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Critical Properties of Charged Filter Membranes for Their Applications in Filtration

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***Abstract*—**Fiber filter membranes have a high surface area-to-volume ratio and high porosity making them ideal for various filtration and separation applications. Using the conventional filter membrane, a filtration efficiency of > 95% can be achieved. Specific applications such as air and fuel filtration require nearly 100% filtration efficiency, which is harder to achieve using conventional filter membranes. To achieve high filtration efficiencies additional costs are incurred due to increasing the cost of membrane and operating cost. Due to the simultaneous electrostatic attraction and mechanical capture, the electret filters have shown nearly 100% filtration efficiency. This article presents an overview of the charged filter membrane, its applications, and a discussion on factors contributing to increasing charge.

***Keywords*—**Charged fiber membrane, piezoelectric materials, filtration, polymeric materials.

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I. Introduction

ELECTRET filters are widely studied to enhance the filtration performance of the fiber membrane. The electret filters [1] have surface charges on the filter membrane and have shown nearly nine times lower air resistance than a conventional air filter while maintaining high separation efficiency. Particle separation occurs based on filtration mechanisms as shown in Fig. 1. In filter membranes where the mechanical capture is dominant, the particles are captured through diffusion, interception, and inertial impaction. In applications for particle filtration, the electrostatic forces dominate an electret filter. After a certain time, the electrostatic forces weaken due to particle accumulation on the surface of the fibers resulting in a drop in filtration efficiency. At this point the mechanical capture takes over and maintains a high efficiency. This combined electrical and mechanical action of the electret filters is of potential interest in various filtration applications.

II. Charged Filter Membrane

Electret filters [3] can be produced by triboelectric charging (polarization of filter membrane), corona charging, and electrostatic charging. Triboelectric charging uses the exchange of charge between two contacting materials. It is appropriate for charging fibers with dissimilar electronegativities. Corona charging is the resultant ion drift under the influence of an external electric field from a point electrode at high potential and a collecting electrode at low potential. It is suitable for charging monopolymer fiber or fiber blends of fabrics. Materials charged by induction during fiber spinning process combine the charging of the polymer and the spinning of the fibers as a single-step process where surfaces can become charged including absorption of ions, protonation, deprotonation, and dielectric charge accumulation with the application of an external field.

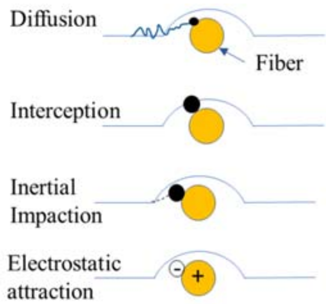

Fig. 1 Mechanism of filtration [2]

Tsai et al. [4] and Brown et al. [2] discuss electret [5] materials. An electret material is a dielectric material exhibiting real charge electret and oriented dipole electret. A real charge electret has an excess of charges on the dielectric surface and within the dielectric volume. Oriented dipole electret contains an electret that has oriented dipoles. The alignment of the dipoles determines the true polarization, with positive and negative charges present near the two surfaces of the dielectric.

Ion exchange membranes are charged electrically conductive membranes. The ion exchange membranes are sub-classified as anionic exchange membranes, cationic membranes, and bipolar membranes. Anionic type ion-exchange membranes transport anions and reject gases such as hydrogen and oxygen from passing through. Cationic type ion-exchange membranes conduct cations to pass through and reject gases such as hydrogen and oxygen to pass through. A bipolar membrane is an ion-exchange membrane that is made up of two polymer layers, with one layer being permeable to anions and the other to cations. The ion-exchange membranes are fabricated with a coating or cross-linking process. The ion-exchange membranes can be classified based on the materials into membranes containing organic materials, membranes containing inorganic materials, and membranes containing perfluorocarbon polymers.

III. Application of Charged Membranes in Filtration

The charged filter membranes with interconnected pore

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structures are useful for a wide range of applications [6], [7] needing high capture efficiency. In many applications, fiber membranes have a low basis weight and corresponding weak mechanical strength due to the small fiber diameter, low mass, and random alignment of fibers. To make the membranes free-standing, the basic weight of the membranes needs to increase, this will improve the tensile properties of the fiber membrane due to an increase in the number of interconnected fibers. The increase in basis weight leads to a smaller pore diameter limiting the particle separation and increasing the resistance for fluid flow.

The type of polymeric material used in the fabrication of the charged fiber membrane depends on the end application. A few of the common applications of the filter membrane as shown in Fig. 2 are in filtration, separations, water treatment, biomedical applications, and fuel cells.

Charged filter membranes are widely used in the manufacturing of air filter membranes. With the ease of manufacturing and fabrication of filter elements using the charged filter membranes, these charged filter membranes show high particle capture efficiency. Charged filter membranes show high filtration efficiency due to mechanical capture and electrostatic attraction.

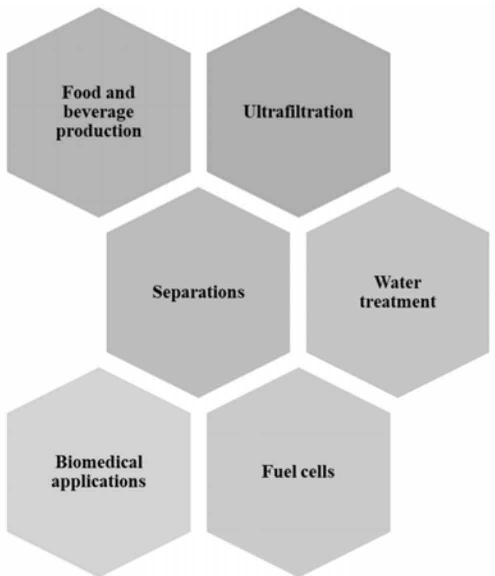

Fig. 2 Applications of the charged filter membrane

Applications of the ion exchange membranes are in the production of drinking water and wastewater treatment. These membranes are produced depending on the requirement of electric resistance and water permeability and have the advantage of reducing fouling.

IV. Critical Membrane Properties

A. Material Properties

Suitable materials for the electret filters are piezoelectric materials. Piezoelectric materials generate electrical charges in response to applied mechanical stress. Polymeric materials such as Teflon, Polyfluoroethylene propylene (FEP) Polytetrafluoroethylene (PTFE), Polyvinylidene fluoride (PVDF), and Polyacrylonitrile (PAN) were studied [8], [9] for applications in filtration and separations.

Piezoelectricity refers to the electric charge accumulation on materials such as crystals, ceramics, and biological materials under mechanical stress. This is a reversible process, the materials exhibiting the piezoelectric effect show the internal generation of a mechanical strain resulting from an applied electrical field.

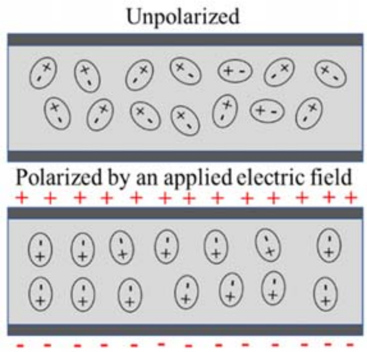

Fig. 3 The concept of a dielectric material is initially nonpolarized in the absence of an electric field and polarized by an applied electric field [10]

Fig. 3 shows a dielectric material with randomly oriented polar molecules when no electric field is applied. When an electric field is applied the dipoles orient to polarize the molecule. PVDF and Polyamides are polymeric materials that exhibit piezoelectricity. Polymeric piezoelectric materials due to their high flexibility, tractable processing, good chemical stability, and readily tunable properties make the piezoelectric polymers attractive for many applications and are of current scientific interest. Polarization of polymeric materials finds applications in electronic devices and medical instruments.

Polymeric materials such as piezoelectric PVDF can be easily fabricated by the electrospinning process and these fibers can be heated and stretched to align the atomic groups in the PVDF molecular structure resulting in the dipole moment in the presence of the applied electric field. Because of this advantage, the PVDF polymer is widely studied for producing a fibrous membrane. This polymer also exhibits polymorphism with common crystalline phases α, β, γ, ε, and δ. Ruan et al. [11] discuss five different crystalline phases α, β, δ, ε, and γ exhibited by PVDF bulk materials. The electronegativities of the hydrogen and fluorine atoms in a carbon molecule naturally give them opposing positive and negative charges, respectively. Yousry et al. [12] study the mechanism for achieving high-performance functional materials using polymeric piezoelectric PVDF material. The PVDF molecule has been of research interest for developing a charged filter membrane [13]-[17]. Two-stage poling of the PVDF molecule is studied by Shu et al. [18] and Lolla et al. [19]. The resulting charged membrane had a higher β crystalline phase resulting in higher polarized charges.

The influence of the feed rate and conductivity on the electrospinning jets of PAN solution was studied by Fallahi et al. [20]. The effect of different composition ratios, temperatures, and electric fields on the polyaniline-polyacrylonitrile blends was studied by Raeesi et al. [21].

TABLE I
VARIABLE PARAMETERS DURING POLARIZATION

Parameter	Electric field	Temperature	Stress
Variables	Intensity of electric field	Constant	Uniaxial normal stress
	Direction of electric field	Ramping rate	Isotropic stress
	Poling time	Dwelling time	Cylindrical stress

Uniaxial stretching of the poly(vinyl alcohol) electrospun nanofiber was studied by Yano et al. [22] by evaluating the macroscopic orientation and microscopic crystallite and molecular chain orientation. Ahmed et al. [23] reviewed the nanofibrous membrane and the microporous membrane to study the parameters that affect the production of fibers and the impact on the mechanical properties and applications of the fibrous membranes. Hence, polymeric material plays a critical role in fabricating a charged filter membrane.

B. Structural Properties

A charged filter membrane needs to have an optimized fiber diameter, porosity, and mechanical strength. Various process conditions affect the filter membrane formation. Filter membranes were typically made up of fibers collected in randomly aligned directions. The random orientation of the fibers and low basis weight results in relatively low mechanical strength. Furthermore, one of the effective methods to charge piezoelectric fibers such as PVDF is by stretching and poling the fibers. By stretching the electrospun fiber membrane, many of the fibers that were randomly oriented may or may not orient in the direction of the stretch resulting in no stretch of the fibers. Also, during stretching, the fibers may re-position relative to each other instead of stretching. Hence, the action of the stretch on the randomly oriented fiber mat was not as effective at creating the piezoelectric effect as one would expect from the intrinsic material property. To improve the effectiveness of the stretch, ideally, the fibers should be more closely oriented in the stretch direction. Teo et al. [24] discuss the progress in electrospinning techniques for the production and construction of various nanofiber assemblies. By manipulating the electric field and collection geometry [25]-[30] several approaches have been developed to control the deposition of nanofibers to obtain continuous electrospun nanofibers. Potentially, if the electrospun fibers were formed into yarns instead of the membrane, then more of the fibers would be aligned along the yarn axis. Production of nanofiber yarns has gained attention as they show significant improvement in the alignment of nanofibers and the mechanical properties by making some design modifications to the electrospinning setup.

Bokka et al. [31] studied the orientation of fiber yarns and its influence on the charge per unit mass. The Fraction of β phase [32] of the aligned fiber yarn was 76% compared to the 48% in the randomly oriented fiber membrane. Additional post-processing steps to polarize the fiber yarns showed a very slight change in charge on the post-processed fiber yarns. It was observed that a high dipole rotation achieved in the liquid phase of the fiber yarn formation caused by the stretching and twisting of fiber was more effective in increasing the charge than the post-polarization process where all the fibers were in solid form. This indicates that the structural properties of the fibers are also crucial for fabricating a highly charged fiber membrane.

Some of the desired properties of the ion-exchange membranes are low electrical resistance, high chemical stability, good mechanical stability, and high selectivity for counterions and impermeable to the co-ions.

V. CONCLUSION

The polymer material and structural properties of the filter membrane are critical factors that enhance the charge on the filter membrane. The orientation of the fibers is shown to impact the charge on the filter membrane. It was observed that the process of producing fiber yarns with piezoelectric PVDF material had a higher charge value per mass for the yarns than post-treated membranes for polarization. The polymeric material and structural properties were summarized to fabricate a charged filter membrane with a high charge per unit mass. The highly charged membrane can be used for various filtration and separation applications.

REFERENCES

[1] J. van Turnhout, W. J. Hoeneveld, J.-W. C. Adamse, and L. M. Van, “Electret Filters for High-Efficiency and High-Flow Air Cleaning,” *IEEE Transactions on Industry Applications*, vol. IA-17, no. 2, pp. 240–248, Mar. 1981.
[2] R. C. Brown, *Air Filtration*. Pergamon, 1993.
[3] G. M. Sessler, *Electrets*. Springer Science & Business Media, 2006.
[4] P. P. Tsai, H. Schreuder-Gibson, and P. Gibson, “Different electrostatic methods for making electret filters,” *Journal of Electrostatics*, vol. 54, no. 3–4, pp. 333–341, Mar. 2002.
[5] D. R. V, “Types of purification technology,” *Air Purification*, Oct. 17, 2017. https://airpurificationweb.wordpress.com/2017/10/17/types-of-technology/ (accessed Jan. 20, 2024).
[6] J. Fang, H. Niu, T. Lin, and X. Wang, “Applications of electrospun nanofibers,” *Science Bulletin*, vol. 53, no. 15, pp. 2265–2286.
[7] N. Bhardwaj and S. C. Kundu, “Electrospinning: A fascinating fiber fabrication technique,” *Biotechnology Advances*, vol. 28, no. 3, pp. 325–347, May 2010.
[8] Q. Zhang, D. Hu, Y. Li, and C. Yang, “Positively charged fibrous membrane for efficient surfactant stabilized emulsion separation via coalescence,” *Journal of Environmental Chemical Engineering*, vol. 9, no. 6, pp. 106524–106524, Dec. 2021.
[9] W. W.-F. Leung and Q. Sun, “Charged PVDF multilayer nanofiber filter in filtering simulated airborne novel coronavirus (COVID-19) using ambient nano-aerosols,” *Separation and Purification Technology*, vol. 245, p. 116887, Aug. 2020.
[10] Dielectrics,” *hyperphysics.phy-astr.gsu.edu*.http://hyperphysics.phy-astr.gsu.edu/hbase/electric/dielec.html#c1 (accessed Jan. 20, 2024).
[11] L. Ruan, X. Yao, Y. Chang, L. Zhou, G. Qin, and X. Zhang, “Properties and Applications of the β Phase Poly(vinylidene fluoride),” *Polymers*, vol. 10, no. 3, p. 228, Feb. 2018.
[12] Y. M. Yousry, K. Yao, S. Chen, W. H. Liew, and S. Ramakrishna, “Mechanisms for Enhancing Polarization Orientation and Piezoelectric Parameters of PVDF Nanofibers,” *Advanced Electronic Materials*, vol. 4, no. 6, p. 1700562, Apr. 2018.
[13] X. Cai, T. Lei, D. Sun, and L. Lin, “A critical analysis of the α, β and γ phases in poly(vinylidene fluoride) using FTIR,” *RSC Advances*, vol. 7, no. 25, pp. 15382–15389, 2017.
[14] G. Zhong, L. Zhang, R. Su, K. Wang, H. Fong, and L. Zhu,

"Understanding polymorphism formation in electrospun fibers of immiscible Poly(vinylidene fluoride) blends," *Polymer*, vol. 52, no. 10, pp. 2228–2237, May 2011.

[15] A. Baji, Y.-W. Mai, S.-C. Wong, M. Abtahi, and P. Chen, "Electrospinning of polymer nanofibers: Effects on oriented morphology, structures and tensile properties," *Composites Science and Technology*, vol. 70, no. 5, pp. 703–718, May 2010.

[16] Seok Ju Kang *et al.*, "Spin cast ferroelectric beta poly(vinylidene fluoride) thin films via rapid thermal annealing," *Applied Physics Letters*, vol. 92, no. 1, Jan. 2008.

[17] A. Salimi and A. A. Yousefi, "Analysis Method," *Polymer Testing*, vol. 22, no. 6, pp. 699–704, Sep. 2003.

[18] H. Shu, C. Xiangchao, L. Peng, and G. Hui, "Study on Electret Technology of Air Filtration Material," *IOP Conference Series: Earth and Environmental Science*, vol. 100, p. 012110, Dec. 2017.

[19] D. Lolla, M. Lolla, A. Abutaleb, H. Shin, D. Reneker, and G. Chase, "Fabrication, Polarization of Electrospun Polyvinylidene Fluoride Electret Fibers and Effect on Capturing Nanoscale Solid Aerosols," *Materials*, vol. 9, no. 8, p. 671, Aug. 2016.

[20] D. Fallahi, M. Rafizadeh, N. Mohammadi, and B. Vahidi, "Effects of feed rate and solution conductivity on jet current and fiber diameter in electrospinning of polyacrylonitrile solutions," *e-Polymers*, vol. 9, no. 1, Dec. 2009.

[21] F. Raeesi, M. Nouri, and A. K. Haghi, "Electrospinning of polyaniline-polyacrylonitrile blend nanofibers," *e-Polymers*, vol. 9, no. 1, Dec. 2009.

[22] T. Yano *et al.*, "Orientation of poly(vinyl alcohol) nanofiber and crystallites in non-woven electrospun nanofiber mats under uniaxial stretching," *Polymer*, vol. 53, no. 21, pp. 4702–4708, Sep. 2012.

[23] F. E. Ahmed, B. S. Lalia, and R. Hashaikeh, "A review on electrospinning for membrane fabrication: Challenges and applications," *Desalination*, vol. 356, pp. 15–30, Jan. 2015.

[24] W.-E. Teo, R. Inai, and S. Ramakrishna, "Technological advances in electrospinning of nanofibers," *Science and Technology of Advanced Materials*, vol. 12, no. 1, p. 013002, Feb. 2011.

[25] W. Teo and S. Ramakrishna, "A review on electrospinning design and nanofibre assemblies," *Nanotechnology*, vol. 17, pp. 89–106, 2006.

[26] R. Sahay, V. Thavasi, and S. Ramakrishna, "Design Modifications in Electrospinning Setup for Advanced Applications," *Journal of Nanomaterials*, vol. 2011, pp. 1–17, 2011.

[27] A. Baji, Y.-W. Mai, S.-C. Wong, M. Abtahi, and P. Chen, "Electrospinning of polymer nanofibers: Effects on oriented morphology, structures and tensile properties," *Composites Science and Technology*, vol. 70, no. 5, pp. 703–718, May 2010.

[28] A. Firych-Nowacka, Krzysztof Smółka, Sławomir Wiak, E. Gliścińska, Izabella Krucińska, and M. Chrzanowski, "3-dimensional computer model of electrospinning multicapillary unit used for electrostatic field analysis," *Open Physics*, vol. 15, no. 1, pp. 1049–1054, Jan. 2017.

[29] F. Dabirian, Y. Hosseini, and S. A. H. Ravandi, "Manipulation of the electric field of electrospinning system to produce polyacrylonitrile nanofiber yarn," *Journal of the Textile Institute*, vol. 98, no. 3, pp. 237–241, Aug. 2007.

[30] Y. M. Shin, M. M. Hohman, M. P. Brenner, and G. C. Rutledge, "Experimental characterization of electrospinning: the electrically forced jet and instabilities," *Polymer*, vol. 42, no. 25, pp. 09955–09967, Dec. 2001.

[31] Sreevalli Bokka, Y. Li, D. H. Reneker, and G. G. Chase, "Achievement of high surface charge in poly(vinylidene fluoride) fiber yarns through dipole orientation during fabrication," *Journal of Applied Polymer Science*, vol. 140, no. 1, Oct. 2022.

[32] R. Gregorio, Jr. and M. Cestari, "Effect of crystallization temperature on the crystalline phase content and morphology of poly(vinylidene fluoride)," *Journal of Polymer Science Part B: Polymer Physics*, vol. 32, no. 5, pp. 859–870, Apr. 1994.