Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1117821

57 (2016) 23038–23051
October

Taylor & Francis
Taylor & Francis Group

Autonomous solar powered membrane distillation systems: state of the art

K. Zhani[a,*], K. Zarzoum[a], H. Ben Bacha[a,b], J. Koschikowski[c], D. Pfeifle[d]

[a]*LASEM (LAboratoire des Systèmes Electro-Mécaniques), National Engineering School of Sfax, B.P. W3038, Sfax, Tunisia, emails: zhani_khalifa@yahoo.fr (K. Zhani), hbacha@Ksu.edu.sa (H. Ben Bacha)*
[b]*Mechanical Engineering Department, College of Engineering at Alkharj, Prince Sattam Bin Abdulaziz University, P.O. Box 655, Alkharj 11942, Kingdom of Saudi Arabia*
[c]*Fraunhofer-Institut for Solar Energie Systeme (ISE), Heidenhofstrasse 2, 79110 Freiburg, Germany, email: joachim.koschikowski@ise.fraunhofer.de*
[d]*SolarSpring GmbH, Hanferstr.28, 79108 Freiburg, Germany, email: Daniel.pfeifle@solarspring.de*

Received 30 March 2015; Accepted 27 October 2015

ABSTRACT

Being a basic element for the every existence of any form of life on earth, water is one of the most abundant resources on earth, covering three-fourth of the planet's surface. However, there is a shortage of freshwater in many areas worldwide. Desalination seems to be the most suitable solution. Major conventional desalination processes, such as distillation and reverse osmosis, consume a large amount of energy derived from oil and natural gas as heat and electricity, which is responsible for harmful CO_2 emission. Solar desalination has emerged as a promising renewable energy-powered technology for producing freshwater. Solar membrane distillation (MD) is the best option in decentralized regions with scattered population and lack of infrastructures jointly with hard climate conditions make it difficult or at least not cost-effective to scale down bigger desalination technologies, such as RO or MSF, designed for very big water productions. Moreover, MD compared to conventional thermal desalination is less demanding regarding vapor space and building material's quality leading to potential lower construction costs. The aim of this paper is to present the state-of-the-art review of developments in solar MD technology. In this review, membrane configurations, module design, and recent applications of this technology were discussed in detail.

Keywords: Solar desalination; Membrane distillation; Thermal efficiency

1. Introduction

Water is indispensable for life but its availability is not assured everywhere. The earth contains about $1.4 \times 10^9\ \text{km}^3$ of water, which covers approximately 70% of its surface area; the percentage of salt water in this large amount is 97%. The remaining 3% is fresh water with 70% of this amount frozen in the icecaps or combined as soil moisture. Both forms are not easily accessible for human use. Twenty-nine percent of all freshwater is underground, most of it in deep,

*Corresponding author.

Presented at EuroMed 2015: Desalination for Clean Water and Energy Palermo, Italy, 10–14 May 2015. Organized by the European Desalination Society.

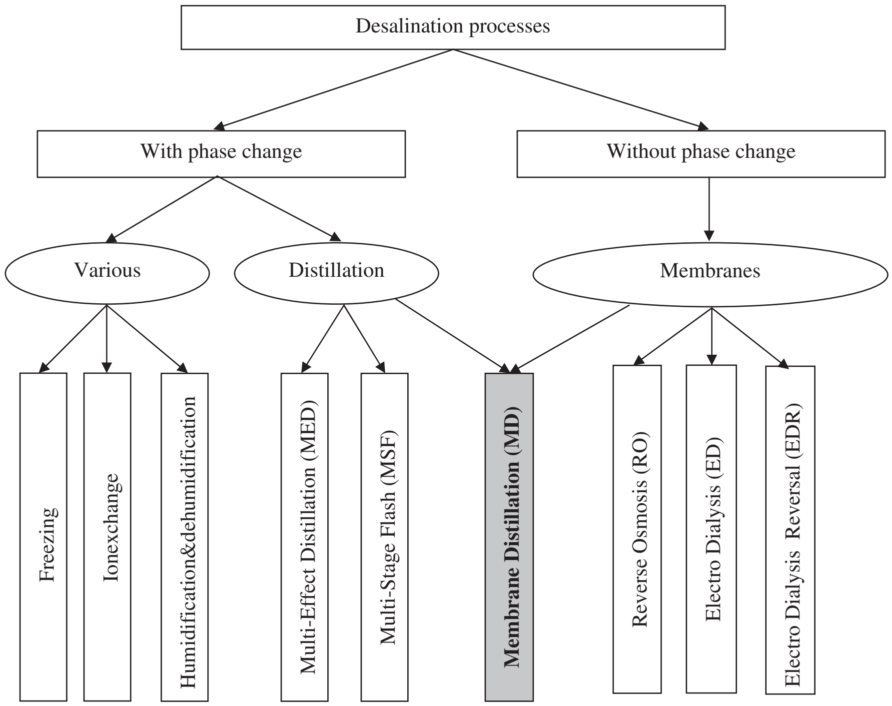

Fig. 1. Classification of water desalination technologies.

hard-to-reach aquifers. The remaining quantity, about 1%, is believed to be adequate to support all life on Earth. So, freshwater can become a great problem since the water resources are limited and the problem will be aggravated by the exponentially growing demand for water due to a progressive urbanization, industrialization process, and growing population. To cope with this issue and to respond to increasing water demand, desalination of seawater, which is abundant, is being considered.

In addition to both freshwater scarcity and environmental degradation due to gas emissions, many countries all over the world are suffering from fossil energy depletion. The immediate response to simultaneously tackle these problems is coupling desalination processes with renewable energy resources, such as solar energy and geothermal water. In Tunisia, as throughout the world, a growing number of municipalities are implementing a development program focusing on the use of renewable energies for brackish and seawater desalination to provide freshwater for some remote regions.

Membrane distillation (MD) is a promising new comer to the desalination processes which can be coupled to low-grade and renewable energy source such as solar energy. As shown in Fig. 1, MD is a hybrid of thermal distillation and membrane processes. MD process is not commercialized yet for large-scale industry. The reasons behind this is that there are few studies about the characterization of the operation at pilot scale and these plants do not use specific membrane for MD, use microfiltration or ultrafiltration membranes. The principle of MD is illustrated in Fig. 2.

Conventionally, MD is a thermally driven process in which a microporous membrane acts as a physical support separating a warm solution from a cooler

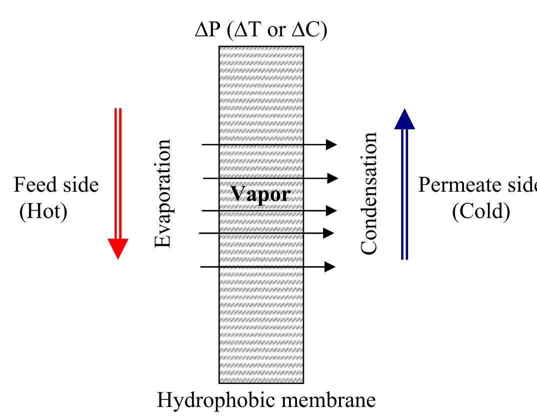

Fig. 2. Principle of MD.

chamber, which contains either a liquid or a gas. As the process is nonisothermal, vapor molecules (water vapor in the case of concentrating nonvolatile solutes) migrate through the membrane pores from the high to the low vapor pressure side; that is, from the warmer to the cooler compartment. The main advantages of MD over conventional separation technologies include [1–4]:

(1) Good compromise between efficiency and complexity (specific heat consumption below 60 kWh/m^3 will be possible).
(2) Feed temperature, depending on MD configuration, can be between 50 and 90°C, possibility of utilizing low-grade heat from alternative energy sources.
(3) Low sensitivity against fouling and scaling due to membrane properties and flow configuration.
(4) Transient operation in temperature and flow rate is possible in a wide range.
(5) High salinities can be treated depending on system configuration (final stage before zero liquid discharge).
(6) High purity of product water.
(7) Huge potential for cost reduction due to use of polymer materials.

In this research paper, we aim to provide a state-of-the-art review on developments in solar MD systems associated with solar energy for seawater and brackish water desalination. This article presents the MD principle, configurations, designs, compact systems, and multimodule two-loop systems.

2. Configurations of MD

The different approaches for establishing the driving force and other process requirements led to the development of various channel configurations that are widely used as classification criteria within MD technology. The most common configurations utilize a temperature difference as the driving force, while alternative approaches are considered rather exotic. Each of the MD configurations has its own advantages and disadvantages for a given application which summarized in Table 1.

MD technologies that establish a vapor pressure difference by temperature are as follows:

(1) *Direct contact membrane distillation (DCMD)* is the most commonly used process mode due to its simplicity in structure, design and process operation. In a DCMD process, seawater or brackish water is passed on one side of a

Table 1
Main advantages and disadvantages of each type of MD configuration

MD configuration	Advantages	Disadvantages
DCMD	High permeate flux	Low-thermal efficiency
	Simplicity in design and operation	High impact of temperature and concentration polarizations
	Internal heat recovery is possible	Risk of mass contamination of the permeate
PGMD	Separation of permeate from the cooling fluid	Additional heat transfer resistances
	Reduces sensible heat losses	
	Internal heat recovery is possible	
	Seawater can be used as cooling stream at the permeate side	
AGMD	Seawater can be used as cooling stream at the permeate side	Further resistance towards water vapor results in lower permeate flux
	High thermal efficiency	Large footprint
	Internal heat recovery is possible	
OMD	The solute retention close to 100%	Concentration polarization phenomena
	High water fluxes	Membrane fouling
	Salt rejection factor above 99.8%	
VMD	High permeate flux	Membrane pore wetting is powerful
	Less conductive heat loss	Heat recovery is difficult
	Low-thermal and concentration boundary layers formed on the permeate side of the membrane	
SGMD	High mass transfer rate	Heat recovery is difficult
	Low heat loss by conduction	Complicated to handle the sweeping gas
		Need larger condenser

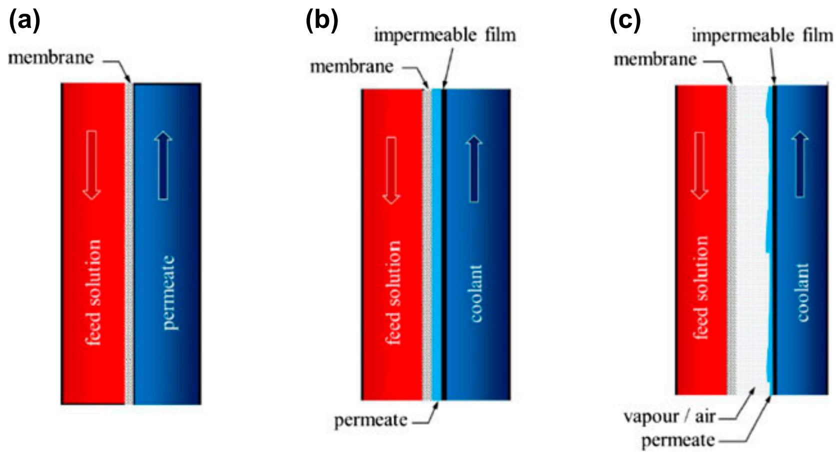

Fig. 3. MD configurations driven by a temperature difference: (a) DCMD, (b) PGMD, and (c) AGMD.

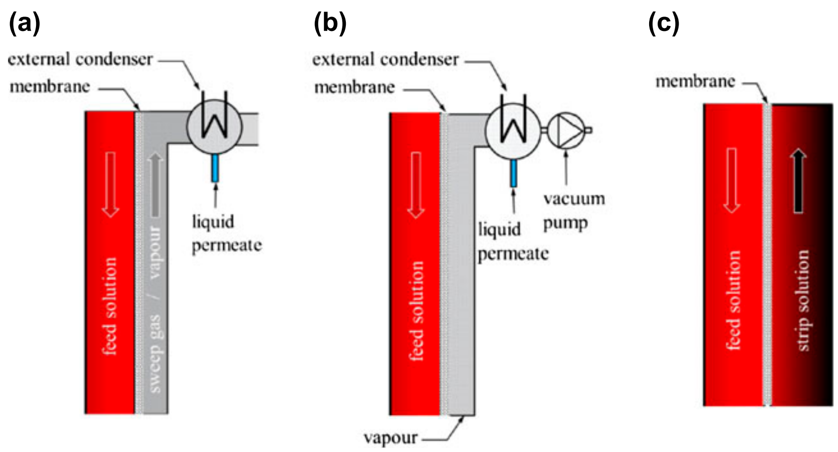

Fig. 4. MD configurations driven by approaches other than a temperature difference: (a) SGMD, (b) VMD, and (c) OMD.

hydrophobic porous membrane while a colder water stream flows on the other side to directly condense the permeate water as shown in Fig. 3(a). Extensive studies on DCMD have been reported [5–7].

(2) *Permeate gap membrane distillation (PGMD)* is closely related to DCMD, since also in this configuration both sides of the membrane are in direct contact with the respective liquid fluids and the driving force is established by means of a temperature difference. As illustrated in Fig. 3(b), a third channel is introduced by an additional impermeable film that is located on the permeate side of the membrane. Since the permeate outlet is located at the highest module position, the gap between the membrane and the impermeable film fills with permeate during operation and is therefore referred to as the permeate gap (PG) or liquid gap (LG) [8,9].

(3) *Air gap membrane distillation (AGMD)* is illustrated in Fig. 3(c). Similar to the PGMD channel configuration, the permeate is separated from the coolant by an impermeable film next to the membrane on the permeate side. Driven by a temperature difference, the volatile compounds of the feed solution evaporate at the feed side liquid–vapor interface, pass the membrane, and the air gap in the gaseous phase and condense at the liquid–vapor interface on the cooled surface of the impermeable film [10–12].

Other MD technologies establish a vapor pressure difference by lowering the concentration of the permeating substance on the product side and include the following:

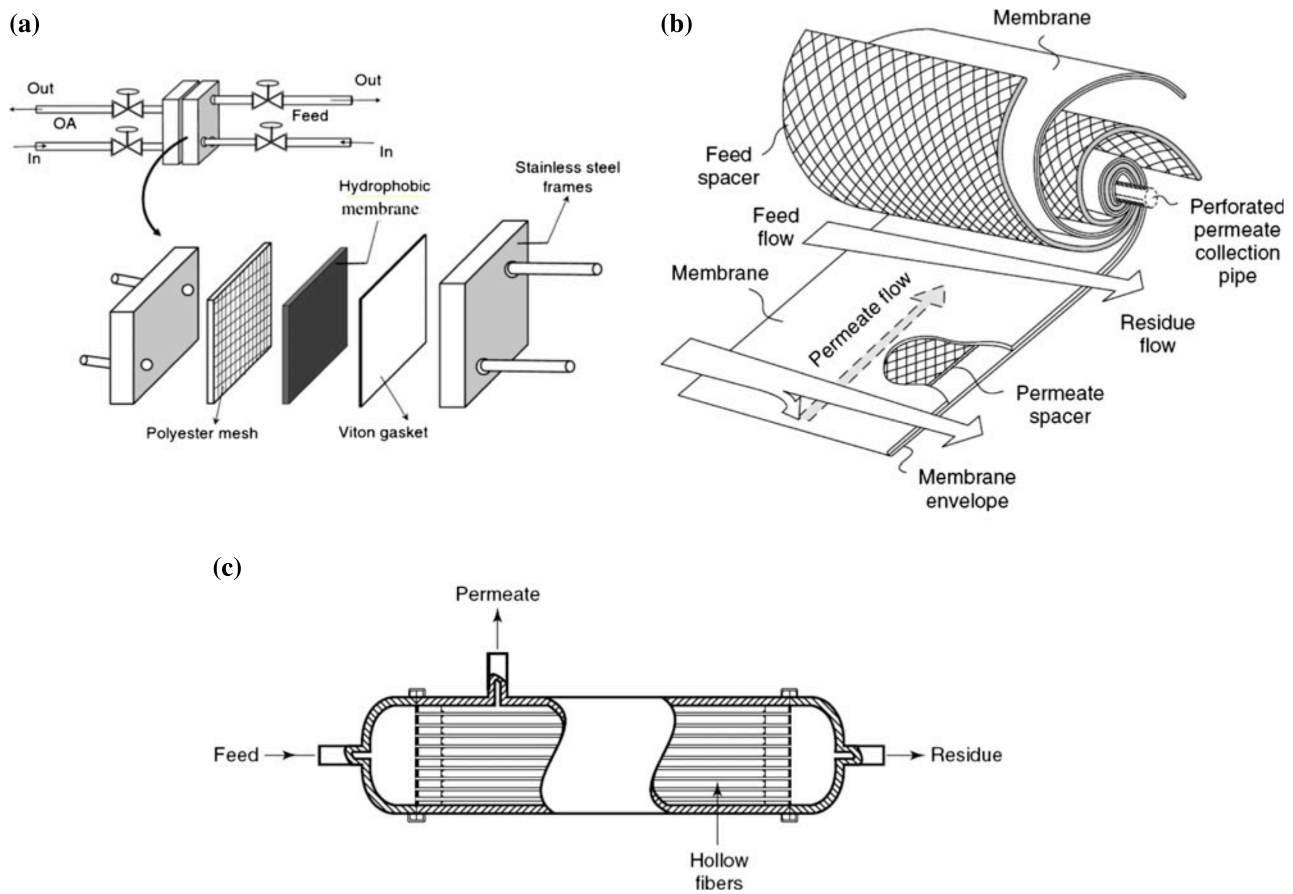

Fig. 5. Schematic illustration of the different basic module design principles: (a) plate-and-frame module, (b) spiral-wound module, and (c) shell and tube.

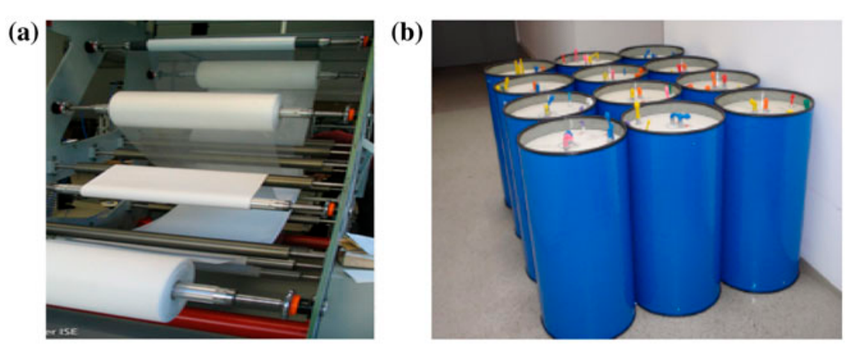

Fig. 6. (a) Spiral-wound winding machine and (b) Picture of the modules.

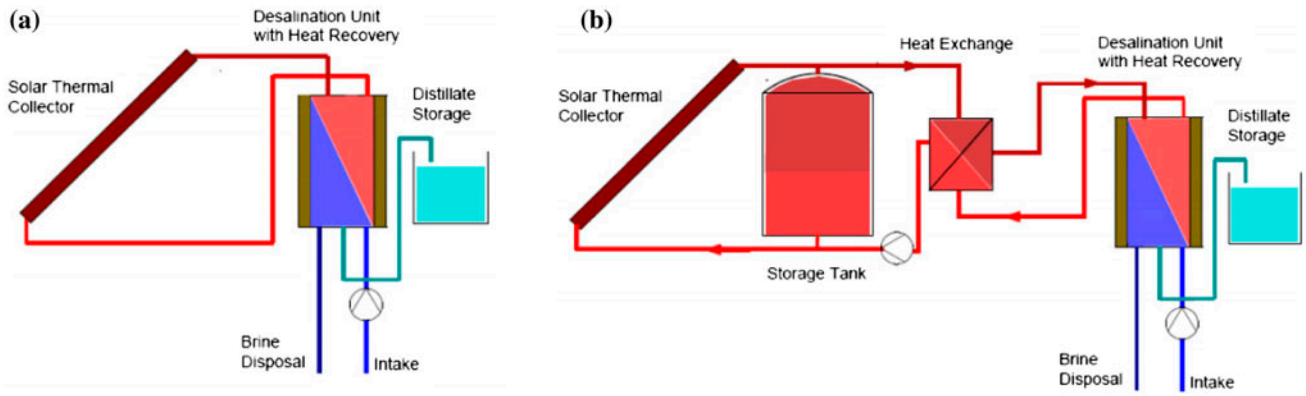

Fig. 7. Two different system configuration: (a) compact system and (b) two-loop system [22].

(1) *Sweeping gap membrane distillation (SGMD)* configuration, illustrated in Figs. 2 and 3(a), the vapor at the permeate side of the membrane is removed by a sweep gas and subsequently condensed by an external condenser. This allows for the reduction of water vapor partial pressure, thus achieving a higher driving force across the membrane Fig. 4(a) [13–15].
(2) *Vacuum gap membrane distillation (VGMD)* configuration, illustrated in Fig. 4(b), considers a two-channel arrangement quite similar to that of SGMD. The feed solution is circulated parallel to the membrane in the evaporator channel and establishes a liquid–vapor interface at the feed side of the membrane. The flow channel on the permeate side of the membrane is designed as a dead-end channel, providing only one access point at which vacuum is applied by means of a vacuum pump. The vapor condensation and subsequent permeate extraction takes place in a condenser located outside of the module [16,17].
(3) *Osmotic membrane distillation (OMD)* is a process that has recently emerged as an attractive alternative to other concentration techniques, when high final concentration and quality are required. Osmotic distillation is shown in Fig. 4(c). The process is driven by the transmembrane water vapor pressure difference, created by the differences in chemical potentials of the two solutions on both sides of the membrane due to their compositions and concentrations [18–20].

3. Design of MD modules

Multitudes of different membrane modules have been developed, addressing a wide variety of different process requirements throughout membrane technologies. The module designs are categorized with respect to the basic design principle and the membrane type [21]. Considering an MD process, the usual design for capillary membrane modules applied shell and tube concepts while the most relevant module designs for flat sheet membranes are plate and frame as well as spiral-wound concepts. Schematic illustrations of the different basic design types are presented in Fig. 5. Any of the module types may be designed and operated in counter-current flow, co current flow or cross flow.

4. State of the art MD systems

The most important organizations specializing in MD modules or high-efficiency systems are:

(1) Fraunhofer ISE and SolarSpring (AGMD).
(2) Memstill (AGMD).
(3) Aquastill.
(4) Scarab (AGMD).
(5) Memsys (vacuum enhanced multi effect AGMD).

4.1. Fraunhofer ISE

Fraunhofer Institute for Solar Energy Systems (ISE) is pioneer in MD. ISE has been working on the development of energy self-sufficient desalination systems based on solar-driven MD technology since 2001. The focus is put on module and system development. One of the earlier MD modules to appear was an AGMD module from Fraunhofer Institute for Solar Energy System (ISE), Germany. The innovative aspect of their design was a spiral-wound AGMD system as shown in Fig. 6. AGMD has the advantage in that the module itself features internal heat recycling to minimize the

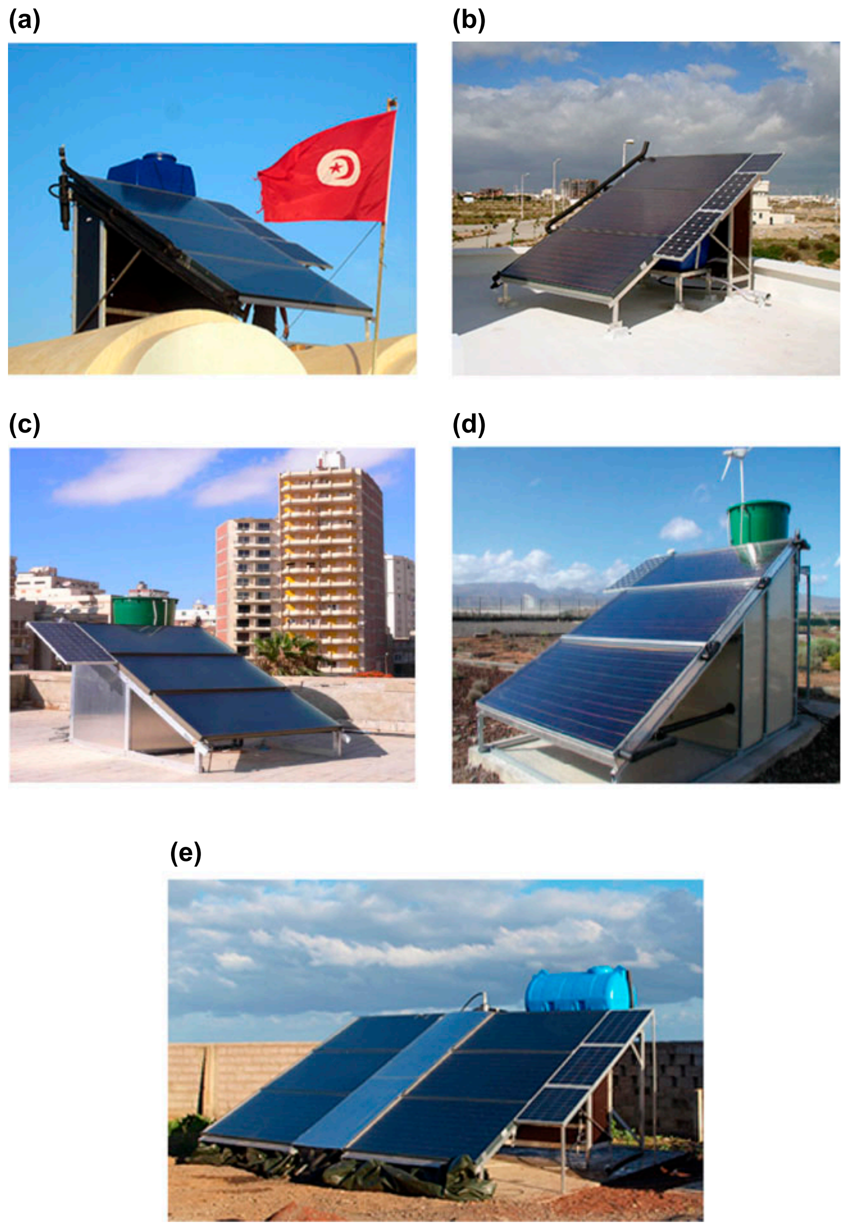

Fig. 8. Different ORYX desalination systems installed worldwide: (a) Jederia, Tunisia 2010 [23], (b) Private house, Tunisia 2010 [23], (c) Alexandria, Egypt 2005 [24], (d) Gran canaria, Spain 2004 [9], and (e) Buen Paso, Tenerife, Italy 2011 [20].

loss of latent heat, thus greatly reducing the thermal energy requirement. They propose to have achieved thermal energy consumptions of 140–200 kWh/m^3 in their 2003 device [22], or greater than 4-fold improvement in the latent heat required to evaporate the same amount of water (GOR up to 4.5).

Solar spring produces all MD-modules in cooperation with the Fraunhofer ISE in Freiburg. They operate a customized constructed winding machine to produce spiral-wounded MD-modules. They can vary many parameters such as channel length, channel height, membrane material, spacer geometry, and material.

Two different system configurations for different capacities ranges were developed, the "Compact system" and the "Two loop system" as shown in Fig. 7.

4.1.1. Compact systems

The Fraunhofer ISE research group Thermal Desalination and Separation (TDS) has developed MD

Table 2
General characteristics of some constructed compact systems

Refs.	[9,22]	[24]	[25]	[26]	[27]	[28]
Location	Gran canaria, Spain	Alexandria, Egypt	Irbid, Jordan	Freiburg, Germany	Hangzhou, China	Xiamen, China
Installation date	2004	2005	2005	2002	N/A	2012
MD configuration	PGMD	AGMD	AGMD	AGMD	VMD	VMD
Membrane materiel	PTFE	PTFE	PTFE	PTFE	PP	PP
Membrane area (m^2)	8.5–10	N/A	10	8	0.09	0.25
Solar collector area (m^2)	6.96	5.73	5.73	5.9	8	2.16
Electricity source	PV	PV	PV	Grid	Grid	Grid
Feed water type	Seawater	Brackish	N/A	Tap water	Brackish	NaCl
Water production (L/d)	5–120	64	120	130	15.6	N/A
Water flux (kg/m^2 h)	N/A	N/A	2.5	1.88	32.19	4
Recovery ratio	0.1–55	N/A	1–4	6.7	0.25–1.26	5
Heat consumption (kWh/m^3)	140–350	N/A	200–300	117	7,850	750

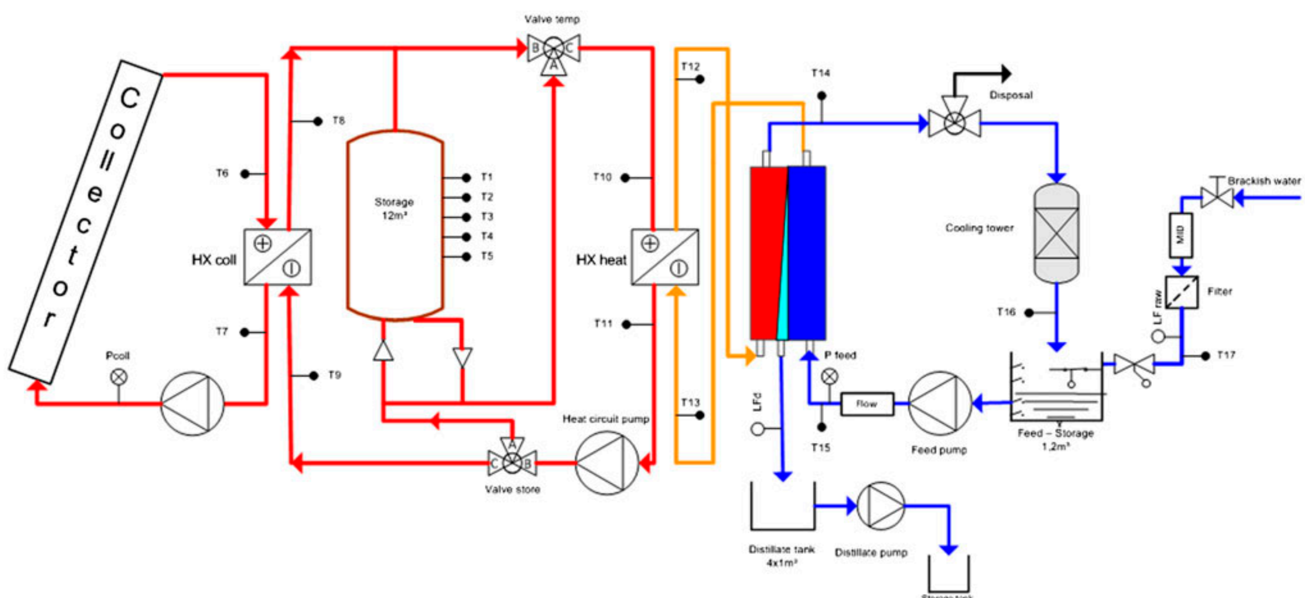

Fig. 9. Schema of the Namibia plant.

modules for use in solar-driven desalination in remote areas. Since 2005, 15 pilot plants for the desalination of sea and brackish water have been implemented within the scope of different international projects. Capacities ranged from 100 L up to 10 m^3 drinking water per day [22]. A fully validated, thermodynamic model was developed to carry out studies on module and plant design. Recent research activities have focused on alternative applications and new types of substances for MD technology. Fig. 8 shows a different ORYX desalination systems installed worldwide. ORYX is a compact and stand-alone system for solar water desalination. Thermal energy for MD is provided by solar thermal collectors and solar PV powers the pumps and control systems. Each unit is designed to operate autonomously, starting and stopping automatically when there is sufficient sunlight. ORYX is robust, has low-fouling tendency and can be used with seawater or brackish wells. No pre-treatment chemicals, no back flushing and low maintenance make ORYX ideal for drinking water supply in remote areas. The ORYX units are able to process seawater up to a salinity of 40,000 ppm. The daily output of these units is about 100–150 L. With the currently used MD

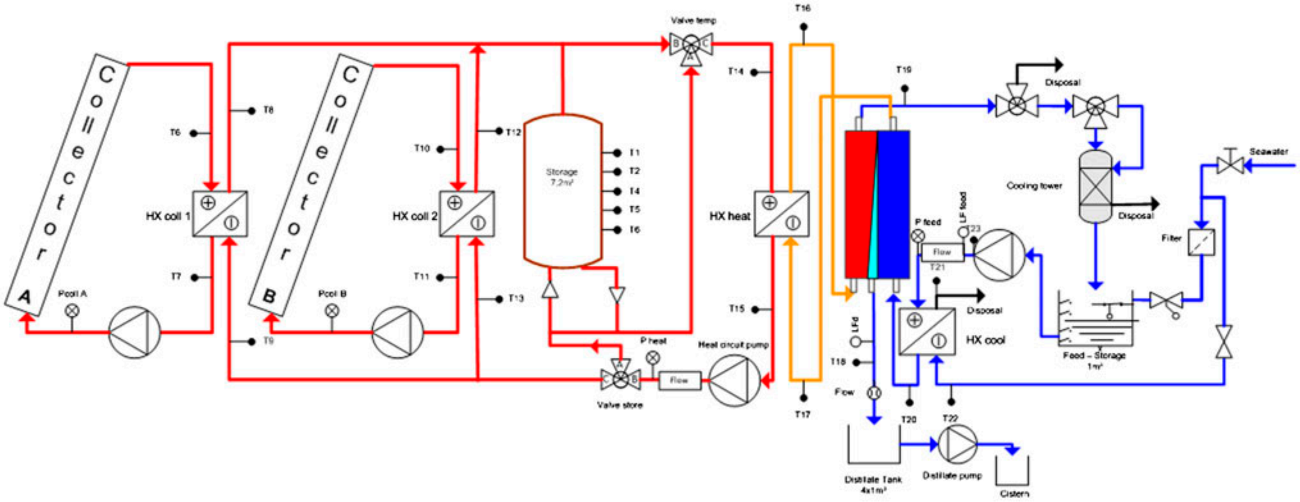

Fig. 10. Schema of the Gran Canary plant.

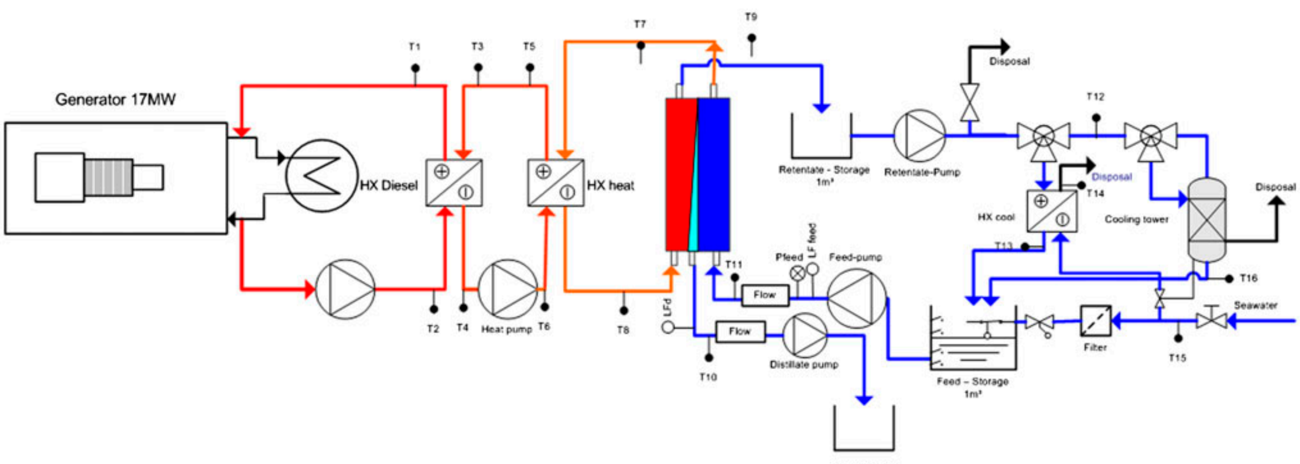

Fig. 11. Schema of the Pantelleria plant.

Table 3
General characteristics of some constructed multimodule two-loop units

Refs.	[22]	[30]	[31]	[29]	[29]
Location	Gran canaria, Spain	Almeria, Spain	Aqaba, Jordan	Amarika, Namibia	Pantalleria, Italy
Running period	–	3 months	Few months	–	–
MD configuration	AGMD	–	PGMD	PGMD	PGMD
Membrane materiel	PTFE	PTFE	PTFE	PTFE	PTFE
Membrane area (m^2)	120	9	40	168	120
Solar collector area (m^2)	186	500	72	232	40 + Waste heat
Electricity source	PV	Grid	PV	PV	Grid
Feed water type	Seawater	NaCl	Seawater	Brackish	Seawater
Water production (L/d)	1,400	–	792	2,080	3,690
Water flux (kg/m^2 h)	–	5.09	1.5	28.57	40
Recovery ratio (%)	–	2.2–4.5	2–4.5	10–30	0–65
Heat consumption (kWh/m^3)	271	294	200–300	171	300

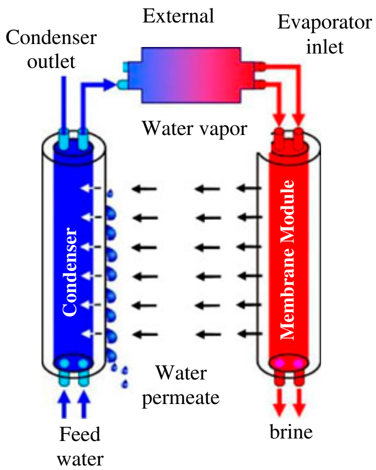

Fig. 12. Schematic layout of one element of the Memstill process.

Fig. 13. Membrane modules for pilot plant.

module, the freshwater output decreases significantly with an increase of feed water salinity [22]. Table 2 summarizes the general information of the pilot plants and experimental setups built in the past decade. Most of the presented compact systems had very low recovery ratio (mass ratio of the produced water and the feed solution), lower than 7%, and high-thermal energy consumption of water production, higher than 200 kWh/m^3.

Fig. 14. Aquastill membrane modules for distillation.

Fig. 15. Aquastill pilot unit at the facilities of PSA (Almería, SE Spain) [36].

Table 4
Summary of constructed Memstill pilot systems

Used module	M28	M32	M33	K1
Location	Singapore, Straits of Johor	The Netherlands, Port of Rotterdam	The Netherlands, Port of Rotterdam	BASF, Port of Antwerp
Running period	17 months	4 months	7 months	14 months
Absolute flux (L/m^2 h)	0.25	2.5	3	5
Internal heat recovery (%)	30	50	90	90
Heat consumption (Mj/m^3)	1,000–2,000	400–800	350–750	400–800

Fig. 16. Scarab membranes for distillation in the experimental installation built at PSA-CIEMAT (Almería, Spain) [39].

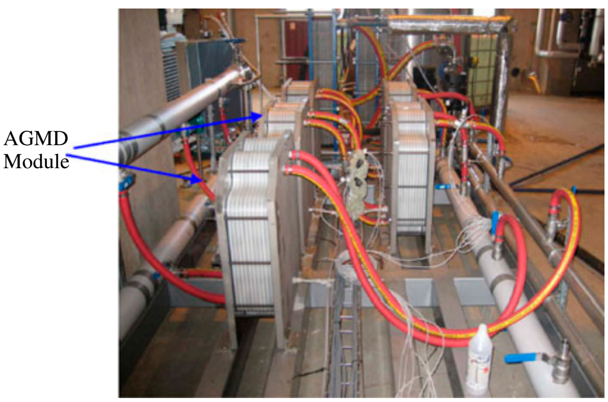

Fig. 17. The five-module Scarab AB system installed at Idbäcken Cogeneration Facility (Nyköping) in Sweden.

4.1.2. Multimodule two-loop systems

The two-loop system is designed for larger capacities (>1 m^3/d). In that case the heat supply, which can be solar thermal collector field or a waste source (e.g. combined heat and power cycle), is connected to the desalination loop by heat exchanger. The desalination systems consist of several MD modules (depending on capacity) connected in parallel. In case of a solar thermal power supply, the system is equipped with heat storage in order to extend the time of operation up to 24 h/d. The heat storage also enables the operation of the MD unit on a fixed set of operation parameters (evaporator inlet temperature and feed volume flow) where the MD unit is designed for [29].

Fraunhofer ISE and solar spring have also developed solar and waste heat-driven multimodule MD systems. The maximum capacity of installed pilot plants is about 5 m^3/d. From a technical point of view, the configuration of parallel connected spiral-wound modules makes sense for capacities of 0.2 to about 50 m^3/d. In the EU FP7 project, MEDIRAS two-loop systems were designed and installed in Pantelleria (Italy) and Gran Canary (Spain) between 2010 and 2011. Another two-loop system was installed in the frame of the BMBF-funded project Cuve Waters in the north of Namibia in 2010. Figs. 9–11 and Table 3 provides general characteristics of some constructed multimodule two-loop units.

4.2. Memstill

The Memstill technology started development by the research and technology organization TNO (the Netherlands Organization for Applied Scientific Research) and emerged around 2006. Memstill system is composed of an AGMD module, in which a cold saline water flows through a condenser with nonpermeable walls, increasing its temperature due to the condensing permeate and then passes through a heat exchanger where additional heat is added before entering in direct contact with the membrane as shown in Figs. 12 and 13.

The Memstill technology reveals important advantages in comparison with conventional desalination techniques such as MSF and MED, comprising:

(1) Low-energy consumption.
(2) Simple construction based on prefabricated modules.
(3) Lower total cost price.
(4) Potential of very high salt separation factors.
(5) Limited corrosion and easy maintenance.
(6) Small footprint.

Some information about the constructed plants using different generations of Memstill modules were reported in Table 4 [32–35].

4.3. Aquastill

Aquastill was founded in 2008 after a period of five years of R&D and is now one of the few companies in the world who apply MD on a commercial scale. Aquastill constantly develops larger and more efficient modules. The current baseline is set around the single largest 24 m^2 AGMD module in the world. Aquastill can provide modules with a membrane surface area of 1–120 m^2. Aquastill is presenting a MD pilot with a production capacity of 10 m^3/d of fresh drinking water. This new development is the cutting edge of renewable technologies which will be the beginning of the new standard in desalination of

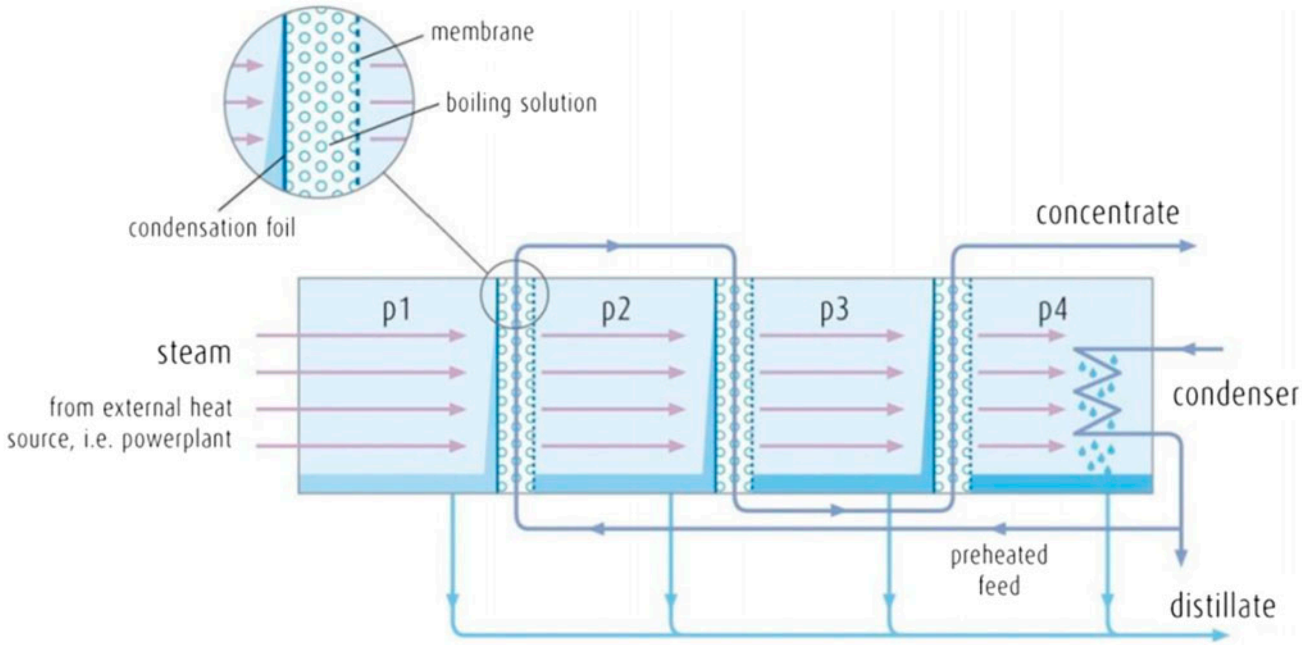

Fig. 18. Basic principles of memsys V-ME-MD [40].

tomorrow. This pilot can be used in either liquid gap membrane distillation (LGMD) or AGMD. The MD modules are in spiral-wound configuration as shown in Fig. 14.

The Aquastill pilot unit of MD using spiral-wound module installed at the Plataforma Solar de Almería (SE Spain) is depicted in Fig. 15 [36].

4.4. Scarab (AGMD)

The Sweden company, Scarab Development AB founded in 1973, developed the heat recovery AGMD module with a plate and frame design [37]. The AGMD Scarab AB system with heat recovery design has been tested in different desalination projects worldwide. In 2011, the MD subsystem of MEDESOL prototype installed at the Plataforma Solar de Almería (CIEMAT) is depicted in Fig. 16. The main components are three MD units manufactured by SCARAB. They are connected to an existing solar field based on compound parabolic concentrators (CPC). In the same year, results were reported utilizing five Scarab AB modules producing 1–2 m^3/d, trialed on a cogeneration facility in Sweden (collecting the exhausted heat from power generation to send to district heating) [38]. The interesting feature of this work was the long-term treatment of municipal water and flue gas condensate. The modules used in this trial, shown in Fig. 17, consists of 10 plastic cassettes each, with a total membrane area of 2.3 m^2. The cassettes are injected molded plastic frames that contain two parallel flat-sheet membranes, feed and exit channels for the hot water and two condensing walls. The channels for the cooling water are formed between the condensing walls of adjacent cassettes by stacking them together; as a result varying module sizes can be assembled. The membrane itself is made of spun-bounded PTFE (polytetrafluoroethylene) with a porosity of 80%, 0.2 mm of thickness, an average pore size of 0.2 m and an air gap width of 1 mm. The module's dimensions are 63 cm width, 73 cm high with a stack thickness of 17.5 cm.

The most recent developments utilizing the Scarab AB system include the installation of a 10-module facility at Hammarby Sjöstadsverket in Stockholm featuring the removal of pharmaceutical residues from treated wastewater.

4.5. Memsys

In recent years, a further MD enhancement was developed and produced by MEMSYS. The latter is a technology company based in Singapore and Germany providing highly effective thermal process modules for different applications of thermal separation. MEMSYS invented vacuum multieffect membrane distillation (V-MED), an MD device based on a multieffect desalination process under vacuum (Fig. 18).

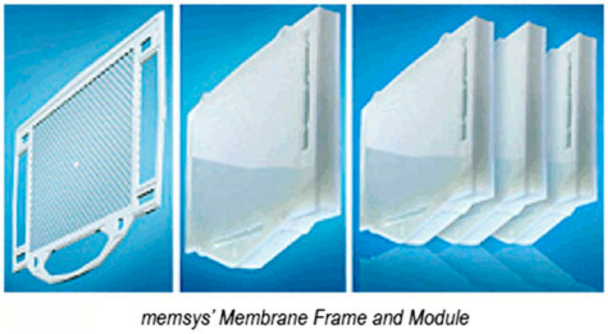

Fig. 19. Memsys's membrane frame and module [40].

PTFE membranes are attached to injection-molded frames (34 × 48 cm) that are illustrated in Fig. 19. Multiple frames are welded to form cassettes in parallel connection in order to adjust the surface area (0.31–2.5 m^2 per cassette) [40]. One integrated module stack consists of multiple cassettes of different functionality including a steam raiser, 4–10 effects and a final condenser. Due to the similarity of the conceptual design to the conventional MED process, the concept is denoted as V-MEMD. Vacuum is applied to the module stages. Temperature and pressure reduce successively from stage to stage during operation. The module's internal latent heat recovery system offers a GOR from 2.5 to 6.0, depending on the number of stages. The active membrane area varies from 6 to 40 m^2, respectively [40].

5. Conclusions

The desalination of saline water has become a sustainable and a reliable source of fresh water and is contributing to tackling the world's water shortage problems. According to previous studies on desalination systems, the MD process appears to be the best method of water desalination with solar energy for the following key advantages of MD processes over conventional separation technologies such as relatively lower energy costs as compared to distillation and reverse osmosis; a considerable rejection of dissolved, nonvolatile species; much lower membrane fouling as compared with microfiltration, ultrafiltration, and reverse osmosis; reduced vapor space as compared to conventional distillation; lower operating pressure than pressure-driven membrane processes and lower operating temperature as compared with conventional evaporation. Although MD has been known for more than 40 years, a number of problems exist when MD is considered for industrial implementation. Most of the conducted MD studies are still in the laboratory scale.

This paper has reviewed a number of autonomous solar MD systems developed during recent decades. The advantages and disadvantages for each membrane configuration has also been covered. In recent years, there have been considerable developments in membrane desalination processes, especially in terms of the design of membrane module, energy recovery, and pretreatment methods that have made it cost competitive with thermal processes. This review will provide an overview of MD processes with focus on recent developments and applications of this technology.

Acknowledgements

The authors wish to thank the Ministry of Higher Education, Scientific Research and Information and Communication Technologies MESRS-TIC for its financial support to the R&D project entitled "Solar Driven membrane distillation for resource efficient desalination in remote areas", and the Fraunhofer Institute for Solar Energy Systems ISE for its collaboration.

References

[1] S. Jeong, S. Lee, H. Chon, S. Lee, Structural analysis and modeling of the commercial high performance composite flat sheet membranes for membrane distillation application, Desalination 349 (2014) 115–125.
[2] S. Lin, N.Y. Yip, M. Elimelech, Direct contact membrane distillation with heat recovery: Thermodynamic insights from module scale modeling, J. Membr. Sci. 453 (2014) 498–515.
[3] Y.M. Manawi, M. Khraisheh, A. Kayvani Fard, F. Benyahia, S. Adham, Effect of operational parameters on distillate flux in direct contact membrane distillation (DCMD): Comparison between experimental and model predicted performance, Desalination 336 (2014) 110–120.
[4] J. Zhang, S. Gray, J.D. Li, Modelling heat and mass transfers in DCMD using compressible membranes, J. Membr. Sci. 387–388 (2012) 7–16.
[5] A. Kayvani Fard, Y.M. Manawi, T. Rhadfi, K. Mahmoud, M. Khraisheh, F. Benyahia, Synoptic analysis of direct contact membrane distillation performance in Qatar: A case study, Desalination 360 (2015) 97–107.
[6] C.D. Ho, C.H. Huang, F.C. Tsai, W.T. Chen, Performance improvement on distillate flux of countercurrent-flow direct contact membrane distillation systems, Desalination 338 (2014) 26–32.
[7] S.Gh. Lovineh, M. Asghari, B. Rajaei, Numerical simulation and theoretical study on simultaneous effects of operating parameters in vacuum membrane distillation, Desalination 314 (2013) 59–66.
[8] D. Winter, J. Koschikowski, M. Wieghaus, Desalination using membrane distillation: Experimental studies on full scale spiral wound modules, J. Membr. Sci. 375 (2011) 104–112.

[9] R.G. Raluy, R. Schwantes, V.J. Subiela, B. Peñate, G. Melián, J.R. Betancort, Operational experience of a solar membrane distillation demonstration plant in Pozo Izquierdo-Gran Canaria Island (Spain), Desalination 290 (2012) 1–13.
[10] G. Meindersma, C. Guijt, A. de Haan, Water recycling and desalination by air gap membrane distillation, Environ. Prog. 24(4) (2005) 434–441.
[11] B. Pangarker, M. Sane, Performance of air gap membrane distillation for desalination of ground water and seawater, World Acad. Sci. Eng. Technol. 51 (2011) 972–976.
[12] A.M. Alklaibi, N. Lior, Transport analysis of air gap membrane distillation, J. Membr. Sci. 255 (2005) 239–253.
[13] M. Khayet, C. Cojocaru, A. Baroudi, Modeling and optimization of sweeping gas membrane distillation, Desalination 287 (2012) 159–166.
[14] M.C. García-Payo, C.A. Rivier, I.W. Marison, U. von Stockar, Separation of binary mixtures by thermostatic sweeping gas membrane distillation: II. Experimental results with aqueous formic acid solutions, J. Membr. Sci. 198 (2002) 197–210.
[15] C.A. Rivier, M.C. Garcia-Payo, I.W. Marison, U. von Stockar, Separation of binary mixtures by thermostatic sweeping gas membrane distillation: I. Theory and simulations, J. Membr. Sci. 201 (2002) 1–16.
[16] A.C. Sun, W. Kosar, Y. Zhang, X. Feng, Vacuum membrane distillation for desalination of water using hollow fiber membranes, J. Membr. Sci. 455 (2014) 131–142.
[17] A. Rom, W. Wukovits, F. Anton, Development of a vacuum membrane distillation unit operation: From experimental data to a simulation model, Chem. Eng. Process. Process Intensif. 86 (2014) 90–95.
[18] W. Kujawski, A. Sobolewska, K. Jarzynka, C. Güell, M. Ferrando, J. Warczok, Application of osmotic membrane distillation process in red grape juice concentration, J. Food Eng. 116 (2013) 801–808.
[19] L. Wang, J. Min, Modeling and analyses of membrane osmotic distillation using non-equilibrium thermodynamics, J. Membr. Sci. 378 (2011) 462–470.
[20] B.R. Babu, N. Rastogi, K. Raghavarao, Concentration and temperature polarization effects during osmotic membrane distillation, J. Membr. Sci. 322 (2008) 146–153.
[21] T. Melin, R. Rautenbach, Membranverfahren—Grundlagen der Modul- und Anlagenauslegung (Membrane processes. Basics of module and system design), 3. Auflage, Springer, 2007.
[22] J. Koschikowski, M. Wieghaus, M. Rommel, V.S. Ortin, B.P. Suarez, J.R. Betancort Rodríguez, Experimental investigations on solar driven stand-alone membrane distillation systems for remote areas, Desalination 248 (2009) 125–131.
[23] Available from: <http://www.mediras.eu/index.php@id=116.html>. [accessed on 4 October 2015].
[24] H.E.S. Fath, S.M. Elsherbiny, A.A. Hassan, M. Rommel, M. Wieghaus, J. Koschikowski, M. Vatansever, PV and thermally driven small scale, stand-alone solar desalination systems with very low maintenance needs, Desalination 225 (2008) 58–69.
[25] F. Banat, N. Jwaied, M. Rommel, J. Koschikowski, M. Wieghaus, Desalination by a "compact SMADES" autonomous solarpowered membrane distillation unit, Desalination 217 (2007) 29–37.
[26] J. Koschikowski, M. Wieghaus, M. Rommel, Solar thermal- driven desalination plants based on membrane distillation, Desalination 156 (2003) 295–304.
[27] X. Wang, L. Zhang, H. Yang, H. Chen, Feasibility research of potable water production via solar-heated hollow fiber membrane distillation system, Desalination 247 (2009) 403–411.
[28] Y. Wang, Z. Xu, N. Lior, H. Zeng, An experimental study of solar thermal vacuum membrane distillation desalination, Desalin. Water Treat. 53(4) (2015) 887–897.
[29] R. Schwantes, A. Cipollina, F. Gross, J. Koschikowski, D. Pfeifle, M. Rolletschek, V. Subiela, Membrane distillation: Solar and waste heat driven demonstration plants for desalination, Desalination 323 (2013) 93–106.
[30] E. Guillén-Burrieza, G. Zaragoza, S. Miralles-Cuevas, J. Blanco, Experimental evaluation of two pilot-scale membrane distillation modules used for solar desalination, J. Membr. Sci. 409–410 (2012) 264–275.
[31] F. Banat, N. Jwaied, M. Rommel, J. Koschikowski, M. Wieghaus, Performance evaluation of the "large SMADES" autonomous desalination solar-driven membrane distillation plant in Aqaba, Jordan, Desalination 217 (2007) 17–28.
[32] P. Nijskens, B. Cools, B. Kregersman, Seawater desalination with Memstill technology—A sustainable solution for the industry, International Workshop on Membrane Distillation and Related Technologies, Ravello (SA) Italy, 9–12 October 2011.
[33] J.H. Haanemaaijer, J.W. Heuvelen. Method for the Purification of a Liquid by Membrane Distillation, in Particular for the Production of Desalinated Water from Seawater or Process Water, WIPO WO2000/72947, published 7 December 2000.
[34] J.H. Hanemaaijer, J.V. Medevoort, A.E. Jansen, C. Dotremont, E.V. Sonsbeek, T. Yuan, L.D. Ryck, Memstill membrane distillation—A future desalination technology, Desalination 199(1–3) (2006) 175–176.
[35] J.H. Hanemaaijer, A.E. Jansen, J.V. Medevoort, H.D. Jong, E.V. Sonsbeek, E. Koele, Membrane Distillation Method for the Purification of a Liquid, WIPO WO2008/054207, published 08 May 2008.
[36] A. Ruiz-Aguirre, D.C. Alarco´n-Padilla, G. Zaragoza, Productivity analysis of two spiral-wound membrane distillation prototypes coupled with solar energy, Desalin. Water Treat. 55(10) (2015) 2777–2785.
[37] A.M. Islam, Membrane Distillation Process for Pure Water and Removal of Arsenic, Department of Materials and Surface Chemistry, Chalmers University of Technology, Sweden, 35.
[38] A. Kullab, A. Martin, Membrane distillation and applications for water purification in thermal cogeneration plants, Sep. Purif. Technol. 76 (2011) 231–237.
[39] E.G. Burrieza, J. Blanco, G. Zaragoza, D.C. Alarcón, P. Palenzuela, M. Ibarra, W. Gernjak, Experimental analysis of an air gap membrane distillation solar desalination pilot system, J. Membr. Sci. 379 (2011) 386–396.
[40] [online] Homepage memsys clearwater Pte. Ltd. Available from: <http://www.memsys.eu/products.html>. Access in 18 February 2014.