REVIEW ON MEMBRANE MODULE CONFIGURATIONS USED FOR MEMBRANE DISTILLATION PROCESS

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ABSTRACT

Nowadays, with the salient advantages of the seawater desalination process, membrane distillation (MD) technology has received increased interests to achieve desalination application. As a heat-based technology, by using the hydrophobic membrane, MD provides high efficiency in the desalination process of seawater, RO water and other solutes with high concentrations of dissolved solids. Besides, this is an alternative technology to significantly reduce the environmental impacts of traditional desalination technologies commonly used, such as distillation or reverse osmosis. In many factors affecting the desalination capacity of the membrane distillation system, membrane module configuration has a strong influence in evaluating the economic and technical efficiency of the technology. This review aims to assess the suitability of MD technology under different perspectives on the current types of membrane module configurations that include flat sheet, tubular, hollow fibre and spiral wound membranes. In addition, the evaluation of the advantages and disadvantages of the membrane module configurations will guide further studies to improve the shortcomings of existing MD technologies.

Keywords: Membrane distillation; hollow fibre; flat sheet; spiral wound; tubular.

1 INTRODUCTION

In the world, there are more than 2.7 billion people worldwide who are facing water scarcity [1]. Therein, about two-thirds of the world population are currently living in this inadequate condition for at least one month in a year, while half of billion people worldwide suffer from lack of water throughout the year [2,3]. According to The United Nation's assessment (2016), this number will not stop there, but will have increased to more than 5 billion by 2025. The main cause of this problem is due to: i) world population increases at a rate of approximately 80 million people per year and is expected to reach about 10 billion by 2050 [4]; ii) industrialization and urbanization in many parts of the world have also created a considerable pressure on water resources [5-8]. With the purpose to address the challenges regarding water scarcity, desalination is considered as a potential technology because of the abundance of seawater source. However, seawater is not yet accessible to be exploited and used directly for drinking and domestic purpose, it is necessary to eliminate the salinity in sea/saline water. Desalination can be accomplished by various technologies including distillation (Multiple-Effect Distillation - MED, Multi-Stage Flash distillation - MSF, Vapor Compression Distillation - VCD) and membrane separation processes operated without heating (Reverse Osmosis - RO, Forward Osmosis - FO, Electrodialysis – ED, Nanofiltration - NF) [9-14]. Nevertheless, through the application process in practice, these technologies have certain limitations. For example, for RO processes, it is necessary to provide a high-pressure pump to exceed the osmotic pressure; membrane fouling can significantly reduce the permeate quality and flux while increasing operating costs due to energy demand; pre-treatment process is required; the removal of contaminants and the cleaning of the membrane with chemicals contribute to reducing the membrane life [14-16]. ED cannot treat non-electrolysis contaminants, and its economic efficiency significantly drops with salinity increase [17-18]. MSF requires high consumption energy and large system area [11,19]; for feed water with high salinity and corrosive, the MED system cannot be applied [19]. These disadvantages affect the economic viability and efficiency of these desalination technologies, leading to the requirement of a new, alternative technology that is environmentally friendly and more sustainable [14].

MD, which is a combination of both membrane technology and distillation technology [14,20], is considered a promising technology for the desalination of seawater and saline water. It has overcome the disadvantages and inherited most of the advantages of distillation and membrane process [15]. One of the main advantages is that MD has a theoretical capacity to remove 100% of the non-volatile compounds [21,22]. This specific feature makes MD become an attractive process to remove organic matter and heavy metal ions from the feed stream [8,22]. MD has a relatively larger membrane pore size compared to other membrane separation processes and low hydraulic pressures on the membrane surface, which makes MD less susceptible to fouling and does not require any pre-treatment processes [15,23]. Besides, because of the low hydraulic pressure, non-corrosive and inexpensive plastic materials can be used for MD, which reduces the investment cost [15]. In addition, MD typically operates at a low feed temperature (below its boiling point), which ranges from 40 to 80°C,

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coinciding with the optimal range of most solar, geothermal energy [8,15,23,24]. In addition to these advantages, there are still some challenges for MD process, such as the problem of membrane fouling and membrane wetting [21], reduced permeate flux due to the polarization of concentration and temperature, and the difficulty in making full-scale [23-25]. These challenges are the main issues preventing industrial and commercial applications of membrane distillation.

During the formation and development period of MD technology, many published reviews have focused on topics regarding the MD process, such as the development of new MD membranes [21,24,26]; performance and optimization of MD processes [27-29]; the process of enhancing or integrating systems [11,30,31]; evaluation of membrane fouling and membrane wetting [16,32,33]; factors affecting the MD process [34]; heat and mass transfer model in MD [35,36]; or evaluations of MD's performance in specific modules [37-40]. However, no full reviews have focused on evaluating the types of membrane modules used in the MD process yet. Hence, this review aims at evaluating the effectiveness of MD technology in terms of the different types of membranes, analyzing pros and cons of each type, then making the most suitable selection in membrane module for future research on MD.

2 MEMBRANE MODULE CONFIGURATIONS IN MEMBRANE DISTILLATION

2.1 Flat sheet

Over the past five decades, the flat-sheet membrane module has always been the most widely studied membrane module configuration in membrane distillation [41]. Plate and frame modules were usually produced in the form of plates or flat-sheets. These flat sheets were placed in the free spaces created by two rectangular frames. This membrane module is suitable for all four MD configurations including Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Vacuum Membrane Distillation (VMD) and Sweeping Gas Membrane Distillation (SGMD) [42]. The structure of this membrane module is shown in Figure 1. As a plate heat exchanger, by the parallel assembly, flat-sheet membranes form the feed and permeate stream channels to move the water to the membrane sides. To reduce the effect of temperature polarization and improve the flow, these spacers were created by inserting plastic mesh in the membrane distillation process.

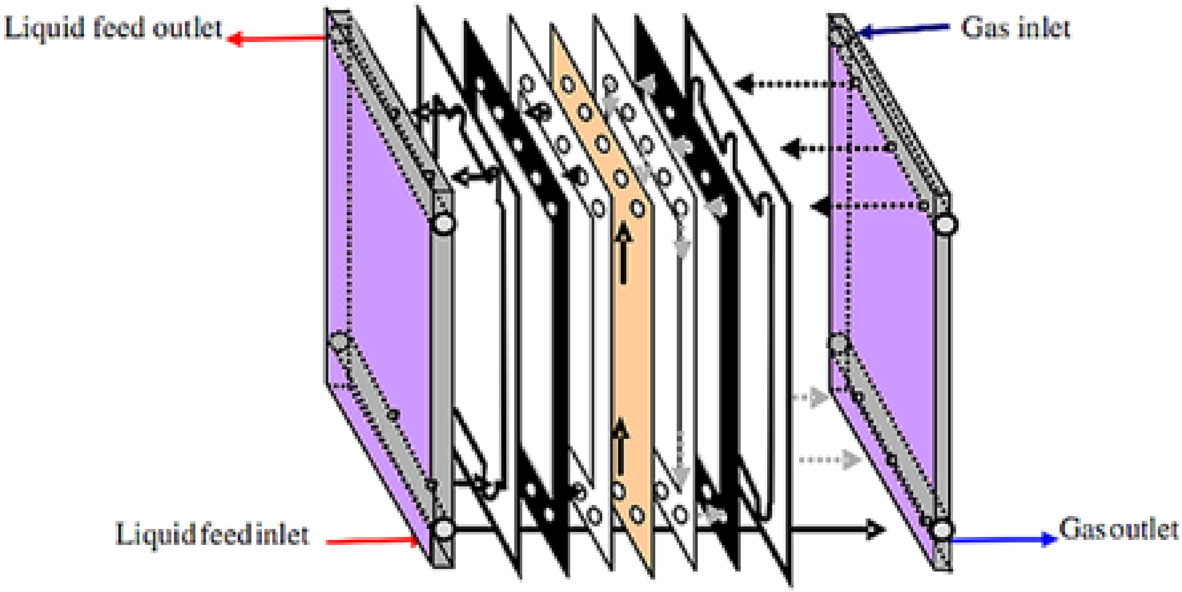

Figure 1. The flat-sheet modules used in Sweeping Gas Membrane Distillation (SGMD) [43]

During seawater desalination using MD technology, flat-sheet membrane modules were commonly used in the research field because of its advantages. Specifically, flat-sheet membrane modules are easy to manufacture, assemble, operate, test and clean [41]. Also, it is easy to remove or replace broken membranes from this configuration [42]. Therefore, this module is widely used in the laboratory to test the effects of operating parameters and membrane properties on energy efficiency or permeate flux of membrane distillation [41]. In addition, the MD process using a flat-sheet membrane achieved the highest flux among different membrane module types at the same operating conditions [44]. This highest flux resulted from the effect of feed flow and convective heat transfer in the membrane monolayers [41]. Also, by using flat-sheet membrane, multiple membranes can be installed in the same membrane frame to increase the membrane area [42]. Furthermore, the removal and replacement of the broken membrane can be done easily.

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Although the flat-sheet membrane module was widely used in the laboratory and predominated in published studies [15,45-47], it was not installed on an industrial scale [41]. The cause of this is the low value of packing density and effective membrane area per unit volume. According to Camacho et al. [42], the packing density of the flat-sheet membrane is in the range of 100-400 m2/m3. In addition, when the active layer was as thin as possible, it would reduce mass resistance. Hence, the membrane support layer was mandatory when using flat-sheet membranes to enhance the mechanical strength of the membrane [23,41,42]. However, the support layer also strongly influenced the membrane distillation process. Jeong et al. [47] used two membranes for research, including PTFE / PP 0.45 and PTFE / PE 0.45 with support layers of 53 µm and 100 µm, respectively. The results of this study showed that the permeate flux of PTFE/PP was 11.3 L/m2h, which was higher than that of PTFE/PE membrane (6.6 L/m2h), although the pore size of the active layers was 0.45 µm and the porosity of both PTFE membranes was similar (72.6% and 72.8%). Therefore, it was found that the supporting layer structure was related to the difference in permeate flux between PTFE/PP and PTFE/PE. Hence, the lower the support layer, the higher the permeate flux. From the above disadvantages, further research on the flat-sheet membrane or its replacement by a different membrane module is needed to be done to apply MD technology in practice.

2.2 Hollow fibre

In recent years, studies on MD technology using hollow fibre membranes have become increasingly attractive. There were many steps forward in publications (published studies have increased from 15% in the initial phase to 21 % in growth period) [41]. The composition of the hollow fibre membrane module was a bunch of hollow fibres that packed in a closed cover. These fibres were usually packed randomly in the cover. According to Camacho et al. [42], materials used to make hollow fibre membranes were mainly composite, PP, PVDF and PVDF-PTFE materials.

Similar to the conventional hollow fibre membrane types, the configuration of membrane used in the MD study also had two types of flows: inside-out flow (feed stream was inside while the permeate stream was obtained on the outside of the hollow fibre) and outside-in flow (the feed stream was kept outside the cover, flew through the hollow fibres while permeate flow was obtained inside the membrane fibre) [23,42]. Because the membrane material's characteristic was hydrophobic, the flow inside the membrane fibres did not mix with the external flows, which easily formed a separated boundary on the hollow surface of the membrane's fibre. In the direction of the outside-in flow, the feed water passed through the membrane's fibre (membrane element) in the form of water vapor. Due to the pressure difference at the interface surface, the mass transfer occurred. Vapor from outside passed through a thin membrane layer of hollow fibres; the salts and impurities contained in the feed water were kept and gathered outside the membrane, then, were removed through the concentrated stream via the bottom outlet pipe. The permeate flow gathered inside the hollow fibres via the outlet line attached to the top of the membrane module and moved to the condenser tank. Figure 2 indicates the flow diagram of hollow fibre module in MD.

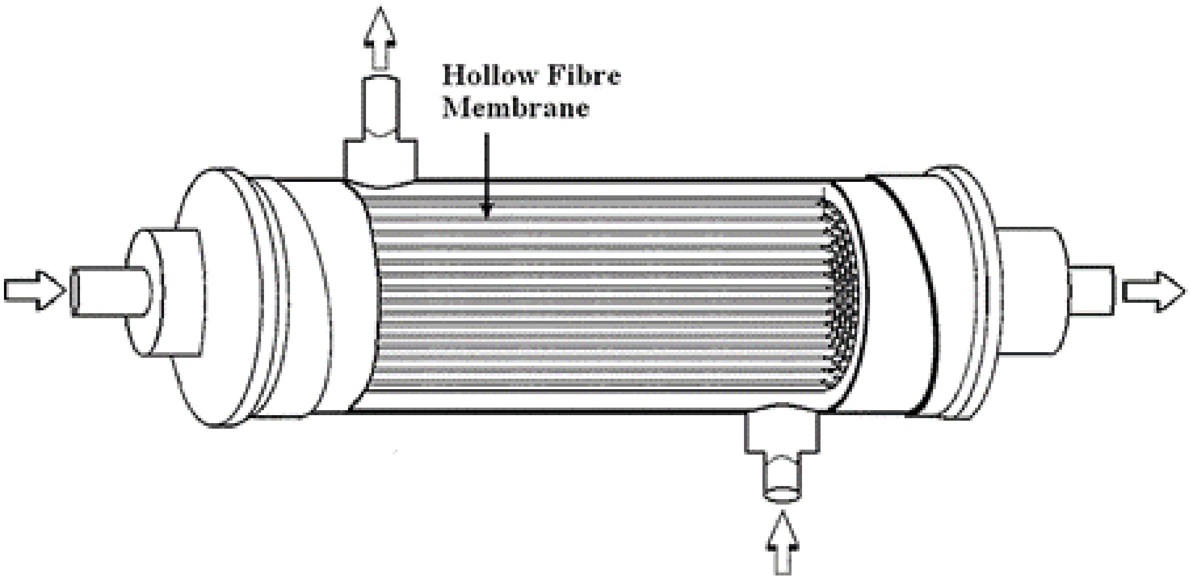

Figure 2. Hollow fibre module for membrane distillation [41]

In all membrane modules used in the MD process, the hollow fibre membrane module had the highest packing density [23,44], better effective surface area per unit volume [41] and was more cost effective. According to Camacho et al. [41], the packing density of this module was 3000 m2/m3. In addition, the hollow fibre

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membrane module could operate at very high pressures (above 100 bars) [48]. Because of these advantages, it had created an attraction for the application of hollow fibre membrane modules on a commercial scale. Besides applications in membrane distillation technology, hollow fibre modules were also used in many other fields, such as liquid-liquid extraction, artificial kidneys, desalination, and wastewater treatment. Moreover, the use of the support layer for the membrane was not required for this type of membrane module [49]. Another advantage of hollow fibre membrane during MD was that the membrane consumes low energy [23]. The details are shown in Table 1.

In addition, compared to other types, hollow fibre membranes were less affected by temperature polarization due to high thermal transfer efficiency and mass transfer [41]. However, the hollow fibre membrane in the MD process could not avoid some disadvantages. According to Wang and Chung [50], the two main weaknesses of this type were low permeate flux and weak mechanical properties. The cause of this problem might result from the difference in convective heat transfer and flow regime. Reynolds of feed flow ranged from 300 to 1425 for flat-sheet membrane module [51] while for hollow fibre modules, they ranged from 106 to 287. Also, the membrane's fibres must be fixed into its cover, forming one of the major disadvantages of MD systems as the cleaning of the membrane is virtually unregulated [23]. Moreover, the fibres also had high potential to foul [52].

Replacement of damaged fibres was very difficult to implement, leading to the expensive cost. If the feed flow (liquid) passed through the membrane pores, the whole module would be changed [23]. The reason was that it had lost the ability to desalinate as the hydrophobicity of the membrane was altered. Furthermore, the pressure decrease along the hollow fibre membrane was the greatest due to the high ratio between the length and diameter of the membrane fibre [44]. Since the packing of membrane fibres into the cover of the module was random, heterogeneously, it could lead to the overlap of membrane fibres, and consequently, decrease a membrane effective area as well as the flow distribution. These are the reasons why the performance was not as good as expected and the permeate flux decreased by 58% [44]. It is a big problem for this type of membrane module, particularly for large-scale industrial applications.

Membrane modules	Membrane configuration	Porosity (%)	Thickness (μm)	Surface area (m^2)	Pore size (μm)	Flux (L/m^2h)	Feed temperature (°C)	Permeate temperature (°C)	Energy consumption (kWh/m^3)	References
Hollow fibre	DCMD	73	450	0.006 and 0.1	0.2	-	65	27	912	[27]
Hollow fibre	DCMD	80	250	0.023	0.46	> 15	55 - 60	30	-	[37]
Hollow fibre	DCMD	81.7	-	-	0.15	7 - 13	50	20	4000 - 6000	[53]
Flat-sheet	DCMD	85	76	0.05	-	9	50	25	4500	[15]
Flat-sheet	DCMD	70	35	0.014	0.2	29	70	30	-	[45]
Flat-sheet	AGMD	80	240	2.3	0.2	8 - 9	70	-	15000	[54]
Spiral wound	PGMD	80	200	5 - 14	0.2	10 - 25	80	25	130 - 207	[55]
Spiral wound	solar-powered membrane distillation (SPMD)	80	35	10	0.2	0.8	-	-	200 - 300	[56]

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2.3 Spiral wound

Spiral wound membranes in MD were applied to desalinate brackish and seawater [56-60]. The materials used to make spiral wound membrane modules were polymeric materials: PP, polyvinyl chloride (PVC), polyethylene (PE), PTFE and synthetic resins [43]. The structure of the spiral membrane included membrane, mesh spacer, permeate carrier and support layer for the membrane forming a cover that was wrapped and curled around a perforated permeate collection tube. The feed flow moved through the membrane surface in an axial direction [23]. After the condensation phase, the permeate flow moved along the central tube and was collected in a perforated permeate collection tube. In this module, the generated flow can be either cross flow or dead-end flow [23]. The process of spiral wound MD is shown in Figure3.

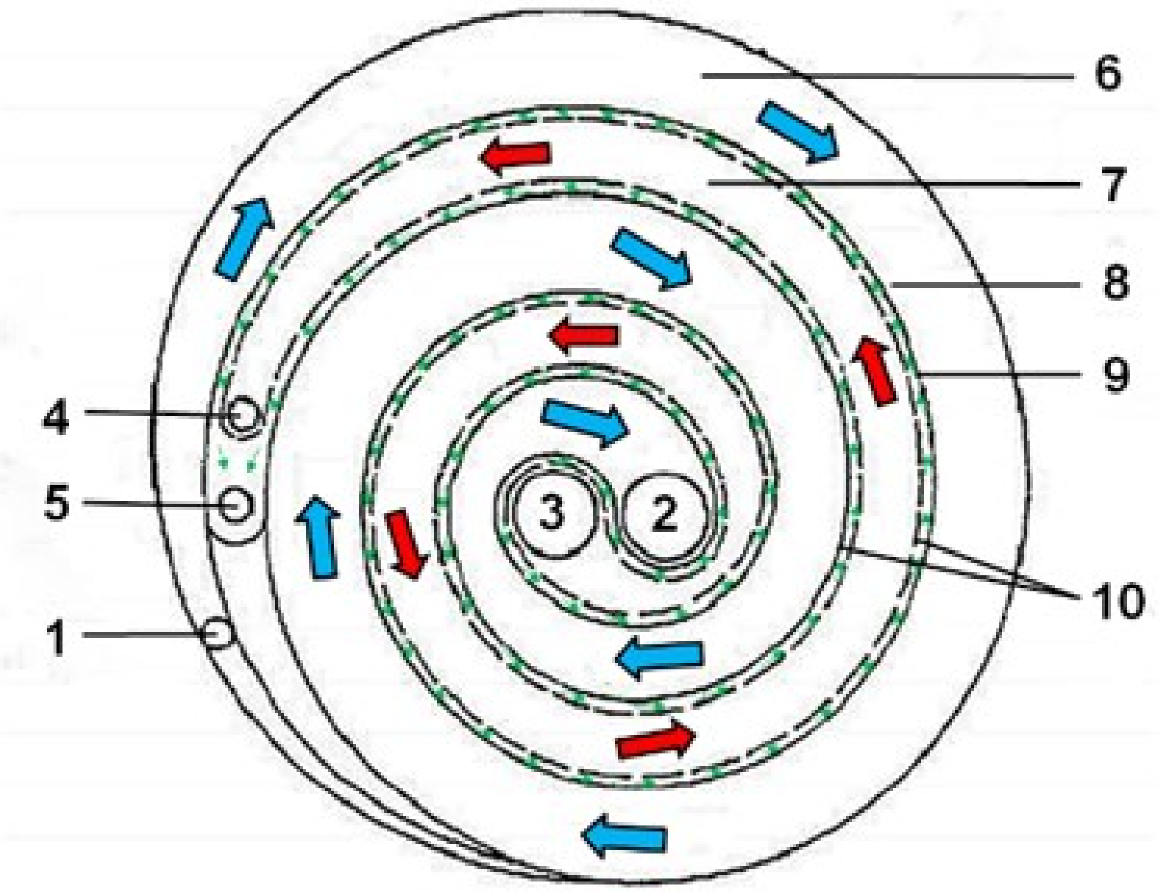

Figure 3. Schematic of the spiral wound module [55]

(1) condenser inlet; (2) condenser outlet; (3) evaporator inlet; (4) evaporator outlet;

(5) distillate outlet; (6) condenser channel; (7) evaporator channel; (8) condenser foil; (9) distillate channel and (10) hydrophobic membrane.

In the MD process, the spiral-wound membrane modules had only developed after two decades of the appearance of membrane modules as described above. After the membrane distillation process had begun to be popular, the spiral-wound membrane modules were applied in MD studies with a very small proportion, approximately 2%. There was also a lack of interest in using spiral-wound membrane module in MD applications at the development stage. Specifically, about 1% of the studies used spiral membrane [41]. The reason for the limited existence of this membrane module research was due to its disadvantages. One of them was the spiral-wound membrane structure formed by the rolling of multiple membranes and support layers, leading to the problem that it was difficult to clean or replace membranes when fouling occurred. Therefore, the spiral–wound membrane module was sensitive to fouling problem. In addition, during the operation of the MD system using the AGMD module, the air gap was flooded with permeate flow, causing the change in MD configuration [41]. Spiral-wound membrane modules indicated that the difference in temperature across the membrane was lower, which led to lower permeability [44]. Because of those disadvantages, the spiral membrane module was seldom investigated world-wide. However, this module still had its advantages, such as the plate-sheet membrane module with high packing density (300-1000 m2/m3), low-temperature polarization [43,61]. In addition, the spiral-wound module integrated heat recovery with solar energy utilization was also investigated. It was carried out using a PTFE membrane with a pore diameter of 0.2 µm, a thickness of 35 µm, 80% porosity, its height was 450-800 mm, and

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diameter was 300-400 mm, effective membrane area of 7-12 m2, permeate flux was 10 – 30 L/h, with specific heat energy consumption which was 100-200 kWh/m3 [43]. In Table 1, according to Winter et al. [55] and Banat et al. [56], this configuration consumes less energy than other membranes. Energy consumption is one of the most concerning aspects in MD technology. For this reason, spiral wound would be a research direction that needs to be considered to improve the existing shortcomings of this configuration in MD.

2.4 Tubular

In the MD process, besides flat-sheet and hollow-fibre membranes, tubular membranes had also been studied to desalinate seawater, treat brackish water, wastewater [21,44,62-65]. The tubular membrane was used in three MD configurations: DCMD, AGMD and VMD [23] and the membrane materials were mainly ceramic, PP, PVDF and PTFE. The membrane module included a hydrophobic membrane and shell. According to Cheng et al. [44], when using a tubular AGMD configuration, the feed stream was externally applied to the membrane, and the cool stream flew in the upstream mode within the hollow copper pipe. The condenser formed between a hollow copper pipe and soft insulation cover. The structure of the tubular membrane module is shown in Figure 4. The diameter of the tubular membrane module varied from 10 to 25 mm with a packing density of about 300 m2/m3 [61].

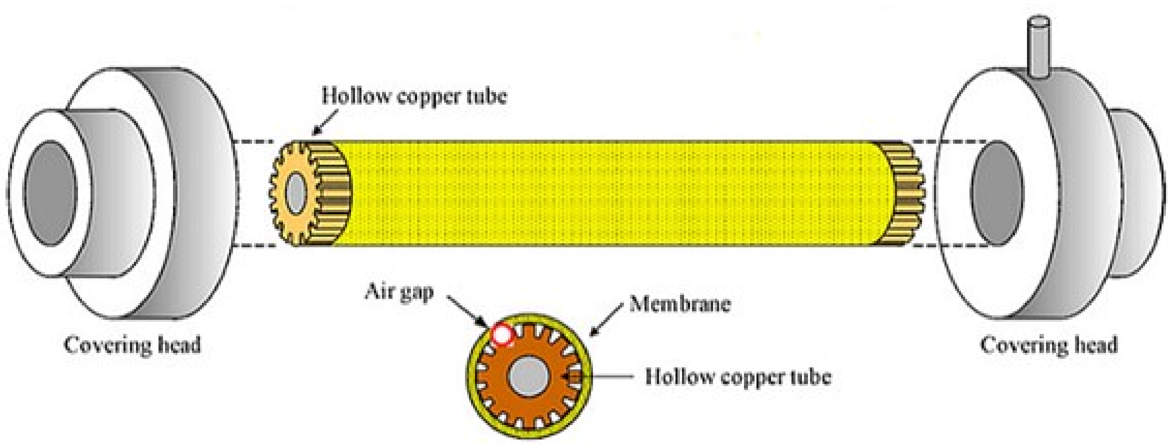

Figure 4. Tubular Air Gap Membrane Distillation (AGMD) module [43]

In the formation and development of MD technology, studies on tubular membrane had received fewer interests than flat-sheet membrane module or hollow fibre membrane. At the initial stage, only 15% of the studies used tubular membrane, but the percentage dropped to only 5% at the development period of MD technology. The cause of this decline might be due to the relatively low packing density of this module (about 300m2/m3) [23]. In the case of membrane wetting by feed stream, it was necessary to change the entire module because the shell and tubes stuck together [43]. Nevertheless, the membrane still had outstanding advantages, such as high flow rates allowance, which contributed to reducing the tendency of membrane fouling and polarization phenomena. Besides, the cleaning process of the membrane was easy to be done [61]. The same as hollow fibre membrane modules, tubular membrane modules included membrane and tubular cover with high force-resistance, so no support layer was needed. In the commercial sector, the tubular membrane modules were more attractive than the flat-sheet module because the surface area of the tubular membrane was much higher than the volume ratio [43]. According to [66], in the same operating condition, if the salt concentration increased from 0 to 3 g/L of NaCl, the permeate flux of the tubular membrane decreased by 7.33%, while that of hollow fibre membrane reduced to 20.48%; the yield of outlet water of the tubular membrane only decreased by 2.7% as the salt concentration increased from 3 to 50 g/L of NaCl but with the hollow fibre membrane, it reduced to 3.6%. Consequently, the tubular membrane module should be further investigated to overcome the existing disadvantages in seawater desalination applications.

3 CONCLUSION

Membrane Distillation, a desalination technology using hydrophobic membranes, was relatively attractive. This process was based on the difference in trans-membrane pressure created by the difference in temperature through a hydrophobic membrane. Four different types of membrane modules had been mentioned in this work, namely flat sheet, hollow fibre, spiral wound and tubular membranes. Each of them has different advantages and disadvantages. From the different viewpoints of the current membrane module configurations, this review evaluated the effectiveness of MD technology, analyzed the strengths and weaknesses of each type, in order to help researchers to make better choices for future research.

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