Development of polyethersulfone and polyacrylonitrile hollow fiber membranes for clarification of surface water and fungal enzyme broth

K. Praneeth, S. Kalyani, Y. V. L. Ravikumar, J. Tardio and S. Sridhar

ABSTRACT

Hollow fiber membranes are of great commercial interest with several applications at the forefront of research to carry out bioseparations, drinking water purification, wastewater treatment besides liquid phase separations and gaseous separations. An experimental study was carried out to synthesize hollow fiber membranes from polyethersulfone (PES) and polyacrylonitrile (PAN) polymers to fabricate modules for surface water treatment and clarification of fungal enzyme broth. Design drawings of a manual hollow fiber spinning machine and spinneret were prepared to fabricate the necessary equipment for extrusion of hollow fibers. Effect of various spinning conditions on specific macroscopic fiber properties, such as outer diameter and wall thickness and membrane pore structure was studied. Concentrations of 15–20 wt% PES in N-methylpyrrolidone (NMP) and PAN in dimethyl formamide (DMF) solvents with important additives and pore formers were prepared. These polymer solutions were extruded through the spinneret and subjected to phase inversion in a water bath. The membranes were characterized by scanning electron microscopy (SEM) and pure water flux studies. PAN and PES exhibited 99.8 and 95.4% turbidity rejection. PAN exhibited a 5 log reduction of Escherichia coli bacteria for surface water treatment at a low hydraulic pressure of 1 bar with a flux of 54.2 L/m² h at a water recovery of 80% whereas PES gave a flux of 36.6 L/m² h with 4 log reduction of E. coli. PAN and PES membranes exhibited 54.9 and 69.3% xylanase enzyme recoveries from fungal broth at reasonable flux with turbidity rejection of 94.8 and 95.7% respectively.

Key words | clarification, equipment design, flux, hollow fiber membranes, rejection, spinning parameters, water purification

INTRODUCTION

The quality of water is influenced by seasonal changes and surface water contains natural organic matter such as humic- and fulvic substances, inorganic salts of monovalent and multivalent metal ions besides microbes like bacteria, viruses, protozoa, etc., that can be removed by means of ultrafiltration (UF). In recent years, membrane UF has become a more attractive technology than conventional clarification for drinking water purification. Membrane filtration offers several advantages such as (i) providing superior quality of treated water using a much more compact system, (ii) easier control of operation and maintenance, (iii) consumption of fewer chemicals, and (iv) producing lower quantities of sludge (Shuiji et al. 1996). Membranes with high separation performances are desired and their synthesis is usually regarded as the major objective of research in this area. It is well-known that asymmetric or thin film composite membranes offer a better choice for separation processes due to the combination of high selectivity of a dense membrane along with the high permeation rate achievable through the ultrathin skin layer (Li et al. 2002; Choi et al. 2010).
Hollow fibers have become one of the most important membrane geometries, mainly due to their superior ratio of membrane area per unit of module volume. The surface area in a hollow fiber module can be three to five times greater than that of a spiral-wound unit of equal volume. It has a self-supporting structure and is flexible to operate. Feasibility of scale-up makes them economically attractive for surface water purification (Chung et al. 2000; Chun et al. 2011). Such membranes are commercially utilized by integrating them into compact packages or modules. Each module contains a bundle of numerous fine fibers capable of withstanding moderate pressure gradient across the fiber wall. These modules can be operated with either tube side (lumen side) or shell side feed flow and the permeate may flow in either a countercurrent or co-current direction relative to the feed. Variations in fiber dimensions and properties within the module could be detrimental to its performance (Lemanski et al. 1993; Santosh et al. 2010).

Researchers have focused their investigation on the preparation of polyacrylonitrile (PAN) membranes for treatment of industrial and domestic wastewaters and as a substrate for preparation of poly(vinyl alcohol) based pervaporation membranes (Saufi & Ismail 2003), whereas polyethersulfone (PES) membranes have been more versatile by virtue of their application in biomedicine, food, hemodialysis, plasma separator, water purification, etc. (Unger et al. 2005; Susanto & Ulbricht 2006; Li & Chung 2008; Nasrula et al. 2008; Hui et al. 2011). Presence of nitrile groups in PAN chemical structure exhibits the hydrophilic nature whereas PES shows both hydrophobic and partial hydrophilic nature due to the presence of aryl groups and sulfone groups in polymer chain, respectively.

PAN is suitable for fabrication of hollow fiber membranes due to its good solvent resistance, thermal stability and highly oriented molecular structure (Donnet & Bansal 1984). PAN polymer can be converted into activated carbon fiber (Yu et al. 2003) or blended with other polymers to alter the final pore size distribution of carbon membranes. Linkov et al. (1994) prepared PAN hollow fibers by varying the viscosity of the precursor solution using methyl methacrylate as an additive. They also applied phase inversion by casting PAN with poly(ethylene glycol) (PEG) and poly (vinylpyrrolidone) (PVP) in order to synthesize membranes with 50–400 nm pore size. PES membranes exhibit outstanding oxidative, thermal and hydrolytic stability with good mechanical strength and film-forming properties. However, application of pure PES membrane in practical situations is severely limited due to its hydrophobicity and low fouling resistance. To overcome this limitation, PES has been blended with hydrophilic polymer additives, such as PVP, PEG, diethylene glycol (DEG), cellulose acetate phtalate (CAP) and Pluronic F127 (Qin et al. 2005; Qiu et al. 2007; Rahimpour & Madaeni 2007; Qian et al. 2009).

In the present study, the authors have presented a schematic diagram of the manual spinning machine that was designed and fabricated indigenously along with the critical spinneret component used for extrusion. PES and PAN hollow fiber membranes were synthesized by the dry-wet spinning method and characterized by scanning electron microscopy (SEM). Additives like PVP, DEG and PEG were added to the PES dope solution to improve its hydrophilicity and membrane fouling resistance. ZnCl2 was added to the PAN dope solution to improve membrane strength. Effect of various parameters such as flow rate of polymer dope, bore liquid, speed of polymer pump on specific macroscopic and microscopic properties of the hollow fibers was evaluated. These membranes were further fabricated into different types of modules (based on the permeate collection type) with single or twin permeate outlets. Flux and turbidity rejection of the fabricated modules were also studied for the treatment of surface water and clarification of fungal broth of xylanase enzyme.

**EXPERIMENTAL**

**Materials and methods**

The polymer solution used in making the membranes is commonly called ‘dope’. Dimethyl formamide (DMF) and n-methylpyrrolidone (NMP) manufactured by S.D. Fine Chemicals were used as solvents for making the dopes. PAN and PES polymers used in this study were supplied by Techno Orbital, Kanpur, India and Solvay, USA, respectively. Additives such as PEG and ZnCl2 from Loba Chemie, Mumbai besides DEG from Aldrich Chemical Co., USA, were used for improving viscosity, phase separation, elasticity and pore formation (Qiu et al. 2007; Rahimpour &
Deionized water for bore fluid was prepared in-house using the laboratory reverse osmosis (RO) system. Tap water was used for gelation of the hollow fiber membranes. Compositions of dopes prepared for membrane extrusion trials are listed in Tables 1 and 2.

## Hollow fiber spinning process

An asymmetric hollow fiber membrane fabricated by a dry-wet spinning process with forced convection in the air gap. Polymer solution of 1 L quantity was charged into the dope reservoir along with bore fluid in a separate storage and coextruded through the spinneret using two different pumps, at ambient temperature. It is feasible to prepare asymmetric membranes by phase inversion method using water as a coagulant (Wang et al. 2000). The nascent membrane moving through the air gap of 13 cm cools and loses solvent due to partial evaporation prior to its entry into the coagulant bath (water). The fiber undergoes rapid cooling/coagulation in the liquid bath leading to the solidification of the polymer-rich region and subsequent formation of the membrane microstructure due to the replacement of solvent molecules with water. The fibers are then collected using a take-up device for post-treatment and storage (Yu et al. 2006; Khulbe et al. 2007). The annular spinneret opening and the polymer dope to bore fluid volumetric flow rate ratio are the primary factors that determine the final fiber dimensions. The ultimate outer to inner fiber radii ratio was determined by the polymer to bore volumetric flow rate ratio.

### Design of manual hollow fiber spinning machine and spinneret

Laboratory schematic diagram of the manual hollow fiber spinning machine is shown in Figure 1. Dope and bore fluid reservoirs besides water coagulation bath were made of stainless steel 316. A gear pump was fixed between dope reservoir and spinneret for delivering the solution to the spinneret during the spinning process. The polymer dope pump speed ranged between 100 and 1,000 rev/sec. The fiber spinning velocity ranged between 40 and 65 m/min and usually maintained around 50 m/min. The length and depth of the water coagulant bath were 2 and 0.8 m, respectively. The take-up winder had a diameter of 200 mm and its rate of revolutions was regulated by a speed controller operating in the range 20–40 rev/sec range.

A spinneret was made of stainless steel plate with orifices through which molten or dissolved polymer could be extruded under pressure. The orifices were of cylindrical shape with the outer orifice having a diameter of 5.5 mm. The inner and outer diameters of the central capillary were 1.5 and 2.5 mm, respectively (Figure 2). This type of spinneret is used to produce large-diameter fibers which are commonly used in UF systems. Diameters of orifice and inlet tubes were selected on the basis of the outside diameter desired for the hollow fiber.

### Module fabrication

The membrane module is the heart of any membrane separation system. Hollow fiber membranes are systematically packed to maximize the membrane area per unit volume as shown in Figure 3. Based on feed flow, hollow fiber modules are classified into two types: (1) inside-out modules, where in the influent is fed inside the membrane’s lumen and the clean water travels from the inside of the membrane

### Tables

**Table 1** | Composition of PES dope solution
<table>
<thead>
<tr>
<th>Component</th>
<th>Batch 1</th>
<th>Batch 2</th>
<th>Batch 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethersulphone (PES)</td>
<td>15.66</td>
<td>18</td>
<td>20.5</td>
</tr>
<tr>
<td>n-methyl-2-pyrrolidone (NMP)</td>
<td>56.7</td>
<td>53.7</td>
<td>–</td>
</tr>
<tr>
<td>Polyvinylpyrrolidone (PVP)</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Diethylene glycol (DEG)</td>
<td>27.3</td>
<td>27.9</td>
<td>–</td>
</tr>
<tr>
<td>Polyethylene glycol (PEG)</td>
<td>–</td>
<td>–</td>
<td>16.27</td>
</tr>
<tr>
<td>Dimethyl formamide (DMF)</td>
<td>–</td>
<td>–</td>
<td>62.83</td>
</tr>
</tbody>
</table>

**Table 2** | Composition of PAN dope solution
<table>
<thead>
<tr>
<th>Component</th>
<th>Solution composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyacrylonitrile (PAN)</td>
<td>15</td>
</tr>
<tr>
<td>Polyvinylpyrrolidone (PVP)</td>
<td>–</td>
</tr>
<tr>
<td>Zinc chloride</td>
<td>3</td>
</tr>
<tr>
<td>Dimethyl formamide (DMF)</td>
<td>82.0</td>
</tr>
</tbody>
</table>
to the shellside; and (2) outside-in membranes, wherein the influent is fed to the shell side and the clean water travels from the external surface into the lumen (Barzin et al. 2004; Khulbe et al. 2004).

Fabrication of inside-out flow hollow fiber modules

Nascent hollow fibers were cut to 15 cm lengths and potted at both ends with epoxy adhesive in 15 cm long acrylic tubes (Figure 3). Acrylic rod was used for making the end caps with openings for feed and reject flow. The feed solution enters the lumen side of the hollow fibers and the permeate is collected from the shell side through a small opening made on the module housing.

Fabrication of outside-in flow hollow fiber modules

The 'U' shape twisted hollow fiber bundle was introduced into the acrylic tube of 45 cm length in which one end was potted with epoxy adhesive. Acrylic polymer based end caps with shell-side feed and reject flow were fabricated and fixed at one end, whereas provision for tube-side permeate flow was made at the other end. Time taken in producing this type of membrane module is significantly lower than that of the double end potted module. In addition, the required potting material is less.

Description of experimental setup

The bench scale system was built to incorporate a manually fabricated hollow fiber membrane module made of PAN or PES. Standard solutions of known molecular weights of

Figure 1 | Schematic diagram of manual hollow fiber spinning machine.

Figure 2 | Design drawing of spinneret.
Dextran were used to determine the molecular weight cut off (MWCO) of the membranes. PAN (20 wt%) was found to have an approximate MWCO of 30 kD (pore size \(\sim 0.01 \mu m\)) and 15 wt% PES revealed a MWCO of 70 kD (pore size \(\sim 0.05 \mu m\)). The input to the system was provided by a feed tank of 10 L capacity. The feed tank also had a provision to collect the recycled reject. Before reaching the membrane module, the feed passes through a 5 \(\mu m\) pore size polypropylene (PP) prefilter cartridge to enable removal of sediments, silt and sand to prevent fouling of the membrane pores. A valve was provided on the reject line for adjusting the applied pressure (1 – 2.5 bar) to the desired value. Fluxes through each hollow fiber module were obtained by collecting permeate for every 5 min until the end of filtration.

**Surface water treatment**

Surface water polluted by domestic and industrial waste was used in the present investigation. A quantity of 5 L influent concentration of 140 FAU turbidity, 88 mg/L suspended solids, \(1.1 \times 10^5\) (MPN/100 mL) Escherichia coli and 6.8 pH was fed into the UF system by means of a booster pump at hydraulic pressures ranging from 1 to 2.5 bar maintained at an ambient temperature (30 \(\pm 3\) °C). The pure water flowing through the membrane pore openings was collected in the permeate tank. The rejection rate of suspended particles, virus, bacteria and other macro-sized particles depends upon MWCO of the membrane. The reject from the hollow fiber membrane module was continuously recycled through the feed tank. The reduction in the turbidity of the feed and permeate samples was determined by DR/890 Colorimeter (Hach), Germany. The number of E. coli present in the samples was estimated by coliform test.

**Clarification of fungal enzyme broth**

Xylanase, which is extracellular in nature is produced by a variety of bacteria and fungi. Therefore, prior to use, these enzymes have to be separated and purified to remove a range of other extracellular enzyme, such as celluloses. Xylanase has become commercially important in recent times due to its wide application in several industries such as: (i) the paper and pulp industry for selective removal of
hemicelluloses from Kraft; (ii) in the animal feedstock industry to increase digestive capacity of products; and (iii) in the brewing and baking industries (Pandey et al. 2000).

A 5 L sample of fermentation broth (comprising biomass and proteins) collected from the paper and pulp industry of 4,120 FAU turbidity, 5.5 pH, enzyme concentration 40 μg/L and protein concentration of 1,120 μg/L was subjected to UF for recovering xylanase enzyme. The clarified enzyme is used in pulp and paper industry for pre-bleaching and improving the brightness of the pulp and for clarification of fruit juices (Polizeli et al. 2005). A view of the bench scale setup and the image of permeate of fermentation broth and surface water by pertaining to PES and PAN hollow fiber membrane modules is shown in Figure 4.

RESULTS AND DISCUSSION

Operating parameters such as speed of pulling motor, speed of polymer pump and bore fluid velocity play an important role in controlling the outer diameter and wall thickness of hollow fiber membranes. The influence of operating parameters on membrane dimensions is projected by Table 3. Structural morphology and pore size of the indigenously developed hollow fiber membranes were characterized by software controlled digital SEM-JEOL JSM 5410, Japan. Pure water flux data at different feed pressures were recorded to compare the performance of all the membranes.

Scanning electron microscopy (SEM) studies

Figures 5(a), 5(b), 5(c) and 5(d) represent cross-sectional and surface SEM images of PES and PAN hollow fiber membranes. The structural morphology of both PES and PAN membranes did not change significantly with increase in the polymer concentration from 15 to 18 wt% when spun at constant extrusion rates (Table 3). In case of 20 wt% PES, an increase in the dope extrusion rate from 3.5 to 7.2 gm/min caused an increase in the wall thickness from 0.4 to 0.8 mm. Similarly, a significant change in the membrane wall thickness from 0.65 to 0.9 mm was observed when extrusion of 20 wt% of PAN was enhanced from 6.0 to 8.1 gm/min. The observations imply that an increase in the dope extrusion rate causes enhancement in the membrane wall thickness at a constant bore fluid velocity. The formation of porous substructure and voids near the inner and the outer edges of the PES and PAN membranes can be observed from Figures 5(a) and 5(c). This can be attributed to the penetration of bore fluid and external coagulant from the inner and outer surfaces of the membrane during the phase inversion process. It can also be seen that the
membranes prepared from more concentrated solutions exhibited chain entanglement which reduces the formation of voids in the skin layer resulting in tighter pore structures (Pesek & Koros 1997).

**Pure water flux measurements**

It is generally accepted that systems which are thermodynamically less stable enhance the rate of polymer precipitation. Such systems are used for preparing membranes with greater porosity (Kim & Lee 1998). Hence, various percentages of polymer dope were prepared to synthesize membranes with porous structures. Feed (distilled water) pressure was varied from 0.2 to 1.5 bar at ambient temperature to study the permeation characteristics of hollow fiber membranes. The relationship between applied pressure and pure water flux for various hollow fiber membranes is depicted by Figure 6. Compared to PES, PAN yielded higher fluxes due to its highly hydrophilic nature arising from the presence of \(-\text{CN}\) group. At a pressure of 0.2 bar, 18 wt% PAN membrane exhibited a flux of 43.7 L/m²h compared to only 29.8 L/m²h yielded by PES. Increase in the pressure to 1.5 bar further enhanced the flux to 74.8 and 68.8 L/m²h for PAN and PES membranes, respectively.

### Table 3 | Experimental observations during hollow fiber spinning process

<table>
<thead>
<tr>
<th>Polymer concentration</th>
<th>Flow rate of polymer solution (gm/min)</th>
<th>Flow rate of bore fluid (ml/min)</th>
<th>Outer diameter (mm)</th>
<th>Wall thickness (mm)</th>
<th>Speed of polymer pump (rpm)</th>
<th>Speed of pulling motor (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 wt%.PES</td>
<td>3.5</td>
<td>6.0</td>
<td>1.6</td>
<td>0.4</td>
<td>280</td>
<td>27</td>
</tr>
<tr>
<td>18 wt%.PES</td>
<td>3.5</td>
<td>6.0</td>
<td>1.63</td>
<td>0.4</td>
<td>290</td>
<td>27</td>
</tr>
<tr>
<td>20 wt%.PES</td>
<td>7.2</td>
<td>6.0</td>
<td>2.0</td>
<td>0.8</td>
<td>425</td>
<td>27</td>
</tr>
<tr>
<td>15 wt%.PAN</td>
<td>6.0</td>
<td>6.0</td>
<td>1.5</td>
<td>0.6</td>
<td>420</td>
<td>29</td>
</tr>
<tr>
<td>18 wt%.PAN</td>
<td>6.0</td>
<td>6.0</td>
<td>1.52</td>
<td>0.65</td>
<td>430</td>
<td>31</td>
</tr>
<tr>
<td>20 wt%.PAN</td>
<td>8.1</td>
<td>6.0</td>
<td>1.6</td>
<td>0.9</td>
<td>453</td>
<td>31</td>
</tr>
</tbody>
</table>

**Figure 5** | (a) Cross-sectional view of PES membrane, (b) Surface view of PES membrane, (c) Cross-sectional view of PAN membrane, (d) Surface view of PAN membrane.
On the other hand, an increase in polymer concentrations in the dope solutions resulted in a reduction in the flux. Increasing the polymer concentration in the dope causes an enhancement in solution viscosity and beyond 20 wt% concentration, the solubility appeared to decrease.

**Effect of time on flux**

Effect of permeate flux with time at a constant applied pressure of 1 bar and feed concentration of 140 FAU turbidity for different polymer compositions (15–20 wt%) of PAN and PES membranes is shown in Figures 7(a) and 7(b). Flux lowers with filtration time due to concentration polarization and gradual fouling of the membrane. High initial permeate flux followed by a rapid flux decline is characteristic for constant transmembrane pressure (TMP) operations. High initial flux causes rapid deposition of rejected solute molecules which results in the build-up of a boundary layer at the membrane surface causing resistance to solvent (water) flow. The variation of TMP with time at constant flux of 60 L/m² h for PAN and 45 L/m² h for PES membranes is described in Figures 8(a) and 8(b). The TMP was increased with filtration time due to the enhancement in the hydraulic resistance of membranes.

The declined flux can be recovered by regular backwashing and chemical cleaning. There are a variety of different chemicals that may be used for membrane cleaning, and each is targeted to remove a specific form of fouling. Citric acid is used to remove inorganic scales. Strong bases such as caustic are typically used to dissolve organic foulants.

Membrane can be stored in aqueous sodium metabisulfite to control biofouling. Due to the variety of foulants present in source waters, it is often necessary to use a combination of different chemicals in series to address multiple types of fouling.

**Effect of polymer dope pumping rate**

At a bore fluid flow rate of 6.0 mL/min and pulling motor speed of 27 revolutions per second (rps), an increase in the wall thickness of PES hollow fiber membrane from 0.4 to 0.8 mm was observed when the speed of polymer pump was enhanced from 280 to 425 rps. At a constant pulling motor speed, an increase in the speed of the polymer pump from 420 to 453 rps resulted in enlargement of PAN membrane wall thickness from 0.6 to 0.9 mm. From Table 3, it can be inferred that the wall thickness of the
extruded hollow fiber membrane increases with a rise in the speed of the polymer dope pump. When the polymer dope rate is increased at a constant bore fluid flow rate, it could result in reduction in the central opening or hollowness being created by the bore fluid which is made up of the coagulant liquid (water) itself. In contrast when the bore fluid rate is increased at constant polymer dope rate the wall thickness would reduce as the central bore in the fiber gets enhanced.

**Effect of bore fluid flow rate and spinneret dimensions**

Variation of membrane wall thickness at different bore fluid flow rates but constant polymer pump speed of 450 rps, pulling motor speed of 30 rps and similar dope concentrations of PES and PAN is presented in Table 4. An increase in bore fluid flow rate from 4 to 10 mL/min resulted in a reduction in the wall thickness from 0.9 to 0.66 mm for PES and 0.84 to 0.62 mm for PAN.

<table>
<thead>
<tr>
<th>Polymer composition</th>
<th>Flow rate of bore fluid (mL/min)</th>
<th>Wall thickness (mm)</th>
<th>Speed of polymer pump (rps)</th>
<th>Speed of pulling motor (rps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 wt%.PES</td>
<td>4.0</td>
<td>0.9</td>
<td>450</td>
<td>30</td>
</tr>
<tr>
<td>18 wt%.PES</td>
<td>6.0</td>
<td>0.8</td>
<td>450</td>
<td>30</td>
</tr>
<tr>
<td>18 wt%.PES</td>
<td>8.0</td>
<td>0.74</td>
<td>450</td>
<td>30</td>
</tr>
<tr>
<td>18 wt%.PES</td>
<td>10.0</td>
<td>0.66</td>
<td>450</td>
<td>30</td>
</tr>
<tr>
<td>18 wt%.PAN</td>
<td>4.0</td>
<td>0.84</td>
<td>450</td>
<td>30</td>
</tr>
<tr>
<td>18 wt%.PAN</td>
<td>6.0</td>
<td>0.77</td>
<td>450</td>
<td>30</td>
</tr>
<tr>
<td>18 wt%.PAN</td>
<td>8.0</td>
<td>0.7</td>
<td>450</td>
<td>30</td>
</tr>
<tr>
<td>18 wt%.PAN</td>
<td>10.0</td>
<td>0.62</td>
<td>450</td>
<td>30</td>
</tr>
</tbody>
</table>

The spinneret dimensions were also found to influence the fiber diameter. An indigenous spinneret with different orifice dimensions was fabricated to compare the effect of spinneret dimensions on hollow fiber characteristics. At constant spinning conditions, hollow fiber membranes of outer diameter (O.D.) 2.4 mm with a wall thickness of 0.6 mm were extruded whereas the previous spinneret yielded fibers with O.D. 2.0 mm and wall thickness 0.8 mm. An increase in the orifice diameter expectedly causes an increase in the O.D. of the hollow fiber membrane.

**Surface water treatment and fungal broth enzyme clarification**

Indigenously synthesized PAN and PES hollow fiber membranes were used to study turbidity rejection, flux and *E. coli* reduction in treating surface water. Extent of enzyme recovery and flux obtained during fungal enzyme broth clarification were also investigated.

**Effect of polymer concentration on turbidity rejection**

Figure 9 illustrates the effect of polymer concentration on turbidity rejection of PAN and PES at a pressure of 1 bar for surface water treatment. With increasing concentration of PES from 15 to 20 wt% in the dope, the turbidity rejection enhanced from 90.1 to 95.4%, whereas PAN exhibited improved rejection in the range 99.60–99.80%. Increasing the polymer concentration induces a tighter pore structure at both the external and internal surfaces of the hollow
fibers which results in an enhancement in turbidity rejection but lower flux.

In addition, 18 wt% PES and 15 wt% PAN have shown an *E. coli* reduction of 4 log (falling in the desirable 4–6 log reduction range) at 1 bar. An observation of 5 log reduction at 20 wt% PAN concentration indicates an improvement in the purity of the permeate water obtained.

**Effect of pressure on flux at different polymer concentrations**

Effect of pressure on flux for PAN and PES membranes is described by Figures 10(a) and 10(b). An enhancement of flux from 54.23 to 57.23 L/m² h for PAN and 36.66 to 46.40 L/m² h for PES was observed when the applied pressure was varied from 1 to 2.5 bar. PAN gave higher flux due to its highly hydrophilic nature whereas PES is only partially hydrophilic due to the presence of sulfone group with its aromatic backbone being predominantly hydrophobic. The relationship between pressure and turbidity rejection is illustrated in Figures 11(a) and 11(b). A reduction in turbidity rejection at higher pressures (1–2.5 bar) shows that these hollow fibers need to be operated at lower pressures (~1 bar) to achieve optimum results.

The potential of hollow fiber membranes for clarification of enzymatic solutions is assessed by studying the influence of polymer dope composition on enzyme recovery and turbidity rejections as illustrated in Figures 12(a) and 12(b). At the PES concentrations studied (15–20 wt%), the membranes exhibited higher enzyme recoveries in the range 57.8–69.3% and turbidity rejections of 89.4–95.7% compared to PAN (45.3–54.9 and 92.3–94.3% turbidity rejection) at a pressure of 1 bar. This could be attributed to the hydrophobicity of the PES which would repel the polar enzyme molecules. Figures 12(a) and 12(b) also reveal an increasing trend in turbidity rejection with increasing dope concentration.

**CONCLUSIONS**

Indigenous hollow fiber UF membranes were synthesized by using a dry/wet spinning process with forced convection in the dry air gap. Tap water was chosen as the external coagulant and distilled water was used as the bore fluid. The influence of polymer concentration on morphology and
performance of UF hollow fiber membrane has been investigated. The experimental results showed that the flux of the hollow fiber UF membranes decreases while the rejection for particular solute increases with an increase in polymer concentration due to tighter pore structures obtained. The wall thickness of the membranes becomes greater with increasing polymer concentration in the dope. PAN (20 wt%) exhibited a turbidity rejection of 99.8% while treating surface water at low hydraulic pressure of 1 bar with a flux of 54.2 L/m² h. Moreover, overhead tank pressure (0.5–1 bar) could be sufficient to treat surface water and generate the desirable flux of pure water without requirement of electric power. 69.3% of enzyme recovery and 95.7% of turbidity rejection was observed with 20 wt% PES membrane module while processing turbid enzyme fungal broth. Hollow fiber membranes offer a commercially viable technology platform for development of inexpensive UF systems for economical treatment of surface water and clarification of turbid solutions such as fungal enzyme broth and wine. The large surface area per unit volume and self-supporting structure makes hollow fiber systems very compact and reliable.

ACKNOWLEDGEMENTS

We are grateful to the Council of Scientific and Industrial Research (CSIR) for granting the funds through XII Five Year Plan Network Project to support our research activities. The first author K. Praneeth is grateful to RMIT, Melbourne, Australia for granting him Senior Research Fellowship under an Indo-Australian Collaborative research programme.

REFERENCES


First received 11 April 2012; accepted in revised form 9 July 2012