Nishad and Rajput, *Journal of Innovation in Applied Research* (2023), 6(1): 21-33
https://doi.org/10.51323/JIAR.2023/6/1/21-23

JiAR
Journal of Innovation in Applied Research
eISSN: 2581-4206

Received: 29 November 2022
Accepted: 004 December 2022
First Published: 10 February 2023

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REVIEW ARTICLE

Membrane Distillation for Desalination and Water Treatment

Vartika Nishad* and Manish Singh Rajput

Abstract: Membrane distillation is a technique used to separate two aqueous solutions at different temperatures. It requires a micro-porous hydrophobic membrane that allows only vapours to pass through to form water droplets. The partial vapour-pressure difference is the driving force for this phenomenon. Direct Contact Membrane Distillation, Air Gap Membrane Distillation, Sweeping Gas Membrane Distillation and Vacuum Membrane Distillation are the processes used in water recovery and wastewater treatment. Various applications of Membrane distillation process are studied. It is seen that membrane fouling and temperature polarization are the disadvantages of the system. This review reports operating parameters, membrane characteristics (pore size, membrane thickness, liquid entry pressure, porosity), membrane modules (plate and frame, hollow fiber, tubular membrane, spiral wound) and water treatment using membrane distillation process. It also covers basic fundamentals of mass and heat transfer phenomenon. MD is probably an economical process and requires less claim of membrane attributes as well.

Keywords: Desalination; Flux; Fouling; Porosity; Membrane desalination

1. Introduction

The demand for pure water has expanded step by step for last few decades. Membrane distillation (MD) is a micro filtration technique that uses heat energy for desalting highly saline waters. This procedure allows only molecules of vapour to pass over a hydrophobic micro porous sheath. Vapour pressure distinction between porous hydrophobic membrane faces is the persuading power for this process (Alkhudhiri, Darwish, & Hilal, 2012). In contrast, with traditional procedures, low operating temperature is an attractive feature of the MD process. In reverse osmosis (RO), hydrostatic pressure is more than in MD. As a result, MD is probably an economical process and requires less claim of membrane attributes as well (Alkhudhiri et al., 2012).

1.1. Membrane Technology

The membrane is a thin barrier which in the presence of an appropriate driving force allows one or more constituents to move across it when placed between two phases or mediums. To perform membrane distillation (MD), the hydrophobic and porous material is required. At high temperature, evaporation of fluid takes place at fluid/vapour interface. Vapour produced during the process crosses the membrane pores and condenses on the other side of the membrane. The difference in vapour-pressure is the motivating force for MD. The desalination of seawater is one of the applications of MD process. Desalination is reliable and economical way of producing drinking water from seawater (Tijing et al., 2015).

1.2. Overview of MD

Organic and inorganic membranes can be used for water and wastewater treatment. Highly selective, chemically stable, resistant to fouling and good mechanical strength membranes are preferred. Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD), and Vacuum Membrane Distillation (VMD) are the processes used in water recovery and wastewater treatment. Mass transfer and heat transfer are the two mechanisms involved in the MD process. Mass transfer is governed by molecular diffusion, Poiseuille flow (viscous flow) and Knudsen diffusion. Mass transfer around boundary layer is considered negligible (Moulik et al., 2016).

To choose a membrane material, following attributes are examined (Eykens, Sitter, Dotremont, Pinoy, & Bruggen, 2017):

- Thermal conductivity of the membrane
- The geometry of the membrane
- The geometry of the module (length, packing fraction)
- Operating conditions of the membrane (feed creation and temperature, downstream temperature, and pressure).

1.3. Operating parameters

Operating parameters that affect MD performance are (Alkhudhiri et al., 2012):

- Feed temperature: Feed temperature exponentially influences distillate flux. High temperature generates high flux. The rise in temperature can cause reduced temperature polarization due to high flux. Energy used for vaporization will increase with increasing temperature difference across the membrane.
- Feed concentration: High concentration of the feed results in reduced flux and increased temperature polarization. Vapour pressure drop caused by an increase in feed concentration reduces flux due to water activity, viscosity, mass and heat transfer coefficient. It has been studied that increase in NaCl concentration in the feed solution can decrease permeate flux.
- Recirculation rate: Higher flux can be achieved by increasing the recirculation rate that maximizes the heat transfer coefficient and minimizes the resistance at the boundary layer.
- The air gap: The air gap results in an increased temperature gradient that ultimately increases the permeate flux. Also, there is difference in flux when the pores are opened or closed on the upper side of the air gap. Flux product doubles with reducing air gap.
- Membrane type: The permeate flux increases with increased porosity and decreases with increased thickness and tortuosity. Higher permeate flux is obtained for a larger pore size membrane.

MD procedure can be applied in treating wastewater, desalinating saline water, removal of organic matter from aqueous solution, treatment of radioactive waste. The disadvantage associated with the MD process is low permeate flux, concentration polarization and temperature polarization, membrane fouling. Solar energy can be utilized by this procedure as an alternative energy source. MD also has an application in biotechnology such as removal of toxic products from cultured broth (Kullab & Martin, 2011).

2. Principle and mechanism of membrane distillation

2.1. Principle

Reverse osmosis (RO) or dialysis is utilized in most procedures for purification. The difference in pressure is the cause for RO and concentration difference is for dialysis. The selectivity of a layer can be because of the connection of the pore size to the size of the substance being held, or its dissemination coefficient, or its electrical extremity (Rezaei et al., 2018). Films utilized for MD restrain entry of fluid water while permitting penetrability with the expectation of free water atoms and therefore, for water vapour. The membranes is made of hydrophobic material like Polytetrafluoroethylene (PTFE), Polyvinylidenefluoride (PVDF) or Polypropylene (PP) and have pores at some standard distances at about 0.1-0.5μm. Strong dipole in water prevents the material from being wetted by the fluid (Warsinger et al., 2017). Despite the fact that the pores are impressively bigger than the particles, the high water surface pressure keeps the fluid stage from entering the pores. A convex meniscus forms into the pore. This impact is named capillary action. The partial vapour-pressure difference among different elements marks the impression of the fluid. The temperature difference is produced by differences in vapour-pressure. The temperature distinction through the film, more often than not somewhere in the range of 5-20 K, carries partial pressure contrast which guarantees vapour formation at the surface of the membrane due to pressure drop, penetrating over the pores to unite on the cooler side (Lee & Karnik, 2010). MD Process relies upon the following conditions:

- The porosity of the membrane
- Non-wettability due to fluids
- The membrane at one side should be in direct contact with the solution
- No capillary action

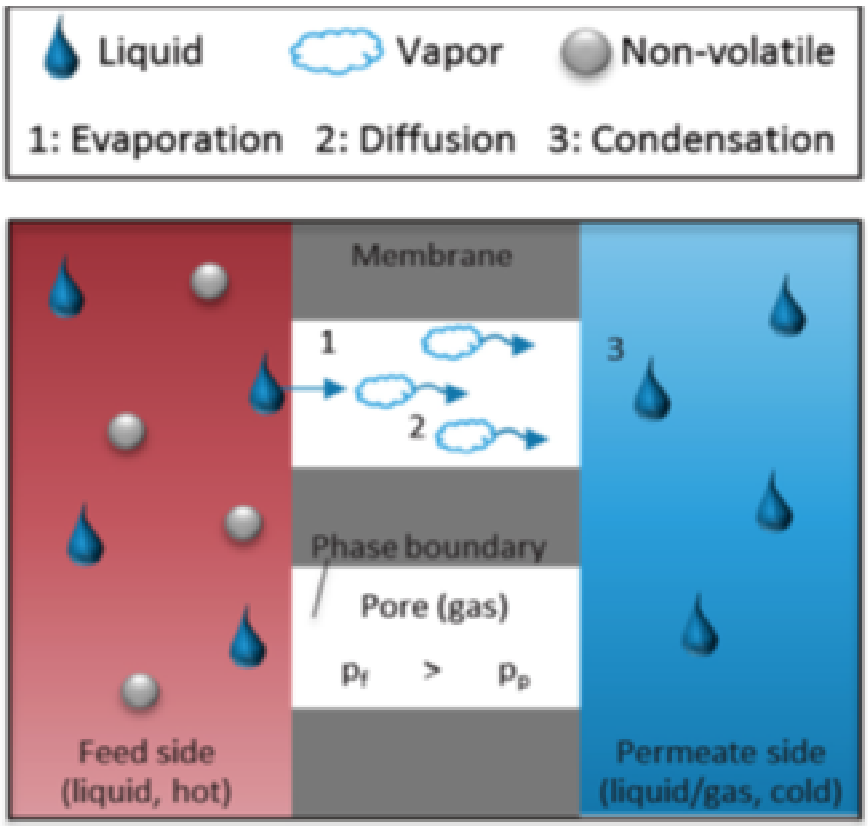

Figure 1. Principleof the MD process (Shirazi and Kargari, 2015)

2.2. Mechanism

In MD procedures, mass and heat transfer takes place from the hot side to the cold side. The feed temperature, T_f, drops while moving from bulk feed side boundary to T_1 at the membrane surface. Evaporation of water occurs during the process and gets transported across the membrane. At the same time, the conduction of heat to the cold (permeate) side occurs. As the water vapour condenses on the permeate side, temperature increases from T_p to T_2. The driving force for this phenomenon is the vapour-pressure variance between T_1 and T_2, which is less than the vapour pressure change between T_f and T_p. This phenomenon is called temperature polarization. The temperature polarization coefficient is defined by Schofield et al. as follows (Camacho,

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Dumée, Zhang, Li, & Duke, 2013):

$$T_P = \frac{(T_1 - T_2)}{(T_f - T_p)}$$

where, T_P= Temperature polarisation coefficient, T_1= Feed side boundary temperature, T_2= Permeate side boundary temperature, T_f= Bulk feed side temperature and T_p= Bulk permeate side temperature

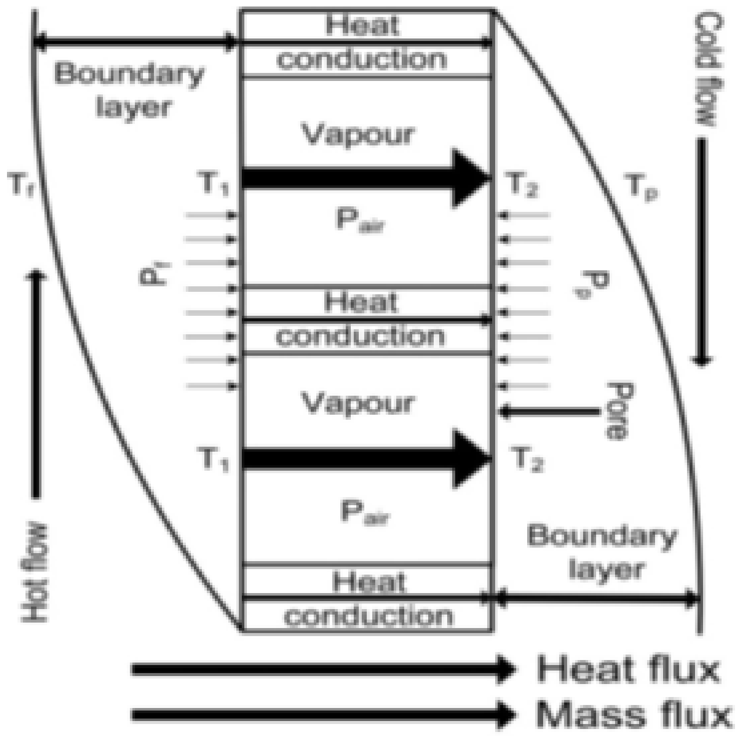

Figure 2. Mass and Heattransfer in DCMD (Camacho et al., 2013)

2.3. Mass Transfer

Mass exchange in MD procedure, incorporates 3 stages: (1) vapourisation of hot feed from the gas/liquid interface, (2) vapour pressure difference drives vapour from hot to cold interface through the pores and (3) condensation of vapour into the cold stream side. Therefore, mass is controlled by two major factors: difference in vapour pressure and membrane permeability. Considering fluid dynamics conditions on both sides of the membrane, the limiting step for mass transfer in MD is the mass transfer across the membrane. Membrane permeability is influenced by the following properties (Eykens et al., 2017):

- Since the membrane is not 100% porous, the effective area for mass transfer is less than the total membrane area.
- It happens that membrane pores are not straight through the membrane rather vapour transport path is greater than the membrane thickness.
- The inside walls of the pores increase the resistance to diffusion by decreasing the momentum of the vapour molecules.

Knudsen-diffusion (K), Poiseuille-flow (P) and Molecular-diffusion (M) or a combination between these govern mass transport and called as the transition mechanism. The Knudsen number (Kn) is used to indicate the dominant mass transfer mechanism in the pores.

2.4. Heat Transfer

Two steps are involved in heat transfer from the feed side to the permeate side. First, the heat transfers from the hot side to the cold side across the membrane as practical heat and latent temperature, so as to form the temperature difference between boundary layer and bulk flow; second, the heat transfers from the bulk flow of the feed to the boundary layer via heat convection, due to the temperature difference arising from the first step (Eykens et al., 2017).

3. Membrane Characteristics

The membrane is microporous and hydrophobic, act as physical obstruction which does not influence separation directly in MD. Water vapour or volatile consituents at the membrane surface cause vapour liquid equilibrium. Membranes used in MD system should have:

- Reduced mass transfer resistance
- Minimum thermal conductivity to inhibit heat loss through the membrane
- Good thermal stability in extreme temperatures
- Higher resistance to some chemicals, such as acids and bases

3.1. Liquid entry pressure

Liquid entry pressure (LEP) is the pressure applied to the system such that the feed does not penetrate through the pores of the hydrophobic membrane. LEP reduces linearly in the presence of organic solutes and feeds concentration (C. Gostoli, 1989). Franken et al. estimated LEP as:

$$LEP = \frac{4\alpha\sigma}{dp, max} cos\theta$$

where, α = geometric factor of membrane pore size, σ = surface tension, θ = contact angle of the liquid on the membrane, and $d_{p,max}$ = maximum pore size of the membrane

The result of the expression above possesses high LEP value for membranes that have minute pore size, high contact angle and high surface tension for feed solution (Alkhudhiri et al., 2012).

3.2. Membrane thickness

There is an inverse relationship between the permeate flux and the thickness of the membrane. As the thickness increases, flux decreases. The thicker the membrane the higher is mass transfer resistance, resulting in reduced permeate flux. 30–60μm is the ideal membrane thickness recorded (Shirazi & Kargari, 2015).

3.3. Membrane porosity and tortuosity

Membrane porosity is characterized as the division of the volume of pores to the mass volume of the layer. It can be estimated by two types of liquids: one that can penetrate the pores (hydrophobic liquid eg. IPA) and the other, that does not pass (hydrophilic liquid eg. water). A highly porous membrane allows larger permeate transport (Khayet & Matsuura, 2001). Porosity determined by Smolder and franken is:

$$\varepsilon = 1 - \frac{\rho_m}{\rho_{pol}}$$

where, ε= porosity, ρ_m= membrane density, andρ_{pol}= polymer density

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Shape of the pores other than cylindrical is referred to as tortuosity (τ). As tortuosity increases, permeate flux decreases (Srisurichan, Jiraratananon, & Fane, 2006). Macki-Meares formulated it as:

$$\tau = \frac{(2-\varepsilon)^2}{\varepsilon}$$

3.4. Mean pore size

Pore size should be optimum. Neither too small to reduce permeate flux nor too large to allow liquid penetration. Hence vapour flux is determined by mean pore size. 100nm-1μm pore size membranes are commonly used (El-Bourawi, Ding, Ma, & Khayet, 2006).

3.5. Membrane materials

Polytetrafluoroethylene (PTFE), polyvinylidenefluoride (PVDF) and polypropylene (PP) are some of the materials used in the MD process. Among the materials mentioned above, PTFE is highly hydrophobic (largest contact angle with water), has good chemical and thermal stability and oxidation resistance. PP also shows good thermal and chemical resistance. PVDF membrane can be easily prepared with better hydrophobic character, thermal resistance and mechanical strength. To enhance the mechanical strength, hydrophobicity and porosity for better performance novel membrane materials are developed such as, carbon nanotubes, fluorinated copolymer materials etc. Fabrication of membranes can be done by stretching, sintering and phase inversion methods (Camacho et al., 2013). Surface energies and thermal conductivities of PTFE, PP and PVDF are mentioned in the table below:

Table 1. Surface energy and thermal conductivity of different materials (Camacho et al., 2013)

Membrane Material	Surface Energy ($\times 10^{-3}$ N/m)	Thermal Conductivity (W $m^{-1}K^{-1}$)
PTFE	9-20	0.25
PP	30	0.17
PVDF	30.3	0.19

4. Membrane modules

4.1. Plate and frame module

In this module, the set of two membranes is sandwiched with a suitable spacer. Because of its advantage of easy cleaning and replacing, it is widely used in laboratory scale. The plate and

frame modules permit for high specific flow rates, causing an increase in the production rate. The packing density is relatively low in the order of about 100–400 $m^2/m^3$and has poor energy efficiency. It is used widely in the desalination of brackish water and wastewater treatment (Camacho et al., 2013).

4.2. Hollow fiber

In the hollow fibre module, many numbers of hollow fibres are bundled and wrapped in a tube. The hot feed solution is allowed to flow through the fibre and the permeate is gathered outside the fibre, or the hot feed solution is allowed to flow from outside the hollow fibres and the permeate is gathered inside the hollow fibre. It has certain advantages such as high packing density (3000 m^2/m^3) and low consumption of energy. On the contrary, it is not easy to clean and has high tendency to foul (Alkhudhiri et al., 2012). To concentrate apple juice, hollow fibre was used by Lagana et al. (Laganà, Barbieri, & Drioli, 2000).

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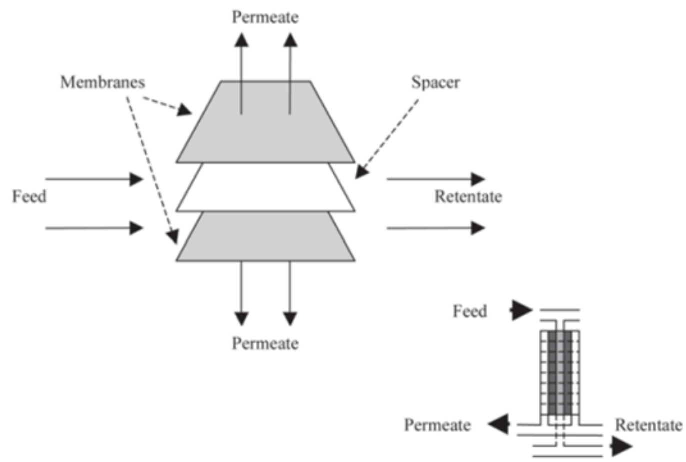

Figure 3. Plate and frame module

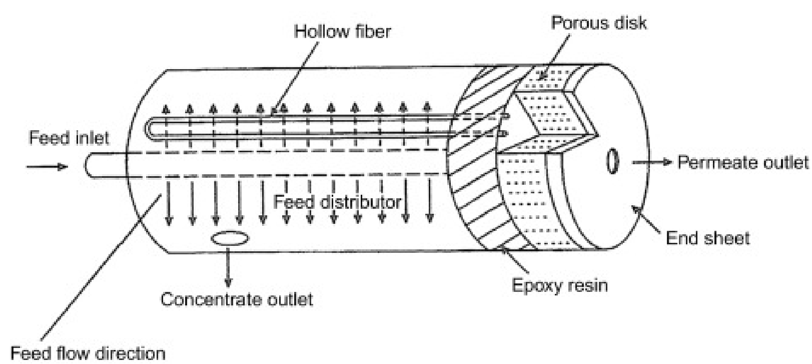

Figure 4. Hollow fibre

4.3. Tubular membrane

This type of module has a tube shaped membrane and it is implanted between two cylindrical compartments (warm and cool fluid compartments). This module has high cost of operation and low packing density. Low tendency to foul, easy cleaning and high effective area, makes this module to be used commercially (Alkhudhiri et al., 2012).

4.4. Spiral wound membrane

In the spiral wound membrane module, there is a central assembly tube that is perforated and is enveloped by spacers and flat sheet membranes. The feed is allowed to move through the surface of the membrane in an axial direction, while the permeate flows radially to the centre and exits from the assembly tube. This module has decent packing density, less tendency to fouling and suitable energy consumption (Alkhudhiri et al., 2012; Eykens et al., 2017).

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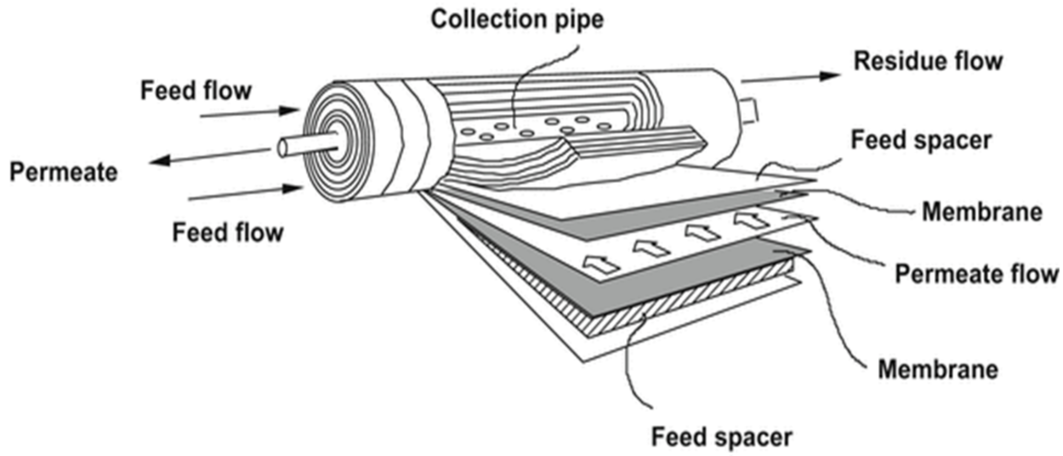

Figure 5. Spiral wound membrane

5. Water treatment using the MD process

5.1. Direct contact membrane distillation (DCMD

In the DCMD process hot feed solution is held in direct contact on one side of the membrane. Over the permeate side cold solution is passed. Membrane applied for DCMD process consists of selective layer that is thin, hydrophobic and microporous on the feed side and support layer that is thicker, less hydrophobic and porous at distillate side. The procedure is described as (Hsu, Cheng, & Chiou, 2002):

- Vapourization of solvent at the hot side
- Dispersion through the apertures
- Condensation at the membrane interface.

More porosity, thickness and less hydrophobicity leads to polarization effect on the distillate side and consequently in the reduction of distillate flux. DCMD process operates on low hydrostatic pressure. The concentration of microbes, chemicals and ions due to leakage, evapouration or wind action leads to corrosion. Heat loss by conduction is the drawback of this design (Hsu et al., 2002). Qu, Sun, Wang, and Yun (2013) performed a study on removal of ammonia from industrial and municipal wastewater, in which a capillary PVDF membrane with 80% porosity, average pore size of 0.22 μm, LEP of 250 kPa and surface contact angle of 87° was used for the experiments. Feed samples were prepared by dissolving ammonia chloride into distilled water, and the pH values were adjusted by adding HCl and NaOH to the feed solution. It was shown that there was 52%, 88% and 99.5% ammonia removal efficiency respectively within 105 min, when the feed solution was passed through these configurations: (a) conventional DCMD, (b) hollow fiber membrane contactor and (c) modified DCMD apparatus. This study concluded that DCMD process could be used for ammonia removal from wastewater (Qu et al., 2013). (Camacho et al., 2013)Xie (Xie, Duong, Hoang, Nguyen, & Bolto, 2009)

5.2. Sweeping gas membrane distillation (SGMD)

On one side of the membrane, feed stream at high temperature is in direct contact with the surface whereas inert gas is passed on the other side and results in sweeping of water vapour from the membrane apertures by the supplied sweep gas at the permeate membrane side followed by its condensation exterior to the membrane component. The gas barrier here is not static but decreases heat and enhances the mass transfer coefficient (Camacho et al., 2013). One of the applications of SGMD process for ammonia removal was studied by Xie et al. PTFE membrane with pore size of 0.45μm, 70% porosity and 100 and 200μm thickness, wastewater containing 100 mg/L ammonia at pH 11.5 was used in the experiment. Distillate flux, effect of feed temperature, flow rate of gas and flow rate of ammonia removal were examined. The experiment resulted in 97% ammonia removal (treated water contained 3.3 mg/L ammonia) and an increase in distillate flux and feed temperature was recorded (Xie et al., 2009). It was concluded that SGMD process could be effectively used for treating wastewater.

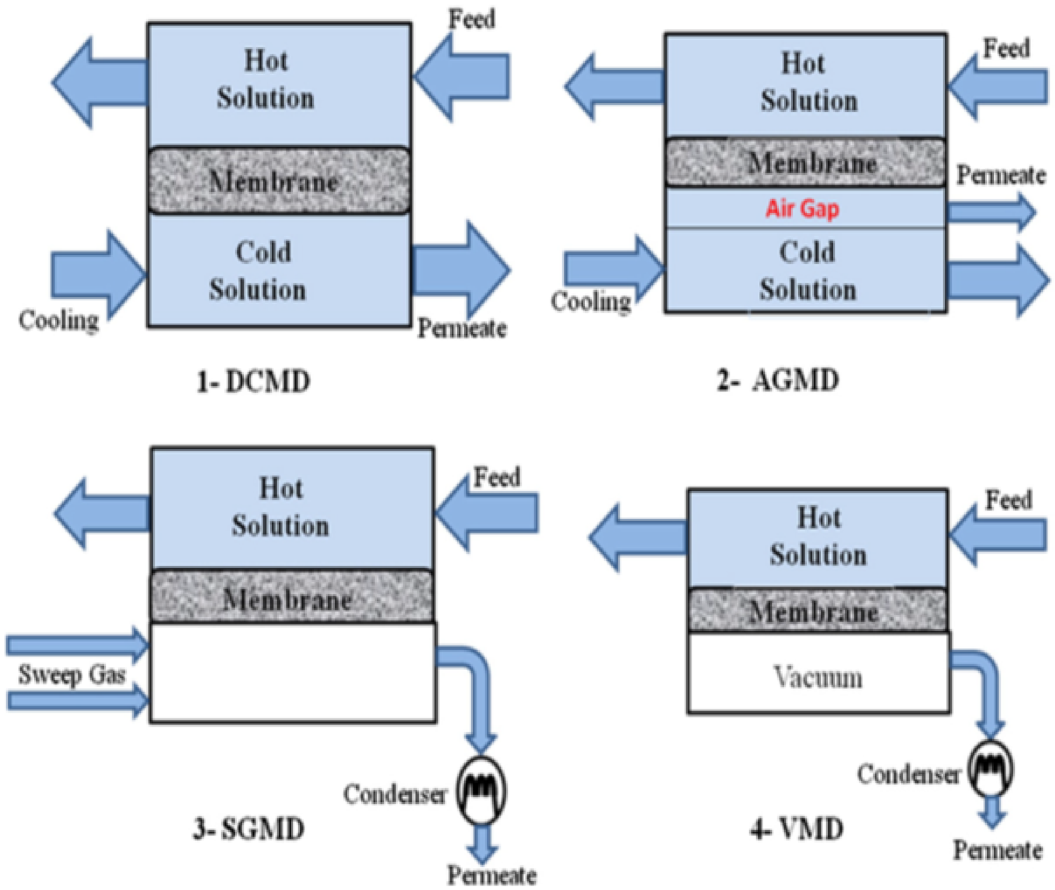

Figure 6. Differentmembrane distillation configurations (Alkhudhiri et al., 2013)

5.3. Air gap membrane distillation (AGMD

In AGMD, there is an immobile air gap between the membrane on distillate side and and cold stream. The air gap is crossed by vapour for condensation on the cold surface. Desalination and volatile organic compound removal from aqueous solutions are apt for this design. The drawback in the DCMD and SGMD led to the introduction of AGMD method. Driving force in this mode is the difference in temperature of the feed liquid and conducting surface (Siddhartha Moulik1 et al., 2016). In the Water gap membrane distillation (WGMD) module, the AGMD design is amended by introduction of immobile water in place of air. For desalination, deionized water is used to avoid contamination. One of the applications of AGMD was studied by Zarasavand et al. for the treatment of oily-saline water from a gas refinery. Solar energy was used with AGMD apparatus and the results showed much decrease in total dissolved solids from 1991 to 91mg/L. The objective of this experiment was to obtain drinking water from high salinity oily water and a good reduction in the contaminants was observed (Zarasvand et al., 2012).

5.4. Vacuum membrane distillation (VMD)

VMD is done by applying a vacuum on the penetrating side of the membrane, which decreases the pressure radically under the equilibrium pressure of the feed and volatile constituents. VMD process is used to increase permeate flux with less heat loss by evacuating the pores of the membrane by deaeration or creating vacuum on distillate side using vacuum pump. VMD gives high flux and vacuum provides insulation against heat loss by conduction and results in reduced resistance to mass transfer (Alkhudhiri et al., 2012). One of the applications of VMD was studied in downstream processing of bioethanol. In the conversion of lignocellulose to bioethanol, hydrolysis is involved that produces certain derivatives such as phenolic compounds, furans and aliphatic acids that act as inhibitors. These by-products reduce the productivity of ethanol. For removal of lignocellulose hydrolyzates by VMD process, Chen et al. studied inhibitor removal. Distillate flux and removal efficiency were studied. They concluded that high distillate flux was achieved at high feed temperature due to high heat transfer and also the removal efficiency increased from 7.26% to 24.79% (Chen et al., 2013). Among all the membrane configurations, DCMD has a widespread application in laboratory research. In commercial applications, AGMD predominates due to its high energy effectiveness and the ability for latent heat retrieval. The air gap in AGMD possesses less heat loss than in DCMD but increases mass transfer resistance.

6. Applications of MD

• The desalination of seawater and ground water, and removal of salts like sodium chloride (NaCl), magnesium chloride ($MgCl_2$), sodium carbonate (Na_2CO_3), and sodium sulfate (Na_2SO_4) from water.

• An AGMD experiment was conducted with four different salts (NaCl, $MgCl_2$, Na_2CO_3 and Na_2SO_4). Two flat-sheet polytetrafluoroethylene (PTFE) membranes of thickness 175μm and pore size of 0.2 and 0.45μm were taken. Operating parameters and salt concentration impact were analysed. It was reported that permeate flux increased with increase in pore size, feed temperature and feed flow rate. The rejection factors were different for different salt solutions. Also permeate flux decreased with feed concentration and temperature of the coolant. The energy consumption was independent of pore size and salt type (Alkhudhiri, Darwish, & Hilal, 2013).

• MD can be used for the removal of iron oxide, arsenic, organic matter, dissolved matter and Ca, Mg, Na, Fe, Zn from water (Pangarkar et al., 2016).

• Removal of water vapour from nitric acid, acetone and ethanol removal from wastewater and VOCs removal can be done by MD (Pangarkar et al., 2016).

• Domestic wastewater purification, treatment of olive mill wastewater purification of potable and cooking water can also be done by the MD process (El-Abbassi, Ha, Khayet, & García-Payo, 2013).

• Some food industries apply the MD process for the concentrating apple or orange juice (Alkhudhiri et al., 2013).

7. Membrane fouling

The growth of undesired materials on the membrane surface or inside the pores of the membrane is known as membrane fouling. It results in the unfavourable effect on the overall performance of MD, formed due to scaling (salt precipitation), inorganic fouling (collides deposition or salt crystallization), organic fouling (organic compounds accumulation) or bio-fouling (microorganism growth). Factors that affect fouling include (a) foulant characteristics (charge, solubility, concentration, diffusivity, molecular size, hydrophobicity, etc.) (b) membrane properties (pore size, hydrophobicity, PSD, surface roughness, surface charge, and functional groups on the surface) (c) operational conditions (solution temperature, flux and flow velocity) and (d) feed water characteristics (ionic strength, pH, solution chemistry, and presence of inorganic/organic matters) (Tijing et al., 2015). Properties of foulant and their concentration govern the nature of fouling that can happen. The temperature of the feed and its velocity as well as interactions between the membrane surface and foulants affect the fouling to a great extent. Fouling decreases permeate flux by obstructing the membrane pores and decreasing its effectiveness. However, the fouling strength can be restricted by the flow rate of the feed and its temperature. The figure given below shows the fouling inside the pores and on the membrane surface (Alkhudhiri et al., 2012).

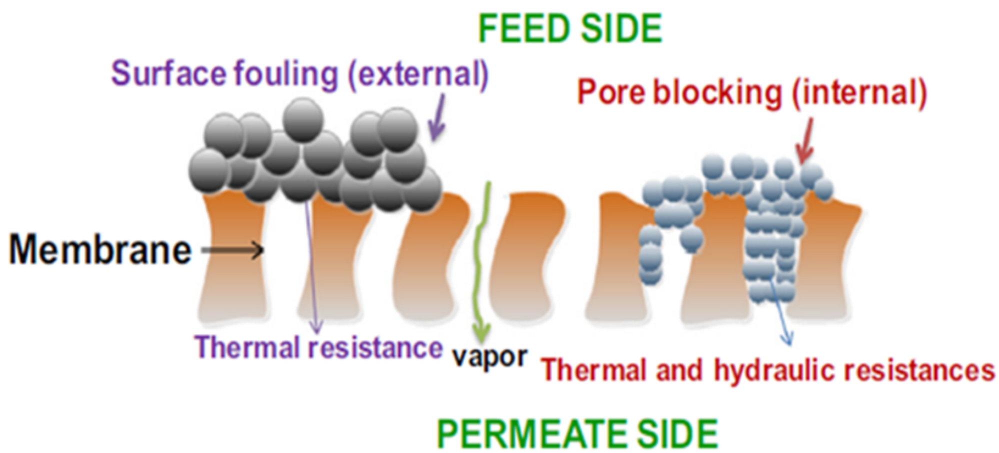

Figure 7. Membrane fouling in the pores and on the surface (Alkhudhiri et al.)

7.1. Cause for membrane fouling

Membrane fouling can happen due to the following ways (Tijing et al., 2015):

1) **Adsorption**: Increase in hydraulic resistance due to the absence of further flux results in the formation of single layer of particles on the membrane.

2) **Pore blockage**: The particles gather inside the membrane pores, resulting in the blockage of the membrane for the transfer of water.

3) **Gel formation**: In gel formation, the particles get deposited in the immediate vicinity of the membrane surface. For example: In the solution of concentration proteins, the protein molecules get deposited in the gel form over the membrane surface.

7.2. Types of fouling (Tijing et al , 2015)

1) **Inorganic fouling**: Precipitation of hydroxides and accumulation of other inorganic species cause this type of fouling.

2) **Colloidal fouling**: Colloidal particle deposition in the membrane pores causes this type of fouling. Colloids can be organic or inorganic.

3) **Organic fouling**: Organic particle deposition like debris, humus cause organic fouling. Surface water contains high organic matter.

4) **Biofouling**: Biofilm formed by microbes due to the release of polysaccharide causes biofouling. A viscous, slimy, hydrated form on the membrane surface.

Analytical separation becomes difficult because of fouling as it increases membrane thickness. Therefore, chemical cleaning is performed that ultimately results in high pollution levels.

8. Conclusion and Future perspective

8.1. Conclusion

Membrane distillation technology is applied for separation processes, such as desalination. In this process vapour molecules are allowed to cross through the membrane where vapour pressure difference acts as the driving force. This technology is capable of treating wastewater and brines, but since there is a lack of experimental data for pilot scale and specific membrane and modules, its use is limited. MD has application in fresh water production, removal of heavy metals and in food industry. Membrane modules, configurations and mechanism including mass and heat transfer is reviewed in this report. Membrane fouling phenomenon is the problem faced in this procedure as the contaminants get deposit on the membrane surface or inside the pores blocking them and ultimately cause flux decline. There is an emphasis on the development of membrane with high hydrophobic character and anti-fouling characteristics so as to achieve better performance and purification of water. A sustainable, robust and cheap technique needs to be developed in order to provide clean water to those areas which are highly scarce so that number of disease caused by water can be reduced and everyone can get access to the clean water.

8.2. Future perspective

MD process has several opportunities in modern industrial sectors. Desalination and other environmental applications are the promising future of MD. MD technique requires high energy input and long-term operation is prone to membrane wetting and fouling. It also has an uncertain economic cost. The process faces problem in shifting from pilot scale to commercial scale. By using different membrane modules, different permeate flux can be noted. Hence, the permeate flux is affected by module design, MD configuration and appropriate operating conditions. Reduction in energy consumption is one of the proposals been made. Hybrid MD systems along with pressure driven process, use of alternative energy sources such as solar and geothermal energy and waste heat recovery by installing MD plant near the nuclear power plant are some of the measures that can be taken. The recent development of MD solar pilot plant affirms that sustainable industrial growth is possible for MD. This may also bring down cost of the process. However, much more intensive and continuous efforts are needed in both basic and applied research operations where the primary objective should be decrease of production cost with low energy consumption and less waste generation, MD process development method, high flexibility and easy scaling up for construction of competitive and innovative pilot plants.

Conflicts of interest

The authors state that they have no known conflicting financial interests or personal ties that may have seemed to affect the work presented in this study.

Data availability

The corresponding author will provide the data that supports the findings of the study on reasonable request.

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Citation information

Cite this article as: Nishad, V., & Rajput, M. S. (2023). Membrane Distillation for Desalination and Water Treatment. *Journal of Innovation in Applied Research, 6(1)*, 21-33. doi: 10.51323/JIAR.2023/6/1/21-23

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