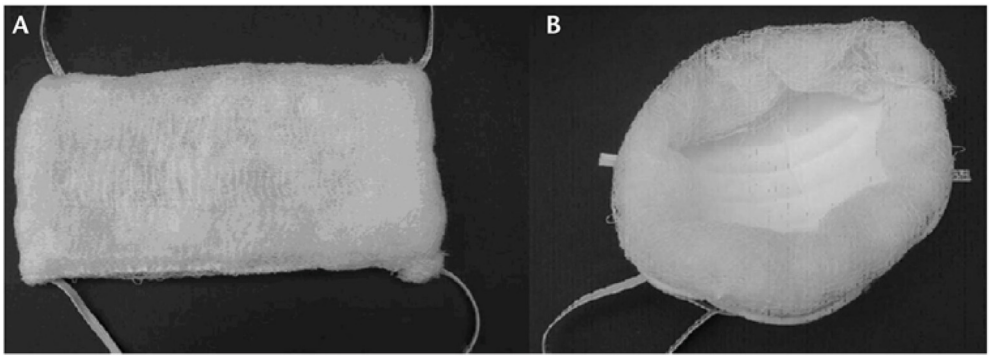

Fig. 6. Displaying the polypropylene mask (A) and polypropylene-insulated surgical mask (b) [45].

media decreased the resistance of mask airflow. As a result, more volume of exhaled air is passed through the face from masks instead of bypassing the filter and going around the shapes. Also, Schlieren optical imaging represented increasing airflow through the nanofiber mask by comparing deflection within and around the standard face masks.

Yang et al. [51], advanced using nanofiber on nanoporous polyethylene (fiber/nanoPE) where the nanofibers with strong particulate matter PM adhesion make secure high PM capture efficiency (99.6% for PM2.5). It should be noted that low-pressure drop and the nanoPE substrate with high infrared (IR) transparency (92.1%, weighted based on human body radiation) develops in active radiative cooling.

It has been indicated that by coating nanoPE with a layer of Ag, the fiber/Ag/nanoPE mask represents a high IR reflectance (87.0%) and can be utilized for warming purposes.

Kharaghani et al. [52] did the design and combining polyacrylonitrile/silver (PAN/AgNPs) nanofibers by using an in-situ method. The goal was to achieve a washable with high-dispersed silver nanoparticles membrane to produce the hierarchically organized antibacterial mask to avoid the two-way effect of bacteria from person to environment and environment to person. For this aim, the electrospun PAN nanofibers were stabilized by taking advantage of the heating method. It has been reported that PAN/AgNPs nanofibers, which were fabricated with one cycle loading AgNPs (2247 ppm/gr nanofiber), create excellent membranes for antibacterial properties in comparison to cycles two and three. It has been indicated that one cycle loading AgNPs could be enough to turn into a washable antibacterial mask. Wang et al. [53] developed the integrating of highly breathable and thermal comfort filter medium consisting of electret polyethersulfone/barium titanate nanofibrous membrane (PES/BaTiO3 NFM) on a nonwoven polypropylene substrate. It should be mentioned that it has high porosity, and injection charge energy is optimized. In addition, the PES/BaTiO3 membrane represents good air and a modest water vapor permeability. Also, the electret PES/BaTiO3 NFM1.5 has a high filtration efficiency of (99.99%) and a low-pressure drop after being treated at 200 °C for 45 min.

Reusability of melt-blown (MB) filter, which belongs to the N95 face mask and nanofiber filter, by considering filtration efficiency, airflow rate, surface, and morphological properties, evaluated after two types of cleaning treatments [54]. It has been reported that the performance of the MB filter was highly decreased after treatment with ethanol, while the NF filter represented consistent high filtration efficiency. So it has been concluded that reusing NF filter for face mask application after treatment can be sufficient in solving the current shortage problem of face masks and improve safety for front line fighters against coronavirus disease.

3.2. Innovative technology for fabrication of mask: Additive manufacturing

PP is commonly utilized for various industrial applications due to its low cost, processability, printability, recyclability, and mechanical integrity [55]. On the other hand, styrene-(ethylene-butylene)-styrene (SEBS) is a polymeric elastomer that has low processing temperature and low distortion during extrusion. Hence, the combination of PP/SEBS can advance the processability of 3D printed N95 masks. In addition, it can control the thermoplastic elastomer ratio tailoring the flexibility and elasticity of the 3D model material to have fitted masks. As a result, 3D printing procedures can create stable and biocompatible N95 masks that are comparable to industrial manufacturing brands [56]. Fig. 7 demonstrates a potential N95 3D printed mask prototype [56]. According to Fig. 7, N95 respirator is made of different parts like nose foam, nose clip, face seal, straps and exhalation valve.

Swennen et al. [57] demonstrated making a reusable face mask by using 3D printing based on materials and techniques (3D imaging and 3D printing). This 3D protective face mask consists of two 3D-printed reusable polyamide composite components (a face mask and a filter membrane support) and two disposable components (a head fixation band and a filter membrane). 3D modeling of these masks can quickly be done by taking advantage of computer-aided design (CAD). It should be noted that testing of leakage and virological is not performed yet, and it is essential prior to its use in real-life situations.

Cai et al. [58] proposed a novel technology for improving the wearing comfort and fit of FFR wearers by scanning faces of three subjects using a three-dimensional (3D) laser scanning method. Acrylonitrile Butadiene Styrene (ABS) plastic using the 3D printing method is used to fabricate the face seal prototypes. It should be mentioned that the force sensing system based on Arduino Uno R3 was advanced, and the force sensor was to measure contact pressure between the FFR and head form. Experimental results indicated that the newly designed FFR face seal supplied the subjects by improving contact pressure.

Provenzano et al. [59] proposed a new model based on a respirator that was developed with PLA (printer filament), a removable cap, a removable filtration unit that consists of two layers of MERV 16 sandwiched between MERV 13, and removable elastic bands to protect the mask. The desired mask was succeeded in passed the suction test protocol to check the leakage and passed the qualitative Bitrix N95 fit test at employee health at GWUH. It has been mentioned that extra caution should be considered to fit the mask and avoid leaks to pass air through the filter to reach the wearer's face.

Liu et al. [60] represented that interfacing an anesthesia circuit filter with reusable elastomeric respirators can be a possible alternative to disposable N95 respirators. In addition, they studied evaluating the performance of modified elastomeric respirators by recording quantitative fit testing, respiratory rate, and end-tidal carbon dioxide on eight volunteers. The results showed that four out of eight subjects had discomfort: two reported facial pressure, one reported exhalation resistance, and one reported transient dizziness on exertion.

4. Mechanisms of filtration

Penetration has an unprecedented dependence on the particle scale

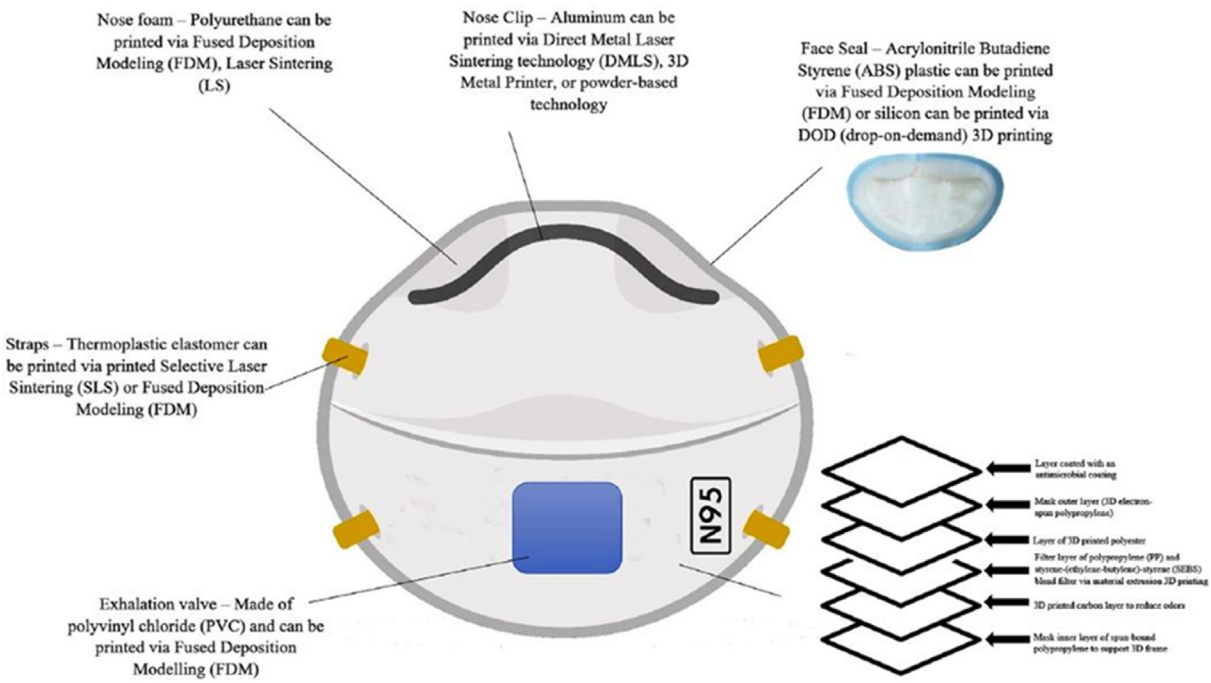

Fig. 7. A potential N95 three-dimensional (3D) printed mask prototype [56].

because in the sub-micron size regime, trapping of the aerosol is occurred by different mechanisms like gravity sedimentation, inertial impaction, interception, diffusion, and electrostatic attraction [42,61]. In the following, the possibility of activation of these mechanisms is examined by considering the sizes of particles.

Fig. 8 shows the schematic of theses mechanisms in which airborne particles may penetrate through the mask.

Kinetics and related mechanisms are firmly depending to the type of the active substance, consisting the physical and chemical properties, such as molecular weight, particle size, and etc.

4.1. Gravity sedimentation

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 [42]. McCullough et al. [11] mentioned that for the size of particles (0.5 > μm) that is expected that inertia and gravity can be the dominant mechanism, and it has been predicted that the aerosol with the smallest size, which is polystyrene latex sphere (0.5 μm) has the most penetrating ability.

4.2. Inertial impaction

Inertial impact occurs when the inertia of the particles becomes too large that induces changes in the direction of particle movement in the airflow [62]. Particles with bigger sizes, larger face velocities, and densities pose higher inertia, and this process makes them more easily captured. These particles have inertia that they are not able to flow around the respirator fibers. Moreover, instead of flowing through the filter of material, the particles with larger size stray from the air streamlines, collide with the fibers, and can adhere to them [30]. Overall, particles of around 1 μm or greater may be effectively removed by this mechanism [63]. But it does not significantly participate in capturing mechanisms for nanoparticles [62,64,65]. The effect of this mechanism in capturing Ultrafine particles and Nanoparticles are neglected [6].

It should be noted that the impact of Brownian motion on smaller particles is significant. Diffusion is commonly used as the primary aggregation mechanism for particles lower than 0.2 μm, and the particles greater than 0.2 μm are governed by detection and inertial impaction [62,64,65].

4.3. Interception

Interception happens as a particle follows the primary streamline to allow interaction between particle and filter media within one particle width of the surface of fiber [62]. This method is successful in extracting particles up to 0.6 μm [63]. Interception is not explicitly determined by particle velocity, but it is more apparent as particle size decreases. There is a crucial distinction between interception and inertial impaction that there is no divergence from the central streamline for an interception, where the filter substance intercepts the particle [6]. It has been reported that by reducing aerosol size in the interval 100 nm to 1 μm, diffusion by Brownian motion and mechanical interception of particles by the filter fibers are prevailing mechanisms [42].

4.4. Diffusion

Based on the random Brownian motion of particles bouncing into the filter media, it is the most effective mechanism for capturing particles with sizes less than 0.2 μm [63]. Indeed, the abnormal motion of particles raises the probability of collision between particles and fiber in a streamline that does not intercept [62]. This makes diffusion of enormously tiny objects, such as ultrafine particles and nanoparticles, more important than interception. As particle size or facial velocity reduces, the rate of diffusion becomes more noticeable. With lower speeds, the particle residence period is increased by means of filter media; hence the likelihood of collision between particle and filter media is increased dramatically [31]. Different investigations represented that when the bulk of the outflow entered the matrix of the mask, its velocity decreased immediately because of diffusion into the mask [66].

For the mechanism of the mass transport there is a general model of the Fick's first law which is corresponding to the mass diffusion across a unit area in the unit of a time, and the Fick's second law which indicates

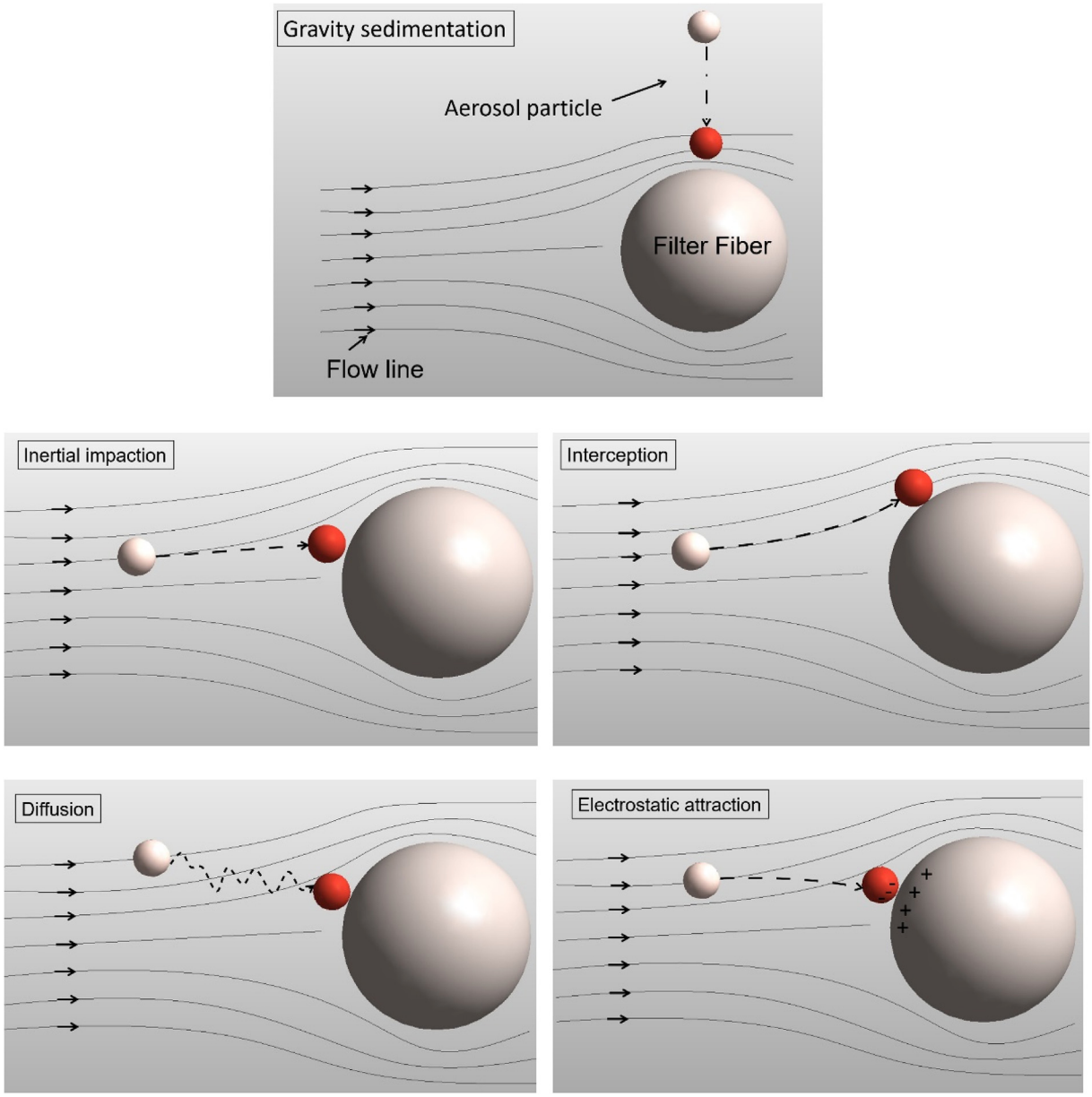

Fig. 8. Schematic of the mechanisms of aerosol penetration through the masks.

the change in the concentration with time in the defined region [62,63].

$$J = -D\frac{dc}{dx} \quad \text{Eq. 2}$$

$$\frac{dC}{dt} = D\frac{d^2c}{dx^2} \quad \text{Eq. 3}$$

Where "J" is the diffusion flux, "D" is the diffusion coefficient in dimensions, "C" is the concentration in dimensions, "x" is the position, "t" is the time.

4.5. Electrostatic attraction and thermal rebound

Electrostatic attraction is a method that is captured both large and small particles from the airstream. In this method, electrically charged fibers or granules are considered in the filter to absorb oppositely charged particles from the airstream [30]. In the case of the nanometer scale, particles are able to slip between the openings in the network of filter fibers; removing of low mass particles has been done by electrostatic attraction, and electrostatic filters can be useful at low velocity like respiratory velocity through facemask [42].

The electrostatic mechanism of attachment is weakened by rising speed. In addition to the mechanisms [66] (diffusion, interception, and inertial impaction), the charged filters displaying the electrostatic attachment are known as electrets filters in literature [63,64,67]. The majority of filters authorized by NIOSH (such as N95 and P100) are defined as the electrets filters [6].

The studies report that the performance of the mechanical and electret filters are different in the aerosol collection at the range size of nano. The particles with 300 nm are described as the most penetrating one for mechanical filters (non-charged); however, lower than this value decreases the efficiency of the electret filters (charged) [10,68]. Moreover, the investigations showed comparing the penetration of charged and uncharged particles. The highest penetration occurs for the uncharged particles for particles sized 30–40 nm; this value is much higher for charged particles [17–22]. Although, it should be mention that the effective value of the size of the particles is different for different types of particles at different flow rates [7], decreasing the

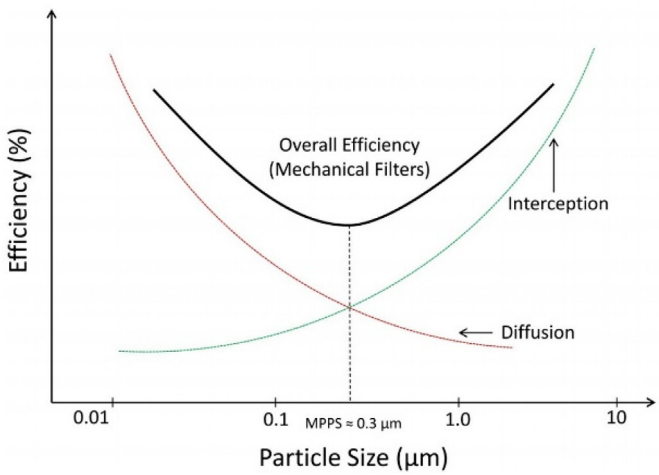

Fig. 9. Contribution of interception and diffusion mechanisms in accordance with the particle size [6].

airflow rate would increase MPPS (most penetrating particle size) [22–24].

5. Influence of different parameters on the penetration

The filtration efficiency of a mask is represented the capacity of holding particles and viruses in the air and is specified as an efficiency ratio and contains particle size, filtrated air quantity, and using time [47]. From the point of view of fluid mechanics, some elements play an important role such as the flow rates, the size of the aerosols, gap size between facial profiles and N95s or surgical masks, corresponding resistance of fluid flow through gaps against the persistence of flow through N95s or surgical masks [61]. In the following, the effect of external parameters on the filtration mechanism, the required properties of the filter, and its efficiency are examined.

5.1. External condition parameters

5.1.1. Particle size and shape

The word nanoparticle essentially applies, at least in one dimension, to the spectrum of particles below 100 nm in size. Referring to the toxicological studies suggest that a given substance is usually more toxic at the nano-metric size level than at the micro-metric size range at the same mass [11,69,70]. It is because of the high particle surface area, surface reactivity, and number concentration [31].

Some studies imply that due to the impact of thermal rebound, the filtration performance of nano-sized particles may be decreased significantly. Two definitions describe the thermal rebound effect: critical velocity and kinetic energy [71].

It has been reported that the mean thermal velocity due to Brownian motion increases the capturing rate with the decrease of particle size under an absolute value and thus increases the likelihood of particle detachment from the filter surface [62]. The probability exists that very small particles do not agglomerate on impact due to their mean thermal velocity, which exceeds the velocity of capture [72]. As the particle size decrease because of their manners, their adhesion reduces.

On the other hand, particles with decreasing sizes would have lower adhesion to the surface of the filter, where the observations of Brown stated that due to their nano-sized dimension, which is near to molecular clusters, they behave more like molecules. When they come in contact with the filter surface; therefore, they wouldn't stick to it because of their manners [62].

It has been reported that the efficiency of N95 respirators for the NaCl particle size in the range of 0.1–0.3 µm and higher than 0.75 µm is about 95% and 99.5%, respectively [31]. As mentioned, the effectiveness of the filter depends on the size of particle; for example, in range of particle sizes of inferior and higher than 300 nm, the values of efficiency are stated in the interval of 5–80% and 5–95% for single layer, respectively.

By considering multiple layers and utilizing a specific combination of different cotton fabrics, the performance of the hybrids (such as cotton − silk, cotton − chiffon, cotton − flannel) was > 80% (for particles < 300 nm) and > 90% (for particles > 300 nm) [42]. It has been reported that the MPPS for P100 filters and N95 are in the range of 0.05–0.2 µm and 0.05 µm, respectively [73].

Several researchers have examined the effect of thermal rebound on the penetration of particles through filters. Wang and Kasper [74,75] showed that the thermal impact velocity of a particle (between 1 and 10 nm) depending on some parameters such as surface adhesion and elasticity, would exceed the critical sticking velocity. However, in another study [76], they didn't observe the thermal rebound for NaCl particles between 4 and 30 nm. Therefore it seems that the results are also depending on the type of particles used in the experiment [6].

It has been shown that some physicochemical parameters like particle structure, the potential of the aggregation of the particles, and coating the surface of the particles affect the behavior of the nano-sized particles [77]. For sub-micrometer particles filtered by mechanical filters, interception and diffusion are the most dominant mechanisms. At the same time, inertial impaction is negligible; the percentages of the contribution of each of these mechanisms relate to the penetrating particle size are represented in Fig. 9 [31].

The particle form often impacts entry into the masks; for example, rode shaped particles have less potential to penetrate, and the value is about half of the spherical particles. Generally, it depends on the aspect ratio, where the aspect ratio of rode shaped to spherical is reported at about 4 [78].

5.1.2. Face velocity or airflow

A review of flow is vital in many ways because people in different situations have a different rate of breathing. It should be mentioned that penetration is strengthened by increasing flow rate, and differences in flow rate do not express more risk of infection because actual infectious or lethal dose one take in, would also be comparable to the total breathing flow rate [61]. One of the factors that considerably influence the performance of the fibrous filters is the airflow rate. This factor impacts on the contribution of the mentioned mechanisms above. Where low flow rate diffusion and electrostatic forces are more contributed mechanisms because of more residence time while increasing the flow rate interception mechanism becomes dominant [6].

Kunda et al. [42] illustrated that increasing the flow rate from high flow (3.2 CFM) decreases the efficiency of filtration. It has been mentioned that during hard work, the inhalation rate can exceed 350L/min, besides it was represented that at both constant and cyclic conditions, the penetration of particles is increased due to shorter residence time through filters [12].

Qian et al. [31], by considering two different flow rates (32 L/min and 85 L/min), investigated the filtration efficiency of N95, dust/fume/mist (DFM), and dust/mist (DM) respirators by using an experimental test of NaCl. The results presented that by considering low flow rate, the efficiency of filtration is increased because primarily the time to remove sub-micrometer particles by the electrostatically charged fibers of the respirator has been expanded. Secondly, additional removal is occurred due to the rising time of particles diffusion [31].

In a study by Richardson et al. [12], they have analyzed the effect of the flow rate at a constant flow on the percentage of the penetration for a range of particles for the N95 Cartridge type of mask. Fig. 10 shows the results of this experiment, whereby increasing the flow rate, the penetration also increases.

The results revealed that the airflow rate has a strong impact on particle penetration through the filter face-piece respirators.

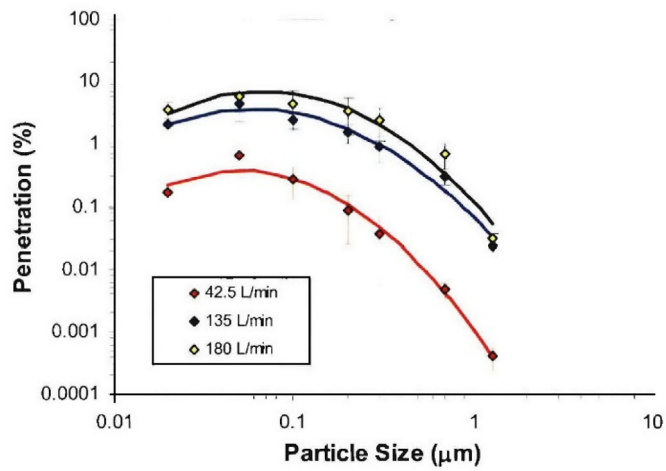

Fig. 10. Effect of particle size and constant flow rate on measured penetration through MSA Flexi-Filter N95 Cartridge [12].

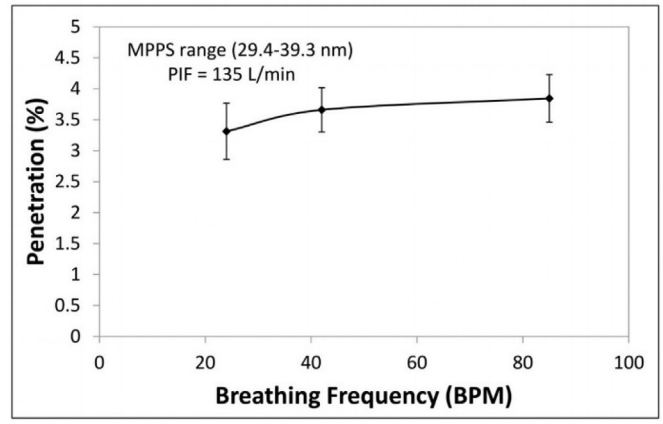

Fig. 11. Penetration of MPPS at the range of 29.4–39.3 nm for cyclic flows (135 L/min) as PIF versus frequency (24, 42 and 85 BPM) for N95 filtering facepiece respirators [6].

5.1.3. Steady or unsteady pattern of flow

Some studies have been conducted in this regard that the steady or unsteady pattern of flow is another parameter that can be effective; however, it is less impressive than the flow rate. As Stafford et al. [12] tested the penetration of the mono-disperse polystyrene latex (PSL) and dioctyl phthalate (DOP) particles at three cyclic flows of 30, 35 and 53 L/min and constant flow of 32 L/min. McCullough et al. [11] also examined this concept with the cyclic flows of 85.1 L/min and constant flow of 32 L/min. The particles chosen for these studies were inferior to 0.47 μm. They have stated that the cyclic flow had higher particle penetration compared to constant flow [31]. Moreover, in another study, they reported that in addition to the higher penetration in the cyclic flow, it could better predict the penetration of the particles as it is the actual case of human respiration [6,31].

Eshbaugh et al. [73] selected three stable flow conditions (85, 270, and 360 L/min) to test and adapt the minute, inhalation means, and inhalation peak flows of the four cyclic flow conditions (40, 85, 115, and 135 L/min). As expected, by enhancing constant and cyclic flow conditions, the penetration has been raised [73].

5.1.4. Charge state of particle

Charged and uncharged particles do not have the same behavior as penetration, and some studies proved that filtration efficiency is considerably lower for uncharged particles than the charged particles. It should be mentioned that decreasing the particle size reduces this difference by considering that the existence of the other parameters affects the results. For example, for the higher face velocity, particle size is less influenced due to the less residence time [79]. As mentioned above, the most dominant mechanism for the nanoparticles is diffusion; it is, therefore, charging the particles is more effective on the diffusion.

Furthermore, for the charged and uncharged filters, this phenomenon is different. For the electret filters, more filtration efficiency was observed for the neutralized particles. Nevertheless, it was not remarkable differences in the penetration of charged and uncharged particles for the mechanical filters.

5.1.5. Frequency of respiration

Frequency and peak inhalation flows (PIF) are essential parameters in the penetration performance; although, the importance of the PIF was reported to be much more than the frequency. Nevertheless, for better simulating, the human breathing flow rate and frequency take priority, which can give a sinusoidal waveform [80].

It is notable that the effect of the frequency changes with the value of the PIF, where this sensitivity is higher for the high PIFs rather than the lower PIFs [31].

This concept was justified in the study of Mahdavi et al. [6]. As shown in Fig. 11, the penetration at the same flow rate of 135 L/min for different frequencies is always below 5%. Moreover, it is concluded that in the case of changing the frequency, the mechanism of filtration hardly varies. However, it is not the same for the variance of the PIFs. For example, when the PIG changes from 135 to 360 L/min at the frequency of 42 min^{-1}, the results of penetration increase 145% [31].

5.1.6. Relative humidity and temperature

One of the factors which affect the filtration performance is the humidity, but because of the lack of study in this field, it is not possible to comment definitively on that. In a study, humidity is considered a non-effective parameter. While further study declared the low efficiency of the masks in the humidity due to the capillary force between the particles and filters [81].

Moreover, for mechanical filters, the reviews for electret filters (charged filters) demonstrated the filtration performance decreases as humidity increases. The reason is that higher humidity would lead to the reduction in the charges on the filter's fiber and particles [82].

In a study of Li et al. [43] they have claimed that high humidity and high temperature in the expired air can cause condensing of water vapor in the mask due to differences in air temperature and mask; in addition, the droplets that are excited during speaking increase the possibility of the wetting process [43]. Moreover, Fig. 12 is derived from a study by Richardson et al. [12].

This figure represents the penetration from different filters of the N95 mask at four different flow rates (static: 85 L/min and 270 L/min, cyclic: 85 L/min and 135 L/min) in both dry and wet conditions. It is notable from the mentioned figure that the mean penetration is increasing by raising the flow rate. The main conclusion is that in the wet case, compared to the dry case mean penetration is highly extended.

Roberge et al. [83] noted that wearing N95 facepiece respirator for up to 2 h at a low-moderate work rate does not inflict a considerable thermal burden on core temperature and uncovered facial skin temperature. On the other hand, it raises remarkably the temperature of the facial skin that is covered by the FFR.

5.1.7. Loading time

The penetration efficiency also varies by the loading time, wherein a study by Mahdavi et al. [6] they have shown that for both cyclic flow and constant flow, the penetration of the nano-particles mostly below 100 nm decreases with increasing the loading time. This parameter affects more on the mechanism of diffusion as it is a time-dependent mechanism. By getting in the time, the filter is more loaded with the particles. Therefore there wouldn't be much enough space for the new particles to attach on the surface of the filter, nonetheless the collision

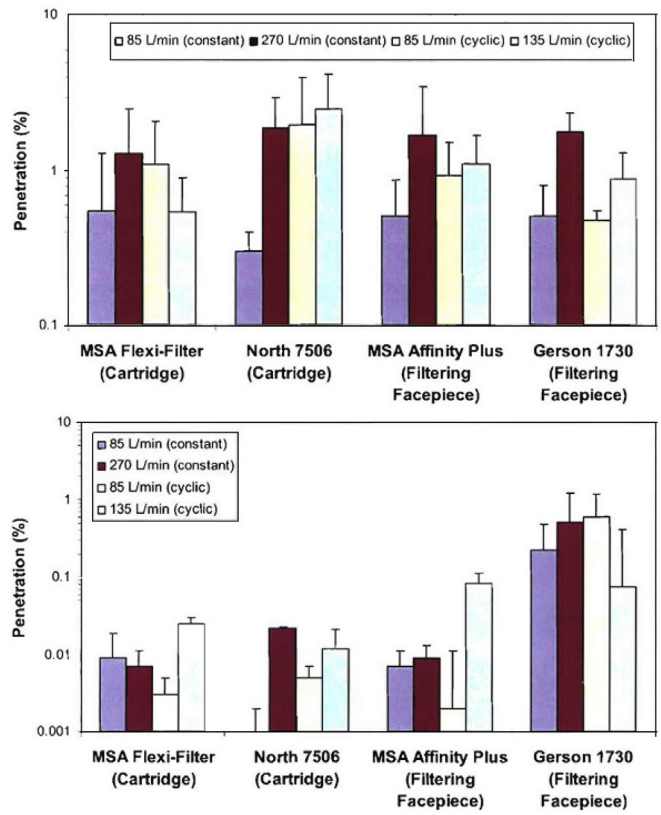

Fig. 12. Comparison of Measured MS2 (a) "Wet" and (b) "Dry" penetrations through N95 filters at different constant and cyclic flow rates [6].

between the particles and also the fibers of the filter increases due to the hazard Brownian motion [6].

In this case the by increasing the loading time, the electrostatic attraction is decreased. Another mechanism, such as interception, was less influenced compared to the diffusion [82]. Loading time is also affected by the particle size, as for the larger size (higher than 100 nm), the penetration increased in the 2nd and 4th hour compared to the previous interval, although it has a slight decrease in 2 next hours. This may be due to the accumulation of the particle in the dendrite form, which prevents penetration [6].

To summarize this section, Table 2 is provided to summarize and compare different external condition parameters.

5.2. Filter characteristic

Filters utilized in respirators and medical masks should permit the user to breathe, and it should be able to prevent clogging of the pore and still allowing air to flow inside the filter. Rising adhesion of particles to the filter fiber can be a problem because when enough particles have been arrested for starting to block the open pores of the woven or nonwoven network. van der Waals bonding and other force hold the particles that have been absorbed by a filter to the fibers; hence, it is hard for captured particles to escape [30].

5.2.1. Filter chemical composition

Respirator and medical mask filters are commonly made of mats of nonwoven fibrous materials, like wool felt, fiberglass paper, or polypropylene [30]. Resins have been added to natural wool fibers to hold an electrostatic charge in the first electrostatic filters [30]. It should be mentioned that polyester woven fabrics are able to maintain a more static charge compared to natural fiber or cotton because of less property in water absorption [42].

5.2.2. Filter thickness and packing density

Kunda et al. [42] mentioned that increasing the number of layers in the masks improve the performance of it, but it depends on the material structures [42]. Shokri et al. [84] measured the thickness of the mask that produced domestically, and the consequences illustrate that their thickness (0.41–0.04 mm) is more than the imported masks (0.38–0.01 mm) because of various kinds of filter. It should be mention that the air pressure drops higher in domestic surgical masks that imported one because of the higher density of fiber, lower pore diameter, and more increased thickness.

Huang et al. [85] proposed a theoretical model to examine different parameters like face velocity, fiber diameter, packing density, filter thickness, and fiber charge density that impressing the filtration characteristics of filters used for respiratory protection. By using electret filters, it has been concluded that the most penetrating particle size increases with raising fiber diameter, face velocity, and reducing thickness; besides, it is decreased by increasing packing density, thickness, or fiber charge density. Nevertheless, for non-electret filter media, the most penetrating particle size extended with dropping face velocity, and the filter quality factor is not influenced by filter thickness. This shows that filter Media have various filtration efficiency patterns with different rates of velocities. To sum up, based on results representing the outcome of fiber diameter and packing density on the quality factor, there is no universal "best" filter.

5.3. Filtration efficiency

Li et al. [43] mentioned that by taking advantage of tests on physical properties, it could be represented that N95 respirators had a lower air-water vapor permeability than surgical masks undoubtedly. Those N95 respirators can protect better against viruses, but it is not comfortable like surgical masks. The in-vivo filtration tests, despite that N95 respirators, can filter 97% of potassium chloride (KCl) solution, while surgical masks are able to filter 95%. Also, in the nano-mask, no difference in usability, comparing with normal N95 and surgical masks, has been observed, but it can indicate more robust water repellency and antibacterial activities [43].

Hence some of the surgical masks and facemasks for pediatric by taking advantage of electrothermal layers can be more applicable that N95s, which have not been tested or typical surgical masks [61].

Table 2
Influence of external parameters on filtration efficiency.

External parameters	Filtration efficiency of the mask	Refs
Particle size	Decreasing particle size, decreases efficiency	[11,31,45,61,68,69,73–76]
Shape of particles	Low aspect ratio, decreases efficiency (rode shaped particles diffuse less than spherical shaped particles)	[78]
Face velocity (flow rate)	Increasing flow rate, decreases efficiency	[12,17,31,42]
Pattern of flow (Steady or cyclic)	Cyclic flow decreases efficiency compared to static flow	[6,11,12,31]
Charge state of particle	Efficiency decreases for uncharged particles	[79]
Frequency of respiration	Increasing frequency decreases the efficiency	[6,31]
Humidity and temperature	Increasing humidity and temperature decreases the efficiency	[12,43,81,82]
Loading time	Increasing loading time, increases the efficiency (However, there is the risk of virus accumulation)	[6,82]

Table 3
Comparing the values related to the bacterial leakage for the case without the mask and with different masks [48].

	Control (no mask)	Standard surgical mask	Polypropylene-insulated surgical mask	N-95 Respirator	Polypropylene-insulated N-95 Respirator
Mean bacterial colony count per trial	209.6	33.18	9.36	8.54	3.66
Total bacterial colony count	10480	1659	468	427	183
Percentage of control	100.00	15.83	4.47	4.07	1.75
Penetration-value: surgical mask versus PP-I surgical mask, < 0.01; N-95 respirator versus PP-I N-95 respirator, < 0.01					

Fig. 13. (a) Unsealed surgical mask in the normal use, (b) sealed surgical mask with crossed straps [86].

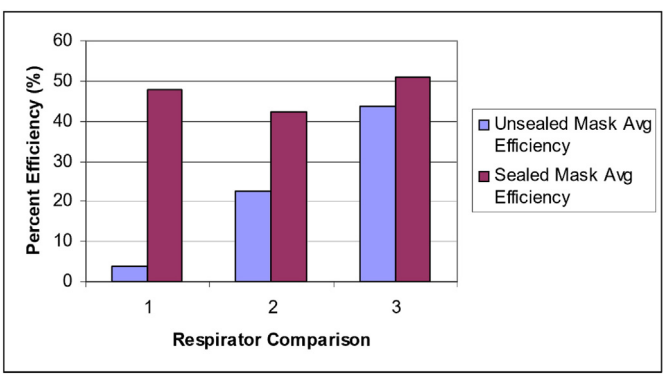

Fig. 14. The efficiency of the unsealed to the sealed surgical masks at the particle size of the 0.5 μm [86].

It has been mentioned that the N95s have the highest filtration performance and, in consequence, the lowest penetration efficiency. Besides, it has the smallest maximum penetrating particle size and a higher drop in pressure about two to three times has been reported in a comparison of surgical and facemasks for pediatric. By considering all of the investigations, approximately for all brands of masks, filtration specification displays a reliance on size [61]. It has been concluded that N95s and surgical masks against airborne are equally effective, as was reported in some cases [22,61].

One can notice that the filtration efficiency (η) is defined as:

$$\eta(\%) = 100 - P = (1 - \frac{C_{Down}}{C_{Chal}}) \times 100 \qquad \text{Eq. 4}$$

6. Leakage

It is significant to note that the leakages can decrease the performance, and it is able to degrade efficiencies by ~50% or more, pointing to the importance of "fit." [42]. Guha et al. [61] reported that there is not a strong relationship between leakage and sub-micron aerosol size. Also, by considering the same gap size or a larger one, leakage of aerosols through surgical respirators perchance be greater in surgical masks and facemasks for pediatric.

The effects of aerosol size on leakage showed that for sizes greater than 100 nm, no crucial dependence has been established; on the other hand, below 100 nm size dependence was observed for some of them at low flow rate [61].

It has been reported that measurements at both the high flow (3.2 CFM) and low flow (1.2 CFM) rates demonstrate considerable fall in performances in the existence of holes [43].

Qian et al. [31], by doing some laboratory tests using NaCl certification aerosols and measuring particle-size spectrometer showed that N95 respirators have better performance in comparison of dust/mist (DM) and dust/fume/mist (DFM) respirators and noncertified surgical masks.

It seems that almost all of the masks have the probability of leakage. In the study by Cho et al. [52] after their experiments with different cyclic breathing flow on the N95 masks, they have resulted even for well-fitted facepiece respirator masks, maximum penetration of the particles is via the face seal leakage. In a study by Huang et al. [48], they have analyzed the penetration of the bacterial in the case without the mask and with different masks: standard surgical mask, polypropylene-insulated (PP–I) surgical mask, N-95 respirator, polypropylene-insulated N-95 respirator in order to show the efficiency of the using different masks. Table 3 shows the values related to these experiments, which are obtained by a volunteer in 50 trials for each mask.

Moreover, in another study by Sanchez et al. [86], they have compared the percentage efficiency of the six different surgical masks at two configurations of unsealed and sealed postures (as shown in Fig. 13). Fig. 14 shows the results of these experiments for the particles at the size of 0.5 μm at 5 times of trial.

7. Numerical models

To complete the studies, numerical simulations in which the methods of Computational Fluid Dynamics (CFD) or Finite Element Method (FEM) have been studied to investigate the parameters affecting the mechanism of penetration and to improve the filtration efficiency.

Lei et al. [87] utilized computational fluid dynamics to simulate

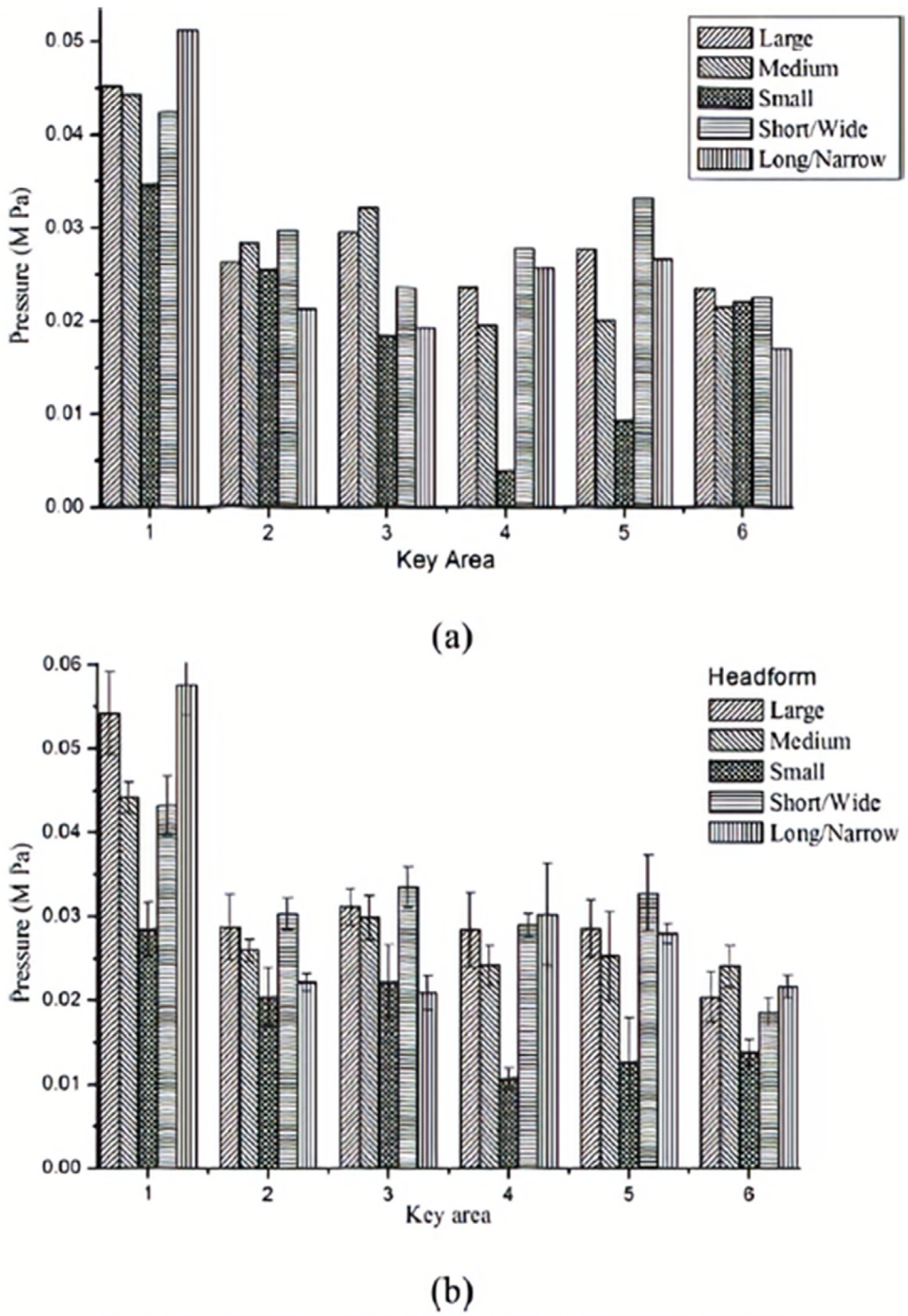

Fig. 15. Contact pressure values of the one-size only system on five headforms for filtering facepiece respirator in six key areas on the face: (a) computational results, (b experimental results, (1) nasal bridge, (2) top of the right cheek, (3) top of the left cheek, (4) bottom of right cheek, (5) bottom of the left cheek, and (6) chin [89].

airflow and heat transfer over the human face and anticipate leakage between an N95 filtering facepiece respirator (FFR) and head form for 10 head forms and 6 FFRs by taking advantages of infrared camera method to validate numerical results. The results represented that by using N95 FFR, the temperature of the skin at the region near the lip has been raised. In addition, the ratio of 'filter-to-face seal leakage' (FTFL) is affected by breathing velocity and the viscous resistance coefficient of the filter, although the freestream flow does not influence on the FTFL ratio.

The governing equations were used are the mass conservation equation, the three-dimensional Reynolds-averaged Navier–Stokes equations, and the energy equation (see Ref. [88] for more detail). In addition; the heat conduction of facemask is like following [87]:

$$\rho_f c_f \frac{\partial T_f}{\partial t} = k_f \nabla^2 T_f + \rho_b w_b c_b (T_b - T_f) \quad \text{Eq.5}$$

Where ρ, T, t, and k are density, temperature, time, and thermal conductivity coefficient. The filter medium was defined as porous media because of randomly oriented fibers to simulate its resistance to flow. Pressure drop is proportional to velocity in laminar flow through porous media, and Darcy's law replaces the momentum equation [87]:

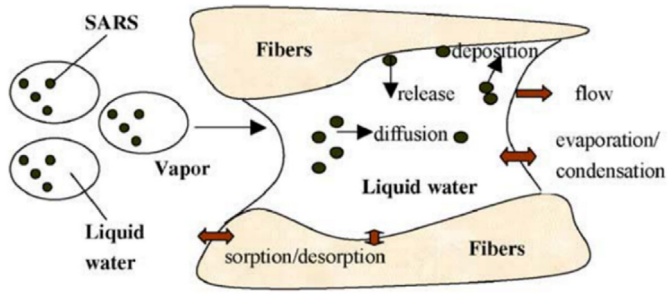

Fig. 16. Schematic of transferring of SARS virus in the mask [13].

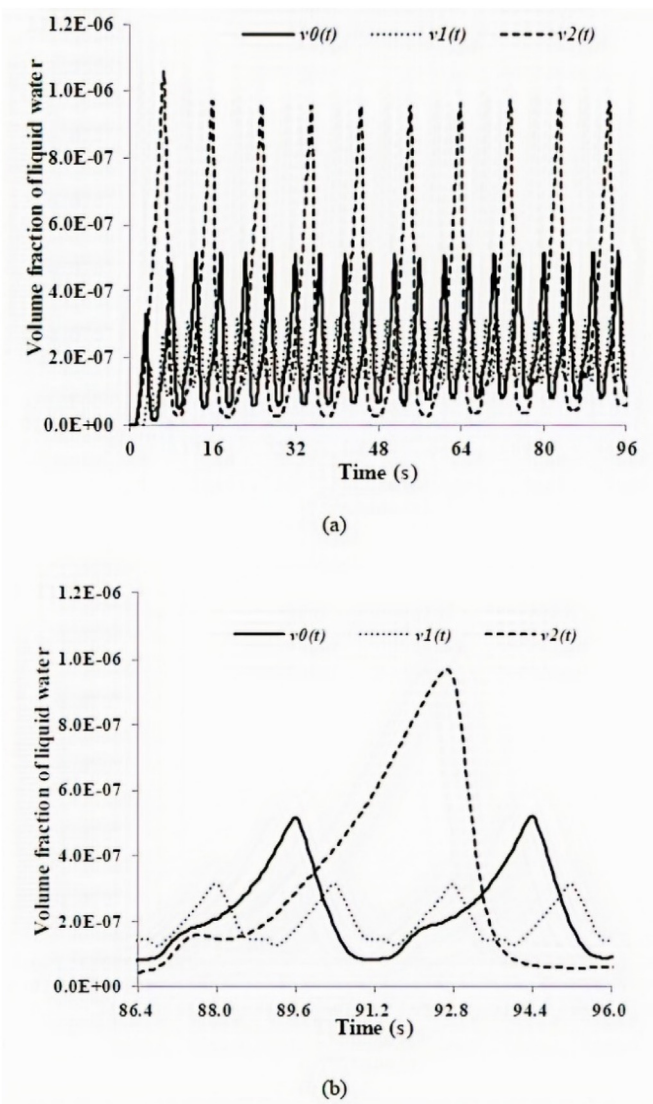

Fig. 17. Volume fraction variation of liquid water in the FFR for (a) full breathing time 0–96.0 s, (b) the breathing time 86.4–96.0 s [94].

$$\nabla p_a = -\frac{\mu_a}{\alpha} V_a \qquad \text{Eq.6}$$

Furthermore; in the filter medium, an effective conductivity was utilized in the heat conduction equation [87]:

$$\frac{\partial}{\partial t}[(1-\varepsilon)\rho_f c_f T_a + \varepsilon \rho_a c_a T_a] + \rho_a \nabla.(V_a T_a) = \nabla.\{[(1-\varepsilon)k_f + \varepsilon k_a]\nabla T_a\} \qquad \text{Eq.7}$$

Leonard et al. [66] utilized computational fluid dynamic modeling to evaluate the effect of wearing a mask over the face on the velocity of gas outflow into the room by considering two models. Besides, the aftereffect of leakage around the mask and the effect of the addition of a mask on the ability of High-Velocity Nasal Insufflation to flush overhead air passage has been discussed. The results showed that the velocity of exhaled gas flow of patients during low flow oxygen or High-Velocity Nasal Insufflation therapy can be decreased by using surgical masks. The initial consequences represented that using a surgical mask can be a useful tool to reduce droplet deposition because of exhaled gas flow, except at leakages of the mask [66].

Lei et al. [89] simulated contact pressure study of N95 filtering facepiece respirators (FFR) by taking advantage of the Finite element method, and it has been generated from 3D digital models of FFRS and shape of heads. Fig. 15 illustrated contact pressure of one-size only system on five head forms for filtering facepiece respirator in six different key areas on the face.

Two N95 models have been considered to simulate the interaction between the respirator and head form, one size that is fit for all, and the other has two sizes (small and medium/large). The results showed that the masks with two types of size supply more appropriate contact pressure distribution than one-size-fits-all masks. It has been reported that the one-size-fits-all N95 had sufficient performance for large, medium, and short/wide head forms, but some potential leakages exist for small and long/narrow head forms. On the other hand, the results of N95 with two sizes despite that the medium/large size is suitable for the large and long/narrow head forms. But it has the potential of leakages for medium head forms; besides, the small size fits well for the medium, small, and short/wide head forms.

Xiaotie et al. [90] proposed transient numerical simulation to model flow characteristics of velocity, Carbo dioxide volume fraction, and temperature distribution by wearing N95 filtering facepiece respirator. It should be mention that the pressure and wall shear stress inside the upper respiratory airway were examined. The results indicated that the accumulation of carbon dioxide inside the mask increases. Besides, the static temperature in the filtering facepiece respirator has been extended because of the higher temperature of exhaled air, and these results are matched with the experiment.

A simple model by taking advantage of computational fluid dynamics two-dimensional has been considered to simulate the loading process of aerosol particles on fibrous filters to represent the effect of recalculating the flow around a single fiber in the full loading process, until the final clogging of the filter [91]. In each degree of particle deposition, the different shape of the fiber is given, and information on the flow field around a fiber and the filter efficiency is calculated. The single-fiber efficiency is confirmed overestimating when the effect of further deposition is neglected. The reality of experimental observation showed that when loading is increased the efficiency is raised. In this study, the physical motion of system components and numerical simulation of Navier–Stokes and a Eulerian simulation of the particle's equations of motion have been considered together to represent the effect of the particle–flow interaction. The particle diameter is chosen 1 μm to hold on physically the low inertia for a small particle and eliminating Brownian motion and diffusional deposition [92,93]. The fiber size is determined 5 μm by considering the size of the particle and decrease the overall number of particles that are released in the system.

Yi et al. [13] proposed mathematical model by considering coupled heat and mass transfer model to discussed in detail the mechanisms of the water vapor molecular diffusion, evaporation/condensation, sorption/desorption of moisture by fibers, Brownian diffusion of the virus, filtration of the virus, capillary penetration of the viruses with the liquid water and latent heat generation due to phase change in a facemask during breathing cycles. In the experimental part, human subjects wear a N95 mask, and walking exercise has been started. The diffusion mechanism of SARS, vapor, and liquid water in the fibers are represented in Fig. 16.

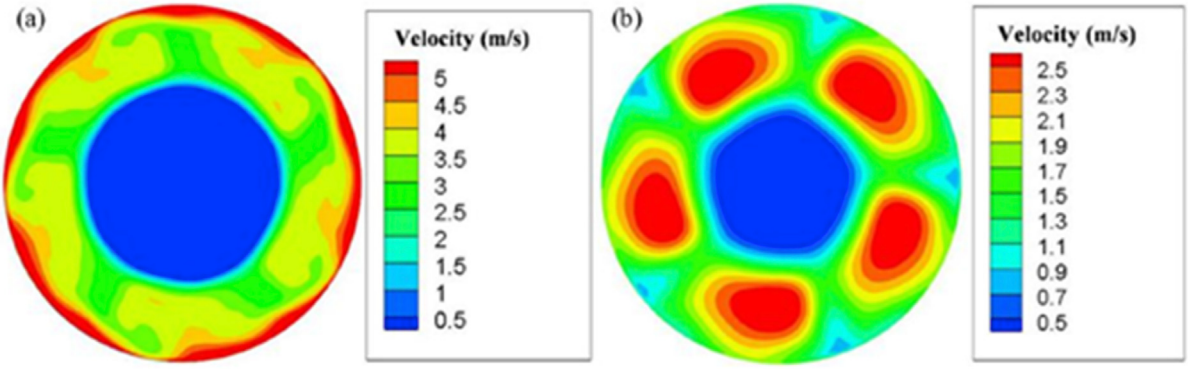

Fig. 18. Air velocity contours of an axial fan. (a) outtake side (b) intake side [95].

The virus-simulation solution was sprayed once every 10 min at a distance of 1 m on the face mask to investigate the transfer progress of K^+ concentration, liquid water, water vapor concentration, pressure, and temperature with active breathing cycles. As a result, the concentration of water vapor, the pressure of the gas in the mask, and the temperature of the mask are changed with the breathing cycles. In addition, the virus transfer from the outer surface to the inner surface of the facemask can limit by reducing the effective capillary radius, raising the thickness and contact angle.

Condensation of water vapor that provides favorable temperature and humidity for growing and reproduction bacterizes, which is a kind of health hazard. Rao et al. [94] used a computational fluid dynamics method to simulate flow-field in the N95 masks to analyze the distribution of temperature water vapor and the fraction of liquid water on the inner surface of the FFR by considering various environmental temperatures. The sudden drop in environmental temperature and different breathing velocities and frequencies was observed. The results are represented that the environmental temperature affected highly to the inside temperature of the FFR when the heat dissipation through the porous FFR to the outside was crucial. It should be mentioned that the volume fraction of liquid water on the inner surface reduced by raising the environmental temperatures because heat dissipation between the environmental temperature and exhaled gas temperature is increased. In addition, more heat dissipation causes more water vapor condensation. Furthermore, the volume fraction of liquid water was raised up by increasing the breathing frequencies and decreasing velocities due to the rising of flow; more water is condensed at a given environmental temperature (Fig. 17).

Zhang et al. [95] improved the design of Filtering Facepiece Respirator (FFR) to increase the comfort of wearers and decrease the dead space temperature and CO_2 level during low flow rate breathing by using an active ventilation fan. Creating the 3d geometric model of this FFR is done by using reversing modeling, and computational fluid dynamics (CFD) is utilized to simulate the flow field. A battery provides the power; therefore, the wearer can switch it on whenever they need, and the results are shown that the ventilation fan can fit the flow field when placed in the appropriate blowing orientation. The CO_2 volume fraction is controlled by optimizing the flow field in the dead space. An experimental prototype was used to validate the simulation results. It has been mentioned that the dead space temperature of FFR-equipped is decreased 2 °C compared to the FFR without a fan; besides, by using the infrared camera, the temperature distribution on the prototype FFR's outside surface and wearer's face have been clarified. However, the rate of transmission of the foreign virus into it and the performance of the mask has been not reviewed. Fig. 18 demonstrates air velocity of an axial fan (Inward-blowing, outward-blowing).

8. Conclusions

In this review, weakness, and strength of different types of protective masks were under study. The filtration efficiency, penetration mechanisms, and affecting parameters related to them were carefully surveyed.

In this regard, it has been shown that the cloth masks and surgical masks are not very efficient for the penetration of the nanoparticles and the range of the efficiency stay about the micrometric particles. However, the efficiency of the respiratory masks is in the nanometric size, where it changes for different types of respiratory masks. They are more efficient in eliminating the entrance of any toxic and contaminable particles. On the other hand, the accessibility and discomfort of the usage of these masks as a common public use decrease their popularity among the people.

Different mechanisms were influential in the penetration of the particles through the masks. Some environmental parameters are playing a significant role in the attributed mechanism and, in consequence, the filtration efficiency. Thus, the choice of the mask also depends on the environmental condition of the usage. Among all the affecting parameters, the particle size and flow rate have resulted as the most important ones.

The studies show that for the particle sizes above 0.5 μm, gravity, inertia, and interception are the dominant mechanisms, but for the particles lower than the 0.2 μm diffusion mechanism becomes dominant. Besides, the electrostatic mechanism is less affected by the particle size, where it shows efficiency up to about 300 nm but is more affected by the flow rate. In the low flow rate, the electrostatic and diffusion mechanisms are dominant, but by increasing the flow rate, interception becomes effective. However, the other parameters are less effective, but by increasing the humidity, temperature, frequency, changing the flow rate to the cyclic flow, the filtration efficiency decreases, whereas by increasing the loading time, it increases.

Moreover, the property referred to as the quality fabrication of the masks is important. Where increasing the thickness and numbers of the layers, packing density, fiber charge density, and decreasing fiber diameter, increase the filtering efficiency.

Over to the mechanisms and external factors and filter characteristics affecting the filtration efficiency, there is another concerning issue, which is about the sealing. This is due to the different contours of the face of each person or dislodges of the masks, especially for the respiratory masks during the sleeping of the wearer. It results in leakage, which highly decreases the efficiency of the masks.

Considering the advantages, disadvantages, and capabilities of the different kinds of masks, it seems that there is much to do in this field in order to propose a special kind of mask for a certain issue, whereby increasing the filtration efficiency, comfortability and accessibility decreases among the people. Nevertheless, it is comprehensible that referring to the different types of climate conditions, diverse

physiological state of humans and etc., one type of mask may not be universal for a certain issue.

For future work, innovative technologies related to 3D printing can be used to prepare masks in quarantine conditions and mask shortages. In addition, more use of nanofibers can improve the performance of masks in different conditions. Moreover, utilizing more numerical simulation to check the performance of the mask can reduce the associated costs.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

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