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Development and Performance Evaluation of Polytetrafluoroethylene-Membrane-Based Automotive Cabin Air Filter

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Cite This: *ACS Omega* 2022, 7, 43738−43746

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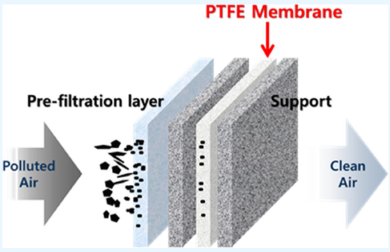
ABSTRACT: A high-efficiency, long-life cabin filter unit is required for the effective purification of the air inside a vehicle. However, conventional cabin air filters that utilize electrostatic effects are less efficient and less effective owing to environmental factors. Polytetrafluoroethylene (PTFE) membranes exhibit a high porosity and surface-to-surface dust-removal performance, and maintain a stable pressure drop, indicating their good potential as filter materials. Therefore, in this study, the use of PTFE membranes for the fabrication of automobile filters and the filtration performance of the filters were examined. To this end, first, the properties of PTFE membranes mainly used in HEPA air conditioning filters and those of membranes used as vehicle cabin filters were compared. Next, the thickness, weight, stiffness, pore size, and filtration performance characteristics of filter media fabricated by blending melt-blown (MB) nonwoven, PTFE membranes, and supporting nonwoven into a total filtration layer were compared and analyzed. Lastly, the environmental change durability performance of the automobile cabin filter based on PTFE membrane and the results of the test after the installation of the filter in a vehicle were demonstrated.



1. INTRODUCTION

Air pollution is an ecological challenge that severely affects human health and life, and one of the most significant contributors to air pollution is particulate matter (PM). PM is a mixture of small particles and water droplets suspended in air, and it consists of various chemical components, inorganic substances (e.g., silicates, sulfates, and nitrates), and organic substances (e.g., organic compounds and carbon elements). PMs are classified based on their aerodynamic diameter and are generally divided into PM10 (diameter < 10 μm), fine PM2.5 (diameter < 2.5 μm), and ultrafine PM0.3 (diameter < 0.3 μm). Typically, PM is produced from industrial and automotive exhaust gases and secondary nitrogen oxides in the atmosphere.[1−6] Given the currently high levels of environmental PM pollution and severe global energy crisis, continuous and increasing research efforts have been devoted to the development of filter materials with a high filtration efficiency that can eliminate particles, while providing ultralow resistance to air to conserve energy.[7]

The adverse health effects of fine dust have attracted attention, thus raising concerns regarding the risk of indoor exposure to high PM concentrations. The primary factor in the exposure to high-concentration PM in the indoor environment of an automobile is the continuous exposure to high-concentration PM emitted from the combustion system. Given the high concentrations of road dust, exposure to PM inside automobile cabins is often very high compared to other outdoor or indoor environments.[8,9] Accordingly, indoor air quality has attracted increasing interest, thus triggering further research on air filters.[10]

Filtration of extremely small contaminants is an important indicator for evaluating the filtration performance of a filter. Small particle contaminants (smaller than 10 μm) and ultrafine particulate contaminants (smaller than 0.3 μm), which endanger the environment and human health, are technically more difficult to filter from air. With the continuous progress of membrane materials science and technology, the emergence of new materials with excellent physico-chemical properties has ushered in new advances in filtration technology.[5]

Some prominent materials, such as polypropylene (PP), polyethylene (PE), spunbond, and polytetrafluoroethylene (PTFE), are considered as promising materials for producing traditional electrostatic electret filters. Among these materials, PP, which exhibits a high wear resistance, chemical resistance, excellent tensile properties, mildew resistance, almost no hygroscopicity, and a negligible moisture recovery rate, is the most commonly used. However, as the cabin air filter is only used for a specific period, environmental factors change, the static electricity effect gradually weakens because of the

Received: July 28, 2022
Accepted: October 25, 2022
Published: November 22, 2022

https://doi.org/10.1021/acsomega.2c04758
ACS Omega 2022, 7, 43738−43746

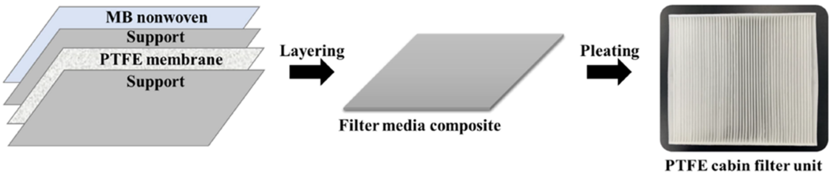


Figure 1. Preparation process of PTFE cabin filter.

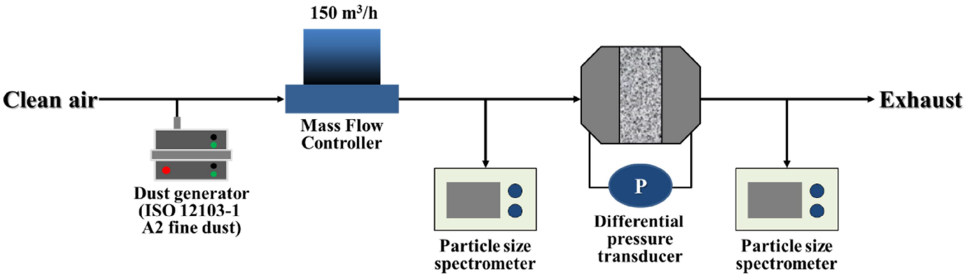


Figure 2. Schematic of the setup of the particulate matter (PM) filtration performance test.

decrease in fountain efficiency, and the filtering effect decreases.[9−12] This is because of the gradual clogging of the filters by PM coating during operation, which considerably increases the air resistance during applications.[13] Thus, the durability and lifetime of filters should be evaluated.

Numerous studies have attempted to improve air filtration technology to overcome the trade-off between the filtration efficiency and pressure drop. Particularly, researchers have adopted diverse approaches, such as developing filter media using nanofibers and analyzing charge methods, to improve the filtration performance of electrostatic filters.[14−16] In addition, filter technologies, such as filter structure optimization and electrostatic interaction enhancement techniques, fiber morphology modification, component hybridization, and interaction-based approaches based on multilayer stacking and charge imposition, have been introduced to improve the performance of air filters.[13,17,18]

Tian et al. designed an electrostatically assisted air filtration device for indoor and vehicle environment air purification and coated a thin layer of polydopamine (PDA) on a PE terephthalate (PET) coarse filter to substantially increase the efficiency air resistance filter life envelope.[19] In addition, Tian et al. developed a multifunctional filter that utilizes polyurethane (PU) foam, which exhibits a very low pressure drop, as a basic filter to further reduce the pressure drop and maintain a high air pollutant removal efficiency.[20] Deng et al. proposed an efficient and breathable air filtration method with a focus on sustainability for the nanofiber membrane material produced by green electrospinning, and reported on bio-based electrospun nanofibers used as a novel eco-friendly air filtration membrane.[5,21]

In this study, a PTFE membrane, which has not been previously used effectively in a cabin filter unit, was applied to address the deterioration of the filter performance of electrostatic filters. Porous PTFE membranes in organic membranes are protected by strong C−C and C−F bonds and a carbon backbone, and they exhibit chemical stability, high thermal resistance, strong hydrophobicity, and high fracture toughness. A uniform spiral cover is formed by electron clouds of fluorine atoms. PTFE membranes can be customized to meet the requirements of various membrane applications, and their high porosity and specific surface area are beneficial for gas−solid separation.[22−26] A PTFE membrane composite fiber filter material is used for surface filtration because of its micropores, superior dust-removal performance, and improved collection efficiency. Furthermore, the proposed PTFE membrane filter material can maintain a stable pressure drop compared to standard filter materials.[27−30]

In this work, a PTFE membrane was applied to a cabin filter unit, and the optimal manufacturing conditions were determined, and the filter performance was analyzed. Furthermore, commercially-used electrostatic cabin filter unit and the proposed cabin filter unit with PTFE membrane were treated in 100 °C, water, and isopropyl alcohol (IPA) environments to evaluate changes in their filtration efficiency and pressure drop, and compare their durability. The results of this study provide insights into the development of high-efficiency ePTFE-based cabin filter units with improved durability.

2. EXPERIMENTAL SECTION

2.1. Materials. Melt-blown (MB) nonwoven media samples were produced from commercial grade PP. PP resin (melt index: 1200 g/10 min) was purchased from LG Chem Co., Ltd. (Seoul, Korea). A melt-blowing pilot line obtained from Clean and Science Co. (Seoul, Korea) was used. The PTFE membrane used in this study was produced by Micro-One Co. (Cheonan, Korea). Low-melting PET and a nonwoven PE/PET blend were used as the PTFE support. Figure 1 shows the preparation process of PTFE cabin filter.

2.2. Characterization. The physical properties of the PTFE membrane and filter media composite, such as thickness, pore size, and air permeability, were evaluated. The thickness was determined using a thickness tester (no. 20465, Mitutoyo Co., Japan) according to the ASTM D 5729-9 standard. The pore size distributions of the specimens were measured using a capillary-flow porometer (CFP-1500-AEX, PMI Inc., Ithaca, NY, USA) according to the ASTM F316-03 standard. Air permeability was measured using an air permeability tester (FX3300, TexTest Instruments, Switzerland). Surface images of the PTFE membrane after sputter coating with osmium (Os) were obtained using field emission scanning electron microscopy (FE-SEM; SU8010, Hitachi Co., Tokyo, Japan) operated at an acceleration voltage of 10 kV.

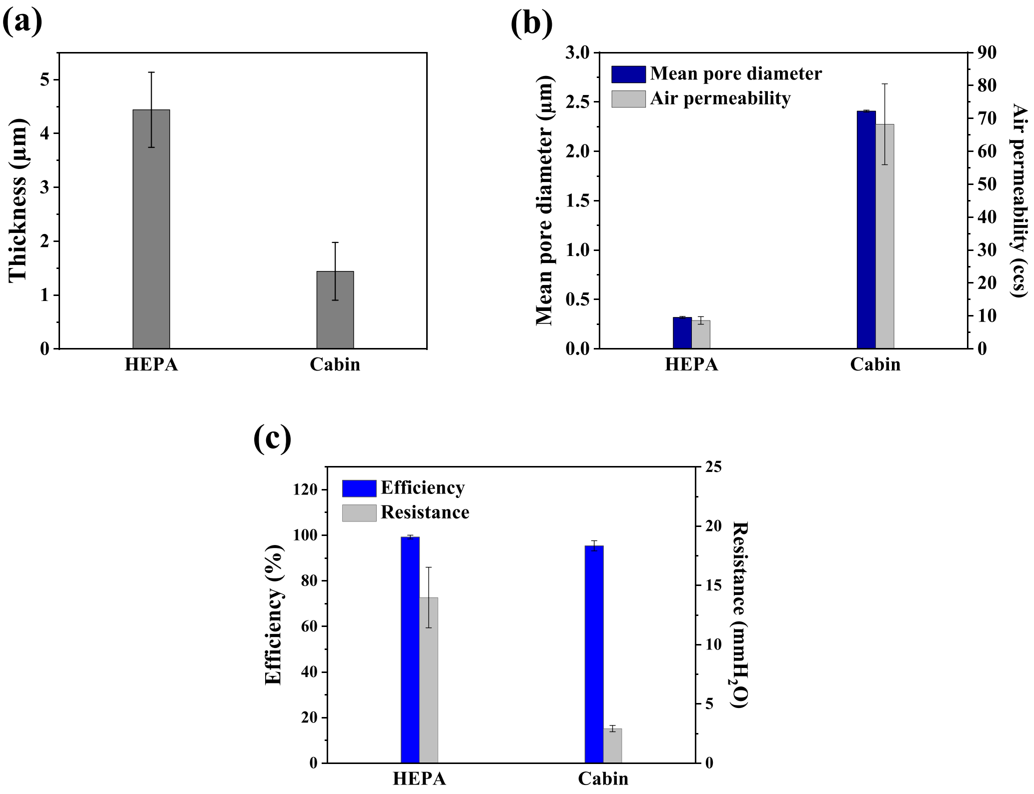


Figure 3. Physical and filter properties of PTFE membrane used in HEPA and cabin filters: (a) thickness, (b) mean pore diameter and air permeability, and (c) efficiency and resistance.

2.3. Filtration Performance Test. The filtration efficiency and resistance of the PTFE membrane were measured using an automated particulate filtration tester (TSI Inc., Shoreview, MN, USA). Sodium chloride (NaCl) was selected as the experimental particle and represented aerosol dust. The tests were based on the EN 1822 standards.

Figure 2 shows the setup of the filtration test used to measure the PM filtration efficiency of the test cabin filter unit according to the DIN71460 part 1 standard using a cabin air filter test system (PAF 111; Topas GmbH, Dresden, Germany). ISO 12103-1 A2 dust particles were generated at a concentration of 20 mg/m^3_{air} using a solid aerosol generator (SAG410; Topas GmbH) and carried using filtered dry air at a flow rate of 150 m^3/h. The dust filtration efficiencies (η) of the test cabin filter units were calculated using the following equation:

$$\eta = 1 - C_{outlet}/C_{inlet} \tag{1}$$

where C_{outlet} and C_{inlet} are the particle concentrations (particles/cm^3_{air}) of ISO 12103-1 A2 dust aerosols at the filter inlet and outlet, respectively. The size and number concentrations of the dust aerosols were measured using a particle size spectrometer (LAP321; Topas GmbH). The pressure drops of all test cabin filter units were measured using pressure transmitters (FCX-AII; Fuji Electric S.A.S., Clermont-Ferrand, France). All measurements were repeated at least three times under each experimental condition.[8]

Ideally, the filter media should exhibit a high filtration efficiency (η) and a low pressure drop (Δp). A low pressure drop is desirable for maintaining low operating costs. Quality factor (QF) is the commonly used quantitative criterion for comparing fibrous filters. The QF was calculated using the following equation:

$$\mathrm{QF} = -\ln(1 - \eta)/\Delta p \tag{2}$$

In addition, the dust holding capacity of the filter was tested according to the ISO 501118 standard and was obtained by measuring the dust load up to 2.5 times of the initial differential pressure.[31]

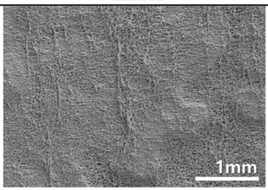
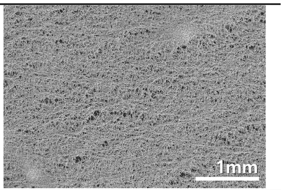
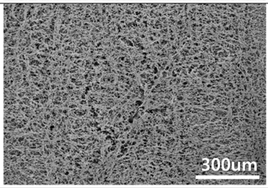
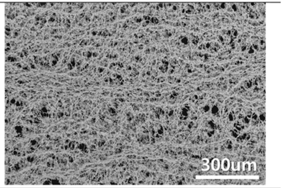
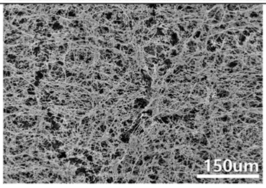
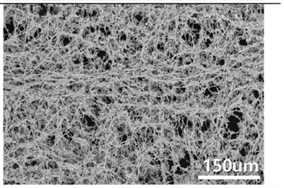
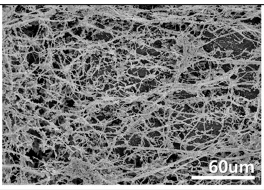
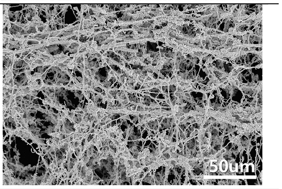
3. RESULTS AND DISCUSSION

3.1. Physical and Filter Properties of PTFE Membrane. Figure 3 shows the physical and filter properties of the PTFE membrane for HEPA and cabin filters. The properties and filter performance of the PTFE membrane for cabin filters, which were sufficiently thin for increased efficiency without an excessive increase in the differential pressure, were confirmed by comparing them to those of a PTFE membrane for HEPA filters (most commonly used). The thicknesses (Figure 3a) of the HEPA and cabin PTFE filters were 4.44 and 1.44 μm, respectively (i.e., the latter was approximately 68% thinner). In addition, the average pore sizes (Figure 3b) of the HEPA and cabin PTFE filters were 0.318 and 2.407 μm, respectively, whereas the corresponding air permeability values were 8.606 and 68.218 ccs, respectively. These values were inversely proportional to the filter thickness and directly proportional to the pore size, which may be attributed to the "stretching process" performed to reduce the thickness of the cabin membrane.[32,33]

Based on the results of the filter performance evaluation conducted using a TSI 8130 automated filter tester (Figure 3c, TSI, Inc.), the efficiencies of the HEPA and cabin PTFE membranes were 99.2275 and 95.3886%, respectively, indicating that the efficiency of the HEPA membrane was slightly higher. However, in terms of resistance, the PTFE filter exhibited improved filter performance, in which the membrane pressure of the cabin filter (2.91 mmH_2O) was approximately 80% lower than that of the HEPA filter (13.98 mmH_2O).

Table 1 summarizes the SEM results of the HEPA and cabin PTFE filter membranes. The surface structures of these membranes were observed using SEM to identify the membrane shape, node, and fibrillation tendency.

Table 1. SEM Images of Various Types of PTFE Membranes

	HEPA	cabin
×300		
×1000		
×2000		
×5000		

Both membrane types were observed to exhibit porous structures, as well as fibrils and nodes, which were formed through stretching.[23,34,35] However, the nodes and fibrils formed in the cabin membrane were thicker than those formed in the HEPA filter (dense thin fibrils were formed in the HEPA filter membrane).

3.2. Analysis of Cabin Filter Media Composites. A filter media composite was prepared using MB nonwoven as a prefiltration layer to improve the cabin filter performance. The optimal filter media composite manufacturing conditions were identified by comparing the dust filtration effect as a function of the MB weight (10, 18, and 30 gsm).

With an increase in the MB weights, the weight and thickness of the filter media composite increased proportionally (Figure 4a). Stiffness is one of the primary physical characteristics of cabin filter units.[36] In terms of stiffness (Figure 4b), the 18-gsm composite exhibited the highest value in the machine direction (MD) and cross direction (CD), regardless of weight.

Typically, permeability increases with an increase in porosity. In this study, both the average pore size and air permeability decreased with an increase in the MB weight to 10, 18, and 30 gsm (Figure 4c). Pore size affects air permeability.[37] Furthermore, the comparison of the filter performance of the three types of filter media composites revealed that their efficiency exceeded 99% (Figure 3d). The differential pressures of the 10, 18, and 30 gsm samples were 3.4, 2.9, and 5.5 mmH_2O, respectively, indicating that the 18-gsm MB filter medium exhibited the lowest differential pressure. Differential pressure affects the filter performance—the filter performance and filter lifespan increase with a decrease in the differential pressure.[38−40] Thus, the most suitable filter medium for manufacturing the cabin filter unit was the 18-gsm MB composite, which was characterized by the lowest differential pressure and high stiffness.

3.3. Filtering Performance of PTFE Cabin Filter Unit. *3.3.1. Environmental Durability and Filter Property.* In this study, a PTFE membrane-based cabin filter unit was fabricated, and its filtration efficiency after exposure to low temperature and high humidity was evaluated to determine the effect of incoming air conditions on its performance. Figure 5a shows a photograph of the manufactured PTFE-based cabin filter unit, and the environmental conditions of this circulation test were set by referring to the environmental stability test method outlined in SPS-KACA014−0144, a Korean cabin air filter test standard (Figure 5b). The test standards specified a minimum filtration efficiency of 50% for dust particles (0.3−0.5 μm) for cabin air filters.

For commonly used electrostatic filters, the presence of water molecules or exposure to various air conditions reduces the number of ions and electrons not properly bound to the surface and reduces the filtration efficiency with a change in the environmental condition.[8,41] Our PTFE-based cabin filter exhibited 100% efficiency in the particle range of 1.0−10.0 μm and high efficiency of above 99.8% after three cycles in the environmental durability performance evaluation test (Figure 5c).

Figure 5d shows the QF values of the cabin filter and filter after three cycles. The cabin filter device exhibited high QF values in the particle range of 1.0−10.0 μm. After three cycles in this range, the manufactured sample (MS) exhibited a QF of approximately two times higher. This result indicates that the PTFE membrane most consistently achieved the best air purification performance in the coarse filtration process.

3.3.2. Comparison between Fabricated PTFE Cabin Filter and Commercial Electric Cabin Filter. A durability test was performed to evaluate the effects of high temperature and solvents on the filtration efficiency of the MB electret fabric composite (i.e., commercial sample (CS)) and PTFE membrane composite (i.e., MS). The results demonstrated that the filtration efficiency decreased as the temperature increased (100 °C), and decreased in the presence of water and IPA (Figure 6a).

The efficiency of the cabin filters constructed using PTFE membranes was above 99% across all particle size ranges, even at 100 °C.[42] In contrast, commercial electrostatic cabin filters exhibited an efficiency of 84.7% for the dust particle range of 0.3−0.5 μm at 100 °C, indicating a degradation in its efficiency. The results of the electrostatic filter are similar to those reported in the literature, indicating that the filtration efficiency decreased as the temperature increased, which may be related to changes in the surface structure of the filter material due to the electret temperature.[43] After immersion in water, both filters maintained a high efficiency with a negligible decrease in the filtration efficiency. However, after immersion in IPA, the filtration efficiency of the filters decreased sharply

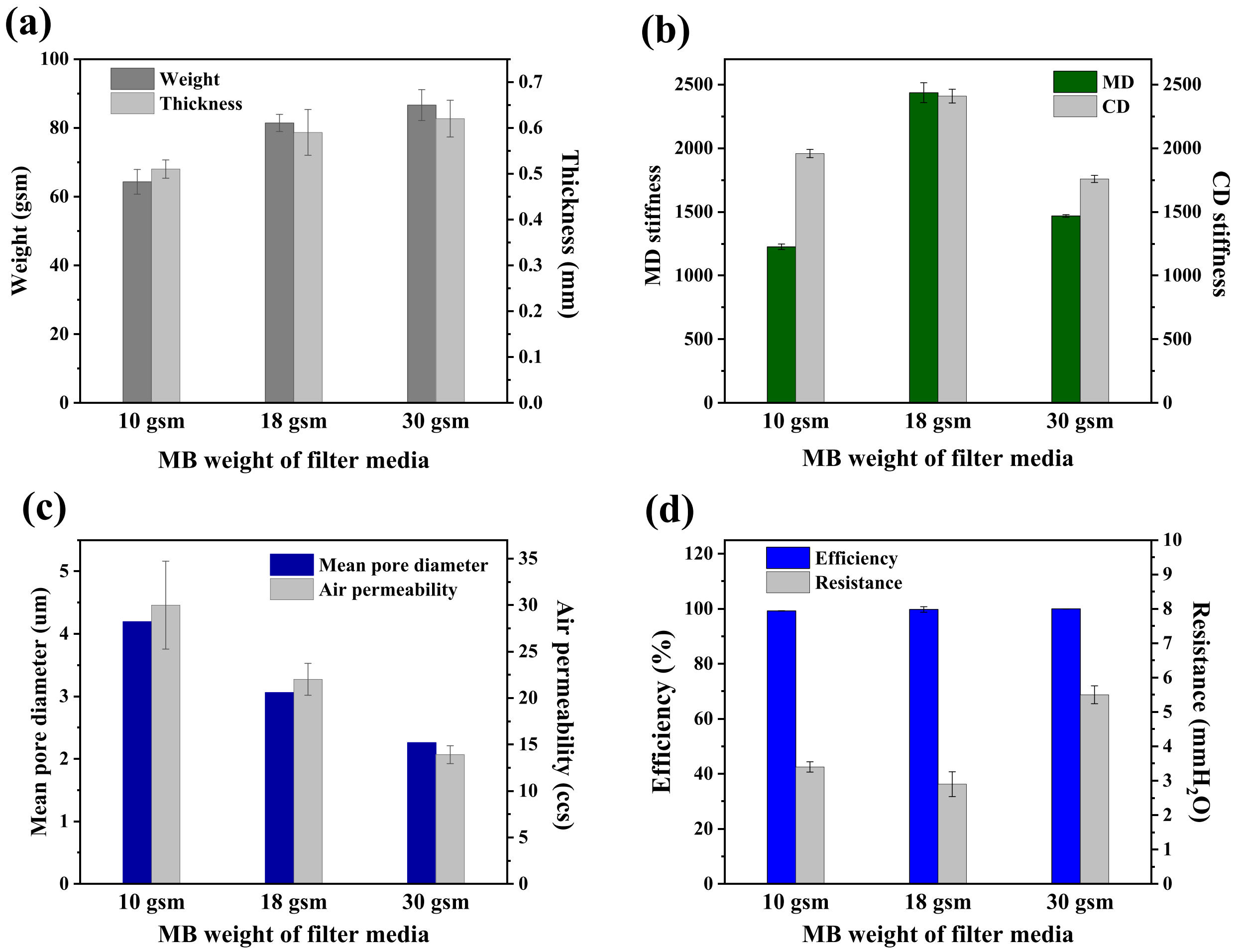


Figure 4. Physical and filter properties of filter media composites: (a) weight and thickness, (b) stiffness, (c) mean pore diameter and air permeability, and (d) efficiency and resistance.

in the particle range of 0.3−0.5 μm, and the efficiencies of the cabin filter and commercial cabin filters stabilized at 82.5 and 41%, respectively. The considerable decrease in the filtration efficiency of the electret filter layer could be attributed to the weakening of the electrical effect when it was immersed in a solvent.[8,44−46]

Figure 6b shows the calculated QF while considering the filtration efficiency and differential pressure after the durability evaluation. The QF of the MS under high-temperature conditions was approximately 0.05 higher than that of the CS. The QF of the MS in water was approximately twice that of CS in the 1.0−5.0 μm particle range. The IPA results revealed that the QF of the MSs increased with an increase in the particle size. Consequently, samples manufactured at a high temperature, and in water and IPA, exhibited higher QFs than CSs. These results suggested that the cabin filter unit constructed using the PTFE membrane was more durable against high temperature, water, and IPA than commercially available electrostatic cabin filters.

3.3.3. Filter Properties after Driving by Installing PTFE Cabin Filter. Figure 7 shows the efficiency (a), QF (b), and differential pressure of the PTFE cabin filter after one month of operation, and its dust loading capacity measurement. To determine whether the PTFE cabin filter maintained an excellent filter performance even in real-world environments, the cabin filter performance was evaluated after installing it on a real vehicle and driving a distance of 2336 km for one month. The cabin filter maintained efficiency of above 99% in all particle ranges (0.3−10.0 μm) even after operation for one month. Particularly, the efficiency was maintained close to 100% in the 3.0−10.0 μm particle range. The performance degradation of the PTFE cabin filter was 0.6% for the 0.3−0.5 μm particle range, 0.4% for the 0.5−1.0 μm particle range, and 0.1% for the 1.0−3.0 μm particle range. It was confirmed that almost no deterioration in filter efficiency occurred. A previous study reported a decrease in the performance of the filter to 58.7% under weak conditions when driving on road for up to 10 months with the existing blackout cabin filter installed.[8]T-Table 2 shows the dust holding capacity of the PTFE cabin filter. The dust holding capacity of the PTFE cabin filter unit decreased by about 27% after one month of driving. It was believed that this could be attributed to various dust and foreign matter accumulated in the filter while driving. Even after running for one month, the differential pressure increased by only approximately 14.6% compared to that of the conventional filter, confirming that it maintained an excellent performance.

Although it is difficult to make an absolute comparison because it was not driven in the same period, it was confirmed that the PTFE cabin filter exhibited improved performance than the existing electrostatic cabin filter. Therefore, it is expected that PTFE membranes can be used as a long-life, high-efficiency filter if applied in cabin filters.

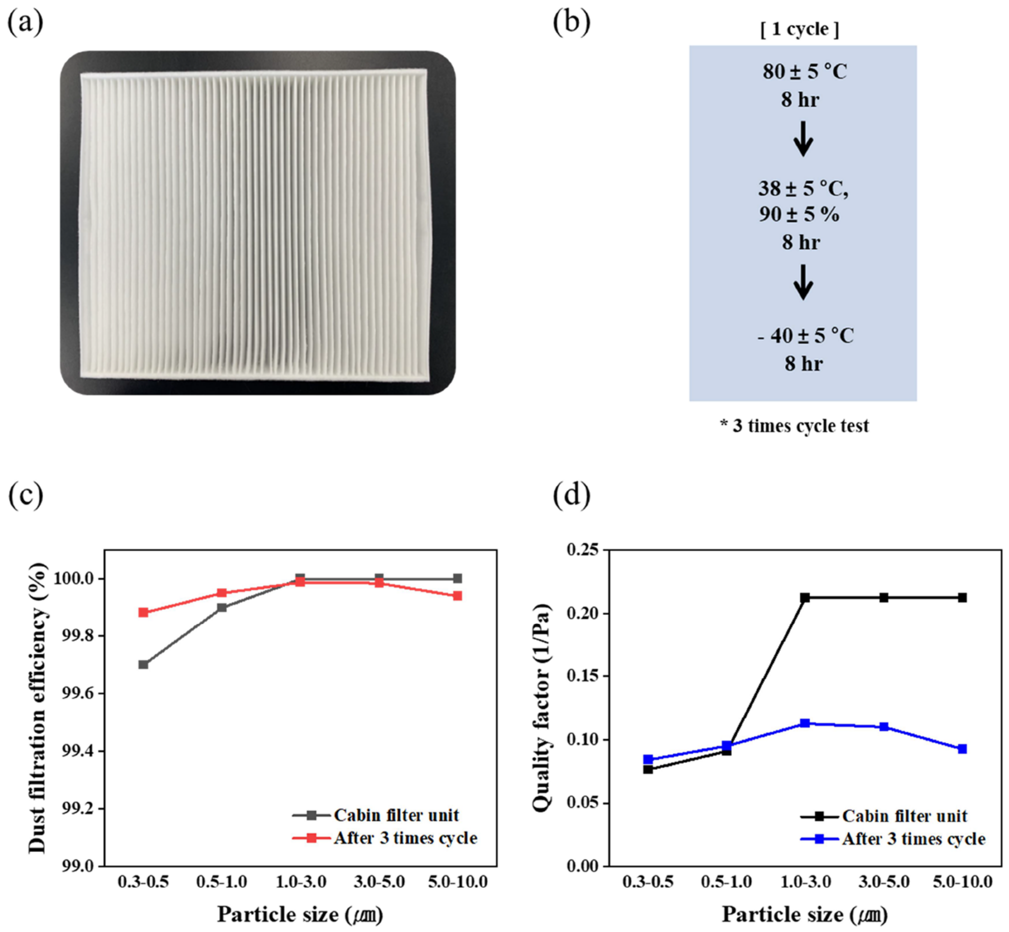


Figure 5. Filtration performance of cabin filter unit after environmental changes: (a) image of manufactured cabin filter unit, (b) test conditions with environmental change cycle, (c) dust filtration performance of cabin filter after test cycles, and (d) QF of cabin filter after test cycles.

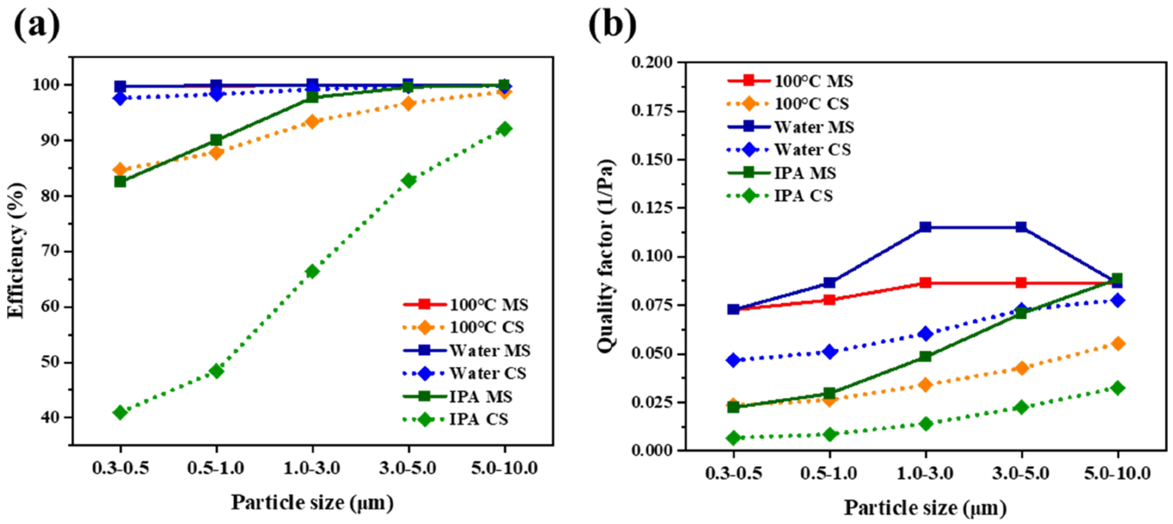


Figure 6. Durability of cabin filter unit: (a) efficiency and (b) QF.

4. CONCLUSIONS

The PTFE membrane used in existing HEPA filters for air conditioning and the PTFE membrane manufactured in this study for application in a cabin filter both exhibited high air permeability and low differential pressure. The properties of the filter media composites composed of MB, support, and membrane were compared based on the MB weight. The results revealed that the sample containing 18-gsm MB was the most suitable composite for manufacturing a cabin filter unit because of its low differential pressure, high efficiency, and high rigidity. The manufactured cabin filter unit exhibited stellar filter performance even in low-temperature and high-humidity environments.

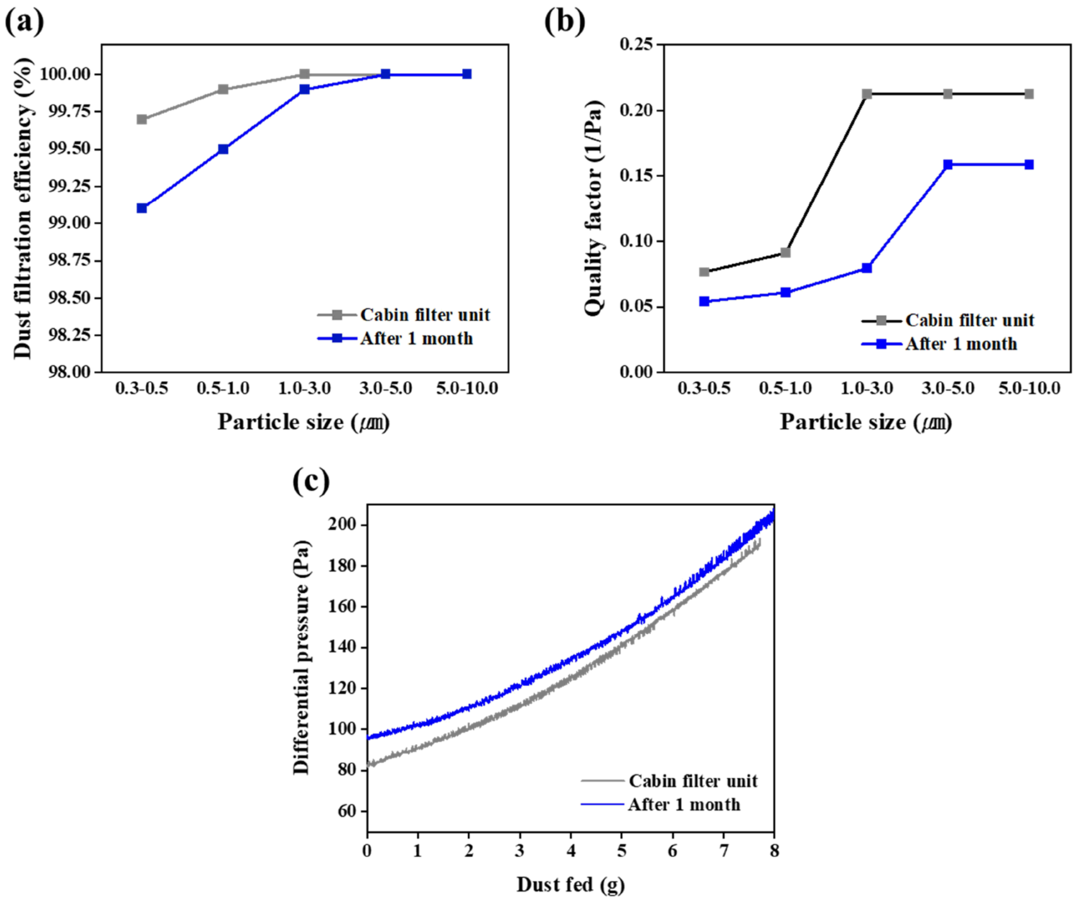


Figure 7. Durability of cabin filter unit: (a) efficiency, (b) QF, and (c) differential pressure during dust loading capacity test.

Table 2. Dust Holding Capacity of PTFE Cabin Filter

	cabin filter unit	after 1 month
dust holding capacity (g/m^2)	15.6	11.4

Furthermore, the comparative durability test of the fabricated filter and existing commercial electrostatic filter revealed that the efficiency of the fabricated PTFE-based cabin filter exceeded 99% in high temperature and water and 80% in IPA. In contrast, the efficiency of the electrostatic cabin filter exceeded 97% in water but decreased to 84% at high temperatures and 40% in IPA. Thus, this study confirmed the high performance of the proposed PTFE membrane-based cabin filter unit as a high-efficiency, long-life filter for automotive air purification.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research was funded by the Technology Innovation Program (20010674, Development of ultrahigh performance (6N) HEPA filter using ePTFE membrane for energy efficiency improvement) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea).

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