Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Micro/nanofibrous nonwovens with high filtration performance and radiative heat dissipation property for personal protective face mask

Yuanqiang Xu a, Xiaomin Zhang a, Xibo Hao b, Defang Teng a, Tienan Zhao a, Yongchun Zeng a,*, a College of Textiles, Donghua University, Shanghai 201620, China, b School of Textile Garment and Design, Changshu Institute of Technology, Changshu 215500, China

ARTICLE INFO
Keywords: Electrospinning Meltblowning Face mask Radiative heat dissipation Air filtration

ABSTRACT
The COVID-19 pandemic and airborne particulate matter (PM) pollution have posed a great threat to human health. Personal protective face masks have become an indispensable protective equipment in our daily lives. However, wearing conventional face masks for a long time cause swelter and discomfort on the face. Introducing thermal comfort into personal protective face masks becomes desirable. Herein, face masks that show excellent filtration performance and radiative heat dissipation effect are successfully designed and prepared by electrospinning Nylon-6 (PA) nanofibers onto polyethylene (PE) meltblown nonwovens. The resultant PE/PA nonwovens have high PM filtration efficiency (>99%) with a low pressure drop (<100 Pa). Moreover, taking the advantage of the property of PE, the designed face mask posses high mid-infrared (mid-IR) transmittance and brings about high radiative cooling power, resulting in effective heat dissipation performance. This face mask design may provides new insights into the development of thermal comfort materials for personal protection.

1. Introduction

Particulate matter (PM), especially PM2.5 (aerodynamic equivalent diameter ≤2.5 μm), which is one of the main sources of air pollution, has raised serious concerns in the past years [1–3]. PM2.5 has a great impact on human health, because toxic substances such as viruses, metals, and particles with various chemicals adsorbed onto PM surfaces tend to inhaled into the lungs [4,5]. Since last year, the outbreak of Coronavirus Disease 2019 (COVID-19) in the world causes a significant human toll [6]. A report from the World Health Organization indicated that COVID-19 has caused over 75.7 million confirmed cases and over 1.69 million deaths by 21 December 2020 [7]. It is known that viruses may spread via small aerosols (generally defined as <5 μm) or larger droplets upon coughing, sneezing, breathing [8,9]. PM2.5 and COVID-19 trigger the development of personal protective face masks, because face masks that are made up of micro/nanofibrous nonwovens filter airborne droplets and particles and prevent the humans from inhaling too much hazardous matters.

Micro/nanofibrous nonwovens for face masks are usually made up of spun-bond fibers, melt-blow fibers, and electrospun fibers. Taking the advantages of small fiber diameter, large surface area-to-volume ratios, high porosity, good internal connectivity, these nonwovens have high filtration efficiency [10–12]. It is known to all that air resistance is the most critical parameter for high-performance filters. It is a serious issue that high air resistance results in low air permeability and wearing face masks for a long time brings about breathing difficulties [13]. Compare these three types of nonwovens, spun-bonded nonwovens cannot be used alone as high efficiency air filters due to their larger fiber diameters and pore sizes [14,15]. Electrospinning is the most convenient method to fabricate nanofiber membranes, which has the highest filtration efficiency among the micro/nanofibrous nonwovens [16,17]. Besides the known poor mechanical properties of electrospun fibers due to the nanoscale diameters, extremely high air resistance forms in thick electrospun fiber membranes [18]. Therefore, electrospun fiber membrane has not been used alone as face masks yet [19]. Currently, electret meltblown nonwovens, with microscale fiber diameters and charged fibers, become core part of personal protective face masks. However, the hidden danger of the charge dissipation of the electret meltblown nonwovens leads to a sharp decline in filtration efficiency of the face masks [20,21]. For example, Zhang and coworkers [22] found that the filtration efficiency decrease ~21% during the storage for 200 days when they investigated the stability of the filtration efficiency of electret meltblown polylactic acid (PLA) fabrics under room storage. It is challenging to produce high-filtration-performance meltblown nonwovens.

* Corresponding author.
E-mail address: yongchun@dhu.edu.cn (Y. Zeng).

https://doi.org/10.1016/j.cej.2021.130175
Received 31 December 2020; Received in revised form 25 April 2021; Accepted 29 April 2021
Available online 5 May 2021
1385-8947/© 2021 Elsevier B.V. All rights reserved.
without electret. Moreover, thermal comfort is also crucial for personal protective face masks, because in many cases people need to wear face masks for a long time. Especially in the present COVID-19 pandemic, it is extremely important for people keep wearing face masks [23]. The thermal properties have not been considered in conventional face masks and are mainly determined by the thickness of the nonwovens. When wearing conventional face masks which have poor heat dissipation performance, the moist warm conditions in face not only cause discomfort for the users, but also generate hazardous micro-organisms [13]. Therefore, it is desirable that the thermal comfort is introduced into personal protective face masks. Cui and coworkers [13] designed a type of composite masks, because in many cases people need to wear face masks for a long time that PE is transparent to the mid-infrared (IR) radiation the human body emitting, their fiber/nanoPE face masks shows excellent special property. Taking the advantage of the PE nonwovens. Specifically, the PE meltblown nonwovens were prepared by dissolving PA-6 powder with a concentration of 18 wt% in formic acid. The engineering illustration of the meltblowing and electrosprinning systems is shown in Figure S2 (Supporting Information).

Different thicknesses of the meltblown PE nonwovens (800, 1126, 1351 and 1570 μm) and the electrosprun PA membrane (3, 4.5, 6 and 8 μm) were prepared and combined to prepare different samples for the filtration and heat dissipation experiments. Filtration performance measurement. An automatic filter tester (TSI 8130) was used to study the filtration efficiency and pressure drop of the samples. Monodisperse charge-neutralized NaCl aerosol particles with a mass median diameter of 0.26 μm and a geometric standard deviation of <1.86, were generated from 2 wt% NaCl aqueous solution and then fed into the filter holder. The flow with air and particles passed through the sample with an effective testing area of 100 cm² at a velocity of 5.3 cm/s (volumetric flow rate: 32 L/min). Filtration efficiency was acquired by the following formula:

\[ \eta = (\epsilon_1 - \epsilon_2)/\epsilon_1 \times 100\% \]  

(1)

where \( \epsilon_1 \) and \( \epsilon_2 \) are the quantities of the NaCl aerosol particles at the upstream and downstream of the samples, respectively. The pressure drop across the upstream and downstream sides of the filter was measured by two electronic pressure transmitters.

Thermal properties evaluation. In this work, we evaluated the heat dissipation effect of the PE/PA two-level structured nonwovens with a device (Figure S3, Supporting Information) that simulated the heat output of human skin. The device contained two silicone-rubber-insulated flexible heaters (10 cm × 10 cm) and a thermal insulating polystyrene foam enclosed in an insulating box. One heater, which was connected to a DC power supply (UTP3305, Uni-Trend Technology (China) Co., Ltd.) acted as simulated human skin, whose top surface temperature was measured by a K-type thermocouple (the precision and resolution: ±0.2%±0.6) and 0.1°C). The other heater was placed below the simulated skin to act as a guard heater. A thermocouple is contacted with the bottom surface of the guard heater to measure its temperature, which was kept the same as the simulated skin heater. The thermal insulating foam was placed at the bottom of the guard heater to ensure the upward heat flux of the simulated skin. During measurements, the temperature of simulated skin heater was set as 34 °C by adjusting the voltage of the DC power supply. The tested sample (5 cm × 5 cm) covered on the simulated skin, blocking the heat transfer from the simulated skin heater to the ambient, results in the increase of the skin temperature. After 20 min, the temperature of the simulated skin was record as the temperature data. Each sample is tested three times to find the average value. Infrared thermal images are taken by a thermal infrared camera (Fotric 226).

Characterization. The fiber morphology was characterized by a field emission scanning electron microscope (FE-SEM, Hitachi SU8010, Japan) at a voltage of 5 kV after the sample was coated with gold using an ion sputtering apparatus (MC 1000, Hitachi, Ltd., Japan). The fiber diameters were measured by Image-Pro Plus 6.0 software from SEM images, and the average diameters were calculated from 100 fibers. The pore size of the sample was measured by a capillary flow porometer (CFF-1100AI, Porous Materials Inc., America). The sample thickness was obtained by a thickness gauge (Aice instrument Co., Ltd., Taizhou, China) from the average of the 12 tests. The porosity was calculated according to the following formula [24]:

\[ \eta = (\epsilon_1 - \epsilon_2)/\epsilon_1 \times 100\% \]  

(1)
Porosity \(= \frac{m_1/\rho_1}{m_1/\rho_1 + m_2/\rho_2}\) (2)

where \(m_1\) and \(m_2\) represent the quality of the isopropanol and the sample, respectively. And \(\rho_1\) and \(\rho_2\) are the densities of the isopropanol and raw materials, respectively.

The infrared transmittance was measured by a Fourier transform infrared (FTIR) spectrometer (Nexus 670, Thermo Nicolet Corporation, USA). The air permeability was tested by an automatic ventilation meter (YG461G, Ningbo Textile Instrument Factory) under the 200 Pa test pressure. The water vapor transmission rate was studied by a computerized fabric moisture permeability meter (YG601H, Ningbo Textile Instrument Factory, China) according to GB/T 12704.1–2009. The water contact angle (WTA) was measured by a contact angle measuring instrument (OCA15EC, DataPhysics Instruments GmbH, Germany).

The Tensile strength was measured by an electronic fabric strength tester (YG026MB, Wenzhou Fangyuan Instrument Co., Ltd., China), as the samples were cut into strips with 2 cm in width and 5 cm in length. The initial measurement distance was 3 cm. The tensile speed was kept at 30 mm/min.

3. Results and discussion

3.1. Design, preparation and morphology of the PE/PA nonwovens

We design PE/PA nonwovens for face mask with both excellent filtration performance and radiative cooling property using melt blowing and electrospinning, which are the two industrial technologies.
for producing ultrafine-fibrous nonwovens. To achieve excellent filtration performance, two-level pore sizes are introduced into the nonwovens. The larger-sized pores can intercept large particles, while the ultrafine airborne particles are expected to be filtered by the smaller-sized pores. Such gradient filtration avoids sharply increment of air resistance due to particle blocking, and helps keep a low air resistance under the high filtration efficiency. To obtain radiative cooling property, PE and PA, which have absorption peaks away from the wavelength of the mid-IR region emitted by human body [13,27], are used as raw materials without any additional modification to develop the nonwovens.

The fabrication process of the PE/PA nonwovens is schematically illustrated in Fig. 1a. Figure S2 shows the detailed pictures of the melt-blowing machine and the electrospinning system that used in the preparation processes. To obtain the two-level structured nonwovens, the PE microfiber nonwovens are prepared in the melt-blowing machine. And then the PA nanofiber membranes are electrospun on the PE nonwovens. It is expected that the designed nonwovens for face mask with the outer layer of PE meltblown nonwovens and the inner layer of PA electrospun membranes can meet excellent particulate matter (PM) removal efficiency and radiative heat dissipation performance, and the schematic demonstration of the mid-IR transmittance and PM filtration process is shown in Fig. 1b. Fig. 1c shows the cross-sectional image of the two-level structured PE/PA nonwovens. The nonwovens contain a thin layer of electrospun nanofibers and a layer of meltblown microfibers, which are bonded in the interfacial region. Fig. 1d shows the FE-SEM image of the electrospun PA fibers with an average diameter of 126 nm, and Fig. 1e shows that of the meltblown PE fibers with an average diameter of 34 μm. It can be clearly seen that both the PA nanofibers and PE microfibers have good morphologies with smooth surfaces and uniform diameters. More importantly, the PE/PA nonwovens possess two orders of pore sizes, a larger pore size (~143 μm) formed by the PE microfibers and a smaller one (~6 μm) formed by the PA nanofibers (Fig. 1f). The PE nonwovens with a thickness of 800 μm shows the pore size distribution in the range of 125–200 μm, whereas the pore size distribution of the PA nanofiber membranes with a thickness of 3 μm is 5–8 μm.

In general, a new design of two-level structured nonwovens is constructed. Figure S4 (Supporting Information) exhibits a piece of the as-prepared PE/PA nonwovens with a dimension of 200 mm × 200 mm. Taking advantage of the combination of meltblowing and electrospinning techniques, it is predicted that the preparation of PE/PA nonwovens can be scaled-up for producing commercial face masks.

3.2. Filtration performance evaluation and 3D simulation

The designed nonwovens for face masks with the outer layer of PE meltblown nonwovens and the inner layer of PA electrospun membranes are tested by the automatic filter tester to evaluate the filtration performance. PM capture is visualized by the SEM images after filtration experiments of the PE meltblown nonwovens and PA electrospun membranes, which are shown in Fig. 2a and 2b, respectively. Abundant particles with various sizes and morphologies are captured and trapped into the meltblown nonwovens (Fig. 2a). Due to the small fiber diameters and pore sizes, as well as the large dipole moments of the PA [28], the PA nanofiber membranes tend to adsorb and block extremely small particles, which are observed to be of the diameters below 0.5 μm (Fig. 2b). This demonstrates that the two-level structured nonwovens with different orders of pore size help accomplish the gradient filtration.

Due to the larger fiber diameters and large pore sizes (Fig. 1e,f), PE
meltblown nonwovens (without electrospun layer) exhibits low filtration efficiency and low pressure drop, which are tested to be 62% and 3.67 Pa. Fig. 2c shows the filtration efficiency and pressure drop of the samples with different thicknesses of PA nanofiber membranes (PA membrane thicknesses are 3 μm, 4.5 μm, 6 μm, and 8 μm, while the PE meltblown nonwoven thickness is kept at 800 μm). As has been expected, the addition of PA nanofibers significantly increases the filtration efficiency of the nonwovens. The combination of 800 μm-thickness meltblown nonwovens and 3 μm-thickness electrospun nanofibers exhibit much higher filtration efficiency of 92.68% and quite low pressure drop of 54.8 Pa. It is obvious that the filtration efficiency increases with the increase of the nanofiber membrane thickness, and the highest value reaches 99.99%. On the other hand, the increase of thickness leads to the increase of pressure drop. It is known that the pore size plays a key role in the filtration efficiency and pressure drop of nonwoven filters. The addition of nanofibers significantly decreases the pore sizes of the PE/PA nonwovens, and the pore sizes keep decreasing with the increase of the PA membrane thickness, resulting in higher filtration efficiency and higher pressure drop (Figure S5, Supporting Information). To evaluate the overall filtration performance of the PE/PA nonwovens, we compare the quality factors (QF) of different filter materials. The quality factor is a trade-off parameter that is applied to evaluate the overall filtration performance of filter materials. The QF takes both pressure drop and filtration efficiency into consideration, which is calculated by the following formula [29]:

\[ QF = -\ln(1 - \eta)/\Delta p \]  

(3)

where \( \eta \) is the filtration efficiency and \( \Delta p \) is the pressure drop of the sample. As shown in Fig. 2d, all samples display a robust QF value. Especially, the PE/PA nonwovens with 4.5 μm-thickness nanofiber membranes and 800 μm-thickness meltblown nonwovens meets the highest QF of 0.0486 Pa \(^{-1}\). We summarize the filtration performance of common filter materials and commercial filters in Table S1. To compare with the mainstream materials, the PE/PA nonwovens are quite competitive in terms of filter performance.

In order to study the features of air passing through the fiber assembly, the airflow field during filtration processes of the PE meltblown nonwovens and PA electrospun membranes are simulated. PE meltblown nonwovens with 800 μm thickness and two PA electrospun membranes with 3 μm and 6 μm thicknesses are chosen for comparison. The software of COMSOL Multiphysics 5.5 is employed to carry out the simulations. 3D models of the samples are based on the parameters of the prepared meltblown and electrospun samples, including fiber diameter, porosity and thickness. The computational domains and the boundary conditions of the three sample units are shown in Figure S6 (Supporting Information). The air velocity at the inlet is set as 5.33 cm/s (i.e. 32 L/min) according to the filtration experiments. The simulation results of the air pressure distributions for the units of meltblown and electrospun samples are shown in Fig. 3a-c. It can be seen that for all the three samples, the upper surface (i.e. \( z = 800 \) μm for the meltblown sample, \( z = 3 \) and 6 μm for the electrospun samples) withstands the highest pressure, and the pressure decreases with the increasing depth (i.e. the distance away from the upper surface) of the samples. Fig. 3d, e further show that the pressure developments with a fluctuating tendency due to the tortuous channel paths formed by the randomly arranged fibers within the nonwovens. The pressure difference between the upper surface and bottom surface (set as ambient pressure) of the unit determines the pressure drop. At the same face velocity of 5.33 cm/s, the pressure differences of the two electrospun units are one order magnitude higher than that of the meltblown nonwovens, indicating that combining electrospun membranes onto meltblown nonwovens greatly increases the pressure drop of the filters, as shown in the experimental results (Fig. 2c). Nevertheless, the pressure drop for the 3 μm-thickness electrospun membranes is much lower than that for the 6 μm-thickness membranes.
membranes. It is expected that the pressure drop can be reduced by controlling the thickness of the electrospun membranes, keeping high filtration efficiency.

It has long been proven that nanofiber membranes with thin thicknesses are difficult to be used as filters due to their poor mechanical properties. Our designed two-level structured nonwovens with combined thin nanofiber membranes and microfiber nonwovens, posses the advantages of high filtration efficiency with relatively low pressure drop, and required mechanical properties for face masks.

3.3. IR radiative heat dissipation performance

In addition to its excellent filtration performance, the PE/PA nonwovens for face masks also have distinctive human body radiative cooling performance. Fig. 4a shows the mid-IR transmittance of the samples for face masks. The human skin with a temperature of 34 °C emits mid-IR wavelength centered at ~ 9.5 μm (the shaded area in the figure) [25], contributing to a large portion of total body heat loss (> 50% under static state [30]). As presented in Fig. 4a, the PE/PA nonwovens, which is a combination of 800 μm-thickness PE nonwovens and 4.5 μm-thickness PA nanofiber membranes for face masks show a high mid-IR transmittance of 82.39% for wavelengths ranged in 2.5–20 μm, which is much higher than those of commercial face masks (31.95% for Com-1 and 27.76% for Com-2), indicating that our designed PE/PA nonwovens reach excellent radiation cooling performance. Our results verify that the PE/PA nonwovens have narrow adsorption peaks in human body radiation region, leading to the good cooling performance of the mask. This excellent performance may be attributed to the specific molecular structure of PE and PA. As mentioned above, PE and PA have absorption peaks (3.4, 3.5, 6.8 and 13.7 μm for PE and 3.0, 3.4 and 6.1 μm for PA) away from the wavelength of the mid-IR region emitted by human body (mainly 7–14 μm with a peak intensity at 9.5 μm) [26,31]. However, polypropylene (PP), which is used in commercial face masks, has additional absorption peaks at 8.5, 10 and 11.9 μm that locates at human body radiation, leading to lower IR-transparent [32]. It is worth mentioning that, the commercial face masks have pore sizes of ~ 10 μm, which are comparable with the human body radiative wavelengths. The designed PE/PA nonwovens have two level pore sizes (~ 143 μm and ~ 6 μm). The interconnected pores are in the sizes away from the human body radiative wavelengths, preventing the strong scattering of mid-IR and resulting in higher heat radiation transfer.

To further show the heat dissipation performance of the PE/PA nonwovens, we use a laboratory-made device to measure the simulated skin temperatures (the details of the measurement can be seen in section Thermal Property Evaluation). The temperatures of bare skin and the skin covered with PE/PA nonwovens with different PE meltblown thicknesses (800, 1126, 1351 and 1570 μm) are measured and the results are shown in Fig. 4b. The figure also shows the temperatures of the

---

**Fig. 4.** Thermal measurements of the PE/PA nonwovens for face masks. (a) The mid-IR transmittance of PE/PA nonwovens (consisting of 800 μm-thickness PE meltblown nonwovens and 3 μm-thickness PA electrospun membranes) and two commercial face masks. The shaded area is the human body radiation. (b) Temperatures of bare skin and skin covered with PE/PA nonwovens and two commercial face masks. The thickness of the PE layers of PE-800 μm/PA, PE-1126 μm/PA, PE-1351 μm/PA, PE-1570 μm/PA nonwovens are 800 μm, 1126 μm, 1351 μm and 1570 μm, respectively, while the PA layer thickness is kept at 4.5 μm. (c) Infrared thermal images of different PE/PA nonwovens and two commercial face masks.
The results show that at an ambient temperature of 25 °C, the bare skin presents a temperature of 34 °C. When the simulated skin is covered with the PE/PA sample of thicknesses of 800 μm, 1126 μm, 1351 μm, and 1570 μm, the samples present skin temperatures from 34.6, 34.7, 34.9 to 35.2 °C, indicating that the thicker PE/PA samples do not reduce their heat dissipation performance significantly. Moreover, two commercial face masks, Com-1 with the thickness of 800 μm and Com-2 with the thickness of 1570 μm, are chosen as comparisons. The skin temperatures for the two commercial face masks are measured as 35.9 °C and 36.2 °C, demonstrating that even with thicker thickness, our PE/PA nonwovens present better heat dissipation performance than the commercial face masks.

Infrared thermal images are also taken by a thermal camera to visualize the temperature of the simulated skin covered with different samples (Fig. 4c). In the images, the red regions outside the samples represent the bare skin temperature. It is clear that the surfaces of the PE/PA nonwoven samples show warm state, especially for thinner thicknesses of PE/PA nonwoven samples are used in the measurements. With increasing thickness of PE layer (800, 1126, 1351, and 1570 μm), the samples present skin temperatures from 34.6, 34.7, 34.9 to 35.2 °C, indicating that the thicker PE/PA nonwovens do not reduce their heat dissipation performance significantly. Moreover, two commercial face masks, Com-1 with the thickness of 800 μm and Com-2 with the thickness of 1570 μm, are chosen as comparisons. The skin temperatures for the two commercial face masks are measured as 35.9 °C and 36.2 °C, demonstrating that even with thicker thickness, our PE/PA nonwovens present better heat dissipation performance than the commercial face masks.

Infrared thermal images are also taken by a thermal camera to visualize the temperature of the simulated skin covered with different samples (Fig. 4c). In the images, the red regions outside the samples represent the bare skin temperature. It is clear that the surfaces of the PE/PA nonwoven samples show warm state, especially for thinner thicknesses of PE/PA nonwoven samples are used in the measurements. With increasing thickness of PE layer (800, 1126, 1351, and 1570 μm), the samples present skin temperatures from 34.6, 34.7, 34.9 to 35.2 °C, indicating that the thicker PE/PA nonwovens do not reduce their heat dissipation performance significantly. Moreover, two commercial face masks, Com-1 with the thickness of 800 μm and Com-2 with the thickness of 1570 μm, are chosen as comparisons. The skin temperatures for the two commercial face masks are measured as 35.9 °C and 36.2 °C, demonstrating that even with thicker thickness, our PE/PA nonwovens present better heat dissipation performance than the commercial face masks.

We introduce a concept of thermal storage power (q) to further quantify the heat dissipation performance of the face masks. The thermal storage power can be calculated by the formula transformed from Stefan-Boltzmann Law [33,34]:

\[ q = \varepsilon \sigma (T_1^4 - T_2^4) \]  

where \( \varepsilon \) is the emissivity of the human body (0.95) [35], \( \sigma \) is the Stefan-Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}), \( T_1 \) is the temperature of the skin covered with face mask, and \( T_2 \) is the bare skin temperature (34 °C). The lower heat storage power indicates that more heat passes through the face mask and less heat is stored on the face. As shown in Fig. 5a, the q of the PE/PA nonwoven face masks (800 μm-thickness PE layer and 4.5 μm-thickness PA layer) is 3.97 W/m², which is considerably low compared with 12.29 W/m² and 13.46 W/m² for the Com-1 and Com-2, further demonstrating that our prepared PE/PA face masks have excellent radiative cooling performance.

Finally, the Infrared thermal images of human face wearing different face masks (Fig. 5b) are captured by the thermal camera. It is clearly shown that the outer surface of the PE/PA face mask appears warm, indicating that the heat is successfully dissipate from the skin to the ambient. In contrast, the outer surfaces of Com-1 and Com-2 appear cold because the body radiation is blocked from transmission. It’s worth noting that this study considers developing the radiative heat dissipation performance, therefore the comparisons in this study are performed with ignoring the variables including the other heat transfer methods, the gap between skin and mask inner layer, and the total active filtering area.

3.4. Wearability properties

In addition to high filtration performance and excellent radiation heat dissipation performance, suitable wearability is desirable for face masks. To this end, we designed PE/PA nonwovens for face masks considering wearability properties including mechanical strength, air permeability, and water vapor transmission (WVT). First, mechanical strength is known as a key wearability performance. The tensile force of the 2-cm-wide samples were tested by an electronic fabric strength tester, and the results are exhibited in Fig. 6a. The combination of PE meltblown nonwovens and PA electrospun membrane can bear a tensile force of about 25 N. Although this strength is lower than 30.2 N of Com-1 and 71 N of Com-2 that are the combination of meltblown and spun-bonded nonwovens, it is enough to be used as face masks. Air permeability, which is a measure of how well a fabric allows the passage of air, is another important wearability index of face masks. Fig. 6b shows that the PA nanofiber layer leads to a lower air permeability than Com-1. However, the PE/PA nonwovens presents a slightly higher air permeability of 188.636 mm/s than that of Com-2, indicating that they are suitable to be used as face masks. Water vapor transmission (WVT) is particularly critical for face masks to alleviate discomfort when moisture comes out of the mouth. Fig. 6c shows that the WVT of PE/PA is 346 g·m^{-2}·h^{-1}, which is slightly higher than that of 336 g·m^{-2}·h^{-1} and 338 g·m^{-2}·h^{-1} for Com-1 and Com-2. The WVT is associated with the wettability of the components. Fig. 6d shows that the water contact angles of the PA and PE fibers are 31° and 151°, respectively, indicating the hydrophilicity of the PA fibers and the superhydrophobicity of the PE fibers. The suitable WVT of the PE/PA nonwoven is obviously attributed to the hydrophilicity of the inner layer (PA). Meanwhile, the superhydrophobic PE surface can block the spread of droplets in the air and reduce the risk of droplet infection. And it can also block the spatter of the blood and tissue fluid from the wound to the face when the surgeon is treating the patients.

![Fig. 5. Heat dissipation performance of PE/PA nonwovens for face masks.](image-url)
4. Conclusions

In summary, a type of face masks that show excellent filtration performance and radiative heat dissipation effect is successfully designed and prepared via meltblowing and electrospinning. The prepared PE/PA nonwovens present a two-level structure with two level pore sizes, which can improve filtration efficiency (>99%) and reduce pressure drop (<100 Pa). Meanwhile, the mid-IR emitted by human body can easily pass through the PE/PA face masks without any energy input and display excellent radiative heat dissipation performance. The heat storage power (q) of the PE/PA face mask is 3.97 W/m$^2$, which is much lower than 12.29 W/m$^2$ and 13.46 W/m$^2$ for conventional commercial face masks Com-1 and Com-2, respectively. In addition, they also possess a differential wettability with hydrophobic outer layer and hydrophilic inner layer, which can rapidly transmit moisture to the outside while blocking the spread of droplets. As new filter materials with radiative heat dissipation performance, PE/PA nonwovens are promising to be used to the personal protective face masks to protect people from microorganisms and PM$_{2.5}$.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/jcej.2021.130175.

References

[1] C.A. Pope, The fight for clean air, Science 364 (2019) 536-536.
[2] C. Lovett, M.H. Sowlat, N.A. Saliba, A.L. Shihadeh, C. Sioutas, Oxidative potential of ambient particulate matter in Beirut during Saharan and Arabian dust events, Atmos. Environ. 188 (2018) 34–42.
[3] S. Heft-Neal, J. Burney, E. Bendavid, M. Burke, Robust relationship between air quality and infant mortality in Africa, Nature 550 (2018) 254–258.
[4] C.A. Pope, D.W. Dockery, Health effects of fine particulate air pollution: lines that connect, J. Air Waste Manage. Assoc. 56 (2006) 709-742.
[5] W.E. Wilson, H.H. Suh, Fine particles and coarse particles: concentration relationships relevant to epidemiologic studies, J. Air Waste Manage. Assoc. 47 (1997) 1238–1249.
[6] P. Zhou, X.L. Yang, X.G. Wang, B. Hu, L. Zhang, W. Zhang, H.R. Si, Y. Zhu, B. Li, C. L. Huang, H.D. Chen, J. Chen, Y. Liao, H. Guo, R.D. Jiang, M.Q. Liu, Y. Chen, X. R. Shen, X. Wang, X.S. Zheng, K. Zhao, Q.J. Chen, F. Deng, L.L. Liu, B. Yan, F. X. Zhan, Y.Y. Wang, G.F. Xiao, Z.L. Shi, A pneumonia outbreak associated with a new coronavirus of probable bat origin, Nature 579 (2020) 270–273.
[7] World Health Organization (2020). Weekly operational update on COVID-19. 21 December 2020.
[8] M. Richard, R.A.M. Fouchier, Influenza A virus transmission via respiratory aerosols or droplets as it relates to pandemic potential, Fems Microbiol. Rev. 40 (2016) 68-85.
[9] World Health Organization (2020). Modes of transmission of virus causing COVID-19: implications for IPC precaution recommendations.
[10] R.S. Barhate, S. Ramakrishna, Nanofibrous filtering media: filtration problems and solutions from tiny materials, J. Membr. Sci. 296 (2007) 1–8.
[11] K. Majchrzycka, A. Brochocka, P. Grzybowski, Modelling the viability of microorganisms of poly(lactic acid) melt-blown nonwoven fabrics for the use of respiratory protection, Fibres Text. East. Eur. 23 (2015) 107–113.
[12] C.S. Wang, Y. Otani, Removal of nanoparticles from gas streams by fibrous filters: a review, Ind. Eng. Chem. Res. 52 (2013) 5–17.
[13] A. Yang, L. Cai, R. Zhang, J. Wang, P.C. Hsu, H. Wang, G. Zhou, J. Xu, Y. Cui, Thermal management in nanofiber-based face mask, Nano Lett. 17 (2017) 3506–3510.
9

[14] J.X. Liu, X. Zhang, H.F. Zhang, L. Zheng, C. Huang, H.B. Wu, R.W. Wang, X.Y. Jin, Low resistance bicomponent spunbond materials for fresh air filtration with ultra-high dust holding capacity, RSC Adv. 7 (2017) 43879–43887.

[15] M. Zhao, L. Liao, W. Xiao, X.Z. Yu, H.T. Wang, Q.Q. Wang, Y.L. Lin, F.S. Kilinc-Balci, A. Price, L. Chu, M.C. Chu, S. Chu, Y. Cai, Household materials selection for homemade cloth face coverings and their filtration efficiency enhancement with triboelectric charging, Nano Lett. 20 (2020) 5544–5552.

[16] S. Zhang, H. Liu, N. Tang, N. Ali, J. Yu, B. Ding, Highly efficient, transparent, and multifunctional air filters using self-assembled 2D nanoarchitected fibrous networks, ACS Nano 13 (2019) 13501–13512.

[17] M.M. Zhu, J.Q. Han, F. Wang, W. Shao, R.H. Xiong, Q.L. Zhang, H. Pan, Y. Yang, S. K. Samal, F. Zhang, C.B. Huang, Electrospun nanofibers membranes for effective air filtration, Macromol. Mater. Eng. 302 (2017) 1600353.

[18] Z.C. Jiang, H.Y. Zhang, M.M. Zhu, D. Lv, J.F. Yao, R.H. Xiong, C.B. Huang, Electrospun soy-protein-based nanofibrous membranes for effective antimicrobial air filtration, J. Appl. Polym. Sci. 135 (2018) 45766.

[19] A. Greiner, J.H. Wendorff, Electrospinning: a fascinating method for the preparation of ultrathin fibres, Angew. Chem.-Int. Edit. 46 (2007) 5670–5703.

[20] X.L. Zhao, Y.Y. Li, T. Hua, P. Jiang, X. Yin, J.Y. Yu, B. Ding, Cleanable air filter transferring moisture and effectively capturing PM\(_{2.5}\), Small 13 (2017) 1603306.

[21] S. Wang, X.L. Zhao, X. Yin, J.Y. Yu, B. Ding, Electret polyvinylidene fluoride nanofibers hybridized by polytetrafluoroethylene nanoparticles for high-efficiency air filtration, ACS Appl. Mater. Interfaces 8 (2016) 23985–23994.

[22] J. Zhang, G. Chen, G.S. Bhat, H. Azari, H. Pen, Electret characteristics of melt-blown polyactic acid fabrics for air filtration application, J. Appl. Polym. Sci. 137 (2020) 48309.

[23] M.C. Howard, Understanding face mask use to prevent coronavirus and other illnesses: development of a multidimensional face mask perceptions scale, Br. J. Health Psychol. 25 (2020) 912–924.

[24] N. Wang, M. Cai, X. Yang, Y. Yang, Electret nanofibrous membrane with enhanced filtration performance and wearing comfortability for face mask, J. Collid Interface Sci. 530 (2018) 695–703.

[25] P.-C. Hsu, A.Y. Song, P.B. Catrypse, C. Liu, Y. Peng, J. Xie, S. Fan, Y. Cui, Radiative human body cooling by nanoporous polyethylene textile, Science 353 (2016) 1019.

[26] J.V. Galmine, P.R. Janissek, H.M. Heine, L. Akcelrud, Polyethylene characterization by FTIR, Polym. Test. 21 (2002) 557–563.

[27] L. Cai, Y. Song Alex, W. Li, P.-C. Hsu, D. Lin, B. Catrypse Peter, Y. Liu, Y. Peng, J. Chen, H. Wang, J. Xu, A. Yang, S. Fan, Y. Cui, Spectrally selective nanocomposite textile for outdoor personal cooling, Adv. Mater. 30 (2018) 1802152.

[28] C. Liu, P.C. Hsu, H.W. Lee, M. Ye, G.Y. Zheng, N.A. Liu, W.Y. Li, Y. Cui, Transparent air filter for high-efficiency PM\(_{2.5}\) capture, Nat. Commun. 6 (2015) 9.

[29] K.M. Yun, A.B. Suryamas, F. Iskandar, L. Bao, H. Niinuma, K. Okuyama, Morphology optimization of polymer nanofiber for applications in aerosol particle filtration, Sep. Purif. Technol. 75 (2010) 340–345.

[30] L. Cai, A.Y. Song, P. Wu, P.-C. Hsu, Y. Peng, J. Chen, C. Liu, P.B. Catrypse, Y. Liu, A. Yang, C. Zhou, C. Zhou, S. Fan, Y. Cui, Warming up human body by nanoporous metallized polyethylene textile, Nat. Commun. 8 (2017) 496.

[31] H.G. Tompkins, T. Tsiwald, C. Bungay, A.E. Hooper, Use of molecular vibrations to analyze very thin films with infrared ellipsometry, J. Phys. Chem. B 108 (2004) 3777–3786.

[32] D.J. Ando, B.H. Stuart, Polymers, Infrared Spectroscopy: Fundamentals and Applications2004, pp. 113-136.

[33] J.D. Hardy, The radiation of heat from the human body: III. The human skin as a black-body radiator, J. Clin. Invest. 13 (1934) 615–620.

[34] Y.N. Song, R.J. Ma, L. Xu, H.D. Huang, D.X. Yan, J.Z. Xu, G.J. Zhong, J. Lei, Z.M. Li, Wearable polyethylene/polyamide composite fabric for passive human body cooling, ACS Appl. Mater. Interfaces 10 (2018) 41637–41644.

[35] J.D. Hardy, The radiating power of human skin in the infrared, Am. J. Physiol. 127 (1939) 454–462.