



# A Review of Membrane Distillation Process: - Before, During and After Testing

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**Abstract-** Membrane Distillation (MD) has garnered much interest as a reassured technology in separation and purification processes. MD separation process used difference of vapor pressure between surfaces of porous hydrophobic membrane as a driving force. The process allows only transport of water vapour molecules through membrane pores. This paper focuses on expectation of MD treatment process primarily for readers who lack knowledge on membrane process. A brief overview of MD before treatment process is given which includes membrane materials, membrane preparation techniques, membrane characteristics, module, and configuration. Membrane performance during treatment process was highlighted. The major drawback of MD which is membrane fouling was also emphasized in this paper.

**Keywords-** Membrane distillation, fouling, separation, membrane, hydrophobic

## I. INTRODUCTION

Transport processes of membrane are mainly isothermal with transmembrane hydrostatic pressure, concentration, electrical or chemical potentials as their driving forces [1]. On the contrary, membrane distillation (MD) is known as non-isothermal separation process. In MD process, difference in temperature between hot feed and cold permeate solutions induces vapor pressure difference over membrane surface (Eykens et al., 2017). The process separates liquid and vapor phase [2]. The term MD comes from resemblance of MD to conventional distillation as these processes involve vapor/liquid equilibrium (VLE) principle for liquid-liquid separation. Both these processes require supply of heat to feed solution in order to attain latent heat of vaporization, [3]. In general, research interest in MD is continuously increasing over the year with an average of 23% from 100 MD articles yearly published particularly focuses on membrane engineering and result in many novel approaches for membrane production [2].

MD can be used as a method for non-volatiles solutes separation from a mixture of volatiles and non-volatiles solutes as only volatiles components can successfully pass through the membrane while membrane retained liquid feed together with dissolved components. Normally, water is the major volatile components recovered in permeate side as water has a low boiling point. Recently, aside from desalination process, MD has been widely explored in application of wastewater treatment involving produced water, textile wastewater, valuable components recovery from seawater or brine and rubber wastewater oil-water emulsion treatment [4]. Besides, MD can be used to remove organic compounds which are volatile from water as they are transferred more easily through pores of membrane compared to less volatile water molecules [2].

MD membrane is the main component of MD system where it is a medium for water vapor transfer and act as a barrier for direct liquid water transfer [5]. Polymeric material that are hydrophobic such as polypropylene (PP), polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) are usually used to fabricate conventional MD membranes. In order to prevent direct permeation of liquid through membrane pores, hydrophobicity is an important factor [6]. Hydrophobic commercial microfiltration (MF) membranes are not particularly optimized for MD; still its usage in MD process is widely implemented. Such optimization is needed to further enhance MD performance. Generally, during MD process, water vapor is formed at hot interface of feed solution-membrane. Water vapor is then transported through membrane pores and then condensed at cold-side of solution interface. Figure 1 illustrates MD separation process.

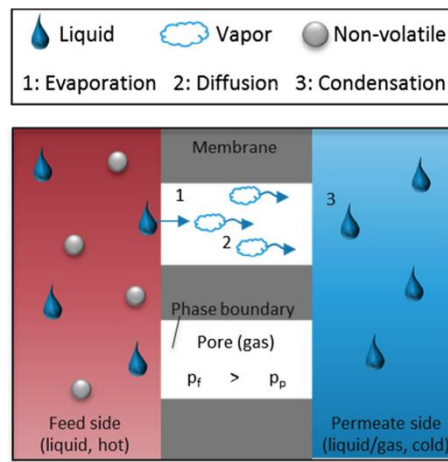


Figure 1: Illustration MD separation process [2]

There are several types of common MD configurations that use microporous hydrophobic membrane to distinguish aqueous feed solution [7] such as air gap membrane distillation (AGMD), direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD) and sweeping gas membrane distillation (SGMD). Among these, DCMD is the most preferable type as it is easy to assemble and flexible to wide application. MD possesses substantial advantages over conventional separation technologies because of low temperature and hydrostatic pressure needed during the process [8]. Besides, there are no phase changes in MD and chemical additives are not needed. On the other hand, modular system that makes it easier to scale up [9], low energy consumption, less requirement of membrane mechanical properties [10]. Also high removal capacity of dissolved, non-volatile species and easy availability of membrane materials [11].

In this paper, expectation of MD treatment process is described primarily for the readers who have no idea about this membrane process. In the first part, a brief overview is given of MD before treatment process which includes membrane materials, membrane preparation techniques, membrane characteristics, membrane modules/housings, and MD configurations. Besides, membrane performance during treatment process was highlighted. Meanwhile, membrane fouling which is one of the main drawbacks of MD after separation process was also discussed.

## II. MEMBRANE MATERIALS

In MD process, polymeric and inorganic membrane with hydrophobic properties can be used but, polymeric membranes especially have garnered more attention as they have potential to modulate intrinsic properties [12]. In MD process, microporous membranes with hydrophobic properties are usually used and the most commonly used membranes are made either from PVDF, PTFE or PP [7,12]. The main reason for using these polymers is credit to their low surface tension [12]. It is believed that decrease in

surface tension increased the membrane pore size and porosity. In general, order of increasing hydrophobicity of these polymers can be expressed as PVDF<PP<PTFE. Not only hydrophobic is the main factor in selecting the best MD membrane, but membranes also have to be porous with good stability in extreme temperatures and low thermal conductivity in order to prevent loss of heat throughout membrane matrix. Moreover, ideal MD membranes must have excellent chemical resistance (acids and bases) to feed solutions, low resistance to mass transfer and low fouling problem [13]. Membrane preparation techniques depend on material that will be used. Details about these membrane manufacturing procedures will be elaborated in the next section.

The applicable materials selected should fulfil certain criteria which include ease of fabrication and assembly, compatibility with other liquid, useful operating temperature and thermal conductivity [12]. As indicated previously, PTFE membranes are the most hydrophobic. It has exceptional chemical resistance and thermal stability properties. Besides, they are easy to dissolve in almost all common solvents. The downside of PTFE membranes is that it is usually prepared by stretching or sintering which is a difficult process [12]. Meanwhile, PP as the second best material behind PTFE demonstrates excellent solvent resistant properties and high crystallinity. However, it is usually fabricated by stretching and thermal phase inversion method that is complex in process [12]. PVDF membranes particularly have been utilized in membrane fabrication due to their high mechanical and chemical stability, good processability [14], better hydrophobicity and heat resistance [15]. In fact, this type of polymer can easily dissolve at room temperature in a variety of common solvents such as dimethylformamide (DMF), dimethylacetamide (DMAc) and N-methyl-2-pyrrolidone (NMP). It can be produced via a simple phase inversion method only [12].

### III. MEMBRANE PREPARATION TECHNIQUES

There are several techniques for preparation of MD membrane including sintering, phase inversion, stretching, template leaching and track-etching [2]. Sintering, track-etching and template leaching are not suitable for MD process because fabricated membranes will have relatively low porosity. Conversely, high porosity membranes can be obtained via phase inversion and stretching method [2]. The techniques are chosen mainly depending on types of membrane materials and targeted application as indicated in Table 2. In practical ways, by choosing correct preparation method together with optimum process conditions, membrane properties can be modify to a certain extent.

#### 3.1 Phase Inversion

Polymeric membrane are usually fabricated by technique of phase inversion [3,16]. The process separate homogenous system into two different phases comprise of a polymer, a solvent as well as other additives [17]. Phase inversion concept involve several techniques including precipitation by controlled evaporation, precipitation by solvent, precipitation from vapor phase, thermal precipitation and immersion precipitation or nonsolvent induced phase inversion [18].

In precipitation through solvent evaporation, an inert gas is used after the dope solution is cast for solvent to evaporate which consequently remove water vapor which then allows a membrane to be formed [18]. For precipitation by controlled evaporation, solvent and nonsolvent mixture is used in dissolving polymer. Due to high volatility of the solvent, evaporation process takes place. Membrane is formed due to the change of mixture content to a higher nonsolvent polymer content [16,18]. In thermally induced phase separation, dissolved polymeric solution is cooled down for separation to happen. Solvent evaporation commonly involves low molecular weight alcohol that induces membrane formation [3]. Microfiltration membranes are usually prepared using this technique [18].

In precipitation from vapour phase, a mixture of polymer and a solvent as dope solution is placed in a vapor atmosphere consisting of nonsolvent saturated with same solvent. Evaporation of solvent from cast film is prevented by high concentration of solvent in vapor phase [16]. Nonsolvent diffuse into cast film forming membrane. Phase inversion via nonsolvent induced phase inversion or immersion precipitation is frequently used method for preparation of membrane [16]. This method is performed by

dissolving polymer in a solvent and homogenous polymeric solution is cast on an appropriate support before immersing in a coagulation bath consists of nonsolvent. Due to interchange between solvent and nonsolvent, precipitation occurs [18]. Mass transfer and phase separation process that take place result in formation of membrane structure [16]. By changing the type and amount of additives, polymer concentration and temperature, pore with variety of sizes can be obtained.

### *3.2 Stretching*

In stretching method, a polymer of partial crystallinity, hollow fiber or film form, is perpendicularly stretched to the axis of crystallite orientation [17]. Polymer is extruded at a temperature just below its melting point combined with a rapid breakdown to produce a film. Mechanical stress is perpendicularly applied after annealing and cooling to the direction of the drawing. The process produced membrane with 90% relatively uniform porous structure and porosity (Khayet & Matsuura, 2011). Common hydrophobic membrane such as PTFE, PP, and PE can be fabricated using this method.

### *3.3 Sintering*

Sintering technique is generally utilized to fabricate ceramic or metallic membranes. This technique produced symmetric membranes. Powder of polymeric particles of a particular size is pressed and heated into a film or plate before sintering process take place, at or just below the melting temperature [3]. In this method, particles size and sintering profile are two main factors besides temperature, heating/cooling rates and dwelling time that affect pore size and porosity of the acquired membranes [17].

### *3.4 Track etching*

Track-etching method produced membrane with uniform cylindrical pores. In this process, polymer matrix is damaged by introducing high-energy particle radiation to the thin dense polymer film. The damage polymer is then etched away in a solution containing an acid or alkaline. [17]. Membrane porosity is affected by residence time in the irradiation and is generally around 10% with pores dimensions within range 0.2-10 $\mu$ m

### *3.5 Template leaching*

Template leaching is suitable process to fabricate isotropic porous membranes from insoluble polymers or from glass, metal alloys and ceramics [17]. In this process, a mixture of polymer and a leachable component undergo homogenization, extrusion process and were pelletized a few times. After extrusion of the film, a suitable solvent is used for removal of leachable component. Microporous membrane is then formed [19].

## **IV. MEMBRANE CHARACTERISTICS**

The membrane ought to fulfil certain conditions before it can be applied in MD system. One of the requirements is that membrane should be made up of a single layer or multilayers with at least one made out of hydrophobic material and be porous [3]. Besides, membranes pore sizes must range in between 10 nm to 1  $\mu$ m. Increase in pore size increase the permeate flux [12]. However, size of the pore should be as small as possible to avoid wettability and to make sure feed liquid cannot penetrate into the pores [1]. The tortuosity factor should be as small as possible [1,20]. Tortuosity refers to average length of pores against membrane thickness. Flux decreases as molecules travel throughout tortuous path where membrane pores do not form straight across the membrane. Therefore decrease in tortuosity increase the permeate flux [12]. Other than that, porosity is also one of the criteria. Membrane porosity is defined

as volume of pores over total volume of membrane. Increase in membrane porosity level increase the evaporation surface area, resulting in higher permeate fluxes [12,20] regardless of the MD configuration [3].

Membrane with befitting thickness are required since permeate flux decrease with an increase in membrane thickness [20]. Therefore, to obtain high permeate flux, membrane thickness must be as thin as possible [3]. In order that the heat loss is reduce, membrane material should possess low thermal conductivity [3,12,20]. Membrane surface that is in direct contact with feed solution should be fabricated with high fouling resistance material to avoid unnecessary fouling [1]. Membrane must also demonstrate good thermal stability [1,20]. Besides, it must possess good chemical resistance to variety of feed solutions [1,20]. Finally, membrane should have a long lifespan with a stable MD performance [1,20].

## V. MEMBRANE MODULE USED IN MD PROCESS

A membrane module is described as a device that is a combination of membrane with another to form a whole functional package. This include membrane mounting, a housing, flow channels with inlets, outlets and mountings respectively [21]. There is four commonly used membrane module which are hollow fiber, plate and frame, spiral wound and tubular [22].

### 5.1 Hollow fiber membrane module

Hollow fiber membrane module consists of two system, inside-outside and outside-inside system. In inside-outside system, feed solution passes through lumen of hollow fiber and permeate is collected outside of membrane fiber. While for outside-inside system, feed solution passes from outside hollow fibers and the permeate is collected inside the hollow fiber [7]. Hollow fiber membrane have high membrane area to modulate volume ratios and this make it more favorable in fabrication of membrane modules [23]. Hollow fiber membrane was more appealing because of its large specific surface area, low boundary layer resistance and high membrane packing density due to small strand diameter [24]. However, irreversible fouling and easy breakage are main problems concerning this type of membrane module.

The polymer used was dried before dissolved in a solvent and additive forming dope solution. Common solvents used to prepare hollow fiber membrane are DMF, DMAc, and NMP. To avoid any lump formation, polymer was added in small amount at a time to solvent mixture and continuously stirred overnight using overhead mechanical stirrer. A dry-wet jet spinning process are usually used to produce hollow fiber membranes by technique of non-solvent induced phase inversion [25,26]. Membrane was then immersed in coagulation bath to remove any residual solvents [25]. Thereafter, membrane was left to dry before tests.

### 5.2 Plate and Frame module

The plate and frame module were based on plate and frame filter press [27]. In plate and frame membrane systems membranes laid on top of a plate-like structure that is held together by frame-like support. The main advantages of plate and frame membrane system are an easy separation of solids from water and membrane can replace and clean more easily. However, there are several problems for plate and frame membrane systems which are low packing density, high-pressure drop, and low efficiency compare to other configurations.

Plate and frame module used flat sheet membrane in their configurations [21]. Flat membrane is made by dissolving a polymer in an appropriate solvent mixture and wait until it becomes a homogeneous dope solution. Then, dope solution is poured directly to a thin film using one of the supporting layer for casting ([18]. As it is easy to clean and replace, flat sheet membrane configuration has been used extensively on a laboratory scale [7].

### 5.3 Spiral wound membrane module

Spiral-wound elements composed of a combination of membranes, feed spacers, permeate spacers, and a permeate tube enveloped and rolled around a perforated central collection tube forming a cylindrical module. The feed solution passes over membrane and permeate spiral to the center collection tube [7,28]. The advantages of this module are that it comes in multiple configurations with different spacers, membrane type, lengths and diameters that allow it to fit multiple applications. These membrane modules have a very high packing density greater than that of plate and frame, tubular, and capillary configurations. Besides, cleaning can be done easily through cleaning in place. However, fouling occurred is more than fouling in tubular filtration processes. Spiral elements also cannot handle mechanical cleaning like tubular elements and contain lower packing density than hollow fiber.

### 5.4 Tubular membrane

In this module, membrane is tube-shaped and is fixed in the middle of hot and cold fluid cylindrical chambers [7]. Tubular membrane filtration works by pressuring feeding water into membrane tube. This pressure forces only water through membrane. The suspended particles exit tube and return back. Fouling occurred in tubular systems is less than plate and frame, but is similar when compared to spiral and capillary. Methods of robust cleaning such as use of harsh chemicals, mechanical cleaning and backwash can be used in tubular systems. The disadvantages of tubular modules are its large size and low packing density. The packing density of tubular module is higher compared to plate and frame systems but lower than hollow fiber, capillary and spiral wound elements. Besides, tubular required higher flow due to its large inner diameter compared to other system configurations.

## VI. MEMBRANE CONFIGURATION

### 6.1 Direct Contact Membrane Distillation (DCMD)

In this configuration, feed and permeate solution are in direct contact with membrane surfaces throughout the entire operation. Hydrophobic characteristics of membrane serve as a physical barrier and holds liquid-vapor phase at membrane pores. Cold permeate solution and hot feed solution comes into contact with membrane surface, resulting in a pressure difference across membrane. Permeation of water vapor and volatile species occurs through pores of membrane [5]. Inside membrane module, both condensation and evaporation processes occur at the same [29]. Among difference type of MD configurations, DCMD process is widely used in desalination processes and in food industries, or acid manufacturing [7]. Besides that, DCMD is employed in industrial wastewater treatment such as olive mill wastewater [30], fermentation wastewater [31], dyeing wastewater [29,32], radioactive wastewater [33–35] and pharmaceutical wastewater [4]. DCMD applications mostly still only in laboratory or small pilot plant phase up to this time [7].

### 6.2 Air Gap Membrane Distillation (AGMD)

In AGMD, membrane and the cooled condensation surface is separated by a thin layer of air. The air gap and condensation plate prevents permeated vapour to be in direct contact with cooling water, which in turn limits heat transfer rate from hot feed side to the cooling water [36]. The evaporation channel in AGMD resembles the one in DCMD. Membrane is separated from cold walling by permeate gap filled with air. For condensation to occur, vapor that permeates through membrane must overcome this air gap. AGMD has been utilized for desalination process [37], boron removal from geothermal water [38], heavy metal removal from wastewater [39] and treatment of produced water [40].

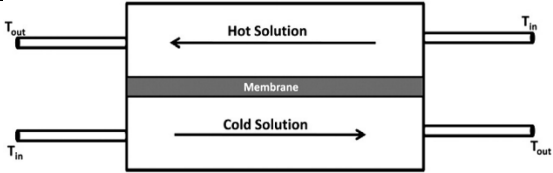
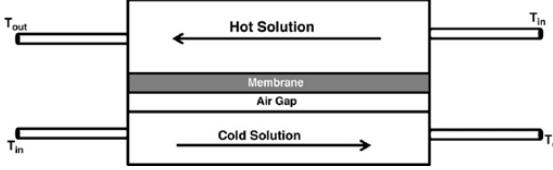
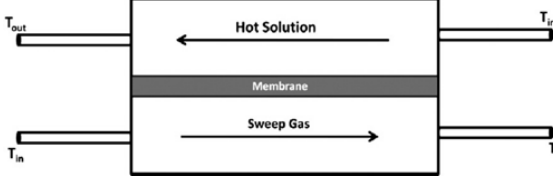
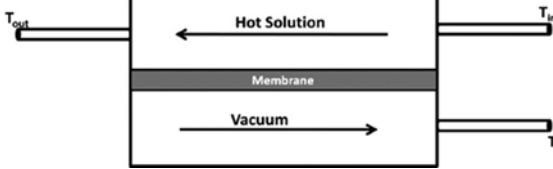
### *6.3 Sweeping Gas Membrane Distillation (SGMD)*

SGMD uses an air stream to collect vapor. To avoid membrane pores wetting, membranes used in SGMD possess hydrophobic properties and microporous. In SGMD, feed solution is heated up reaching the suitable temperature before transferring to membrane surface. The volatile compounds permeate through membrane pores to permeate side where carrier gas collects and transfer vapor for further process. Meantime, non-volatile compounds get concentrated and would recirculate back to the feed tank [41]. SGMD is useful in removing volatile compounds from aqueous solution. It have been used for removal of water from dilute glycerol-water solution [42], treatment of triethylene glycol wastewater [41] and removal of ammonia from wastewater [43].

### *6.4 Vacuum Membrane Distillation (VMD)*

In this configuration, cold permeate is substituted with vacuum, thus there are no resistance by the permeate [13]. Feed solution is brought into direct contact with porous hydrophobic membrane [44]. Condensation process occurs outside the membrane module. VMD is used to separate aqueous volatile solutions [7]. This configuration has been used in various MD applications such as for removal of dye from textile wastewater [45], water recovery from produced wastewater [46], removal of antibiotics from pharmaceutical wastewater [4], strontium ions and cobalt ions removal from radioactive wastewater [34,47] and recovery of polyphenols from olive mill wastewater [30]. Table 1 shows schematic diagram of each MD configuration and their advantages and disadvantages.

**Table 1:** Configurations and their advantages and disadvantages

Configuration	Advantages	Disadvantages
 <p style="text-align: center;">DCMD [7]</p>	<ul style="list-style-type: none"> <li>• High flux</li> <li>• Simple design [48]</li> </ul>	<ul style="list-style-type: none"> <li>• Cannot use cold feed as coolant</li> <li>• High heat loss through conduction [48]</li> <li>• Cannot obtain pure distillate [49]</li> </ul>
 <p style="text-align: center;">AGMD [7]</p>	<ul style="list-style-type: none"> <li>• Low operating temperature</li> <li>• Low hydrostatic pressure</li> <li>• Low heat loss [49]</li> <li>• Internal heat recovery [48]</li> </ul>	<ul style="list-style-type: none"> <li>• High mass transfer resistance</li> <li>• Low permeate flux [50]</li> </ul>
 <p style="text-align: center;">SGMD [7]</p>	<ul style="list-style-type: none"> <li>• The flux generated is not influence by inlet gas temperature [41]</li> <li>• Less heat loss [48]</li> </ul>	<ul style="list-style-type: none"> <li>• Require a large condenser [7].</li> <li>• Additional cost for sweep gas [48].</li> </ul>
 <p style="text-align: center;">VMD [7]</p>	<ul style="list-style-type: none"> <li>• Negligible heat loss [14],</li> <li>• Decrease influence of membrane wetting</li> <li>• The membrane flux increases with increase in the mass transfer driving force of the system [47].</li> </ul>	<ul style="list-style-type: none"> <li>• Limited vacuum pressure</li> <li>• Limited heat recovery</li> <li>• High electricity consumption vacuum pump [48]</li> </ul>



**Table 2:** Overview of the membrane distillation process in previous studies

	<b>Membrane module</b>	<b>Polymers</b>	<b>Solvents</b>	<b>Additives</b>	<b>Membrane preparation technique</b>	<b>MD configuration</b>	<b>Objectives</b>	<b>Performances</b>	<b>References</b>
1	Hollow fiber	PVDF	NMP	EG	Phase inversion (dry-wet jet spinning inversion)	VMD	Purification of diluted liquid desiccants	Desalinated water collected has a very low salt concentration	[26]
2	Hollow fiber	PVDF	NMP, NMP-TEP & TEP	-	Phase inversion (dry-jet wet spinning process)	DCMD	Fabricate highly porous membrane using non-toxic solvent	Membrane fabricated have porosity higher than 80%	[25]
3	Hollow fiber	PP	-	-	-	AGMD, PGMD	AGMD and PGMD process was compared	Salt rejection was greater than 99.8% in all experiment	[51]
4	Hollow fiber	PVDF	-	-	Non-solvent induced phase separation process	PGMD, DCMD, SGMD	PGMD, DCMD and SGMD process was compared	PGMD has lower STEC compared to SGMD and DCMD when flux is equal	[52]
5	Hollow fiber	PVDF-HFP	DMAc & TMP	PEG	Phase inversion (Wet-wet spinning technique)	DCMD	Effect of the corrugation size and shape on DCMD process	Salt rejection factor was greater than 99.9%	[53]
6	Hollow fiber	PVDF-HFP	DMAc & TMP	PEG	Phase inversion (dry-wet spinning technique)	DCMD	Change of the outer layer structure was observed	HF with 50% wt DMAc has the highest permeate flux with good salt rejection factor	[54]
7	Hollow fiber	PTFE	-	-	Stretching	DCMD	Compose stretching conditions to integrate membrane with high permeate flux and salt rejection	Rejection rate of salt was high up to 99.99% for membrane fabricated at stretching ratio 2.4	[55]

(Continued)

8	Hollow fiber & flat sheet	PVDF	-	-	-	DCMD	Performance of flat sheet membrane and HF at high temperature	Flat sheet and HF membrane achieved desalination without any salt leakage	[56]
9	Hollow fiber	PDMS & PVDF	DMAc, TEP & THF	PVP	Non-solvent induced phase separation	VMD	Production of HF membrane with high flux	High salt rejection of over 99.9% under optimum conditions	[24]
10	Spiral wound (flat sheet)	PTFE	-	-	-	DCMD	Optimization of DCMD module operation	-	[21]
11	Plate & frame (flat sheet)	PVDF	NEP	LiCl	Phase separation	DCMD	Comparison of polyelectrolyte in thermopervaporation with the porous membrane	Membrane showed a high permeate rate for water	[57]
12	Spiral wound (flat sheet)	PTFE	-	-	-	PGMD	Desalination process	High salt rejection rate	[58]
13	Spiral wound (flat sheet)	PTFE	-	-	-	PGMD	Desalination process	Distillate output increased while the thermal energy demand reduced with an increase in deaeration effort	[59]
14	Plate & frame (flat sheet)	PVDF	DMAc	LiCl & PEG	Wet phase inversion process	DCMD	Influence of nano-particles on membrane properties	Exhibit satisfying performance stability and obtain maximum transmembrane permeate flux of 49.37 kg/m <sup>2</sup> .h	[60]
15	Plate & frame (flat sheet)	PVDF, PTFE & PP	-	-	-	SGMD	Effect of membrane structure and operational variables on distillate production rate		[61]
16	Plate & frame (flat sheet)	PVDF	DMAc	SiO <sub>2</sub>	Phase inversion precipitation method	VMD	Effect of SiO <sub>2</sub> on PVDF membrane performance	Obtain salt rejection rate of more than 99.98%	[62]

(Continued)

17	Tubular (flat sheet)	PTFE	-	-	-	AGMD & DCMD	Investigate permeate flux of finned tubular AGMD module	High permeate flux obtained in the proposed AGMD-based finned tubular membrane module	[63]
18	Tubular	Al <sub>2</sub> O <sub>3</sub>	-	-	-	VMD	Effect of membrane thickness and pore size on water flux and salt rejection rate	High permeate flux (30kg/m <sup>2</sup> .h) and salt rejection rate (99.99%)	[64]
19	Spiral wound	PE	-	-	-	AGMD	Water recovery	95% water recovery	[65]
20	Hollow fiber	PVDF	-	-	Phase inversion	DCMD	Treatment of wastewater from rubber processing effluent	Permeate produced is of high quality with 95% removal efficiency of TOC, TDS, sulfate, color, turbidity, conductivity	[66]
21	Hollow fiber	PTFE & PVDF	-	-	-	DCMD	Treatment of industrial dyeing wastewater	Excellent rejection under mild temperature and limited pressure obtained	[32]
22	Hollow fiber	PVDF	NMP	-	Phase inversion	DCMD	Water recovery from hot dyeing solution	Excellent dye rejection rate with 99.78%	[67]
23	Hollow fiber	PVDF	NMP	EG	Phase inversion (dry- jet wet spinning technique)	DCMD	Treatment of industrial textile wastewater for clean water production	Excellent results in eliminating almost all dye components	[68]
24	Hollow fiber	PP	-	-	-	DCMD	Treatment of fermentation wastewater with high organic concentrations	95% COD, TOC and protein rejection rate	[31]
25	Hollow fiber	PP	-	-	-	MDC	Recovery of water and minerals from shale gas produced water	Water and mineral recovered with low energy consumption	[69]

## VII. EFFECT OF PROCESS PARAMETER ON MEMBRANE PERFORMANCE

### 7.1 Effect of feed temperature

Feed temperature highly influences permeate flux [7,12]. Vapor pressure increase with increase in temperature. Therefore, permeate flux is affected by the operating temperature. At constant temperature difference, increase in hot solution temperature increase the permeate flux. This indicates that permeate flux relies on hot fluid temperature [7]. Table 3 displays on previous studies carried out at different feed temperature and operating conditions.

**Table 3:** Effect of feed temperature on permeate flux

	<b>MD configuration</b>	<b>Membrane type</b>	<b>Feed</b>	<b>Operating condition</b>	<b>T<sub>f</sub> (°C)</b>	<b>Permeate (kg/m<sup>2</sup>.h)</b>	<b>Referances</b>
1	DCMD	PTFE, PP,PVDF	Industrial wastewater	V =1L/min pH=3-11.5	30-70	≈2-52 kg/m <sup>2</sup> .h	[70]
2	AGMD	PTFE	Produced water	V = 0.5-1.89L/min	40-80	≈1-7g/m <sup>2</sup> .s	[40]
3	SGMD	PTFE	Wastewater containing ammonia	V = 250mL/min pH = 11.5	50-70	≈5-15 kg/m <sup>2</sup> .h	[43]
4	VMDC	PP	Simulated radioactive wastewater	V = 41.8 L/h	30-70	≈0.2-7 L/m <sup>2</sup> .h	[33]
5	VMD	PP	Simulated radioactive wastewater	V = 41.8L/h P =0.98 atm	30-70	≈0.5-6 L/m <sup>2</sup> .h	[47]
6	DCMD	PVDF	Boron solution	V <sub>f</sub> =60 L/h V <sub>p</sub> =65 L/h pH = 6.5-8.5	30-80	≈3-35 kg/m <sup>2</sup> .h	[15]
7	DCMD	PVDF	Arsenic solution	T <sub>p</sub> =20 V <sub>p</sub> =0.10 m/s	40-70	≈3-21 kg/m <sup>2</sup> .h	[71]

### 7.2 Effect of pH

Hou et al. [15] in their study stated that feed pH does not greatly influence permeate flux and rejection of boron. MD is less dependence on feed pH as it driving force is temperature gradient exists on membrane surfaces. Therefore, higher rejection of boron can be achieved throughout DCMD process no matter the feed is either alkali or acid [15]. In another study, the results show that solution pH in weak alkaline and acidic medium did not influence ion rejection rate during DCMD process [71]. Table 3 illustrates effect of pH on permeate flux from previous studies.

**Table 4:** Effect of pH on permeate flux

	<b>MD configuration</b>	<b>Membrane type</b>	<b>Feed</b>	<b>Operating condition</b>	<b>pH</b>	<b>Permeate (kg/m<sup>2</sup>.h)</b>	<b>Referances</b>
1	DCMD	PTFE, PP,PVDF	Industrial wastewater	V =1L/min T <sub>p</sub> =20°C T <sub>f</sub> =60°C	3-11.5	≈10-39 kg/m <sup>2</sup> .h	[70]
2	DCMD	PVDF	Boron solution	V <sub>f</sub> =60 L/h V <sub>p</sub> =65 L/h T <sub>f</sub> =50°C T <sub>p</sub> =20°C	3-11.0	≈3-35 kg/m <sup>2</sup> .h	[15]

3	DCMD	PVDF	Arsenic solution	$T_p=20$ $V_p=0.10$ m/s	4,9	$\approx 3-21$ kg/m <sup>2</sup> .h	[71]
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### 7.3 Effect of feed flow rate

In MD, higher flow rate of feed leads to greater permeate flux [12]. This is supported by Alkudhiri et al. [40] in their study for treatment of produced water using AGMD. Different feed flow rates were investigated on production of permeate flux. Result obtained show that increase in feed flow rate leads to an increase in the permeate flux. This can be illustrated by phenomena of temperature and concentration polarization. Shearing forces generated at high flow rate reducing thickness of hydrodynamic boundary and thus reducing polarization effect. Hence, at the bulk feed solution, concentration and temperature at the liquid-vapor interface become closer to the corresponding values [12]. Table 5 shows effect of flow rate on permeate flux based on previous studies.

**Table 5:** Effect of flow rate on permeate flux

	MD configuration	Membrane type	Feed	Operating condition	Flow rate	Permeate (kg/m <sup>2</sup> .h)	Referances
1	AGMD	PTFE	Produced water	$V = 0.5-1.89$ L/min	0.5-1.89 L/min	$\approx 1.6-2.8$ g/m <sup>2</sup> .s	[40]
2	SGMD	PTFE	Wastewater containing ammonia	$V = 250$ mL/min $pH = 11.5$	50-250 mL/min	$\approx 7-9$ kg/m <sup>2</sup> .h	[43]
3	VMD	PP	Simulated radioactive wastewater	$V = 41.8$ L/h $P = 0.98$ atm	10.5-41.8 L/h	$\approx 4-6$ L/m <sup>2</sup> .h	[47]
4	DCMD	PVDF	Arsenic solution	$T_p = 20^\circ\text{C}$ $V_p = 0.10$ m/s	0.23-0.98m/s	$\approx 3-21$ kg/m <sup>2</sup> .h	[71]
5	DCMD	PP,PTFE	Synthetic brackish water	$T_f = 80^\circ\text{C}$ $T_p = 20^\circ\text{C}$ $V = 4$ L/min	1-4 L/min	$\approx 39-90$ L/m <sup>2</sup> .h	[72]

### 7.4 Effect of feed concentration

The increase in feed concentration decreases permeate flux [7,12]. This may be due to lower vapor pressure of feed solution, driving force, with addition of non-volatile solute in water due to a decrease in water activity in the feed [3] and exponentially increase viscosity of feed with increasing concentration [12]. Effect of feed concentration on permeate flux was also investigated by Liu & Wang [35]. They found that feed concentration in their study could affect vapor pressure of feed solution at liquid-vapor interface. Their results showed that permeate flux dropped linearly as salt concentration increased [35]. However, in a different study of the DCMD process of boron removal, permeate flux stabilized at about 10.5kg/m<sup>2</sup> even though feed concentration increase [15]. It shows that feed concentration did not influence permeate flux. It can be said that MD can tolerate feed solution at high concentrations without suffering large drop in permeability [12].

**Table 6:** Effect of concentration on permeate flux

	MD configuration	Membrane type	Feed	Operating condition	Concentration	Permeate (kg/m <sup>2</sup> .h)	Referances
1	VMDC	PP	Simulated radioactive wastewater	V = 41.8 L/h	0-100 g/L	≈6.2-5.5 L/m <sup>2</sup> .h	[33]
2	DCMD	PVDF	Boron solution	V <sub>f</sub> =60 L/h V <sub>p</sub> =65 L/h pH = 6.5-8.5	0-5000 mg/L	≈10.5 kg/m <sup>2</sup> .h	[15]
(Continued)							
3	DCMD	PP,PTFE	Synthetic brackish water	T <sub>p</sub> =20°C T <sub>f</sub> =80°C V =4L/min	1000-10000 ppm	≈80-90 L/m <sup>2</sup> .h	[72]
4	DCMD	PVDF	Radioactive wastewater		0-100 g/L	≈7.25-4.75 L/m <sup>2</sup> .h	[35]

### VIII. MEMBRANE FOULING

Even though fouling phenomenon in MD is considerably less than those faced in other processes of pressure-driven membrane, but it is part of major disadvantages in membrane distillation that degrades membrane performances [22]. Theoretically, MD only allows water vapors to pass through membrane pores and has a 100% rejection rate of non-volatile compounds. Despite that, few factors among which poor long term hydrophobicity of materials, damage and degradation of membrane and membrane thickness can lead to fouling. Besides, existence of inorganic, organic macromolecules and microorganisms, colloidal and particulate in feed water could also lead to deposition of fouling substances which will negatively affect rejection efficiency and deteriorate performance of MD [10].

Membrane fouling pertains to the deposition or accumulation of suspended or dissolved substances on the membrane surface and/or within its pores that lead to deterioration of membrane performance [12]. Fouling occurred when unwanted substances comprise of biological and suspended particles, corrosion products as well as variety of crystalline deposits [8] attached themselves on membrane hydrophobic surface. The accumulation of more substances will ultimately increase net resistant to heat and mass transfer as a thick cake layer formed and result in flux decrease. Membrane heat and mass transfer depend on the fouling layer thickness [13]. Besides, foulant species could cause flux decay due to plugging at the entrance of membrane pore and eventually results in membrane pore wetting. Pores of the membrane are very small. Therefore, accumulation of fouling substances at the surface of membrane may cause pressure drop to increase to the point that hydrostatic pressure surpassing liquid entry pressure (LEP) of feed or permeate solution into membrane pores [8].



**Figure 3:** Schematic diagram of membrane fouling [10]

Commonly, fouling can be classified into four types; inorganic, organic, biological, and particulate or colloidal fouling [66]. Deposition of inorganic substances on the membrane surfaces or inside the pore

structure causes inorganic fouling [12]. Organic fouling occurs when there are organic matters presence inside the pores or on membrane surface [12]. Particulate or colloidal fouling are formed when there is presence of solid particles on membrane surface [8]. Biological fouling usually occurred when feed solution used contain biological substances [66].

Wu et al. [31] stated that permeate flux decreased with time mainly because of membrane fouling. Organic and inorganic matters in feed wastewater block membrane pores by depositing on membrane inner surface, thus blocking the transfer of water molecules. Besides that, Cho et al. [73] reported that increase in temperature difference increases the initial flux rate lead to an increase in fouling rate. In another study, results show that presence of organic matters cause a slightly higher flux decline and a significant loss of membrane hydrophobicity [66,74].

Fouling is a persistent problem [10] and is the major drawback in MD which limits commercialization of full-scale plant [75]. Fouling reduce effective separation area, contributing to a permeate flow rate reduction, pore wetting and change in permeate water quality, membrane damage, increased temperature and concentration polarization and chemical degradation [76]. This will disrupt process operation as membrane need to be clean or replace, thus increases the operation cost. An early warning system that will detect the fouling problems in membranes processes is important to improvement of membrane operation and the development of a fouling strategy [22]. The main fouling prevention tools utilized in MD are feed pre-treatment and chemical cleaning [76]. It is said that first step to solving the fouling problem is to understand fouling phenomena and the processes involved.

## IX. CONCLUSION

MD has gained interest as a favourable alternative as substitution to other separation processes for its lower operating temperature and pressure, lower energy requirement than conventional distillation and higher rejection rate than in pressure driven process. It is said that MD process is a promising separation technique, but surprisingly the information regarding the process is still insufficient. Based on the knowledge acquired and gathered information on MD processes, a framework for better understanding of MD processes has been presented in this study. This framework is an attempt to highlight the expectation MD treatment process, before, during and after the test

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### *Nomenclature:*

AGMD	<b>Air gap membrane distillation</b>
Al <sub>2</sub> O <sub>3</sub>	Aluminium oxide
DCMD	Direct contact membrane distillation
DMAc	Dimethylacetamide
DMF	Dimethylformamide
EG	Ethylene glycol
LEP	Liquid entry pressure
LiCl	Lithium chloride
MD	Membrane distillation
MDC	Membrane distillation crystallization
MF	Microfiltration
NEP	N-ethyl-2-pyrrolidone
NIPS	Nonsolvent induced phase separation

NMP	N-methyl-2-pyrrolidone
PE	Polyethylene
PEG	Polyethylene glycol
PGMD	Permeate gas membrane distillation
PP	Polypropylene
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
PVDF-HFP	poly(vinylidene fluoride-co-hexafluoropropylene)
PVP	Polyvinylpyrrolidone
SGMD	Sweeping gas membrane distillation
SiO <sub>2</sub>	Silicon dioxide
TEG	Triethylene glycol
TEP	Triethyl phosphate
T <sub>f</sub>	Temperature feed
THF	Tetrahydrofuran
TIPS	Thermally induced phase separation
TMP	Trimethyl phosphate
T <sub>p</sub>	Temperature permeate
V <sub>f</sub>	Flow rate feed
VMD	Vacuum membrane distillation
V <sub>p</sub>	Flow rate permeate

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