



Rapid Communication

Thermostable, water-repellent, moisture-permeable Nomex nanofibrous membranes with a connected PTFE network for personal protective fabrics

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ABSTRACT

Water-repellent and moisture-permeable membranes are highly desirable for improving wearing comfort and protection; however, constructing thermostable fabrics with excellent moisture permeability and high resistance to water penetration in high-temperature personal protection remains a great challenge. Therefore, we fabricate Nomex nanofibrous membranes via electrospinning, and further perform dip-coating with polytetrafluoroethylene (PTFE) emulsion and hot-pressing for constructing connected PTFE network. The Nomex membranes possess hydrophobic PTFE networks and retain porous structures, improving their water repellent without influencing water vapor transmission. Furthermore, the membranes demonstrate prominent thermostability due to the synergistic effect of the high-temperature-resistant Nomex substrate and PTFE hydrophobic agent. Consequently, the Nomex/PTFE membranes exhibit prominent water-repellent and moisture-permeability with high hydrostatic pressure of 58 kPa and satisfactory water vapor transmission rate of $6008 \text{ g m}^{-2} \text{ d}^{-1}$, as well as remarkable thermostability to maintain structural stability under 300°C , suggesting great promise as exceptional candidates for high-temperature personal protection and comfort management.

1. Introduction

The total high-performance fabrics with respect to personal protection and thermal-wet comfort are on course for profits of \$596.4 billion by 2026, in light of the latest survey, and an increasing number of corporations associated with sports and healthcare have already carried out studies. [1–3] Thereinto, the moisture-permeable and water-repellent textiles could transmit water vapor and resist the penetration of liquid water, which is a promising utility for fabricating functional fabrics to enhance personal protection and thermal-wet comfort. [4,5] The current commercial moisture-permeable and water-repellent materials mainly include densely woven fabrics, polyurethane membranes, and biaxially-stretched PTFE membranes. [6–8] These materials demonstrate a certain water-repellence and moisture permeability but still exhibit some fatal defects in high-temperature personal protection and comfort management, such as firefighter uniforms, boiler worker's suits, and field uniforms. Obviously, densely woven fabrics and polyurethane membranes are typically devoid of structural stability and

function stability over 150°C . [9] Significantly, PTFE membranes show high temperature stability but possess some inextricable drawbacks, i.e., complex procedures, high cost, and weak bonding fastness with the shell fabric. [10] Accordingly, it remains a serious challenge to develop a versatile and scalable approach to construct thermostable, water-repellent, and moisture-permeable fabrics.

High-temperature-resistant polymers would be of promising utility as raw materials to construct a new type of thermostable, water-repellent, and moisture-permeable fabric. [11–13] Nowadays, a great deal of effort has been devoted to fabricating heat-resistant fabrics based on various types of high-temperature-resistant polymers, including Nomex, polyimide, and polyether-ether-ketone. [14–16] Among these, Nomex, which exhibits the integrated properties of ultrahigh thermostability (300°C), various kinds of good solvents, and low cost, is the most exceptional candidate for engineering heat-resistant fabrics. [17–19] Over the last ten years, researchers have concentrated on engineering Nomex fabrics via different processing technologies, including weaving, knitting, and spunlacing. [20–22] However, these fabrics

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generally suffered from poor water-repellence due to thick fiber and large pore size ($>5\ \mu\text{m}$). Significantly, with the unique combination of extremely low cost, a simple production process, and good structural controllability, electrospinning has been regarded as a versatile and effective approach to fabricating fibrous membranes with small pore sizes. [23,24] A large variety of Nomex nanofibrous membranes have been constructed with diverse solvents, including *N,N*-dimethylacetamide, *N,N*-dimethylformamide, *N,N*-dimethylsulfoxide, and *N*-methyl-2-pyrrolidone. [25–27] These Nomex nanofibrous membranes showed improved water-repellence, but their hydrostatic pressures were no more than 5 kPa because of the intrinsically high surface energy, which failed to satisfy practical requirements. On the other hand, many types of hydrophobic polymers have been applied to fabricate the water-repellent and moisture-permeable nanofibrous membranes, including polyvinylidene fluoride, polysulfone, polyethersulfone, and fluorinated polyurethane. But these membranes showed thermostability and failed to maintain structural stability over $200\ ^\circ\text{C}$, which are not applicable to high-temperature personal protection and comfort management. As a result, it remains an urgent task to enhance the hydrophobicity of Nomex nanofibrous membranes to obtain thermostable, water-repellent, and moisture-permeable fabrics.

Herein, we present a simple and scalable method to fabricate Nomex nanofibrous membranes with a connected PTFE network to improve the

thermostability and thermal-wet comfort of textiles for personal protection (Fig. 1a). We fabricated Nomex membranes with uniform nanofibrous and small pore sizes via solution electrospinning, then dipped the Nomex nanofibrous membranes with PTFE emulsion to decrease the surface energy of the nanofibrous membranes, and finally implemented hot-pressing technology on the Nomex/PTFE membranes to reduce the pore size of the nanofibrous membranes. This method engenders PTFE nanoparticles to be connected with each other along Nomex nanofibrous, and consequently, the Nomex membranes possess hydrophobic PTFE networks and retain porous structures, improving their water repellent without influencing water vapor transmission. In addition, the effect of the PTFE concentration on the hydrophobicity of nanofibrous membranes is investigated in detail, and the influence of the heat treatment temperature on the porous structure of the nanofibrous membranes is also revealed. Ultimately, the resultant Nomex/PTFE membranes showed intriguing thermostability with the combined effect of a PTFE hydrophobic agent and a high-temperature-resistant Nomex nanofibrous substrate.

2. Experimental procedures

N,N-Dimethylacetamide (DMAc) was purchased from Shanghai Macklin Biochemical Co., Ltd., China. Nomex was purchased from

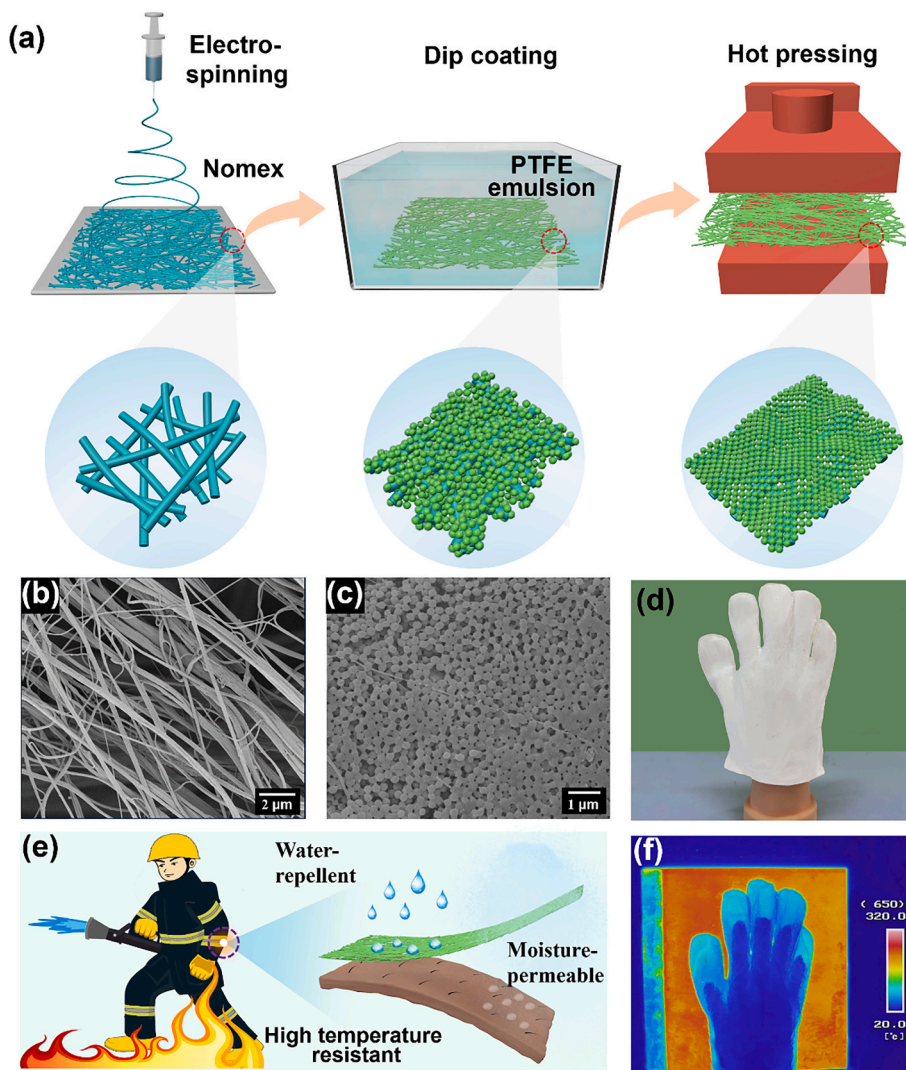


Fig. 1. (a) Schematic illustration of the fabrication and structure of the Nomex/PTFE membranes, (b-c) SEM images of the Nomex membranes and Nomex/PTFE membranes, (d) The optical image of prepared glove, (e) The optical picture of prepared glove, (f) Infrared image of the glove on $300\ ^\circ\text{C}$ heating stage.

Shenzhen Nanfang Co., Ltd., China. Silicone emulsion was brought by Dongguan Hongyun textile Co., Ltd., China. PTFE emulsion was obtained from Wujiang Jinfeng Chemical Co., Ltd., China. Fluorinated polyurethane (FPU) emulsion was purchased from Daikin Co., Ltd., Japan. Paraffin emulsion was brought by Dongguan Diya high-tech materials Co., Ltd., China. The spinning dopes of 6%, 8%, 10% and 12% were prepared by dispersing Nomex1313 in *N,N*-Dimethylacetamide (DMAc). The solution was added into five syringes attached with a 0.7 mm inner diameter steel needle and injected through the needle with a constant feed rate of 1 mL h^{-1} . The applied voltage was fixed at 20 kV, resulting in the generation of a continuous jet stream. The collection distance was fixed at 10 cm and a grounded metal roller with a rotating speed of 100 rpm was used to obtain uniform membranes. The environmental conditions were kept constant at 25°C and relative humidity of 35%. The membranes were prepared with a thickness of $100 \mu\text{m}$. Then, put a few membranes prepared by 10% of the prepared Nomex1313 concentration into Silicone emulsion, PTFE emulsion, FPU emulsion and Paraffin emulsion with a concentration of 2% for impregnation modification. Put the treated membranes into the oven at 60°C for 30 min. Some films of 10% concentration were impregnated into PTFE emulsion of 4%, 6%, 8% and 10% concentration, soaking for 10 min. Finally, hot-pressing technology was applied to these membranes after impregnation and modification with 8% PTFE emulsion, pressing pressure of 10 MPa, pressing time of 20 min and the different pressing temperature (140 , 160 , 180 and 200°C).

3. Results and discussion

The construction of a thermostable, water-repellent, moisture-permeable nanofibrous membrane requires sophisticated regulation of chemical composition and interface energy. [28,29] We fabricated the nanofibrous membranes according to three criteria: (i) the main electrospinning polymer and the additives should be high temperature resistant; (ii) the nanofibrous should possess a low surface energy surface to resist wetting by liquid water and prevent water penetration; and (iii) the materials should accumulate to form robust membranes with porous structures for transmitting moisture easily. To meet the three important criteria, as illustrated in Fig. 1a, we employed high-temperature-resistant Nomex as the main polymer and used heat-resistant PTFE as a hydrophobic agent. PTFE nanoparticles with low surface energy were incorporated into the Nomex nanofibrous membranes via dip-coating and enhanced the hydrophobicity of the intrinsic membranes. Nomex nanofibrous were accumulated randomly to constitute nano-nonwoven fabrics with a small connected porous structure under the electric field (Fig. 1b), and PTFE nanoparticles were connected with each other along Nomex nanofibrous after hot-pressing technology to form a porous network (Fig. 1c).

The synergy of high-temperature resistance between the Nomex nanofibrous and PTFE nanoparticles endowed the composite membranes with prominent thermostability. Notably, the synergistic effect of the porous Nomex nanofibrous structure and the porous PTFE network allows water vapor to be transmitted. The incorporation of PTFE nanoparticles endowed the Nomex nanofibrous membranes with good hydrophobicity. And it is also noteworthy that the PTFE nanoparticle network showed a smaller pore size than the Nomex nanofiber membranes, thus making the composite membranes more water-repellent. Therefore, the composite Nomex/PTFE nanofibrous membranes demonstrate impressive comprehensive moisture-permeability and water-repellency with a satisfactory WVT rate of $6008 \text{ g m}^{-2} \text{ d}^{-1}$, a high hydrostatic pressure of 58 kPa, as well as remarkable thermostability to maintain structural stability under 300°C (Fig. 1f), suggesting great promise as exceptional candidates for high-temperature personal protection and comfort management (Fig. 1e). Besides, the method was easily scalable through multi-jet equipment, and large-size Nomex/PTFE membranes were fabricated. Meanwhile, the membranes demonstrated good sewing processability, so we prepared the first wearable

nanofibrous thermostable, water-repellent, moisture-permeable gloves, which had never been implemented before (Fig. 1d). More importantly, the method was easily scalable through multijet electrospinning equipment and large-scale membranes with a size of $50 \text{ cm} \times 40 \text{ cm}$ were fabricated (Fig. S1).

The structure of the Nomex nanofibrous membranes was adjusted via the alteration of the concentration of Nomex solution (6%, 8%, 10%, 12%), and the influence of solution composition on the structure was studied. As displayed in Figs. 1b and S2, with the increase in the concentration of Nomex, the electrospinning solution fluid became more viscous and generated sufficient stretching of the whipping fluid jet, resulting in the alteration of the membranes from bead to uniform nanofibers. [30,31]. Nomex-10% nanofibrous membranes showed a connected porous structure but failed to resist water penetration because of their weak hydrophobicity with a water contact angle of 97° . Thus, we intended to modify their wettability with hydrophobic agents, including FPU, silicone, paraffin, and PTFE emulsions. We adjusted the hydrophobic agent with the same concentration of 2% and implemented the same soak time (10 min) and oven drying under 60°C . The morphologies of the modified Nomex-10% nanofibrous membranes are illustrated in Fig. 2a–d. It was obvious that the Nomex/FPU-2% membranes and the Nomex/paraffin-2% membranes possessed a covering layer along the nanofibers, which were derived from the nanoparticles in the emulsion and were tightly integrated. On the contrary, the Nomex/silicone-2% membranes and the Nomex/PTFE-2% membranes exhibited well-bedded structures with nanoparticles. The loading with hydrophobic agents was also confirmed by the FTIR test. The spectra of the FPU and Nomex/FPU-2% membranes showed correlative characteristic peaks of polyurethane at 1730 cm^{-1} , which arose from the stretching vibration of the carbonyl group ($\text{C}=\text{O}$). As for the Nomex/PTFE-2% membranes, the spectra possessed distinct double peaks around 1250 cm^{-1} , which arose from the stretching vibration of $\text{F}-\text{C}-\text{F}$. With respect to the Nomex/paraffin-2% membranes and the Nomex/silicone-2% membranes, both spectra exhibited the same correlative characteristic peaks, which consisted of the spectra of paraffin and silicone, as demonstrated in Fig. 2e and f.

The incorporation of the hydrophobic agent resulted in a change in the intrinsic physicochemical structure of the Nomex membranes, ranging from the porous structure to the wettability. Undoubtedly, the hydrophobic agent stuck with the Nomex nanofibers and caused a rapid decline in the pore size. As illustrated in Fig. 2g, the Nomex membranes showed a maximum pore size of $4.7 \mu\text{m}$ and a mean pore size of $1.2 \mu\text{m}$. Significantly, the modified Nomex membranes showed a maximum pore size in the range of $0.6\text{--}1.5 \mu\text{m}$ and a mean pore size in the range of $0.3\text{--}0.5 \mu\text{m}$. With respect to the wettability, it could be seen that the weak hydrophobicity with a water contact angle of 97° and the modified Nomex membranes exhibited enhanced hydrophobicity markedly, as displayed in Fig. 2h. In natural structures, it has been demonstrated that water repellence is closely associated with the porous structure and the wettability of the materials. [32,33] As displayed in Fig. 2i, the Nomex membranes showed poor water-repellence with a hydrostatic pressure of 0.5 kPa, but the modified Nomex membranes demonstrated markedly improved water-repellence. Notably, the Nomex/silicone-2% membranes possessed the highest hydrostatic pressure of 12 kPa, and the silicone showed the most excellent hydrophobic performance among the four hydrophobic agents because of its high content of hydrophobic functional group (C-F) and ultra-low surface energy. On the other hand, modified Nomex membranes demonstrated reduced moisture permeability slightly, as shown in Fig. 2j, which was because the hydrophobic agent filled the pore and decreased the porosity of the Nomex membranes. In addition, the mechanical property of membranes was of important significance in the practical application; thus, the stress-strain diagrams are depicted in Fig. 2k. The modified Nomex membranes showed a more compact accumulation structure from Fig. 2a–d; thus, the modified Nomex membranes exhibited improved tensile breaking stress, and the Nomex/FPU membranes showed the strongest

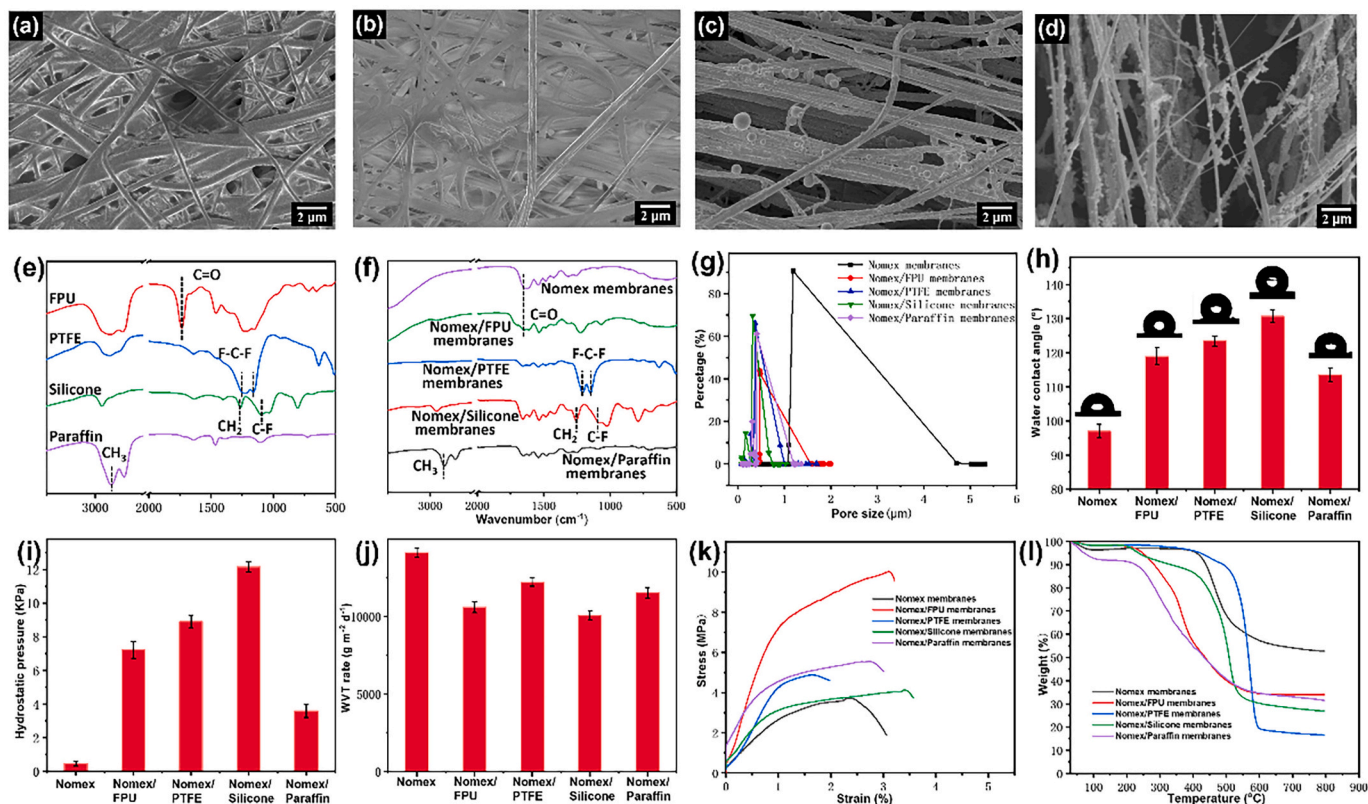


Fig. 2. (a-d) SEM images of the Nomex-8% membranes modified with FPU, silicone, paraffin, PTFE emulsion respectively, (e-f) FTIR spectra of the FPU, silicone, paraffin, PTFE, the Nomex membranes, and the modified Nomex membranes, (g-h) Pore size distribution of the Nomex membranes and the modified Nomex membranes, (i-j) Hydrostatic pressure and WVT rate of the Nomex membranes and the modified Nomex membranes, (k-l) The stress-strain diagrams and TGA thermograms of the Nomex membranes and the modified Nomex membranes.

performance with a breaking stress over 10 MPa. The most noteworthy feature of the membranes was their thermostability, and we employed Thermogravimetric analysis as shown in Fig. 2l. It was obvious that the Nomex membranes exhibited good thermal stability and began to decompose at 400 °C. Among the modified Nomex membranes, the thermal stability of the Nomex/paraffin-2% membranes was the worst and began to decompose at 70 °C and decomposed rapidly at 220 °C. The thermal stability of the Nomex/FPU-2% membranes and the Nomex/silicone-2% membranes was slightly better than that of the Nomex/paraffin-2% membranes. Notably, the Nomex/PTFE-2% membranes began to decompose at 419 °C, indicating that the Nomex membranes still have good high temperature resistance after soaking. The Nomex/PTFE-2% membranes could be applied in a high-temperature environment for a long time, which was suitable for high-temperature personal protection and comfort management; thus, PTFE emulsion was accordingly chosen in further study from the four hydrophobic agents.

To further improve the hydrophobicity of the Nomex membranes, we adjusted the concentration of PTFE emulsion (4%, 6%, 8%, 10%). The surface morphology of the Nomex/PTFE membranes is shown in Fig. 3a-d. The PTFE nanoparticles were attached to the Nomex nanofibers and failed to fill the pore between the Nomex nanofibers when the PTFE concentration was 4%. With the increase in PTFE concentration, more and more PTFE nanoparticles closely contacted and covered the Nomex nanofibers. When the PTFE concentration was 10%, too many PTFE nanoparticles were merged together to form the impurity layer. The FTIR spectra of Nomex/PTFE membranes were shown in Fig. S3 and possessed distinct double peaks at 1155 cm⁻¹ and 1215 cm⁻¹. Notably, the intensity of the double peaks increased along with the rise in PTFE concentration, which also reflected that more and more PTFE nanoparticles were incorporated into the Nomex membranes. And the maximum pore size of the Nomex/PTFE membranes decreased distinctly

with the raised PTFE concentration, as shown in Fig. 3e. We also studied the R_a of the Nomex/PTFE membranes via atomic force microscopy in Figs. 3f and S4, and it was found that the R_a was increased with the raised PTFE concentration, but the R_a of Nomex/PTFE-10% was reduced slightly because of the fusion of PTFE nanoparticles. It was well known that its chemical constitution and roughness were crucial for its wettability. [34,35] As shown in Fig. 3g, it turned out that the water contact angle of the Nomex/PTFE membranes gradually increased with the increase in the concentration of PTFE emulsion. Notably, the Nomex/PTFE-8% showed prominent superhydrophobicity with a water contact angle of 155°, which was derived from the synergistic effect of low surface energy and micro-nano-rough structure. Besides, we also studied the dynamic behaviors of water on the Nomex membranes and the Nomex/PTFE-8% membranes in Fig. 3h and Movie S1 and S2. One can see that the 3 μL of water was adsorbed on the surface of the Nomex membranes, but the water droplet detached from the Nomex/PTFE-8% membranes completely without deformation, suggesting an excellent anti-wetting property and ultra-low adhesion between the membranes and the water droplet. And the water contact angle of the Nomex/PTFE-10% membranes decreased to 137° because of the reduced R_a . With the enhanced hydrophobicity of the Nomex/PTFE membranes, it can be observed that the hydrostatic pressure increased gradually and reached the highest (22 kPa) when the concentration of PTFE was 8% (Fig. 3i). The WVT rate of the Nomex/PTFE membranes overall decreased in the meantime, which was in light of the fact that more and more PTFE nanoparticles blocked the pore passages. Besides, the original Nomex nanofibrous membranes was kept as 100 μm, and thickness of Nomex membranes coated with 8%PTFE was 84 μm, because the nanofibers in the treated Nomex membranes tended to huddle together after drying because of the hydrogen-bond interaction in water. We also calculated the difference between the Nomex membranes and the Nomex/PTFE-8%

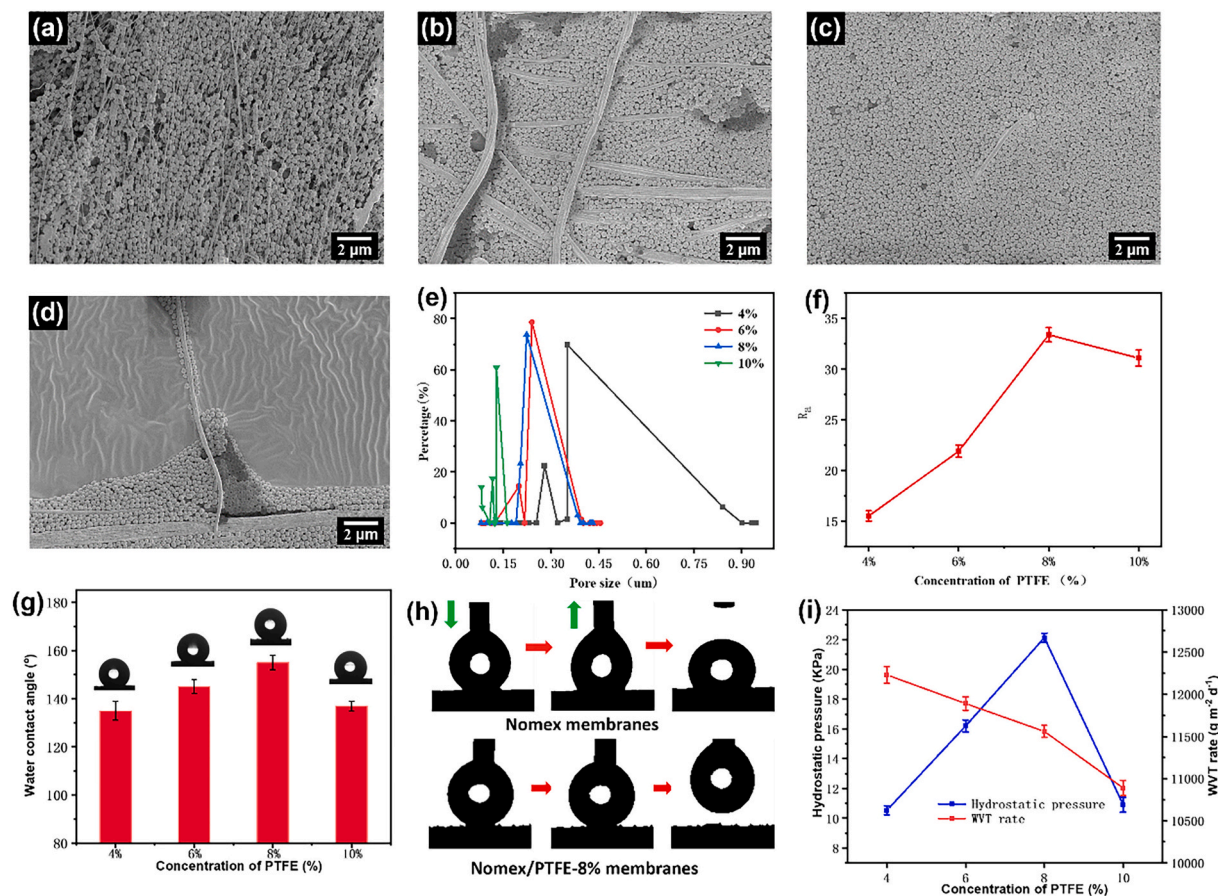


Fig. 3. (a-d) SEM images of the Nomex/PTFE membranes with different concentration of PTFE, (e-g) Pore size distribution, R_a , and water contact angle of the Nomex/PTFE membranes with different concentration of PTFE, (h) Dynamic behavior of water on the Nomex membranes and the Nomex/PTFE membranes, (i) Hydrostatic pressure and WVT rate of the Nomex/PTFE membranes with different concentration of PTFE.

membranes, and it was found that the weight ratio between Nomex/PTFE was 80.2:19.8.

The Nomex/PTFE-8% membranes demonstrated impressive heat stability and satisfactory permeability but only displayed moderate water repellency with a hydrostatic pressure of 22 kPa, which was unable to satisfy practical requirements. The hydrostatic pressure was inversely proportional to the maximal pore size according to the Young-Laplace equation; thus, we intended to perform hot-pressing technology on the Nomex/PTFE-8% membranes to reduce their pore size to enhance water repellency. [36–38] We confirmed the hot-pressing processing parameter with a pressing time of 20 min and a pressing pressure of 10 MPa after the preliminary experiment and then studied the effect of the different pressing temperatures (140, 160, 180 and 200 °C). The morphologies of thermally treated Nomex/PTFE-8% membranes are displayed in Figs. 1c and 4a–c. It is revealed that the Nomex/PTFE-140 membranes showed an obvious structure change, and sectional PTFE nanoparticles connected with each other slightly. It was well known that the melting point of conventional PTFE materials was 327 °C, but the PTFE nanoparticles started merging at 140 °C because of their nano-scale. [39–41] When the pressing temperature was increased, more and more of the PTFE nanoparticles were connected tightly. It was obvious that the PTFE nanoparticles merged together to form a hydrophobic network and retain a porous structure (Fig. 1c). However, most PTFE nanoparticles merged into an imporous layer, further increasing the pressing temperature to 200 °C, suggesting that 200 °C was slightly high for the hot-pressing technology. [42] The corresponding result was that the water contact angle of the heat-treated Nomex/PTFE membranes decreased with the reduced roughness, as shown in Fig. S5. In addition, the porous structure of thermally treated Nomex/PTFE-8% membranes

was also investigated, as displayed in Fig. 4d. Stupendously, the thermally treated Nomex/PTFE-8% membranes showed a rapid decline in the pore size, and the maximum pore size decreased dramatically from 0.3 to 0.15 μm. Undoubtedly, the rapid decline in pore size engendered an improvement in water repellency, as shown in Fig. 4e. The hydrostatic pressure of the Nomex/PTFE-8% membranes increased from 22 to 60 kPa. In the meantime, the WVT rate of the Nomex/PTFE-8% membranes decreased from 8600 to 2600 g m⁻² d⁻¹. It was found that the Nomex/PTFE-180 membranes showed prominent hydrostatic pressure (58 kPa) and a high WVT rate (6008 g m⁻² d⁻¹). And the thickness of Nomex/PTFE membranes could become to be thin (68 μm), because the nanofibers in the treated Nomex membranes would get closer together under pressing pressure of 10 MPa in high temperature. We also studied the mechanical property of the Nomex/PTFE-180 membranes under high temperatures and the stress-strain diagrams (25, 50, 100, 150, 200, 250 and 300 °C). With the increasing test temperature, the breaking strain of the Nomex/PTFE-180 membranes increased gradually, and the breaking stress decreased, as displayed in Fig. 4f. After dip-coating and hot-pressing, the Nomex/PTFE membranes exhibited tight structure and the nanofibers could not slip facilely, thus the Nomex/PTFE membranes possessed low elongation of 8.8%. It is noteworthy that the waterproof and breathable membranes are usually laminated on the substrate fabrics during subsequent use. The fabricated Nomex/PTFE membranes were also prone to be laminated with conventional fabrics with adhesive dispense as showed in Fig. S6. And the laminated fabrics demonstrated robust mechanical properties with break stress of 55 MPa and elongation of 135%. The result reveals that the laminated fabrics could ease the problem of the poor mechanical property of the Nomex/PTFE membranes in subsequent use. Besides, the abrasion resistance of the Nomex/

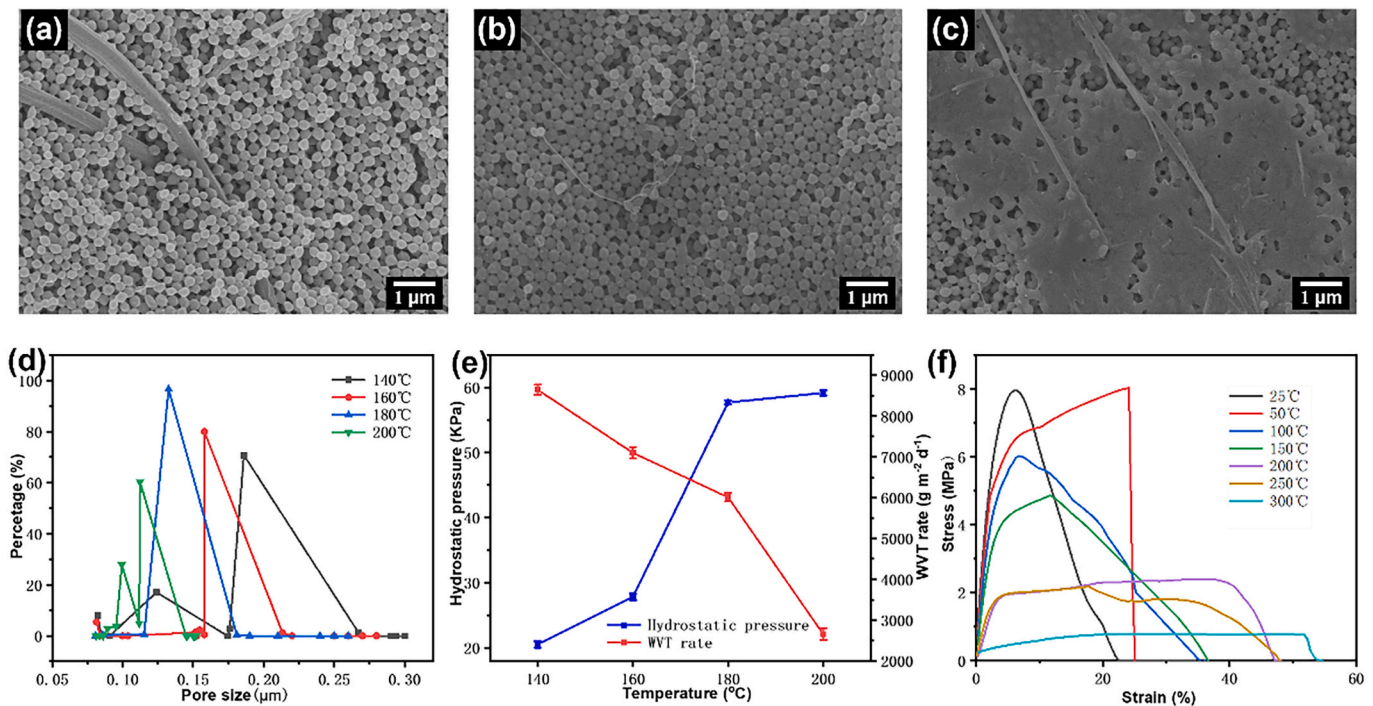


Fig. 4. (a-d) SEM images of the Nomex/PTFE-8% membranes after hot-pressing under 140, 160, 200 °C respectively, (d-e) Pore size distribution, hydrostatic pressure, and WVT rate of the Nomex/PTFE-8% membranes after hot-pressing under 140, 160, 180, 200 °C, (f) The stress-strain diagrams of the Nomex/PTFE-8% membranes under different temperatures.

PTFE membrane was investigated via multicycle loading friction with 200CN weight, as illustrated in Fig. S7a. Significantly, there were no obvious differences in the optical morphology of the membranes after loading friction in 50 cycles, and the microstructure of Nomex/PTFE membrane after 50 cycles of loading friction had no significant change (Fig. S7b and c), revealing their prominent structural stability. To it corresponding was, the Nomex/PTFE membrane after 50 cycles of

loading friction still possessed durable hydrophobicity with almost invariably water contact angle of 137°. As illustrated in Fig. S7d, the membranes after loading friction in 50 cycles demonstrated almost unchanged waterproof/breathable performance with hydrostatic pressure of 58 kPa and WVT rate of 6125 g m⁻² d⁻¹.

Because the Nomex/PTFE-180 membranes displayed a tailored composition and a particular porous structure, they exhibited good

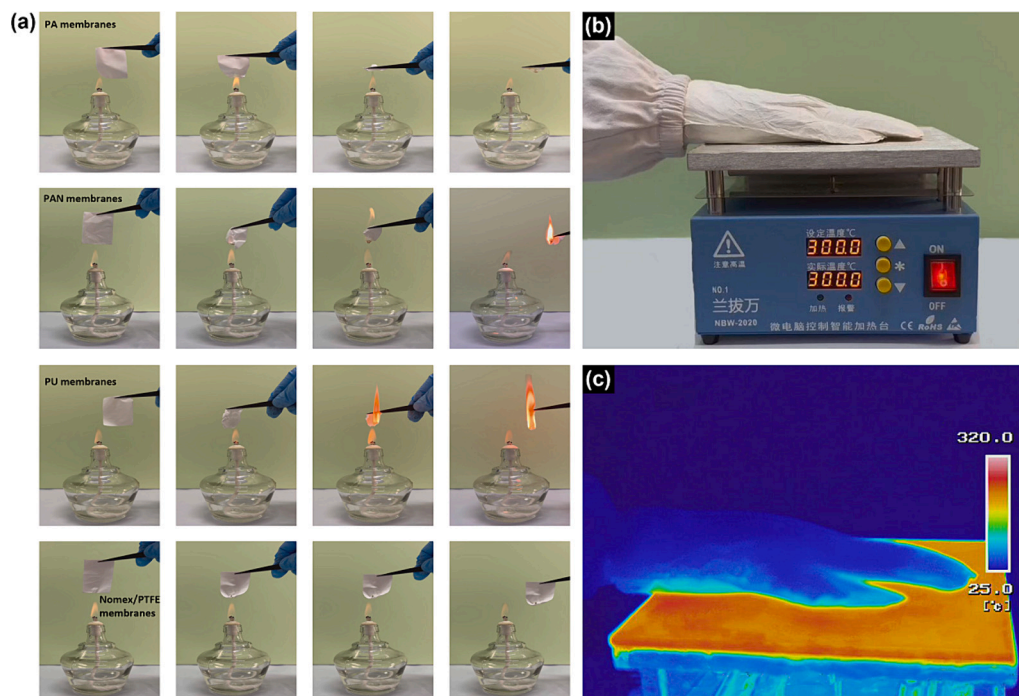


Fig. 5. (a) The optical images of flame contact test with PA membranes, PAN membranes, PU membranes and the Nomex/PTFE membranes, (b-c) The optical image and infrared image of the glove on 300 °C heating stage.

thermostable performance. As a proof of concept for the thermostable performance of the membranes in practical conditions, we implemented the Nomex/PTFE-180 membranes and several other common electrospinning membranes (PA, PAN, and PU membranes) to touch the outer flame of the alcohol lamp, as shown in Fig. 5a. It can be observed that the PA membranes shrank dramatically and melted into viscous fluid immediately when closed to the flame. The PAN membranes and PU membranes burned rapidly when closed to the flame and kept flaming away from it. In contrast, the Nomex/PTFE-180 membranes crimped slightly and maintained structural stability. The Nomex/PTFE-180 membranes would be laminated with other fabrics in practical applications and be difficult to shrink. Meanwhile, we used the Nomex/PTFE-180 membranes to tailor a glove, and the glove showed good flexibility. Besides, we also employed a temperature-controllable stage to evaluate the thermostability of the glove, as illustrated in Fig. 5b. It should also be noted that the glove maintained good structural stability until the temperature was raised to 300 °C. Astoundingly, the glove showed no obvious change after a long time of contact, as displayed in Fig. 5c and Movie S3, suggesting that the Nomex/PTFE-180 membranes could provide high-temperature personal protection to wearers in practical applications.

4. Conclusion

In this work, we have presented an efficient and facile approach to constructing Nomex nanofibrous membranes with a connected PTFE network to enhance the thermostability and thermal-wet comfort of textiles, which showed prominent thermostability, excellent hydrostatic pressure, and a high WVT rate. Originating from the utilization of high-temperature-resistant Nomex and heat-resistant PTFE hydrophobic agents, the fabricated Nomex/PTFE membranes exhibited prominent thermostability. And the thermal property of the Nomex membranes with the other three kinds of hydrophobic agents were also investigated. More importantly, after the hydrophobic modification with PTFE emulsion, the Nomex membranes realized the alteration from weak hydrophobicity to super-hydrophobicity. In addition, the hot-pressing technology has vastly reduced the pore size of the Nomex/PTFE membranes, and the composite membranes obtained a small porous structure that could resist the penetration of liquid water effectively. Notably, the hot-pressing technology causes PTFE nanoparticles to be connected with each other to form the porous network, improving their water repellent without influencing the water vapor transmission. Eventually, the resultant Nomex/PTFE membranes exhibit prominent comprehensive water-repellent and moisture-permeability with a high hydrostatic pressure of 58 kPa, a satisfactory WVT rate of $6008 \text{ g m}^{-2} \text{ d}^{-1}$, and remarkable thermostability to maintain structural stability under 300 °C, suggesting great promise as exceptional candidates for high-temperature personal protection and comfort management. Furthermore, the novel structural design and outstanding performance pave the way for new types of nanofibrous membranes for membrane distillation, oil/water separation, and sewage treatment. [43–46]

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Declaration of generative AI in scientific writing

The authors declare that no AI or AI-assisted technologies were used in the writing process.

CRediT authorship contribution statement

Xi Yu: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis. **Wenxiu Wu:** Data curation, Conceptualization. **Guiying Xu:** Data curation. **Lihuan Wang:** Validation, Supervision, Methodology, Funding acquisition. **Hui Yu:** Validation, Supervision, Methodology, Funding acquisition. **Chi-wai Kan:** Funding

acquisition. **Jianhua Yan:** Validation. **Xianfeng Wang:** Formal analysis. **Ziqiong Wang:** Methodology. **Yeer Wu:** Methodology. **Lingrui Wen:** Methodology. **Qiang Zhou:** Methodology.

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.

Data availability

The data that has been used is confidential.

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