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PERSPECTIVE OPEN

Commercial scale membrane distillation for solar desalination

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Membrane distillation is an attractive technology for solar-powered decentralized desalination that has not yet reached commercial breakthrough on a large scale. The main barriers are energy consumption and cost. Since the latter are mostly related to the former, thermal energy efficiency is key to assessing the potential of the different available membrane distillation systems at a commercial scale. As discussed here, existing membrane distillation technologies use mostly flat sheet membranes in plate and frame and spiral-wound modules. Modules based on hollow fibre membranes are also considered, as well as the concept of multi-effect vacuum membrane distillation for improved heat recovery. The heat efficiency of each system is analysed based on available experimental results. Better internal heat recovery and capacity for upscaling are found to be important elements of distinction which make multi-channelled spiral-wound modules working in air-gap configuration stand out currently, with the lowest heat consumption of all large scale modules. Potential for improvement of this and other technologies is also discussed, and an estimation based on the associated costs for solar energy is used for establishing boundary conditions towards the implementation of membrane distillation for solar desalination.

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INTRODUCTION

Membrane distillation (MD) is a separation technique driven by a vapour pressure difference at two sides of a microporous hydrophobic membrane. It has been thoroughly studied,[1] and technology developments have been reviewed recently.[2–6] However, commercial implementation of MD has not been achieved yet. As pointed out by many authors,[7,8] this is due to the high energy consumption and water production costs. Cost data given in the literature for MD have a very large variation[7] and only a few works address commercial modules or even MD at pilot scale. Moreover, they are not always for the same application, so the available studies are hardly comparable. However, authors working with commercial modules[9–11] coincide that the costs for thermal energy are the most important in MD, so when heat has a price, heat efficiency must be maximized. This is the case of solar energy, and consequently, since the object of this perspective paper is MD for solar desalination, the analysis is based on the energy efficiency of the different available MD technologies, considering mostly the heat, which is the main energy needed in the process. This is evaluated in terms of the specific thermal energy consumption or the gained output ratio (GOR), a dimensionless parameter defined as the ratio of the latent heat of evaporation of the produced water to the total heat supplied to the system.[12] Electrical consumption is highly dependent on the size of the system and the hardware related to the installation, so it is hardly monitored in the experiments, but should also be regarded, especially when discussing upscaling.

The main application for MD considered in this work is desalination. The use of solar energy is proposed in order to mitigate the carbon footprint of the increasingly growing desalination industry.[13] Since thermal energy is more easily and economically stored than photovoltaic energy, thermal desalination technologies have a clear advantage for coping with the natural variability of the solar radiation than reverse osmosis (RO).[14] Moreover, they can treat brine from RO for extended recovery. In many cases, decentralized desalination is needed, which makes a modular and simple technology like MD a more feasible option than large-scale thermal desalination technologies such as multi-effect distillation (MED) or multi-stage flash distillation (MSF).[15,16]

A list of commercial MD technology developers and promoters was recently given by Thomas et al.[17] A revised and streamlined list is presented in Table 1, and the different technologies will be discussed in the following sections.

PLATE AND FRAME MODULES

Scarab AB build plate and frame modules consisting of 10 cassettes, which are injection moulded plastic frames containing two parallel membranes, feed and exit channels for the warm water, and two condensing walls. Cassettes are stacked together and channels for the cooling water are formed between the condensing walls of adjacent cassettes. Generally, total membrane surface area (MSA) is 2.3 m^2. The modules, based on AGMD configuration, were characterized by Kullab,[18] and an evaluation of the performance with simulated sea water resulted in a GOR value not larger than 0.72, with maximum flux 5.2 l/h m^2.[19] The lack of internal heat recovery in the module raises the thermal energy consumption and thus the only feasible application is when free waste heat is available.

Two pilot plants were built in Sweden with Scarab modules in cascade configuration for improved performance. The first was for water purification in a thermal cogeneration plant with total production of 1–2 m^3/d of distillate. Reported energy consumption (5–12 kWh/m^3) was highly underestimated because the cooling energy was subtracted from the heating energy, thus

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Table 1. Revised list of commercial MD technology developers and promoters

Main technology reference[a]	Comments	Type of technology
Scarab development AB	Xzero AB build practically the same modules, HVR water purification develop complete systems	Plate and frame (AGMD)
TNO Keppel Seghers	TNO licensed the Memstill patent to Keppel Seghers, no longer working on MD, and Aquastill, who never exploited it	Plate and frame (AGMD/PGMD)
Solar spring Gmbh	Spin-off of Fraunhofer ISE	Spiral-wound (mostly PGMD)
Aquastill BV	Develop their own technology, not related to Memstill	Multi-channelled spiral-wound (mostly AGMD)
Memsys	Build modules, used in commercial applications/developments by Aquaver, Condord Enviro Systems and GE, and Abengoa	Plate and frame (multi-effect vacuum MD)
KmX corporation	No references in scientific literature	Tube and shell hollow fibre VMD
Econity	No references in scientific literature	Tube and shell hollow fibre VMD
Blue gold technologies	Listed in ref. [17], allegedly developing BlueStill technology but no information found in the scientific literature or the web	
i3 innovative technologies BV	New development, no references in scientific literature yet	Spiral-wound (mostly PGMD)

[a] Main developer/owner's name

assuming ideal full heat recovery regardless of the temperature difference.[20] The second was for purification of effluents from a municipal wastewater treatment plant, using district heating network as thermal energy source. Despite connecting two modules in series, thermal energy demand was larger than 650 kWh/m^3, equivalent to GOR lower than 1,[10] more in line with the results observed by Guillén-Burrieza et al.[19] connecting three modules in series.

TNO patented an AGMD system based on counter-current flow pattern by connecting a number of cross-flow module segments together.[21] Based on this, the Memstill process was developed, claiming a GOR in the range of 9–29, although with no technical evidence of actually achieving it.[22] Keppel Seghers developed plate and frame modules with a PGMD configuration (flooding the air-gap with permeate).[23] An experimental evaluation showed maximum GOR of 0.4 in a module with MSA 9 m^2, and 1.5 when arranging three modules of MSA 3 m^2 in a series configuration.[24] Again, the efficiency was too low for use with solar energy to be feasible.[25] Indeed, all the pilot plants testing the Memstill concept used waste heat, the latest with a production capacity of 100 m^3/day in a petroleum refinery facility in Jurong Island (Singapore). However, soon after that Keppel Seghers stopped their activities MD. On the other hand, Aquastill never really exploited the Memstill license, which can be confusing since they followed a completely different path by developing their own multi-channelled spiral-wound modules.

Besides the hydraulic challenges of coping with dead zones and observed leakages,[19,24] insufficient internal heat recovery is the main limitation of current plate and frame modules.

SPIRAL-WOUND MODULES

Spiral-wound modules (Fig. 1) can have much better heat recovery by achieving better counter-current circulation and higher packing density than plate and frame modules. That configuration was first proposed by Gore et al.,[26] and the concept was developed by the Fraunhofer Institute for Solar Energy Systems (ISE) in PGMD modules applied to several pilot installations for solar desalination built in the framework of the EU FP5 and FP7 programme.[27–29] The modules are now commercialized by spin-off SolarSpring Gmbh and have larger GOR than plate and frame ones (for example, a full characterization of the module with 10 m^2 MSA and 7 m channel length for seawater desalination showed maximum GOR of 2.6 and flux 2.7 l/h m^2).[30] Feed temperature is the most influential factor on the performance, and there is a strong influence of the feed flow rate due to the changing bulk temperature difference and hydrodynamics, which reflects on a trade-off between permeate flux and GOR, due to the fact that the energy efficiency is improved by preheating the feed which acts as coolant, thus reducing the driving force and therefore the productivity.[31]

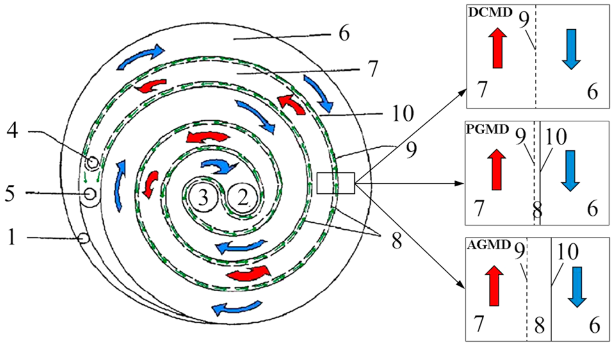

Fig. 1 Schematic diagram of the spiral-wound module with a single pair of main flow channels; 1 condenser inlet, 2 condenser outlet, 3 evaporator inlet, 4 evaporator outlet, 5 permeate outlet, 6 condenser channel, 7 evaporator channel, 8 air gap/permeate channel (PGMD, AGMD only), 9 hydrophobic membrane, 10 polymer film (PGMD, AGMD only). Reproduced with permission from ref. [32], copyright (Elsevier 2017)

Extensive research on modules fabrication, characterization and performance has already been published, comparing DCMD, PGMD and AGMD configurations with experimental validation with different full-scale prototype modules.[9] A discussion of upscaling spiral-wound modules was made by Winter et al.[32] On one hand, the connection of several modules in parallel is limited by the hydraulic difficulties of flow parallelization from a technical and also economical point of view. On the other hand, since channels must be oriented vertically for removing air, upscaling the module by increasing the height is limited by the hydrostatic pressure at the bottom. Instead, several channels can be arranged in parallel inside one single module, as already done in RO. This also reduces the pressure drop inside each channel and thus the electrical energy consumption for water circulation, so it is the most favourable design for upscaling. As a matter of fact, Fraunhofer ISE has now reported participation in the development of a new spiral-wound DCMD module with six parallel flow channels (3.1 m long) and MSA of 27.5 m^2, demonstrated on board a ship using low grade waste heat for seawater desalination.[33]

The multi-channelled spiral-wound module (Fig. 2) was the main invention of Aquastill after leaving the Memstill concept. They mostly have six evaporator channels, six condenser and twelve distillate channels. A module of MSA 7.2 m^2 (channel length 1.5 m) implemented in a pilot plant for concentration of coal seam gas RO brine (14.1 g/l) reached a GOR of 2.5 and distillate flux of 1.4 l/h m^2 when operating in continuous mode at 80% recovery.[12] A model optimization for seawater desalination showed that for very low circulation rate and feed temperature 70 °C, GOR could be up to 6–7, although permeate flux was only 1 l/h m^2.[34] Similar values of GOR and flux were obtained by Ruiz-Aguirre et al.[35] with a larger module (24 m^2) with longer channels (5 m long) using four times more circulation feed rate. This can be explained using the heat exchanger theory applied to MD by Swaminathan et al.[36] Reducing the feed flow rate is equivalent to lengthening the channel, increasing the number of heat transfer units (NTU) and improving heat recovery. Since the module with longer channels has 24 m^2 MSA, it is the one that produces the most with the highest heat efficiency.

The trade-off between productivity and energy efficiency is the main challenge of spiral-wound modules. The largest heat efficiency is achieved with the largest channel length in multi-channelled modules. Regarding configurations, DCMD is discarded unless free waste heat is available, with all commercial products focused on PGMD and AGMD (more adequate for high salinity feeds).

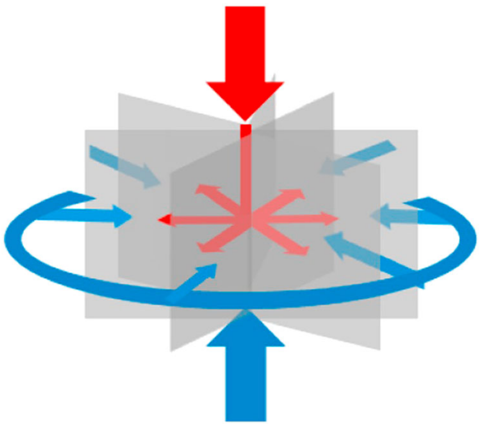

Fig. 2 Scheme of the integration of multiple parallel channel in a MD spiral-wound module. Reproduced with permission from ref. [32], copyright (Elsevier 2017)

HOLLOW-FIBRE MODULES

The main attraction of using hollow fibre (HF) membranes is the high specific surface area and the ease for cleaning and dealing with scaling, which facilitates treating higher concentration feeds. KmX Corporation (http://kmxcorporation.wixsite.com/kmx-corporation) produce modules with their own HF membranes. They build VMD systems from 10 to 1000 m^3/day, advertised to operate with waste heat and no indication of heat recovery. For brine concentration, they state that 30% less energy is required per unit of water recovered, but the comparable reference is not indicated (and most likely this refers to electricity only). Similarly, Econity build HF modules with fibres 0.6 m long and MSA 10 m^2, which they have installed in the largest pilot plant operating in the world for seawater desalination, at 400 m^3/day in South Korea.[37] It operates in VMD configuration coupled with thermal vapour compression, which requires a source of heat at high temperature (a boiler is used). No figures of heat efficiency have been provided yet.

VMD is potentially the most efficient MD configuration, since there are no heat losses through the membrane and mass transfer resistance is reduced to the minimum. However, there is no condensation channel but an external condenser is required, so multi-stage concepts for heat recovery are more complicated.

Internal heat recovery in HF-based AGMD modules (Fig. 3) was started early in the Memstill consortium by University of Twente using a module consisting of several vertical membrane fibres with a cooling plate parallel placed on both sides separated by air gap.[38,39] This approach has been subsequently followed in China. Chembrane Research & Engineering, Inc. patented an AGMD HF module with internal heat recovery by combining porous fibres (acting as evaporators) and dense wall fibres (acting as condensers) in a parallel arrangement inside a tube and shell module, with the space between the adjacent fibres filled with air.[40] High values of GOR were reported for modules 0.85 m long,[41,42] and a trade-off between flux and GOR was also observed when comparing modules of different length using a 2 g/l NaCl solution: maximum GOR 13.8 (corresponding distillate flux 1.85 l/h m^2) for modules with effective length 1.2 m (total evaporation area of 0.625 m^2) and maximum flux of 9.20 l/h m^2 (GOR 2.3) for modules 0.62 m long (total evaporation area of 0.362 m^2).[43] A scaled-up module with 2 m^2 MSA gave GOR 5.27 when applied to high saline water (70 g/l).[44] Internal heat recovery in larger modules has not been demonstrated, and seems more complicated than in spiral-wound modules because lower hydraulic diameters involve higher electrical costs for feed circulation. Therefore, heat recovery in HF modules at large-scale must rely on external equipment which requires more investment and electrical consumption.

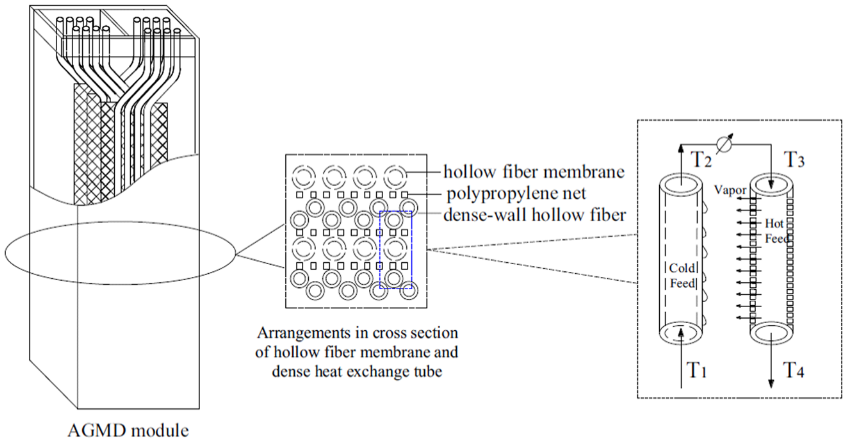

Fig. 3 Scheme of the HF module with internal heat recovery. Reproduced with permission from ref. [42], copyright (Elsevier 2014)

MULTI-EFFECT VACUUM CONFIGURATION

The trade-off between energy efficiency and productivity is a limitation of multi-stage configurations, where latent heat is recovered in the form of sensible heat to preheat the feed, hence increasing the heat recovery decreases the driving force and the permeate flux. A different concept of heat recovery is to reuse the latent heat of condensation for further evaporation in different effects, approaching the concept of MED. This is the principle of the V-MEMD technology patented by W. Heinzl and later commercialized by memsys using plate and frame multi-effect modules.[45] Typically, they comprise a steam raiser or evaporator, several distillation effects and a condenser. Effects consist of frames thermo-welded one after the other (to avoid leakage), alternating membranes and condensation foils, separated both by a polypropylene spacer forming a channel between them. Few systems are analysed in the literature. Maximum reported values of GOR are below 3 for four-effect modules,[46–48] and below 4 for six-effect modules,[49,50] with fluxes of 3 l/h m^2 for real seawater in the first case[46] and up to 4.9 l/h m^2 in the latter with feed salinity around 35 g/l.[49] Fluxes were up to 7–8 l/h m^2 with artificial 20 g/l saline water[48] and 3–5 l/h m^2 for concentration of inland saline groundwater from 6.3 to 10.2 wt%[47] in four-effect modules.

The V-MEMD concept exploits the benefits of VMD and multi-effect heat recovery, which is more thermodynamically efficient than multi-stage schemes which are more similar to MSF, but only if a large number of effects are used. As in the case of a MED plant, a means to establish vacuum is required (usually a vacuum pump), and a larger cooling flow in the condenser than the feed, which can also be a limitation. The plate and frame modules can be significantly upscaled and installations of up to 100 m^3/d have been reported.[17] However, upscaling is usually focused on building larger effects. Increasing the number of effects is not only limited by the hydraulic resistances of the feed flow (which is established by the vacuum pump) but by the boiling point elevation with salinity, especially in the case of highly concentrated solutions.

OUTLOOK FOR DEVELOPMENT

In desalination applications where energy is costly, spiral-wound modules are currently in the best position for market implementation, while V-MEMD manages to demonstrate its full potential and hollow-fibre modules achieve effective energy recovery in pilot scale. In the case of V-MEMD, the challenge is increasing the number of effects without a negative impact on the electrical consumption. In the case of HF, upscaling the modules with internal heat recovery or finding viable means of external heat recovery are the challenges.

Potential for improvement in the case of spiral-wound modules lays on semi-batch operation, which has been shown to decrease energy consumption by 10%.[51] Regarding the optimal configuration, at pilot scale AGMD modules can reach higher flux and efficiency than DCMD,[52–54] which, furthermore, as in the case of VMD, need external means for heat recovery. The influence of membranes has not been considered in the discussion of heat efficiency in spiral-wound modules. However, the effect of membrane thickness has been demonstrated less important in pilot than on lab-scale.[55]

The beneficial effect of feed water de-aeration (elimination of dissolved air to reduce the presence of air in the membrane pores) has been demonstrated for spiral-wound modules working in AGMD and PGMD.[56] A further step can be the use of vacuum-enhanced configurations, where a slight suction is applied in the condensation channel. This is not enough to induce evaporation by decreasing the pressure below that of liquid saturation, but typically just to evacuate the non-condensable gases from the pores for enhancing the vapour flow. This can increase the heat efficiency up to 30% according to simulations validated at lab-scale.[9,54] Large scale demonstration is currently ongoing at Plataforma Solar de Almería (Spain) with Aquastill modules in vacuum-enhanced AGMD configuration with minimum electrical consumption. Given the experimental figures obtained with the module of 24 m^2 MSA, the projection is that its operation in v-AGMD could reach a GOR 10, which would be outstanding for a module producing about 24 l/h.

The scarce implementation of MD technology hampers the performance of a proper comparative economic analysis. Moreover, there are no standards for the calculation of desalination water costs,[57] which complicates the comparison even more. Existing studies are mostly based on simulations validated at lab-scale than in results from pilot plant experiments.[9,50,54,58] In an evaluation of stand-alone solar powered MD systems, Saffarini et al.[58] concluded that solar energy costs were 70% of the total costs of the systems, and Schwantes et al.[54] also found similar percentages. Thus, the cost of solar thermal energy can set up boundaries for the economic viability of solar MD. It was found that GOR had to be 8 for solar thermal heat costs to be less than 3 \$/m^3 for a small size installation.[59] Based on that work, Table 2 indicates an estimation of the costs of solar thermal energy for a MD system of GOR 8 sized to reach a total production of 10 m^3/day operating during 8 h per day solely with solar heat and no backup. The levelised cost of water obtained with photovoltaic reverse osmosis (PV-RO) installations using batteries for continuous operation can be estimated with better reliability, since the technology is more developed than MD. Thus, considering the values of 5.4–5.8 \$/m^3 determined for an off-grid 250 m^3/day plant,[61] solar MD can only compete with PV-RO for seawater desalination in regions with high radiation and temperature (such as Abu Dhabi), if the GOR is at least 8 and if the investment costs of the MD plant (plus operational costs excluding heat) are less than 1–1.2 \$/m^3. For brine concentration, however, the operational limitations of RO open a clear niche for MD.

CONCLUSIONS

Although plate and frame modules were the first to reach the market, their low heat recovery restricts their application to the availability of free waste heat. Spiral wound modules dominate the market due to their better internal heat recovery and potential for low electrical consumption with hydraulic optimization. Most of the implementations of MD for solar desalination are based on these modules, which also find a better chance of upscaling via the multi-channelled construction. Their highest heat efficiency is reached in air gap configuration for modules with channels 5 m long (GOR about 7 for seawater desalination). Although modules using hollow fibre membranes with internal heat recovery show great results at lab-scale, they have not shown commercial progress so far, most likely due to upscaling difficulties. Thus, technologies based on hollow fibre membranes are not applied with heat recovery in large scale. The potential of vacuum multi-effect MD for better heat recovery is not demonstrated yet with a large number of effects that could reach GOR larger than 5. In addition, vacuum-enhanced operation is a potential improvement

Table 2 Thermal energy cost for a MD system of GOR 8 producing 10 m^3/day from seawater

	GHI per year[60]	Cost of solar heat[a]
Almería (Spain)	1850 kWh/m^2	5.2 \$/m^3
Abu Dhabi (UAE)	2200 kWh/m^2	4.4 \$/m^3

[a] 8 h/day operation of stationary solar collectors with high efficiency (50%) at 85 °C

for spiral wound modules, which needs to be demonstrated. However, even for systems with high heat efficiency (GOR = 8), the large cost of the solar thermal energy hinders the commercial viability of solar MD when PV-RO is feasible, so the niche for solar MD in desalination is mostly brine concentration.

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AUTHOR CONTRIBUTIONS

G.Z. was responsible for the article's layout and most of the writing. A.R.-A. and J.A.A.-M. were responsible for searching for some information and collaborated on the writing.

ADDITIONAL INFORMATION

Competing interests: The authors declare no competing interests.

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