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Research Article

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Fabrication techniques of a Hollow Fiber Membrane

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Abstract Hollow fiber membranes are widely used in applications including water treatment, desalination, biomedical applications, and gas separation applications. The hollow fiber membranes have the advantage of a high surface area-to-volume ratio. A hollow fiber membrane is a semipermeable barrier that has good permeability and shows high packing density. Hollow fibers are fabricated using melt spinning, dry spinning, wet spinning, and dry jet wet spinning processes. Although hollow fibers were developed half a decade ago, the widespread use of hollow fiber membranes is still limited due to the challenges of limited material and solvent combinations, cost of fabricating, low mechanical strength, and fouling. This work is focused on reviewing the fabrication techniques and promoting the future development and growth of hollow fibers in related applications/fields.

Keywords Hollow fiber membrane, Fabrication, Fiber Properties, Applications.

1. Introduction

Environmental regulations are put in place by government and regulatory bodies to protect the environment and public health and safety. Industries are required to reduce or eliminate greenhouse gas emissions (GHSs) such as sulfur dioxide (SO2) and nitrogen oxides (NOx), into the atmosphere to meet environmental standards while maintaining and enhancing the process efficiency is critical for industry.

Hollow fiber membranes offer an energy-efficient method for traditional separation methods such as distillation and chemical absorption. Fiber membranes such as flat sheet and hollow fiber membranes have gained attention for carbon dioxide removal, hydrogen recovery, vapor and gas separation, nitrogen generation and oxygen enrichment, sulfur removal, helium separation and recovery, sour gas treatment, and other applications. The gas separation membranes are prepared by hollow fibers, spiral wound membranes, and plate and frame modules. The advantage of using a hollow fiber membrane over other filter membranes is it provides a high surface area to volume ratio shows a lower resistance to fluid flow and desirable membrane properties for various applications. In this review, a discussion is provided on the materials and fabrication techniques of hollow fibers, their applications, and limitations.

2. Materials

A good understanding of the physiochemical properties of polymeric materials is required to fabricate a hollow fiber structure [1] compared to a flat sheet membrane. The primary material property difference between fabricating a flat sheet and a hollow fiber membrane is the viscosity of the dope polymer solution. A lower dope polymer solution viscosity is required to cast a flat sheet membrane whereas a relatively high viscosity is required for spinning a hollow fiber membrane. Hollow fiber fabrication uses inner and outer coagulants, that control the inner layer and outer layer morphology. The high dope polymer viscosity complicates the phase inversion process affecting the fiber morphology. Polymeric materials such as cellulose acetate, Polyvinylidene fluoride, polyimide, polysulfone, and cellulose acetate are widely used in the hollow fiber fabrication process.

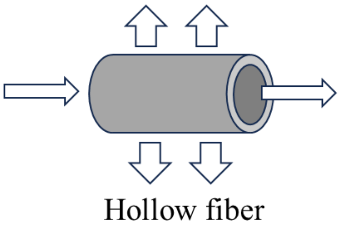

Figure 1: Hollow fiber membrane

3. Methods

In addition to the viscosity of the dope solution, the hollow fiber geometry is affected by the hollow fiber spinning conditions and the method of fabricating a hollow fiber membrane. Hollow fibers are produced using Melt spinning, Dry spinning, Dry-Jet wet spinning, and Wet spinning [2].

Dry spinning is the fiber formation process that transforms a high vapor-pressure polymer solution to a solid fiber by controlled fiber evaporation in the air gap. The key variables in dry spinning are heat transfer, mass transfer, and stress on the fiber. The solvent evaporation occurs leading to a skin core structure with a spongy porous structure. Diffusion of this residual solvent can lead to the collapse of cylindrical fiber. The shape of the hollow fiber lumen determines the physicomechanical properties. Cellulose acetate (CA) and Cellulose triacetate (CTA) are the most common materials used in dry spun fibers.

The wet spinning process uses a dissolved polymer to extrude through a spinneret. The spinneret is dissolved in the coagulation bath containing a non-solvent. The polymer precipitates in the coagulation bath leading to the formation of the hollow fibers. Acrylic and aramid are a few of the polymeric materials used for the wet spinning process.

A spinning solution when passed through an air gap before being passed into a coagulation bath results in a Dry-jet wet spinning process. The air gap provides higher stretchability of the spinning solution resulting in high orientation of polymer molecules compared to the wet spinning process.

Thermally Induced Phase Separation process or TIPS is a thermally and chemically stable process of producing a flat sheet membrane using various polymeric materials. Polymeric materials with poor solubility are very ideal for the Thermally induced phase separation process. The polymer is mixed with solvent and a non-solvent mixture so that the polymer melts above a certain temperature and doesn’t melt at a lower temperature. The mixture is mixed at elevated temperature to attain a homogeneous mixture that is then extruded through a die for flat sheet membrane and spinneret for hollow fiber membrane. The extruded material is allowed to pass through a temperature-controlled air gap followed by a solution tank for solvent extraction, drying, and winding. The processability, microscopic, and macroscopic properties of the membrane are very critical to curating the membrane for specific needs. TIPS membranes are widely used in the medical industry, semiconductors, microelectronics, food and beverage industries.

Solvent-induced phase separation or SIPS is a process the polymer is dissolved in the solvent and a homogeneous mixture is obtained. The polymer solution is extruded through a spinneret where the bore fluid is selected as a non-solvent to allow the formation of the ring structure. The polymer solution is extruded into the coagulation bath containing a solvent allowing for solvent extraction and allowing the polymer to solidify forming a membrane. For producing a flat sheet membrane through SIPS, the membrane is cast through a slit and allowed to cool onto a chill roll. The applications of the SIPS membrane is in the medical industry, microelectronics, and wastewater treatment.

Melt spinning is the process of casting molten metal by jetting it onto a rotating wheel or drum. The rotating drum is cooled internally, usually by water or liquid nitrogen. The molten material rapidly cools down as the material touches the drum and is removed as the material solidifies, exposing the surface of the drum to molten material. The nozzle gap, nozzle shape, flow rate, drum rotating speed, and drum temperature are critical factors for preparing a desired product. Planar flow casting, twin roll melt spinning, and auto ejection melt spinning are a few of the different processes and techniques to develop a melt spinning process.

The dry stretch process is another membrane production technique where the polymer is extruded to form a flat sheet or hollow fiber. Process control for membrane extraction controls the formation of macro voids.

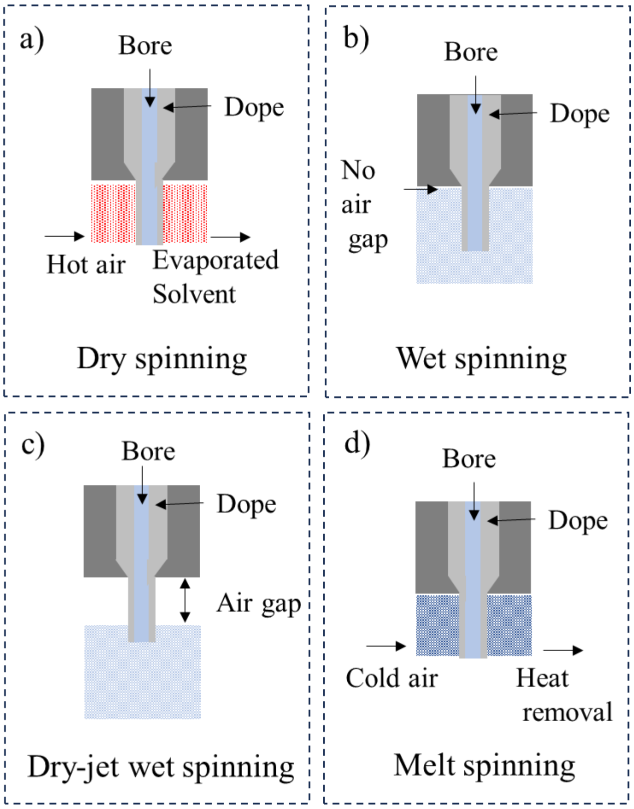

Figure 2: Applications of the charged filter membrane

4. Discussion

Material selection and fabrication process is very critical to produce a hollow fiber membrane that has good fiber morphology [3]. A few key parameters of the hollow fiber membranes are the pore size, spinneret design, thickness of the functional separation layer, and chemical and mechanical properties of the hollow fiber membrane material.

A uniform hollow fiber pore structure is desired for good permeability, high mechanical strength, and high selectivity of the membrane. Defects such as macro voids are often formed in the hollow fibers where the viscosity of the dope solution is low. The formation of the macro voids results in reducing the mechanical strength and separation efficiency of the hollow fibers. When the inner coagulant has non-uniform flow through the hollow fiber, it results in non-circular lumen formation resulting in an increase in flow restriction through the hollow fiber. Membrane orientation and morphology are greatly dependent on the spinneret design. The spinneret usually consists of a reservoir and annular channel where a ratio of high annulus length over the flow gap results in a good pore structure of the hollow fiber membrane. For applications requiring a high flux and separation efficiency a desired selective layer thickness is critical.

A few challenges with using hollow fiber membranes are limited availability for material selection, low permeability, fouling, high cost of fabrication, and low mechanical strength. Fouling of the hollow fiber membrane is a critical concern affecting the hollow fiber performance. The particle build-up on the surface of the hollow fiber membranes over time results in reduced performance and high cost of operation to clean the membrane. Selecting the suitable polymer material and solvent combination could be challenging and limit the application of the hollow fiber membrane. Fouling on the hollow fibers is removed using chemical cleaning and ultrasound techniques. The hollow fiber membranes could break under high strain and pressure conditions compared to the other filtration membranes. The hollow fiber fabrication and operating costs are still higher limiting the large-scale production of the hollow fibers.

Hollow fiber membranes are characterized by the Scanning Electron Microscope and the porometer for studying the hollow fiber morphology and the tensile tester evaluates the mechanical properties of the hollow fiber membrane.

A hollow fiber membrane is used in the filtration industry as Microfiltration (MF), Ultrafiltration (UF), and Reverse Osmosis (RO) membranes for industrial separation and water filtration. Hollow fiber membranes are used for membrane distillation applications. Hollow fiber membranes are used in the oil and gas industry, semiconductor industry, and gas separations.

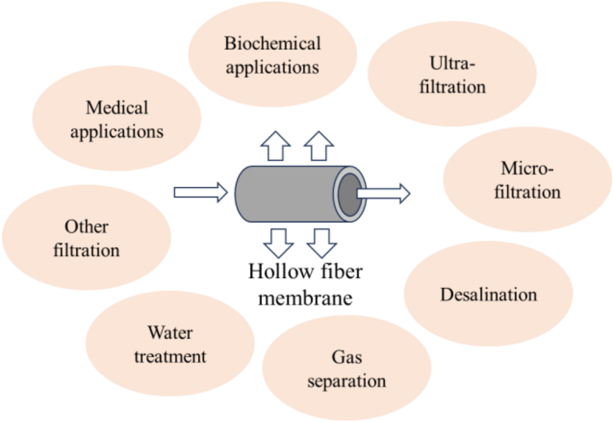

Figure 3: Application of hollow fiber membrane.

5. Conclusion

Although hollow fibers were first developed half a decade ago, the hollow fiber market is evolving. Researchers have evaluated various techniques and materials for the fabrication of the hollow fiber membrane, but the applications are still limited. This review summarizes the fabrication techniques for the hollow fiber membranes, critical properties of the hollow fiber membranes, and their applications.

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