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Performance of a newly developed titanium oxide nanotubes/polyethersulfone blend membrane for water desalination using vacuum membrane distillation

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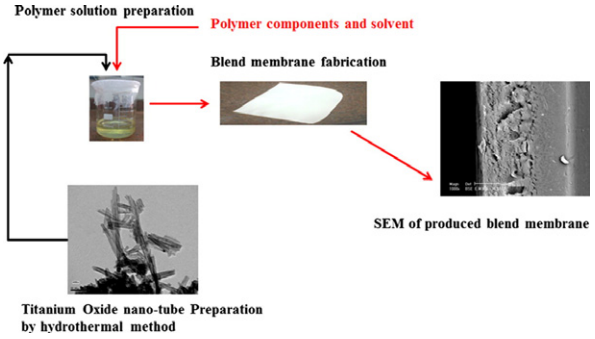
HIGHLIGHTS

- Fabrications of (TNTs-PES) blend membrane by immersion precipitation.
- Performance of (TNTs-PES) membrane was investigated for desalination using VMD.
- The developed (TNTs-PES) membrane was superior in terms of salt rejection.
- The permeate flux was significantly affected by the time of the VMD experiment.
- At optimum conditions the permeate flux reached 15.2 kg/m2h, where the salt rejection was 98%.

GRAPHICAL ABSTRACT



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ABSTRACT

The present paper introduces a comprehensive study of the performance of newly developed titanium oxide nanotubes (TNTs) incorporated into a Polyethersulfone (PES) blend membrane for desalination using vacuum membrane distillation (VMD) process. The study examines the effect of different operating conditions. The results showed a maximum salt rejection of 98% and a permeate flux of 15.2 kg/m^2 h at 7000 ppm feed salt concentration for the TNTs–PES membrane at a temperature of 65 °C and a vacuum pressure of 300 mbar with feed flow rate of 11 mL/s. A comparison between the performance of the developed TNTs-PES membrane, and commercial Polytetrafluoroethylene (PTFE) membrane was performed at different feed salt concentrations. The achieved results showed a significant improvement in the performance of the new membrane compared to the commercial PTFE membrane, where the salt rejection reached 99.3% at feed concentration 3000 ppm and 96.7% at 35,000 ppm using the new membrane, compared to salt rejection of up to 90.6% at 3000 ppm and 62.5% at 35,000 ppm using PTFE membrane. The dense TNTs layer formed on the top surface of the TNTs-PES blend membrane is considered a selective layer that prevents salt passage through the membrane. The decline in permeate flux may be overcome by membrane washing every hour.

1. Introduction

Membrane technology is considered a very effective separation method, particularly in the area of water/wastewater treatment and

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water desalination. The application of nanoparticles or nanotubes to polymeric membranes has attracted the attention of many researchers recently. Moreover, the family of inorganic nanotubes has been expanded extensively from carbon nanotubes to sulfides [1], nitrides [2] and oxides [3]. One-dimensional nanostructured titanium oxide is of great interest for possible applications in high effect solar cells [4], photocatalysts [5,6], gas sensors [7], molecular straws [8] and semiconductor devices due to its nanotubular structure, high specific surface area, ion-changeable ability, and size-dependent properties. Currently, methods developed for fabricating titanium oxides-based nanotubes, include the assisted-template method [9,10], the sol–gel process [11], electrochemical anodic oxidation [12,13], and hydrothermal treatment [14,15]. The latter process is of great interest due to its ability to yield very low-dimensional, well-separated crystallized nanotubes, and a pure-phase structure [16].

During membrane fabrication, nanoparticles and nanotubes have recently shown significant potential in improving polymeric membrane performance. The remarkable effect of the addition of nanoparticles/nanotubes during membrane preparation may be attributed to the interactions between nanoparticle surfaces and polymer chains and/or solvents, which lead to the production of desirable structured membranes. These modifications of membrane structure result in favorable selectivity, permeability, and satisfactory performance in ultrafiltration and nano-filtration membranes [17]. Moreover, the nanoparticle functional groups and their hydrophilic properties were found to be able to control membrane fouling phenomena, which is a major drawback of membrane separation technology [18–20]. There are two major ways of incorporating nanoparticles into polymeric membranes; (i) assembling engineered nanoparticles on the surface of the porous membranes, where these are deposited/coated on top of the membrane surface [21–33], or (ii) blending them with polymeric casting solution, wherein the nanoparticles are dispersed uniformly in the membrane solution by one of the well-known methods; melt, solvent, sol–gel mixing and in-situ grafting [34–40].

Polyethersulfone (PES) is a widely used polymer in membrane preparation, and is now rapidly becoming the material of choice for membrane applications. Its advantages include being a high performance engineering thermoplastic, given its high glass transition temperature, good mechanical properties, and excellent thermal and chemical stability. However, the hydrophobicity of PES limits its application, especially in the field of water desalination [41,42]. Thus, the introduction of nanoparticles to PES membranes is very useful in overcoming many of the disadvantages.

Among the different operational membrane techniques, namely micro-, ultra-, or nano-filtration, and reverse osmosis, dialysis, etc., membrane distillation (MD) is considered one of the most popular techniques utilized for seawater desalination applications. The idea of MD is based on separating two components present in phase equilibrium; vapor/liquid or liquid/liquid. The main driving force for such separation is the vapor pressure gradient resulting from a temperature difference between hot feed (salt water) and cold permeate (pure water). MD provides many advantages over other distillation separation methods. These advantages include; the (i) capability to produce ultra-pure water, regardless of the salt concentration in the feed stream, (ii) lower operating cost, (iii) the unique feature of the possibility of achieving complete rejection of non-volatile substances, and (iv) commercially long life with saline solutions [43–45]. Among the four well-known modes of operation of MD, direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweep gas membrane distillation (SGMD), and vacuum membrane distillation (VMD) [46–49], the latter configuration is utilized in the current study.

In this study, titanium nanotubes synthesized using the hydrothermal method were blended into PES during polymeric membrane preparation in order to enhance its performance. VMD operational techniques were utilized in desalination experiments. The performance of the developed TNTs-PES blend membrane was tested in terms of permeate flux and percent salt rejection at different operating conditions. In addition, the performance of the developed TNTs-PES blend membrane was compared with the well-known commercial Polytetrafluoroethylene (PTFE) flat-sheet membrane at different feed salt concentrations.

2. Experimental work

2.1. Materials

Polyethersulfone (PES), Ultrason E 6020P, molecular weight of 58,000 g/mol and glass transition temperature of $T_g = 225$ °C and N-Methylpyrrolidone as a solvent were purchased from BASF chemical company. TiO_2 nano powder, NaOH, HCl, acetonitrile, and tetramethylsiloxane were purchased from Sigma Aldrich Company. Commercial Polytetrafluoroethylene (PTFE) flat-sheet membranes were supplied by Millipore Corporation. The specifications of the supplied membrane are as follows; diameter of 4.7 cm, thickness of 120 μm, porosity of 75%, and pore diameter of 0.2 μm. Synthetic salt solutions were prepared with different concentrations using distilled water and commercial NaCl, where the commercial NaCl used as a food salt, and contains 98.5% sodium chloride and 70–30 ppm potassium iodine.

2.2. Synthesis of titanium oxide nanotubes

The approach of self-organized synthesis using the hydrothermal method is applied in the present study for the preparation of the titanium oxide nanotubes. TiO_2 nanopowder was dispersed in 150 mL of 10 M NaOH and stirred for 15 min. The dispersion was then transferred to a Teflon lined autoclave (KH-300) and heated at 150 °C for 16 h. The white precipitate obtained was washed with 1 M HCl first, then with distilled water, and finally dried at 80 °C for 4 h. A detailed description of the preparation method is described elsewhere [50,51].

2.3. Titanium oxide nanotubes membrane fabrication

For the preparation of the titanium oxide nanotube solution, 5 wt.% of tetramethylsiloxane was added first to the acetonitrile solvent, then 5 wt.% of the titanium oxide nanotube powder was added under constant stirring for 3 h. For the preparation of the polymer casting solution, 18 wt.% of PES was dissolved first in the N-Methylpyrrolidone (NMP) solvent and then added to 9% of the previously prepared nanotube solution under constant stirring for 6 h at room temperature. The prepared polymer solution was cast on a smooth flat glass plate by a casting knife with uniform speed, where the membrane thickness was sustained at 0.2 ± 0.01 mm. Subsequently, the polymer solution on the glass plates was solidified by immediate immersion in a coagulation bath containing distilled water. The membrane was spontaneously released from the plate and kept for 24 h to ensure complete removal of solvent from the membrane. Finally, the membranes were dried by placing them between two sheets of filter paper for 24 h at room temperature.

2.4. Desalination experiments

A flat sheet membrane module supplied by Millipore was utilized in the desalination experiments. The effective area of the membrane in the module was determined to be 17.34 cm^2. A one liter jacketed mixer vessel was filled with different concentrations of previously prepared feed salt solutions. The salt solution in the mixer feed vessel was heated using a circulation water bath to the jacket, which was controlled by a thermostat to be kept in the range of (25–65 °C). The feed temperature inside the mixer feed vessel was continuously monitored using a thermometer fitted to the feed vessel. The saline solution was continuously fed to the membrane module from the jacketed feed mixer by a peristaltic pump. The permeate water vapor was drawn from the membrane module to a chiller condenser with the aid of a vacuum pump connected