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Meltblown fabric *vs* nanofiber membrane, which is better for fabricating personal protective equipments

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ABSTRACT

The coronavirus disease 2019 (COVID-19) pandemic has led to a great demand on the personal protection products such as reusable masks. As a key raw material for masks, meltblown fabrics play an important role in rejection of aerosols. However, the electrostatic dominated aerosol rejection mechanism of meltblown fabrics prevents the mask from maintaining the desired protective effect after the static charge degradation. Herein, novel reusable masks with high aerosols rejection efficiency were fabricated by the introduction of spider-web bionic nanofiber membrane (nano cobweb-biomimetic membrane). The reuse stability of meltblown and nanofiber membrane mask was separately evaluated by infiltrating water, 75% alcohol solution, and exposing under ultraviolet (UV) light. After the water immersion test, the filtration efficiency of meltblown mask was decreased to about 79%, while the nanofiber membrane was maintained at 99%. The same phenomenon could be observed after the 75% alcohol treatment, a high filtration efficiency of 99% was maintained in nanofiber membrane, but obvious negative effect was observed in meltblown mask, which decreased to about 50%. In addition, after long-term expose under UV light, no filtration efficiency decrease was observed in nanofiber membrane, which provide a suitable way to disinfect the potential carried virus. This work successfully achieved the daily disinfection and reuse of masks, which effectively alleviate the shortage of masks during this special period.

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic [1–4] was first detected and reported in Dec. 2019, which has spread in more than 200 countries around the world, and has caused more than 23.5 million cases diagnosed (24,Aug., 2020). It has been confirmed that the droplets/aerosol released by breathes, coughs, or sneezes of the patients carry a large amount of viruses, which are highly infectious [5,6]. At the same time, the diameter of droplets/aerosol ranged from several hundred nanometers to millimeter [7,8], the droplets smaller than 5 micro can easily float and spread beyond 30 meters [9,10]. The transmission distance of the viruses carried by the droplets and aerosols are shown in Fig. 1, which demonstrate the high infectivity of COVID-19 viruses. As the most important personal protective equipment used by medical staff and general public, masks play a vital role in epidemic prevention [11–13], which can effectively intercept the micro-droplets or aerosols released by the virus carriers and protect people from being infection.

The filter materials of the masks mainly include cotton gauze, polypropylene, *etc.* [14]. In speak of cotton gauze masks, due to the large fiber diameter, the number of gauze layers was increased to improve the filtration efficiency, resulting in a higher breath resistance and poor thermal and wet comfort performance [15]. Therefore, meltblown fibers with static charge was invented and employed to reconcile the aerosol interception efficiency and air permeability [16–18]. Compared with cotton gauze masks, meltblown fibers masks exhibit higher aerosol interception efficiency with lower breath resistance due to the electrostatic adsorption effect in aerosol filtration process [19–22]. However, the filtration performance of the meltblown fabrics may rapidly decline after the

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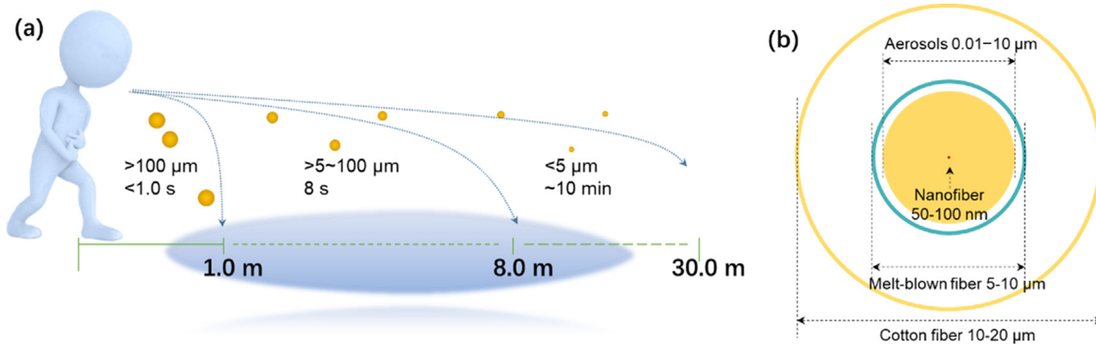

Fig. 1. (a) Schematic of the transmission distance of the aerosols released by human coughing and sneezing behavior. (b) Schematic of the diameter of aerosols, and the cotton fiber, meltblown fiber, and nanofiber that are used to fabricate masks.

degradation of electrostatic. Therefore, nanofiber membrane masks were proposed and developed to fabricate the masks. The nanofiber membrane with its fiber diameter tens to hundreds of nanometers is suitable for fine aerosols interception [23,24]. The higher specific surface area of nanofiber compared to microfiber provides more contact opportunity to aerosols and fiber [25–28]. In addition, the diameter of nanofiber can be controlled comparable with the mean free path of the air molecules (66 nm under normal conditions), which means the non-zero of gas velocity on the nanofiber surface due to the "slip" occurs. The "slip effect" can significantly reduce the drag force of gas flow and resulting in a lower filtration resistance. Therefore, nanofiber membrane can break the trade-off effect between filtration efficiency and gas permeability [29].

In this work, the protective performance of the masks prepared by the meltblown fabrics and nanofiber membrane (nano cobweb-biomimetic membrane) was evaluated in detail. The reusability of the two kind masks were investigated by testing the filtration performance before and after disinfection of 75% alcohol and UV irradiation. The three-day and seven-day long-term filtration performance were also performed to verify the reusability of

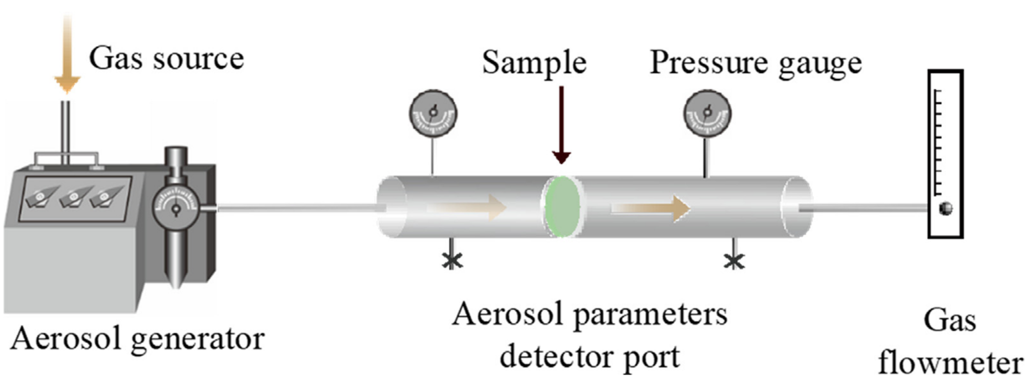

Fig. 2. Oil and NaCl aerosol filtration performance test rig.

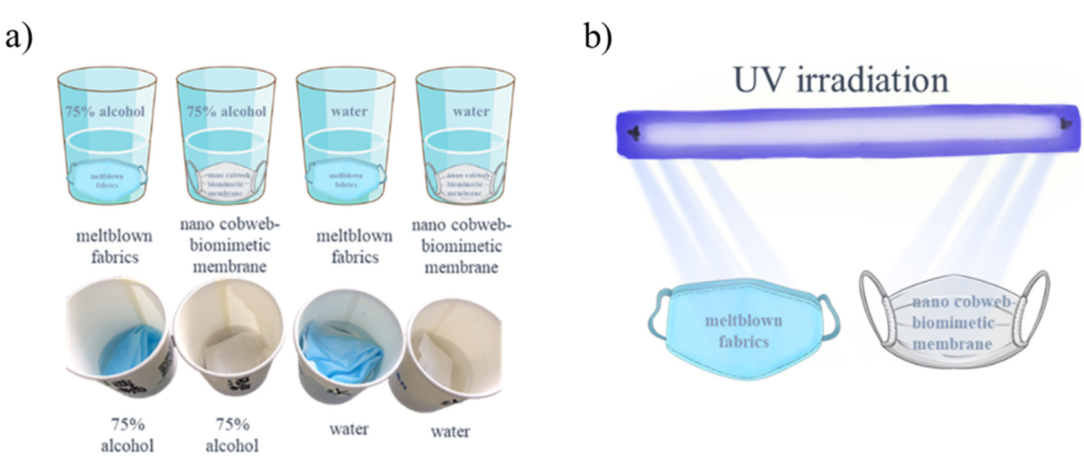

Fig. 3. (a) Experimental strategies of water dipping, 75% alcohol disinfection, and (b) UV-irradiate disinfection for meltblown fabrics and nanofiber membrane masks.

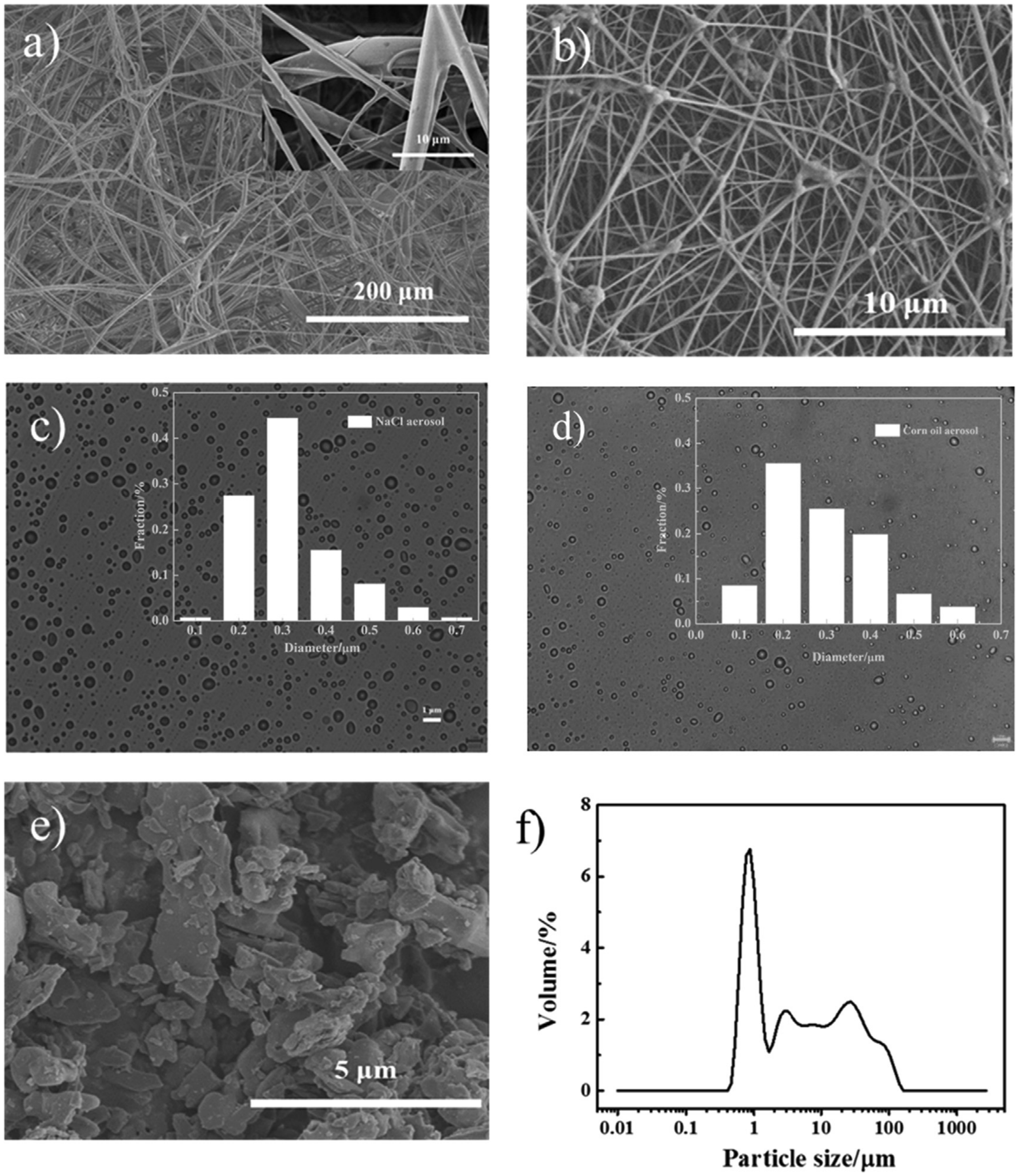

Fig. 4. SEM images of meltblown fabrics (a), nanofiber membrane (b), optical microscope images of NaCl aerosol and corn oil aerosol, inset are the diameter distribution (c and d), SEM image of the coal ash (e); coal ash diameter distribution (f).

masks. The filtration and interception mechanisms for aerosols of the masks were proposed. This paper will provide general public with an overall understanding of the filtration materials, and help them choose appropriate mask and disinfecting masks with correct strategies.

2. Experimental

2.1. Materials and reagents

The meltblown fiber fabricated masks were purchased from Guangzhou Sunrise Nursing products Co., Ltd., which are in line with GB2626-2006 standard. Thenano cobweb-biomimetic membrane (Porous PTFE membrane prepared *via* biaxial stretching) masks with its protective level of KN95were obtained from Jiangsu Jiulanghigh-tech Co. ltd. 75% alcohol was purchased from Sinopharm Chemical Reagent Co. Ltd., China. Coal ash was obtained from the Zhejiang Satellite Petrochemical Co. Ltd.

2.2. Filtration performance evaluation

The filtration efficiency of the masks was determined by the comprehensive aerosols with its diameter ranged 0.01–10 μm was generated *via* the Huada setup, the test area of the sample is 100 cm^2 while the gas flow rate is 85 $L\cdot min^{-1}$. The penetrated NaCl aerosol particles were counted and displayed with the form of filtration efficiency on the setup screen. A home-made test rig (the schematic as shown in Fig. 2) was employed to evaluate the corn oil and NaCl aerosol filtration performance. Samples with their effective area of 12.56 cm^2 were clamped in the tube module to conduct the experiment, the aerosol flow was controlled at 2 $L\cdot min^{-1}$, while particle sizer parameters (SMPS-3938, TSI, USA)

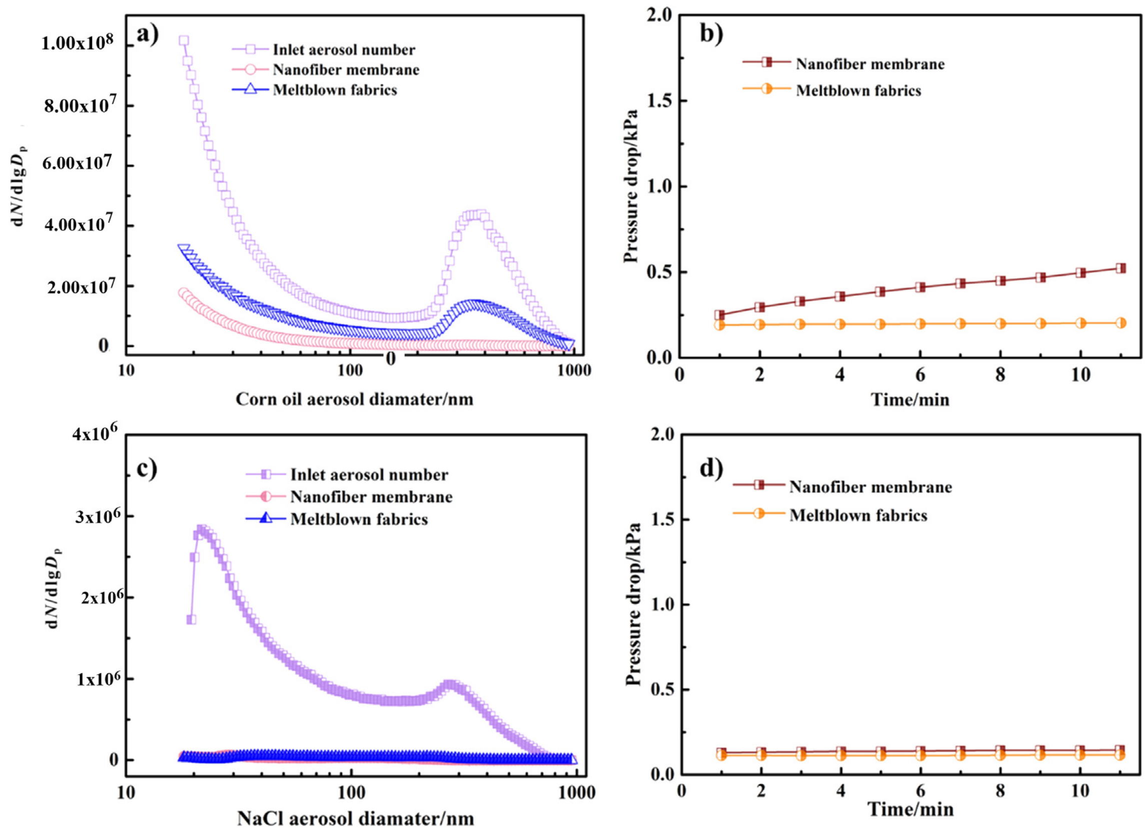

Fig. 5. Corn oil and NaCl aerosols filtration performance, the counts of the corn oil (a) and NaCl aerosols with different diameter before and after filtration (c); the pressure drop of nanofiber membrane and meltblown fabrics in corn oil aerosol (b) and NaCl aerosol filtration system (d), respectively.

were used to evaluate the filtration efficiency of the samples. The integral area of the particles before and after filtration were calculated to evaluate the particles interception rate(R):

$$R = \left(1 - \frac{\sum_{10}^{1000} \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 \rho N_{\text{outlet}}}{\sum_{10}^{1000} \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 \rho N_{\text{inlet}}}\right) \times 100\%$$

where ρ, D, and N are the density, diameter, and number of the aerosol.

2.3. Disinfection treatment

As shown in Fig. 3a, the meltblown fabrics and nano cobweb-biomimetic membrane were disinfected with tap water and 75% alcohol for 10 min, respectively. The naturally dried materials were then conducted to the Huada setup to test the filtration performance of the masks. The reusability of the masks was measured by repeating the above operation for another two times.

The UV irradiation disinfection experiment was performed under UV light with a wavelength of 254 nm, and a power of 8 W. The masks were exposed under UV light for 10 min and then tested for filtration performance. Same as forementioned, three times of irradiation treatment were performed to evaluate the reusability of the masks.

2.4. Life-span and reusability

The masks fabricated by meltblown fabrics and nano cobweb-biomimetic membrane were conducted in the filtration setup for 2 h every 24 h to investigate their service life. The filtration performance was recorded at 72 h (3 days), and 168 h (7 days), respectively.

2.5. Characterizations

Microstructure of the meltblown fabrics, nano cobweb-biomimetic membrane and the coal as hwere investigated by Scanning Electron Microscopy (SEM, Hitachi S-4800, Japan). The coal ash particle size distribution was measured by the Laser particle sizer (Mastersizer, 3000, UK). The NaCl aerosols generated by the Huada setup was collected by the glass slide and the particle size distribution of NaCl aerosol was observed by the metallurgical microscope (CX40M, Sunny optical technology Co., Ltd.). The static electricity on the surface of the melt blown cloth is detected by the Electrostatic tester(EST101, Jiangxi Zhongdian high-tech electrostatic control Co., Ltd).

3. Results and Discussion

3.1. Microstructure of meltblown fabrics, nanofiber membrane, NaCl aerosols and coal ash

To make an intuitive sense of the difference between meltblown fabrics, nanofiber membrane and the aerosols, the microstructure of the corresponding samples were obtained as shown in Fig. 4. The meltblown fabrics with diameter around 5–10 μm are stacked one by one (Fig. 4(a)), while the nanofiber membrane existence much fine fibers (50–100 nm) with node-fiber connected structure (Fig. 4(b)). The interwoven pores of meltblown fabrics are much larger than that of nanofiber membrane. Generally, the smaller the pore size of the membrane means that more dust can be trapped through the sieving effect. The optical microscope image of NaCl aerosol was shown in Fig. 4(c), indicating that the aerosols were even dispersed on the glass slides. Based on Fig. 4(c), the diameter dispersion of aerosols

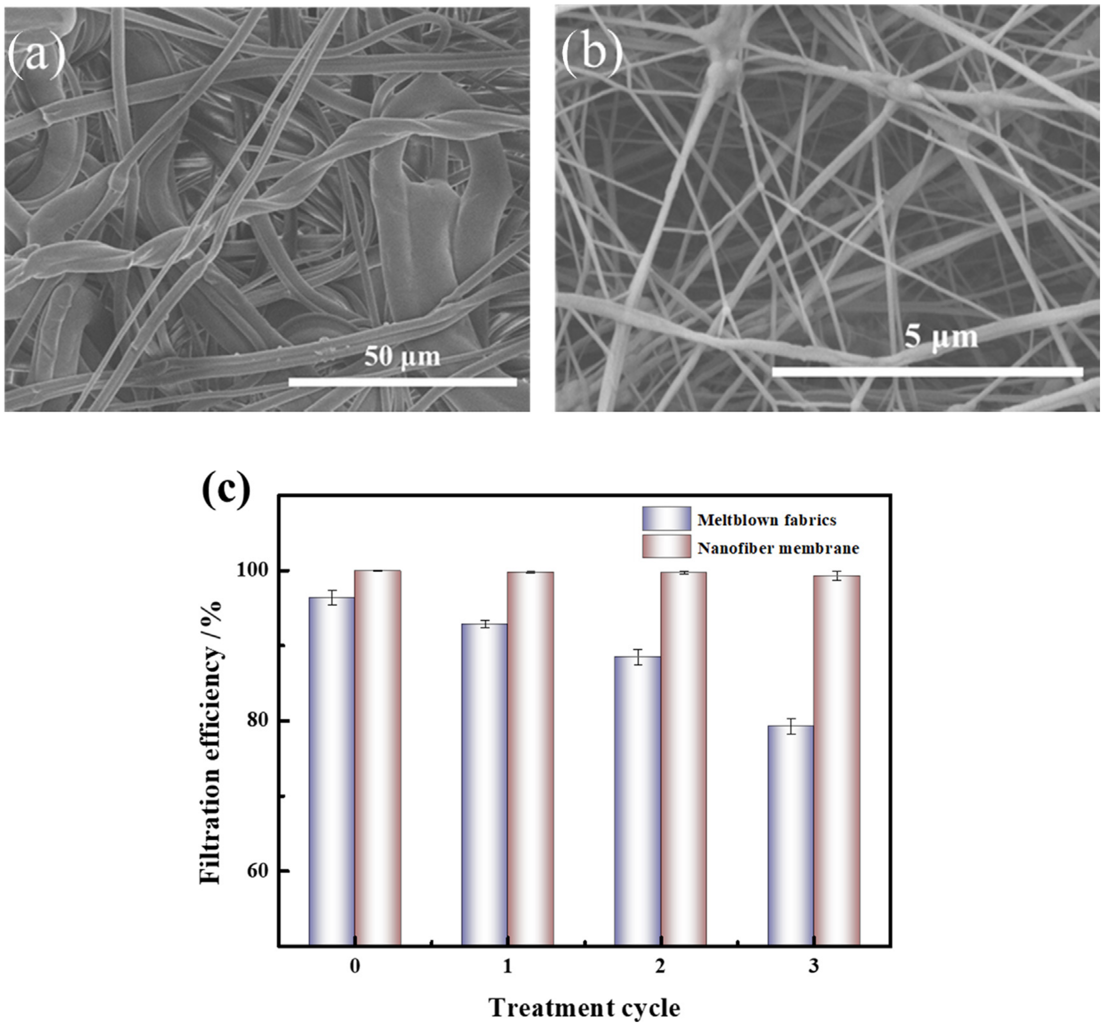

Fig. 6. SEM images of meltblown fabrics (a) and nanofiber membrane after water disinfected (b); NaCl aerosol filtration efficiency of meltblown fabrics and nanofiber membrane masks before and after water dipping (c).

was measured by an image processing software (Nano Measurer). The smallest particle of NaCl aerosol is about 100 nm, while the largest one is about 1 µm, which are comparable to the size of droplets and aerosols released by human. The coal ash was employed to verify if the masks still have static electricity. As seen from Fig. 4 (e and f), the coal ash shows irregular shape with the size ranged from 1 to 100 µm.

3.2. Corn oil and NaCl aerosol filtration performance

The corn oil and NaCl aerosols filtration performance of nanofiber membrane and meltblown fabrics were evaluated. As shown in Fig. 5(a), the diameter of corn oil aerosols was mainly distributed at 0–100 nm and around 400 nm. For meltblown fabrics, the counts of outlet aerosols was obviously higher than that of nanofiber membrane, especially for the most probable distribution of the corn oil aerosols. The calculated interception of nanofiber membrane and meltblown fabrics were 99.4% and 62.5%, respectively. The pressure drop of meltblown fabrics can maintain well in 10 min, while that for nanofiber membrane has a slight increase. Since large counts of corn oil aerosols were intercepted on the surface of the nanofiber membrane, partly of them may block the pores and resulting an increase of pressure drop, while corn oil aerosols penetrated through the meltblown fabrics has few effects on increasing the pressure drop. The NaCl aerosol filtration performance demonstrated that both meltblown fabrics and nanofiber membrane can well intercept the aerosols at comparative low pressure drop. It has proved elsewhere that the net charge of NaCl aerosol (+70.5 to +72.6 fA) is much higher than that of corn oil aerosol (+0.02 to +1.13 fA) [30]. Therefore, ignoring the interface effect between aerosols and filter media, meltblown fabrics is more suitable for charged aerosol interception.

3.3. Disinfection methods

3.3.1. Dipped with water

Masks with core materials of meltblown fabrics and nanofiber membrane were dipped in deionized water for 10 min and then evaluated their NaCl aerosol filtration performance. From Fig. 6 (a), there was no obvious morphology changes could be observed in both meltblown fabrics and nanofiber membrane, since NaCl aerosols with much smaller diameter can be easily vapored and escaped from the fabrics and fibers before they were conducted in SEM characterization. The results reveal that the NaCl aerosols filtration efficiency of meltblown fabrics mask was around 95%, while nanofiber membrane-based mask exhibit higher interception efficiency about 99%. After dipping in water for 10 min, the filtration efficiency of the meltblown fabrics was slightly decreased. Continuous dipping the meltblown fabrics mask in the water for two more times have obvious negative effect on the filtration efficiency (~79%). As shown in Table 1, it can be seen intuitively that the static electricity on the surface of the meltblown fabrics decreases after water disinfection. That is because water can accelerate the degradation of the electrostatic of the meltblown fabrics. While the nanofiber membrane still maintains an ideal aerosol filtration efficiency of ~99%. It should be noted that the electrostatic value of nanofiber membrane-based mask was zero.

3.3.2. 75% alcohol treatment

It has been confirmed that dipping the masks in DI water has barely effect on virus inactivation, while 75% alcohol can denature the virus [31]. Similar to the water dipping results, the microstructure of the meltblown fabrics and nanofiber membrane still has no significant change (Fig. 7 (a, b)), demonstrating both materials have good alcohol tolerance. Fig. 7(c) reveals that the aerosol filtration efficiency of meltblown fabrics was sharply declined from 95% to ~59% after the first alcohol treatment cycle. Subsequently, the further alcohol treatment has few effects on the filtration efficiency of meltblown fabrics (~59% to ~48%). The results (Table 2) reveals the meltblown fabrics has an obvious decline of electrostatic value after dipped in 75% alcohol solution, since the low surface free energy alcohol can easily infiltrate in the fabrics and leading to a rapid degradation of the electrostatic. While for the nanofiber membrane, the filtration efficiency was maintained at 99% after three alcohol treatment cycles, which means the alcohol treatment has few effects on influencing the membrane filtration performance.

Table 1
Surface electrostatic value after dipping meltblown fabrics in water

Disinfection times	0	1	2	3
Electrostatic value/kV	4.3	3.7	2.4	1.7

Table 2
Surface electrostatic value after dipping meltblown fabrics in 75% alcohol

Disinfection times	0	1	2	3
Electrostatic value/kV	4.3	0.6	0.2	0

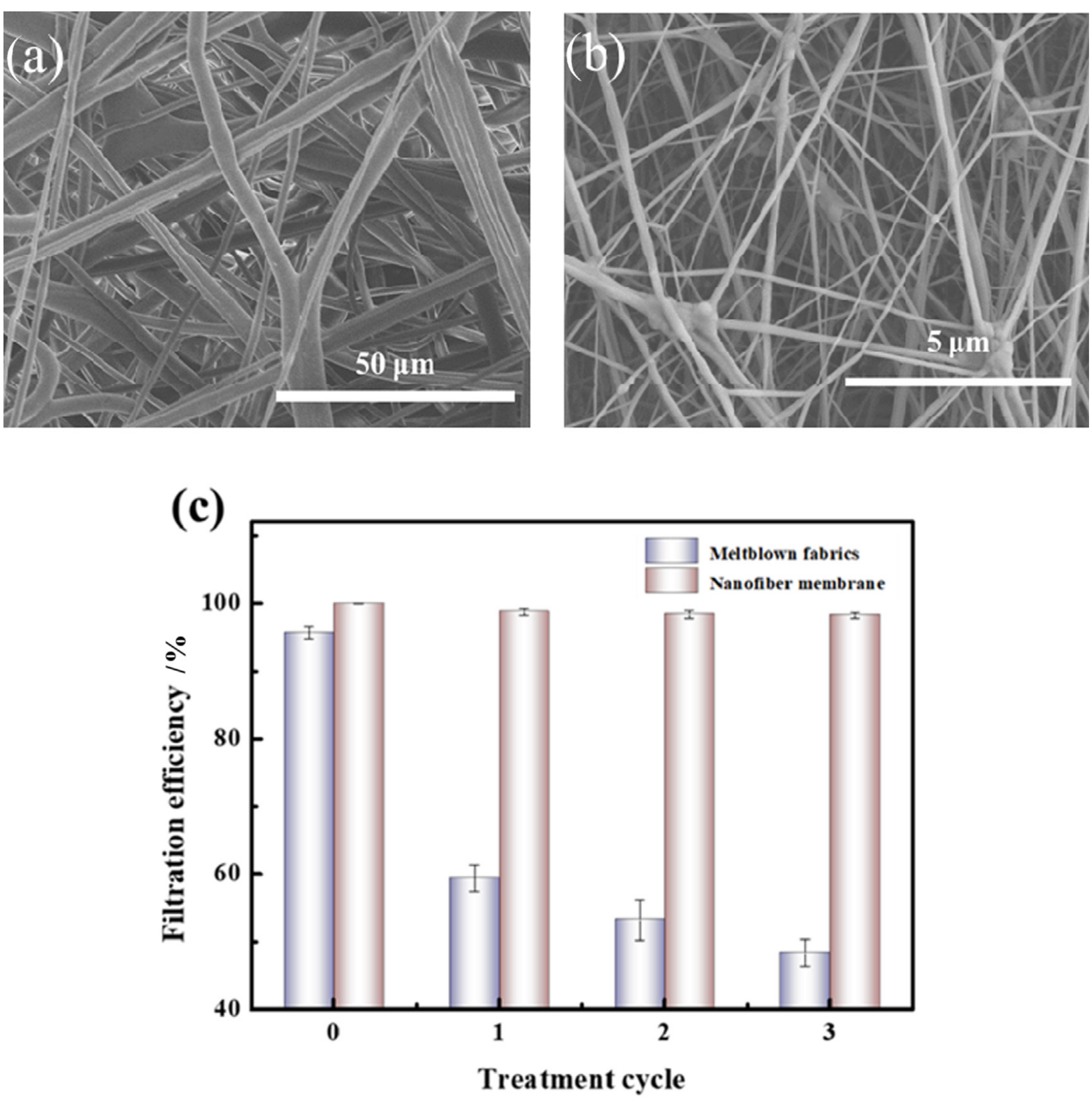

Fig. 7. (a) SEM images of meltblown fabrics (a), nanofiber membrane after 75% alcohol treatment (b), NaCl aerosol filtration efficiency of meltblown fabrics and nanofiber membrane masks before and after 75% alcohol treatment (c).

To further demonstrate the effect of alcohol on dismissing the static charge of the fabrics, a simple verification experiment was performed. Excessive amount of dried coal ash was scattered on the glass slide, the meltblown fabrics mask was put on the surface of coal ash and then reversed to capture the surface condition of the mask. As shown in Fig. 8, original meltblown fabrics masks

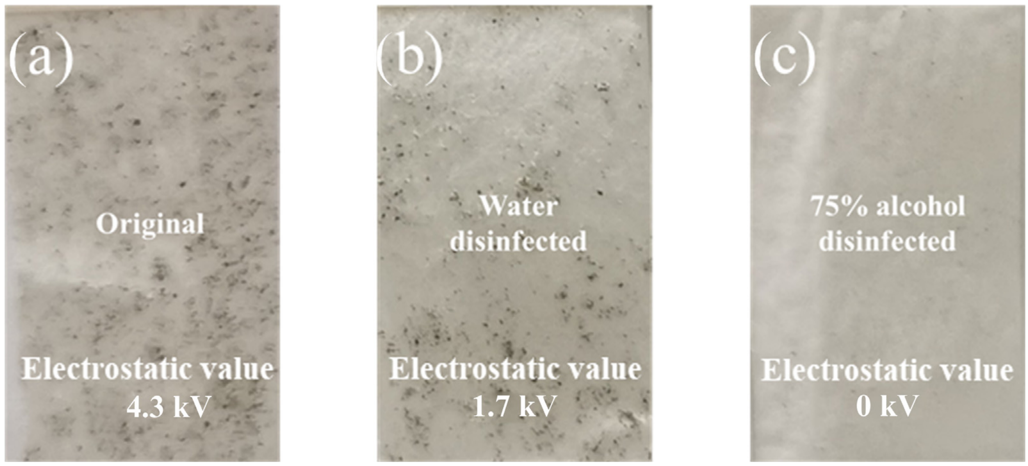

Fig. 8. Cling-test of meltblown fabrics mask after water and 75% alcohol treatment. (a) Original mask, (b) after water dipping, (c) after 75% alcohol dipping.

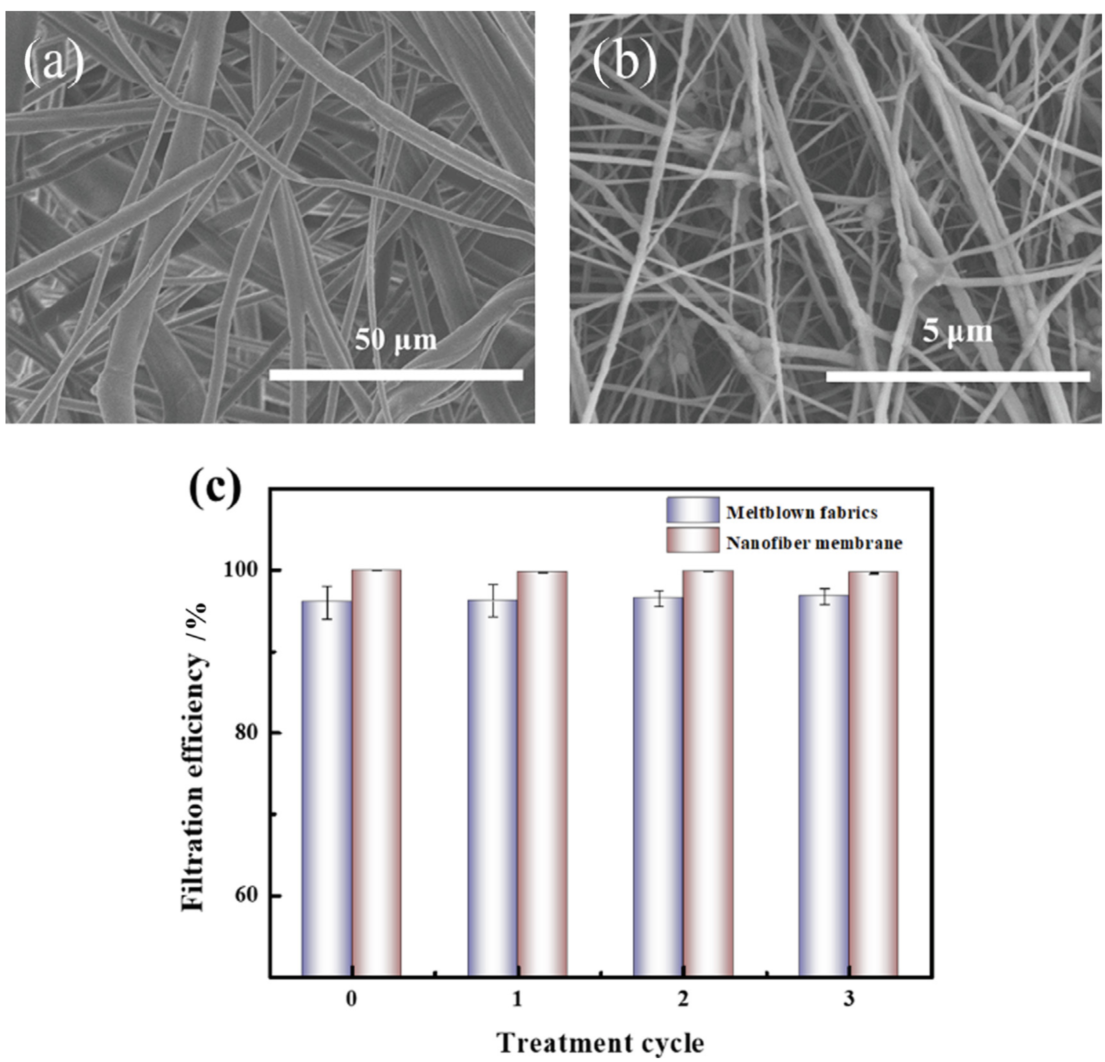

Fig. 9. SEM images of meltblown fabrics (a) and nanofiber membrane after exposure under UV irradiation (b), NaCl aerosol filtration efficiency of meltblown fabrics and nanofiber membrane masks before and after UV irradiation treatment (c).

seem adsorbed more coal ash than that after water dipping treatment. At the same time, it can be clearly seen that there is almost no coal ash on the surface of the mask that treated by 75% alcohol. This phenomenon verified that the alcohol treatment lead to the static charge degradation in meltblown fabrics mask.

3.3.3. UV irradiation treatment

Ultraviolet irradiation is the most common and user-friendly method to sterilize bacteria and virus in daily life. However, the introducing of UV irradiation may cause the degradation of polymer molecules, and then decrease the filtration performance. Therefore, the masks were exposed under UV light to investigate the influence of UV irradiation on the filtration efficiency. The SEM images in Fig. 9(a, b) show that the fabrics and fibers of both materials are well maintained without any break or microstructure changes. The filtration efficiency results (Fig. 9(c)) show both the masks possess a comparable stable filtration efficiency after UV irradiation for 3 cycles. The electrostatic value of meltblown fabrics after treated with UV can maintained well, which means UV irradiation has no effect on decrease the charge of the meltblown fabrics.

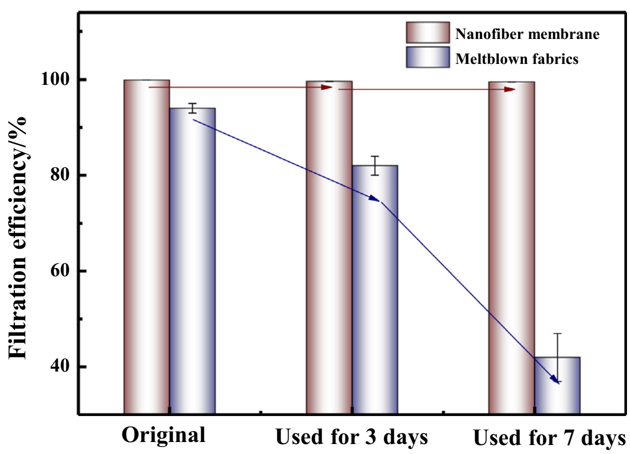

Fig. 10. Filtration efficiency of meltblown fabrics and nanofiber membrane masks before and after periodic filtration for 3 days and 7 days.

Compared with water or 75% alcohol treatment, ultraviolet irradiation may be more suitable for masks disinfection.

3.4. Life-span and reusability

Although the UV irradiation treatment was proved has little effect on degrading the static charge of the meltblown fabrics masks, the reusability of the masks is still unclear for general public. Herein, masks fabricated by meltblown fabrics and nanofiber membrane were conducted to the periodic test. As shown in Fig. 10, after 3 days of filtration test, the filtration efficiency of the meltblown fabrics was quickly decreased by about 12%, while nanofiber membrane still retained a high filtration efficiency of 99%. When reused for another 4 days, the filtration efficiency of meltblown fabrics drops sharply (55%) while the filtration efficiency of nanofiber membrane masks remains stable at 99%. Obviously, nanofiber membrane fabricated masks have better stability, longer service life and protection performance than that fabricated by meltblown fabrics.

3.5. Filtration mechanism of meltblown fabrics and nanofiber membrane

Dust filtration mechanisms of fabrics and nanofibers have been reported before [32]. According to the present research results and difference between microscale fabrics and nanoscale fibers, the mechanisms for aerosol capture was described in Fig. 11. Meltblown fabrics usually constructed pores on the micrometer scales, therefore the sieving effect of meltblown fabrics only works for particles that larger than the fabrics constructed pores. Partly of aerosols may intercept by the inertial collision, while the bulk of aerosols are captured by electrostatic effect of the meltblown fabrics. For nanofiber membrane, it has great amounts of fine fibers to pile up nano-porous structure. Compared with microscale fabrics, the higher specific surface of nanofiber provides more contact opportunity for the aerosols, therefore the diffusion effect of the aerosols may significantly increase the possibility of fine particles interception. In addition, the nanofiber diameter can be controlled comparable with the mean free path of air molecules (66 nm under normal conditions), which means that the gas velocity on nanofiber surface is non-zero due to the “slip”. The “slip effect”

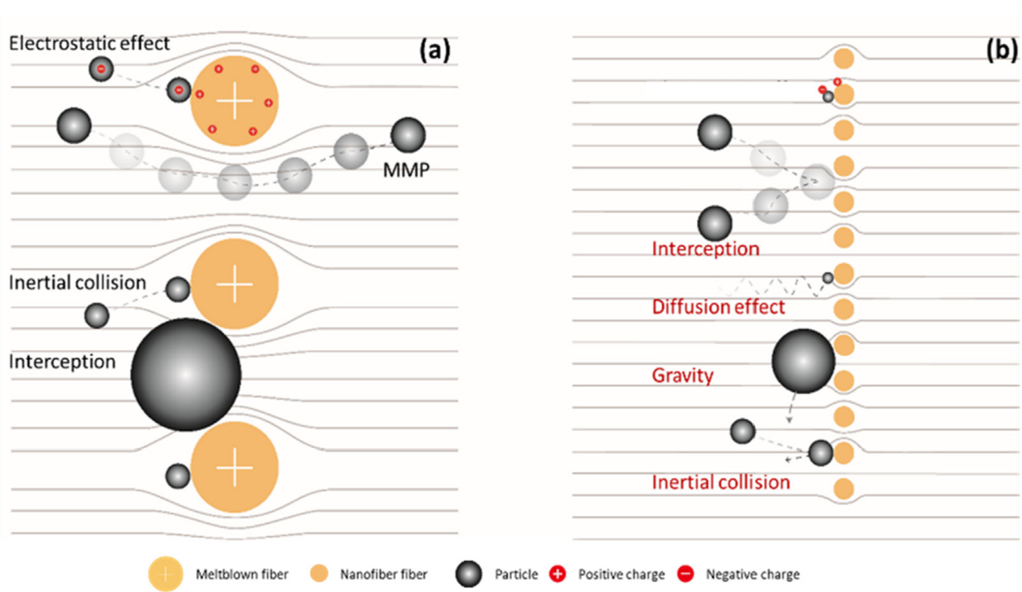

Fig. 11. Filtration mechanism of meltblown fabrics (a) and nanofiber membrane (b).

significantly reduce the drag force of gas flow and resulting in a lower filtration resistance. Furthermore, the weak electrostatic of the nanofiber is beneficial for blown off the large particles under the gravity effect, therefore resulting a comparative clear surface of the nanofiber membrane masks.

4. Conclusions

The outbreak of COVID-19 led to the great demand of personal protective products like medical masks. Herein, a novel reusable mask was fabricated by nanofiber membrane to alleviate the mask shortages. After that, a systematic experiment was designed to evaluate the efficiency and reusability of masks, in which the effects of common-used disinfection strategies were compared, and the protective mechanisms of different masks were explained. Generally, masks fabricated by meltblown fabrics and nanofiber membrane can intercepted more than 95% of NaCl aerosols at the initial stage. Liquid disinfection *via* water or 75% alcohol rapidly dismiss the static charge of the meltblown fabrics masks, while nanofiber membrane masks maintained well. After UV irradiation treatment, the static charge of meltblown fabrics will not dismiss and masks shows better reuse protective performance than that of water or 75% alcohol treated masks. The long-termperiodic filtration experiment shows the static charge of the meltblown fabrics may dismiss with the prolongation of the test. Nanofiber membrane masks shows better protective performance after long-term filtration experiment. Therefore, masks fabricated by nanofiber membrane are independent of the static charge, which means it has better repeatability and disinfection tolerance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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