Review Article

Desalination: A review on Principles, Methods, and Materials

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Abstract

Desalination is a global technology which is widely used to convert the salt water into potable water. Water is a major resource and basic need for the world. From the available source of water, less than 1% is potable and remaining is the sea water. Membrane Technology plays a major role in desalination process because of its high efficiency and low energy consumption compared to conventional thermal technology. Membrane Technology involves the process of Microfiltration, Ultrafiltration, Nanofiltration and Reverse Osmosis in which Reverse Osmosis is generally and specifically used for desalination. Different types of membranes like polymeric, ceramic and nanocomposite membranes are used for desalination in order to prevail over the drawbacks like fouling and low permeation flux. High permeate flux and salt rejection can be achieved through membrane technology. This review critically discussed about principles, methods and materials used for desalination.

Keywords: Desalination, Polymer, Nanocomposite, Electrospinning, Permeation Flux

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Introduction

Water, the basic need for all living organisms on the earth. Water scarcity is increasing day by day due to increase in population, climatic changes and global warming. Hence the seawater has to be desalinated which will be useful for future generation. About 3.5% (35g/L) of salt is present in seawater in which the major component is sodium chloride (NaCl). Desalination is a process which is used to separate salts and minerals from the groundwater, brackish water andseawater to make the water for suitable domestic and industrial applications. Though the process is difficult and expensive, several technologies like Thermal Distillation, Membrane Technology, Electrodialysis, Capacitive Deionization, Geothermal and Solar desalination were used for desalination. Membrane Technology is a separation technique which is widely used in the field of medical, environmental, biotechnology, biomedical, pharmaceutical, chemical, food, textile and leather [1]. In membrane separation process, membranes will act as a semipermeable barrier for the transport of substances between two phases such as permeate and retentate. Membrane technology plays a dominant role in water purification process due to its high energy efficiency. Membrane Technologies are having more advantages than other techniques. The membrane performance was enhanced by adding various functional materials. Polymer based membranes with functional additives show enhanced performance than other desalination techniques.

General Terminologies in Membrane Technology

The **feed** is the passage of stream which is fed into the filtration equipment and it can be air or water. After passing through the filtration equipment, the particles which diffuse or penetrate through the membrane is called **permeate** and the particles which do not penetrate through the membrane is called retentate. Based on the direction of feed flow it can be classified into Cross-Flow Filtration (tangential or parallel to the membrane surface) and Dead-End Filtration (perpendicular to the membrane surface).

Concentration polarization

In membrane separation process, each component in the feed stream infiltrate at different rates with the help of pressure. The membrane has the ability to transfer selective component (permeate) more readily than the other components (retentate) which get deposited on the membrane surface. Due to this phenomena, there is an emergence of concentration gradient at the membrane-solution interface called concentration polarization.

Fouling

The solute particles in the feed solution gets deposited on the membrane surface and inside the pores results in decreasein permeability is defined as fouling and also it is classified as reversible fouling (non-permanent) and irreversible fouling (permanent). Adsorption, pore blockage, deposition and gel formation on the membrane surface by solutes results fouling.

Permeate flux

Permeate flux is defined as the volume of the permeate flowing through per unit area of the membrane per unit time (Equation 1) [1].

$$J = \frac{Q}{A}.t$$

Where, J- Permeation flux m^3/m^2. S; Q-Volume of permeate; A-Area of the membrane

t- Time (1)

Selectivity

Selectivity is defined as the ability of the membrane to separate the solute partly or completely from the feed solution while allowing the solvent molecules to pass freely through the membrane. It is based on retention factor (R) which is dimensionless [1] (Equation 2).

$$R = 1 - \frac{C_p}{C_f} * 100\% \qquad (2)$$

Where, R- Retention factor; C_p – Solute concentration in permeate; C_f– Solute concentration in the feed.

Mechanism

Themechanism of membrane separation is classifed asSolution-diffusion model and Pore flow model. In solution-diffusion model, the component which has to be transported dissolves in the membrane. By the process of diffusion, the component moves from the region of higher concentration to lower concentration by the constant applied pressure through the non-porous membrane like reverse osmosis, gas permeation, and pervaporation [2]. In pore-flow model, the transport of component across the membrane is by convective motion due to the pressure gradient [2]. Mechanism is explained in **Figure 1**.

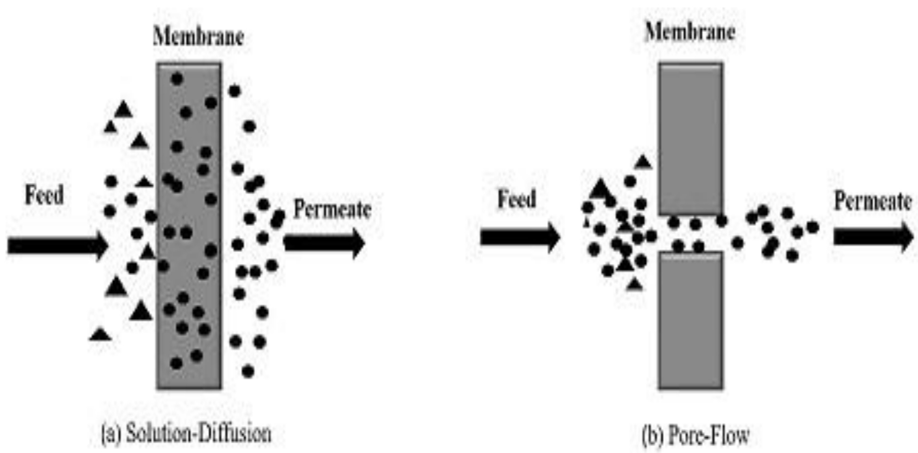

Figure 1 Mechanism of desalination

Desalination Techniques

In general, the desalination techniques are classified as Membrane and Thermal. The detailed classification is described in **Figure 2**.

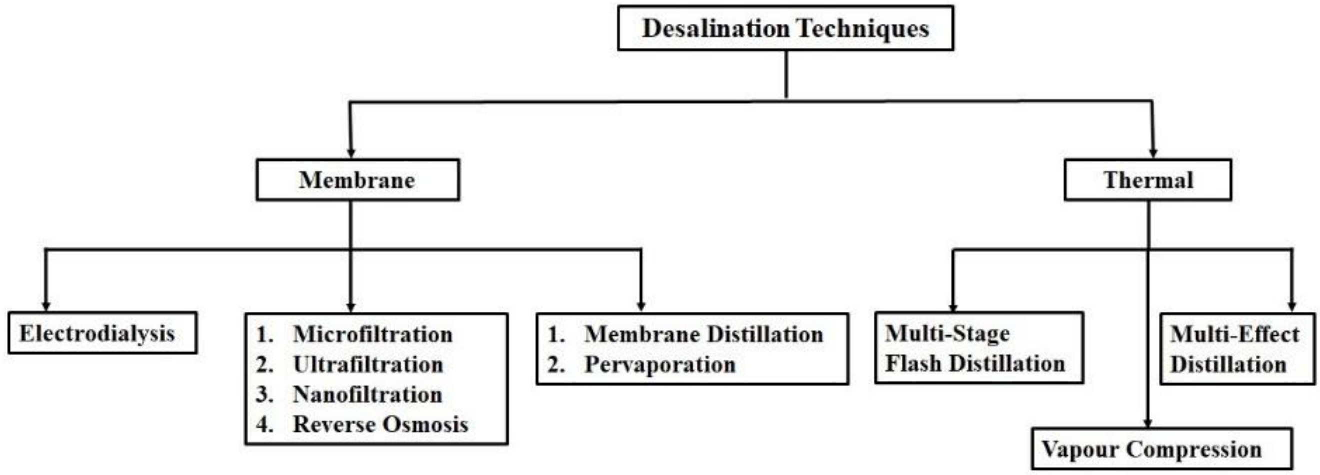

Figure 2 Desalination techniques

Membrane based techniques for desalination

Electrodialysis

Electrodialysis is a separation technique used for desalination. In this technique, the impact of electric potential removes the specific ions through the ion-exchange membrane [3]. In between the anode and cathode, a number of cation and anion exchange membranes are arranged alternatively like plate and frame model. The cation exchange membrane bears a negative charge and anion exchange membrane bears a positive charge. When a salt solution is passed through the cells and direct current is applied, the positively charged sodium ions (cations) will migrate towards the cathode and the negatively charged chloride ions (anions) will migrate towards the anode. The sodium ions will pass through the cationic exchange membrane but are retarded by anionic exchange membrane and vice versa. But the water molecules are impervious to both the membranes. As a result, the cations and anions are more concentrated in the alternating compartments, simultaneously there is a decrease in the concentration of ions in other compartments. Finally, the concentrate or brine and diluate are withdrawn from the alternating compartments.

Membrane filtration

In general, the membranes are classified based on the size of the pores. The detailed classification with respect to various parameters is shown in the **Table 1**.

Table 1 Membrane filtration based on pore size

Membrane process	Pressure (bars)	Pore Size (nm)	Filtrate
Microfiltration	1-4	80-10,000	Bacteria and fine solids[4,5]
Ultrafiltration	5-15	1-100	Suspended solids and Virus[4,5]
Nano filtration	20-40	0.5-5	Sugars, dyes and Inorganics[4,5]
Reverse Osmosis	30-70	<1	Salt, minerals and metal ions [4,5]

Membrane distillation

Membrane distillation is a thermal based membrane-separation process. In this process, the membrane is porous and hydrophobic in nature, which allows the vapour to pass through the membrane. The temperature difference induces a vapour pressure gradient across the membrane that acts as a driving force for the membrane distillation process. It is a cost-effective process [6]. The mechanism of membrane distillation was carried out by Knudsen diffusion and molecular diffusion principles. The Membrane Distillation process are formation of vapour gap (Hot-side) at the feed membrane interface, flow of vapours through pores and at the membrane-permeate interface (Cold side) condensation of vapour.

Types of Membrane Distillation used for Desalination process. Direct contact membrane distillation (DCMD) is a technique in which the membrane is in direct contact with the hot feed solution results in evaporation of liquid at the feed-membrane interface. Due to the vapour pressure gradient, the vapour penetrate across the membrane and condensation takes place inside the membrane module. This is the simplest configuration of membrane distillation which is widely used for desalination process and produces high flux and disadvantage of this method is heat loss by condensation [6, 7]. Invacuum membrane distillation (VMD), a vacuum is created at the permeate-membrane interface using a pump and the condensation takes place outside the membrane module using a condenser without any heat loss [6,7]. Inair gap membrane distillation (AGMD) an air interferes between the membrane and the condensation surface. The feed solution is in direct contact with the membrane surface results highest energy efficiency but the flux is low with minimum heat loss by conduction [6, 7]. In Sweeping Gas Membrane Distillation (SGMD) a sweeping cold inert gas acts as a carrier for the vapour molecules with minimum heat loss by conduction is less but the use of separate condensation technique outside the membrane module cost is high [6,7].

Pervaporation

Pervaporation is a membrane separation process in which the feed solution is in direct contact with one side of the membrane and the vapour permeate is collected from another side of the membrane and then condensed. The chemical potential gradient acts as a driving force for the transfer of permeate from the feed stream to permeate stream of the membrane. The membranes act as a selective barrier for separation, which must be dense and hydrophilic in case of polymeric material and molecularly porous for inorganic material [8]. The mechanism of pervaporation is based on solubility and diffusivity of membrane material [9].

Thermal based distillation techniques

Distillation is a thermal process, in which the sea water is converted to pure water by evaporation and condensation Three types of distillation used for desalination are as follows. In multi-stage flash distillation, three sections namely heating (brine heater), heat rejection and heat recovery (flash chambers). The seawater gets pre-heated in the condensing coils of the flash chambers before entering into the brine heater where it is actually heated. Simultaneously, the condensing coils preheat the seawater and condense the flashed steam to produce pure water. After reaching the brine heater, the water is boiled at 70-110°C and enters the flash chambers where the flashing (sudden evaporation) takes place. While the hot brine entering the flash chambers, the vapour pressure of each flash chamber must be controlled in order to avoid violent evaporation. The vapour rises to the upper part and condenses to form pure water. The brine gets deposited in the bottom of the chamber and the remaining brine enters the next chamber where the process repeats again [10].

Multiple effect distillation (MED) consists of multiple chambers (Effect). The seawater feed is preheated before sending into the first effect. In the first effect, the feed is sprayed on the evaporator tubes and where a part it gets converted into hot vapour. This hot vapour is fed into the second effect which acts as a heating medium for the evaporation process. The remaining feed that is not vapourized gets settled at the bottom of the effect and transferred to next effect for the process to repeat again. Vapour compression distillation consists of an evaporator, a condenser and a compressor (Mechanical or Thermal). Seawater is sprayed on the evaporator tube, which gets evaporated. The water vapour after evaporation gets compressed by the compressor, mechanical or steam jet. This compressed air acts as a heating source for the incoming seawater to vapourize and condenses inside the tubes to get pure water (distillate). The seawater that is not evaporated gets collected at the bottom of the vessel and recirculated.

Membrane fabrication methods

The membrane fabrication methods are described in **Figure 3**.

Electrospinning

Electrospinning is a process used to produce non-woven fibres in the range of micrometer to nanometer using electrostatic forces. It is a simple and versatile technique for the production of nanofibres. The fibres exhibit characteristics of fine, thinner diameter and a large surface to volume ratio compared to fibers produced from other conventional techniques. The apparatus consists of three major components High Voltage Power Supply, Syringe Pump and Grounded Collector. When an electric potential is applied to the polymer solution or melt which is held by its surface tension, an electric charge is developed on the liquid surface. This electric potential is further increased for the formation of Taylor Cone. A liquid jet is ejected from the Taylor cone when the applied electric potential overcomes the surface tension of the liquid. The dry polymer fibers are formed on the collector as a result of evaporation of solvent [11, 12]. The polymer parameters that affect the process are solution properties like surface tension, viscosity, molecular weight distribution, polymer structure and conductivity and other parameters like humidity, temperature and air velocity in the chamber; Equipment Parameters like electric potential at the tip, hydrostatic pressure in the syringe pump, flow rate and distance between the collector and tip of the needle.

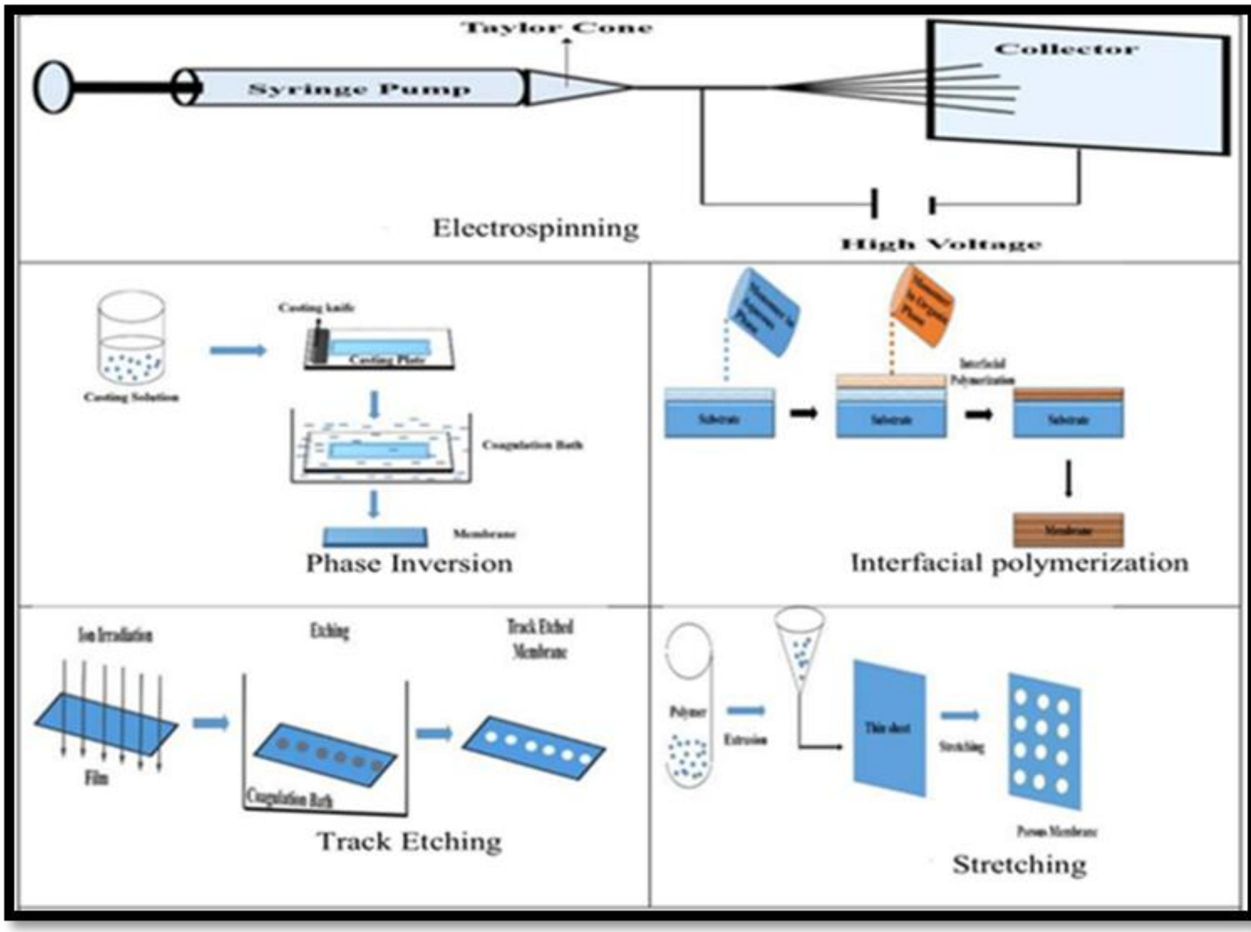

Figure 3 Membrane fabrication techniques

Phase inversion

A homogeneous polymer solution is prepared by dissolving the polymer in its solvent, and in a controlled manner the polymer is laid on a sheet or thin film. Additives and pore former are used to achieve the required properties of the membrane. In general, polymers used to prepare membranes by phase inversion technique are Polyvinylidene fluoride, Cellulose Acetate, Polysulfone, Polyethersulfone and polyamide [13].

Different types of phase inversion techniques are used to construct polymeric membrane. In thermally induced phase separation (TIPS) process polymer is mixed with the diluent at a high temperature, precipitation is induced by decreasing the temperature of the polymer solution and the solvent is removed by evaporation or extraction [13]. In immersion precipitation or non-solvent induced phase separation (NIPS) process, the casting solution is immersed in the coagulation bath which contains non-solvent generally water. Due to the exchange of solvent and non-solvent membranes are formed and the condition is solvent and non-solvent must be miscible [13]. In evaporation-induced phase separation (EIPS) process the casting solution is prepared with a polymer and a mixture of volatile solvent and less volatile non-solvent. Evaporation of solvent results formation of membrane and also called as solution casting method [13]. In vapour induced phase separation (VIPS) process the casting solution is exposed to vapour atmosphere containing non-solvent, which results in absorption of non-solvent inducing precipitation [13].

Interfacial polymerization is a method which is used to prepare thin-film composite membrane. In this process, two reactive monomers are dissolved in immiscible solvents (aqueous phase and organic phase) and are brought into contact by stirring results polymerization at the liquid-liquid interface of the two solutions. The factors that affect the membrane morphology are reaction time, the concentration of monomer, type of solvent and post-treatment conditions [13]. In track etching, a film is irradiated with energetic heavy ions in the perpendicular direction and the ions will penetrate in the film which results in the formation of linear tracks. This film is etched along the tracks by immersing in acid or alkaline bath which results in the formation of uniform cylindrical pores. The parameters like porosity, pore size, and pore density can be controlled by track etching method [13]. Stretching: The polymer is heated above its melting point followed by extrusion. These extruded films are a thinsheet-like structure which is stretched three hundred percent of its original length for the formation of pores. It is a solvent-free technique and is suitable for highly crystalline polymers [13].

Membranes used for desalination

Polymer-based membrane

Polymeric membranes are commonly used for desalination because of their low cost, simple design, improved perm-selectivity and excellent physical and chemical properties. Polymers which are used for the preparation of membranes are Cellulose acetate, Polyvinylidene fluoride, Polyethersulfone, Polysulfone, Polyacrylonitrile, Polyamide, Polyimide and Polyvinyl alcohol. The drawback of polymeric materials is that they exhibit properties like low stability, short lifespan and hydrophobicity which leads to a flux decline and fouling. In order to cope with these drawbacks, the membranes are prepared by incorporating nanomaterials or inorganic fillers inside the polymer matrix called as Nanocomposite and Mixed Matrix Membrane respectively.

Cellulose acetate membrane

In 1960, the first membrane was developed by Loeb and Sourirajan from Cellulose acetate by phase inversion technique for reverse osmosis process. Cellulose Acetate is a chlorine resistant polymeric membrane and low in cost. The Cellulose Acetate- polydopamine-modified halloysite nanotubes (CA-DHNT) membranes were prepared for forward osmosis by phase separation technique. Different concentrations of DHNT was added to the cellulose acetate matrix. The membranes possessed an asymmetric structure with dense top layers and sponge-like structured porous sublayers. The 0.5wt% of CA-DHNT membrane exhibited a water flux 16 L/m^2h and better salt rejection (10mM NaCl) compared with commercial HTI FO membrane [14].

Graphene Oxide-Cellulose acetate (GO-CA) nanocomposite membrane for desalination was prepared by phase inversion method which resulted in high flux. The GO-CA nanocomposite membrane consists of dense skin layer and sponge-like sub-layer. Different concentrations of Graphene Oxide (0 to 0.01wt%) was added to Cellulose Acetate matrix and the membrane performance was analyzed for reverse osmosis of 2000ppm NaCl by comparing with Cellulose Acetate membrane. The GO-CA membrane with the concentration of 0.005wt% exhibited a water permeation of 13.65 $L\ m^2\ h^{-1}$ at 30 bar which is 129% greater than pure Cellulose acetate membrane with a slight decrease in salt rejection [15]. The flat sheet Cellulose triacetate Reverse osmosis (CTA-RO) membrane was synthesized by non-solvent induced phase separation technique. Quaternary ammonium compounds, such as 3-chloro-2-hydroxypropyltrimethyl ammonium chloride (CHPTAC) was covalently immobilized on the surface of the CTA-RO membrane by etherification procedure in order to obtain QCTA-RO membrane. The morphology of the membrane was irregular with rough surfaces and no significant influence was observed on mechanical, thermal stability and crystallinity. The membrane performance was studied for reverse osmosis and the salt rejection rate was found to be 92% [16]. Cellulose triacetate flat sheet reverse osmosis membrane was synthesized by embedding graphene oxide nanoparticles by melting method. By incorporation of graphene oxide into cellulose triacetate the tensile strength and permeate flux of the membrane was increased from 10.2 MPa to 23.1 MPa and 1.67 $Lm^{-2}h^{-1}$ to 4.74 $Lm^{-2}h^{-1}$ respectively. Due to the formation of channels by the incorporation of GO resulted in maximum permeate flux and minimum salt rejection compared to pure cellulose triacetate membrane [17].

Polyvinylidene fluoride membranes

Polyvinylidene fluoride membranes are most commonly and broadly used for Membrane distillation process due to its hydrophobic nature. Polyvinylidene fluoride hollow fiber membrane was prepared by thermally induced phase separation method using glyceryl triacetate (GTA) and dibutyl sebacate (DBS) as mixed diluents for air gap membrane distillation. This bicontinuous membrane exhibited good mechanical performance and narrow pore size distribution. The membrane performance was analyzed using 7 wt% NaCl which resulted in 99.9% salt rejection and can be operated continuously for 240h without any significant change in permeate flux (5.5 kg/m^2h) [18]. PVDF membranes were surface modified by depositing fluorographite particles. The hydrophobicity and anti-wetting properties of the membrane increased due to the deposition of fluorographite particles on the surface. The efficiency of the membrane for direct contact membrane distillation was evaluated using 10% NaCl solution which can be operated for 200h compared to pristine PVDF and the salt rejection was 99.9% [19].

PVDF nanofiber support was prepared by electrospinning method. This PVDF nanofiber support was modified by dip coating and cross-linking method to increase the hydrophilicity of the membrane. Then polyamide layer was deposited on the PVA coated PVDF nanofiber through interfacial polymerization. This thin film composite membrane exhibited high porosity, hydrophilicity, and mechanical strength. The flux for forward osmosis was found to be 34.2 LMH using 1M NaCl as draw solution [20]. A novel dual layer membrane was prepared by coating octadecylamine functionalized graphene oxide on the surface of the polyvinylidene fluoride membrane. The membrane performance was evaluated by Air-Gap Membrane Distillation.Modified novel dual layer membrane exhibited higher hydrophobicity, excellent stability, salt rejection and significant surface [21].

Polysulfone/Polyethersulfone membrane

Polysulfone/Polyethersulfone membranes are extensively used because of their high chemical and thermal resistance [22]. Graphene oxide-polysulfone, mixed matrix membrane was synthesized by wet phase inversion method. Graphene oxide is hydrophilic in nature because of the presence of different types of hydrophilic functional groups which helps in water uptake easily. Due to the incorporation of graphene oxide, the mechanical strength and hydrophobicity of polysulfone membrane has been increased. The GO-PSF mixed matrix membrane exhibited a salt rejection (Na_2SO_4) of 72% [22].

Polysulfone/Polyacrylonitrile (PSF/PAN) nanofibers were prepared by electrospinning which acts as a substrate for the membrane. The blending of PSF and PAN resulted in increase in hydrophilicity, higher porosity, mechanical strength and high water flux. Polyamide thin layer was fabricated on the PSF/PAN nanofiber substrate through interfacial polymerization. The performance of the nanofiber thin film composite (NFTC) membrane (PSF/PAN/PA) was compared with PSF/PAN membrane (TFC) in which the substrate is prepared by phase inversion method for forward osmosis. Different types of draw solution like NaCl, KCl, $MgCl_2$ and $MgSO_4$ were used. The NFTC membrane exhibited a higher water flux 38.3 LMH for KCl as a draw solution [23]. The disulfonated poly(arylene ether sulfone) (BPS-20K) membranes were prepared for desalination by solvent free melt extrusion process using a different concentration of PEG (20wt% to 30wt%) as a plasticizer by varying PEG extraction temperature. The results concluded that molecular weight, concentration and extrusion temperature of PEG plays a prominent role in water uptake studies. As the extrusion temperature, molecular weight and concentration of PEG increases, the water uptake and permeability also increased [24].

Polyacrylonitrile membrane

Polyacrylonitrile – Graphene Oxide (PAN-GO) composite membrane was prepared by vacuum filtration-assisted assembly method. This PAN-GO membrane has a very high performance for desalination since it can be treated with the salt concentration of 100,000ppm. The performance of the membrane was analyzed using different concentrations of NaCl solution at different temperature by pervaporation. The membrane exhibited a salt rejection of 99.8% at 90℃ and high water flux of 65.1 $Lm^{-2}h^{-1}$. This PAN-GO composite membrane is capable ofusing in seawater desalination, brackish water desalination and also for reverse osmosis concentrate treatment [25]. A bi-component nanofibrous membrane composed of poly (vinylidene fluoride-co-hexafluoropropylene) (PVDF-co-HFP) and Polyacrylonitrile (PAN) was fabricated by electrospinning of PVDF-co-HFP on top of the electrospinned PAN membrane. The PVDF-co-HFP nanofibers exhibited high porosity and superhydrophobic property and the thickness of the membrane was found to be 80-82µm. The membrane performance was analyzed by Direct-Contact Membrane Distillation and a comparison study was made with the polytetrafluoroethylene membrane. The salt rejection was about 98.50% and permeate flux of 30 $Lm^{-2}h^{-1}$. The results suggested that thinner, high porosity and more hydrophobic membrane results in high Direct-Contact Membrane Distillation flux [26].

Polyimide membrane

Polyetherimide membrane was prepared by immersion precipitation method. The TiO_2 and sulfonated polymers like polyether ether ketone (SPEEK) and Polyethersulfone (SPES) were used as an additive to embed on polyetherimide (PEI). The parameters required for salt rejection antifouling, ion-exchangeable mechanism, hydrophilicity, and miscibility are possessed by sulfonated polymers. To study the membrane performance, a comparison is made with pristine polyetherimide (PEI) and polyetherimide along with the additives (PEI/SPEEK and PEI/SPEEK/TiO_2, PEI/SPES and PEI/SPES/TiO_2). The sulfonated polymer polyether ether ketone/ TiO_2/Poyetherimide membrane showed good hydrophobicity, water permeability and salt rejection were found to be in the order of Na_2SO_4>NaCl> $MgSO_4$[27].

Graphene Oxide incorporated into polyimide to produce mixed matrix membrane by wet phase inversion method and analyzed for desalination by pervaporation. The incorporation of graphene oxide into polymer matrix improved fouling, water permeability, and salt rejection. The nature of the membrane was found to be highly stable and asymmetric porous with the dense top layer and finger-like projection on the sub-layers. The water permeability and salt rejection of the membrane was 36.1 kg/m^2 h and 99% respectively [28].

Polyamide membrane

A sulfonated diamine monomer, 4,4’-((1,4-phenylenebis(methylene)) bis(azanediyl))dibenzenesulfonic acid (PMABSA) was used to fabricate a reverse osmosis membrane with trimesoyl chloride (TMC), instead of *m*-phenylene diamine (MPD) by interfacial polymerization. This *m*-phenylene diamine was usually used for the preparation of polyamide membrane, which is the top layer of the reverse osmosis process. The performance of the novel membrane PMABSA/TMC was studied by comparing with trimesoyl chloride and *m*-phenylene diamine TMC/(MPD), 4,4'-(1,2-ethanediyldiimino)bis(benzenesulfonic acid)/ trimesoyl chloride EDBSA/TMC and with an SW30HR membrane which is commercially available by experimental and molecular dynamics study. The salt concentration of 2000mg/L at a temperature and operating pressure of 25℃ and 1.55MPa respectively. The novel PMABSA/TMC membrane had a lower water permeation and higher salt rejection of 98.2% [29].

Polyamide cross-linked graphene oxide (PA-GO) membrane was prepared for forward osmosis process. Polyethersulfone acts as support layer for the PA-GO membrane by which Graphene oxide was intracross-linked via m-xylylenediamine monomer (MXDA) and inter-cross-linked via trimethyl chloride (TMC). Since it is a forward osmosis, three draw solutions were used 0.25 M trisodium citrate (TSC), 0.33 M Sodium Sulfate (Na_2SO_4), and 0.33 M Magnesium Chloride ($MgCl_2$) and compared with commercially available forward osmosis membrane. The water flux for PA-GO membrane was higher when trisodium citrate used as draw solution, moderate to sodium sulfate and zero for magnesium chloride while the permeate flux was in reverse order [30].

Ceramic-based membrane

Ceramic membranes have been used for desalination because of their chemical and thermal stability. The ceramic membrane used for desalination process are made from metal oxides such as titania, zirconia and silicon carbide [1]. Yttria-stabilized zirconia (YSZ) bi-layer membrane was prepared by using screen printing and freezing drying tape casting method. This bi-layer membrane has a hierarchically-structured thick support layer and a thin functional layer. The hydrophilic nature of the ceramic membrane surface was manipulated using the grafting agent 1H,1H,2H,2H-Perfluorooctyltriethoxysilane in order to obtain a hydrophobic membrane. The YSZ functional layer had a thickness of 20µm and pores not larger than 1µm which was coated on the YSZ support layer. This hierarchically-structured Yttria-stabilized zirconia bi-layer membrane had a porosity of 42.6%, tortuosity value of 1.58 to improve the water flux. The YSZ bi-layer membrane performance was evaluated by Direct Contact Membrane Distillation for desalination using a 2wt% salt solution. The salt rejection rate was 99.5% and water flux of 28.7 Lm^{-2} h^{-1} [31].

The hydrophilic TiO_2 and Al_2O_3 ceramic membranes (planar and tubular) were modified with grafting agents n-octyltriethoxysilane, n-octyltrichlorosilane,and trichloro(octadecyl)silane which are non-fluorinated and hydrophobic in nature used for altering the nature of TiO_2 and Al_2O_3 ceramic membranes from hydrophilic to hydrophobic. In case of the tubularmembrane, the efficacy of grafting was evaluated by water liquid entry pressure determination and for planar membranes by contact angle measurement. The type of grafting agent and time of exposure have an impact on hydrophobization process which results in the change in physico-chemistry properties (surface free energy and surface roughness) of ceramic membrane. The grafting agent trichloro(octadecyl)silane exhibited the highest value for contact angle and water liquid entry pressure compared to other agents. The alumina grafted membrane have higher permeate flux value compared to titania grafted membranes. The efficiency of the membrane in the process of desalination is assessed by Air Gap Membrane Distillation which had an overall rejection rate of 98% [32].

Alumina hollow fiber membranes with different morphology were prepared using phase inversion technique. The different types of structural morphologies of the membranes were induced by altering the spinning conditions. In order to change the hydrophilic nature of the ceramic membrane, grafting was done using the grafting agent 1H, 1H, 2H, 2H- perfluorodecyltriethoxysilane. The morphology of the membrane had an effect on the performance of Air-Gap Membrane Distillation. The permeate flux was greater for the membrane with larger micro-channel. Different concentration of salt solution 1,2,3 and 6.5wt% were used to study the membrane efficiency by Air-Gap Membrane Distillation and the salt rejection was 99.8% [33]. The ceramic membrane was prepared from the raw materials Moroccan red clay and natural phosphate acts as a pore former through dry compaction method. Different concentration of natural phosphate (10-40%) was added and the morphology structure was examined. Uniform pores were observed for membrane containing 40% phosphate. The average pore size of the membrane was 2.5µm. The efficiency of the membrane for microfiltration was analyzed against tannery beamhouse effluent, raw seawater, and synthetic saltwater and achieved a good water permeability of 928 L/ ($h \cdot m^2 \cdot bar$). The turbidity removal of tannery beamhouse effluent, raw seawater, and synthetic saltwater was 99.8%, 99.62% and 99.86% respectively [34].

Graphene membrane

Graphene membrane is emerging as a new trend for desalination because of their, tuneable pore-forming properties, high tensile strength and mechanical strength. Single layer graphene was synthesized by chemical vapour deposition under ambient temperature pressure and then transferred to silicon nitride microchip by polymer transfer method. Nanopores were produced on the graphene layer by exposing to oxygen plasma. Salt rejection of 100% was attained using the single layer graphene membrane [35].

Stacking of Graphene Oxide membranes is used for desalination. The water permeation in the graphene oxide membrane occurs through the interconnected nanochannels by a tortuous path and results in high water flux due to their high surface area. These nanochannels are the space in between the graphene oxide layers that can be controlled by creating stabilizing force in between the layers. Graphene Oxide is hydrophilic, pH sensitivity in nature and has different functional groups like epoxide, hydroxyl and carboxyl [27]. So, graphene oxide is incorporated into the polymer matrix to produce GO-polymer composites. By incorporation of Graphene Oxide into the polymer matrix the properties of polymer like hydrophilicity, mechanical strength, water permeability, salt rejection and fouling are enhanced [36].

Carbon nanotubes is an emerging technology in the field of desalination. Carbon nanotubes can be incorporated into continuous polymer matrix called the mixed matrix membrane in order to increase the mechanical stability of the membrane. Mixed matrix membrane was prepared by incorporating multi-walled carbon nanotube into an electrospun polyvinyl alcohol to enhance the water flux. Polyamide membrane resulted in increased salt rejection by incorporating 10% carbon nanotubes into it. Similarly, carbon nanotubes are incorporated into polyvinylidene fluoride membrane in membrane distillation process which was performed at lower temperature and the resulted flux was six times higher [37].

Directional solvent extraction process

Directional Solvent Extraction process is an alternative desalination technology to the distillation and membrane-based processes. For directional solvent extraction process, the solvent must possess four conditions as follows 1. Water must be soluble in the solvent; 2. Increase in temperature increases the solubility of water in a solvent; 3. The solvent must be insoluble in water; 4. Salt does not dissolve in the solvent. The solvents used for directional solvent extraction process are hexanoic acid, soyabean oil, decanoic acid and octanoic acid [38]. The solvents extract the water leaving behind the salts and other contaminants [39]. The advantages of directional solvent extraction process are membrane free, low thermal and electrical energy consumption compared to reverse osmosis and distillation process [38].

Aquaporins

Aquaporin proteins (AQP) are present in living organism for the selective water transport across the membrane [40]. These aquaporin proteins are used in the biomimetic membrane for desalination because of their high permeability and salt rejection [41]. Aquaporin is incorporated into the biomimetic membrane and can be classified into two types 1. AQP incorporated supported membrane layer where lipids or polymers act as supported layers (SMLs) and 2. AQP incorporated vesicle encapsulated membranes where proteoliposomes or proteo-polymersomes acts as a vesicle (VEMs). Aquaporin incorporated biomimetic membrane is used for nanofiltration, reverse osmosis and forward osmosis. The AQP incorporated proteoliposome was deposited on the hollow fiber polyethersulfone membrane which was prepared by the dry-jet wet spinning method and it was coated with polyamide layer by interfacial polymerization. This biomimetic membrane exhibited a permeate flux of 40 L m^{-2} h^{-1} and salt rejection (NaCl solution 500ppm) of 97.5% in reverse osmosis process. Moreover, it has also been used for forward osmosis process which exhibited a superior water flux compared to other forward osmosis thin film composite membrane [42]. The surface modification of cellulose acetate membrane was done by (trimethoxy-silyl) propyl methacrylate which acts as a substrate. The selective layer was deposited on the surface modified cellulose acetate substrate by vesicle rupture and UV polymerization of triblock polymer (ABA) vesicles. The different ratio of Aquaporin (AQPZ): ABA was prepared 1:50 1:100 and 1:200. Finally, a planar biomimetic aquaporin membrane was prepared and exposed to UV radiation. The biomimetic membrane performance for nanofiltration was elucidated. The membrane with the 1:50 of AQPZ: ABA ratio showed a water permeability of 34 LMH $bar^{-1}$and a salt rejection more than 30%.The quantity of aquaporins plays a major role in water permeability and salt rejection. This increase in water flux was observed when there is an increase in the concentration of AQP [43].

Solar desalination

Thetwocategories of solar technology are concentrating solar power technology and Photovoltaic technology. Concentrating Solar power technology includes a Parabolic trough, Linear Fresnel reflector systems, and central tower receiver. Photovoltaic includes the flat-plate photovoltaic module. Solar energy is coupled with desalination technology which can use in combination as Photovoltaic/Reverse osmosis, Parabolic troughs/Multi-stage Distillation and Parabolic troughs/Multi-effect Distillation [44]. Water can be desalinated using solar energy based on the principle of humidification and dehumidification. The principle humidification and dehumidification is based on evaporation and condensation process compatible with the solar energy. The evaporation takes place in the humidification chamber by mixing of hot water with dry air and condensation takes place to yield pure water in dehumidification chamber. The system is open water closed air cycle in which air is circulated between the humidification and dehumidification chamber between the connected duct in a closed circuit made up of polyvinyl chloride pipes. The water is partially recirculated into humidification chamber to recover heat. The hot water inlet temperature of humidification temperature has a great impact on water productivity as the inlet temperature increases the water productivity also increased [45].

Conclusion

The developments in the field of desalination are focused in order to achieve high permeate flux and selectivity at low cost. Polymeric, ceramic, nanocomposite, andgraphene-based membranes are used in the desalination process and the pros and cons are critically discussed. Membrane construction principles, improvising technologies, role of additives are discussed in detail. Polymer with additives and incorporation of inorganic fillers into its membrane matrix increases the mechanical stability, hydrophilicity, salt rejection, high permeate flux and other functionalities of the membrane.

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