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5th Water Arabia Conference

Air gap membrane distillation: its trends in desalination process

Dr Habis AlZoubi

Department of Environmental Engineering
Imam Abdulrahman Bin Faisal University, Dammam

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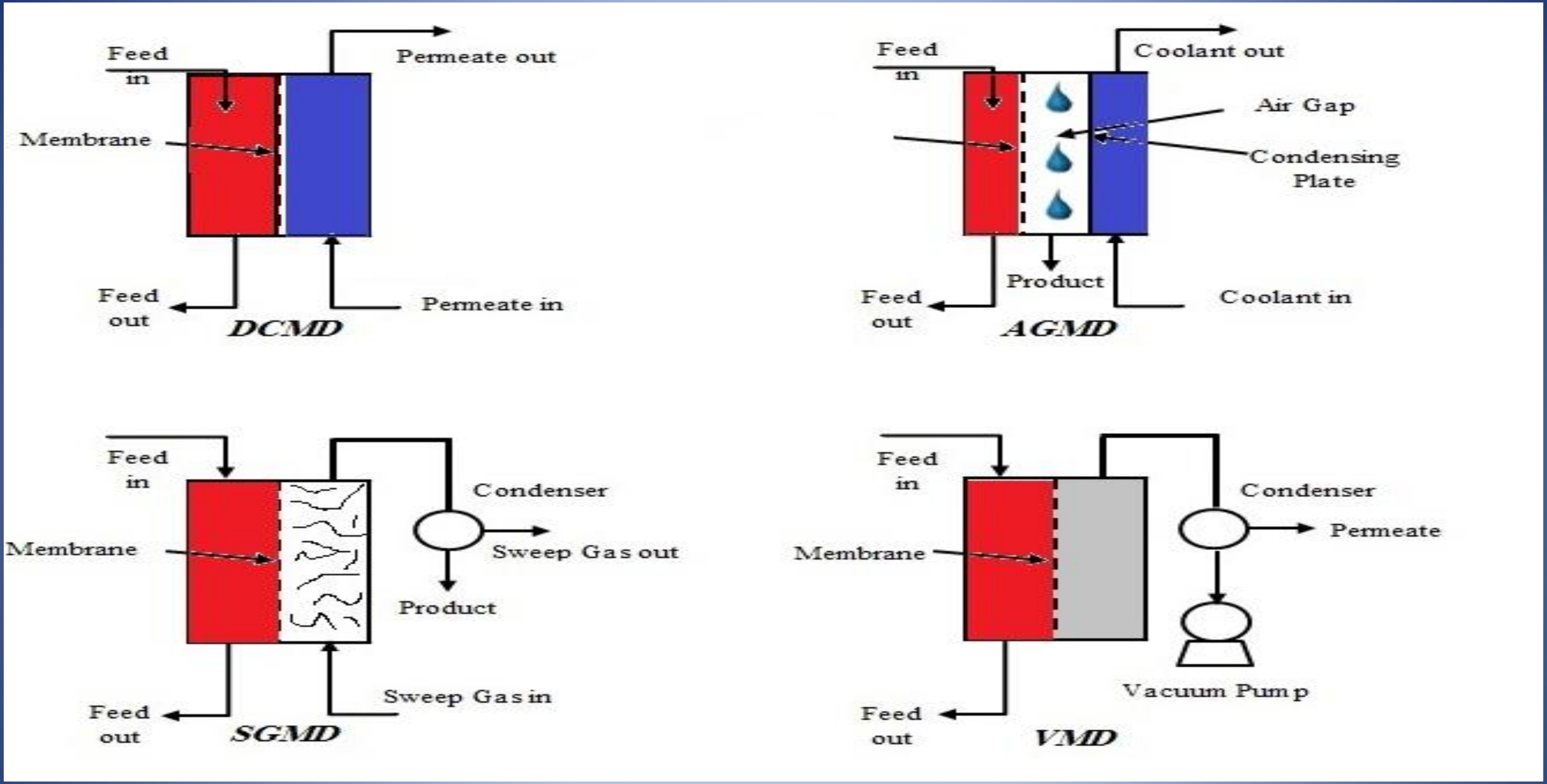
Introduction

- Membrane distillation (MD) is a thermally driven membrane separation process, in which only vapor molecules are transported through hydrophobic membranes.
- The driving force for the process is the trans-membrane vapor pressure difference.
- MD process has many advantages:

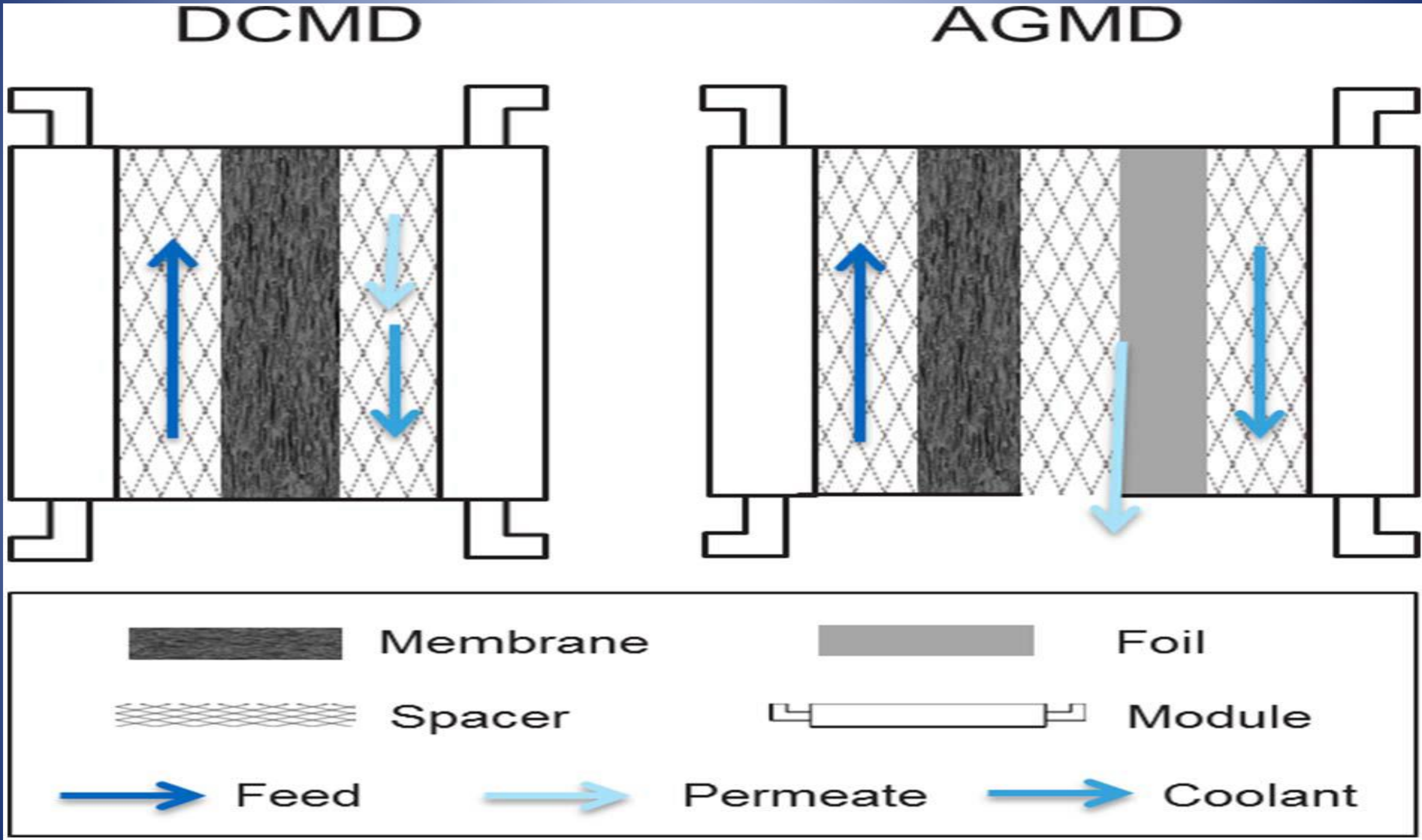
1. low operating temperature and hydraulic pressure
2. high rejection of solutes
3. performance independent of high osmotic pressure
4. less-sensitive to feed concentration for seawater desalination
5. less requirements on membrane mechanical properties and potentially good permeate flux

MD configurations



Direct contact membrane distillation (DCMD)
Air gap membrane distillation (AGMD)
Sweeping gas membrane distillation (SGMD)
Vacuum membrane distillation (VMD)

AGMD .vs. DCMD



Desalination 422 (2017) 91–100

AGMD process

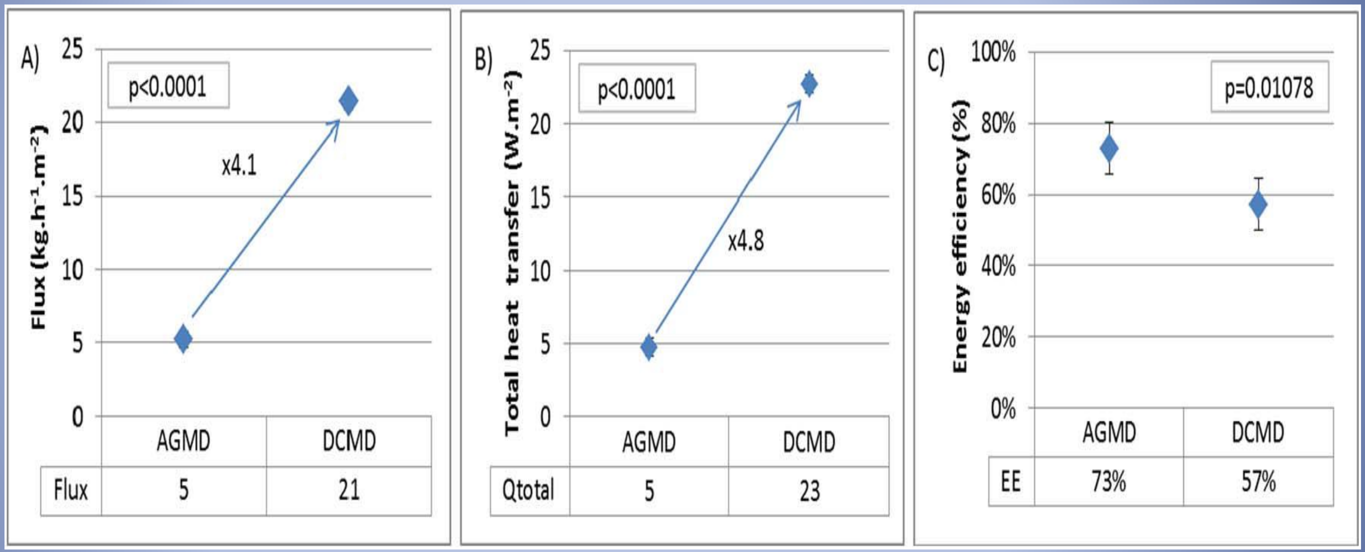
- a thin air gap is interposed between the membrane cold surface and a condensation surface. The evaporated volatile molecules pass through both the membrane and the air gap, and then condense on the cold surface.

- The main benefits of the air gap are:

1. Using any coolant as it does not mix with the condensate as for the case in DCMD.
2. AGMD has high thermal efficiency due to air insulation between the heated feed stream and the coolant stream
3. AGMD can deal easily with membrane leakage and in case of membrane damage, in which the MD process can be stopped for a while and the distillate does not have the chance to get contaminated like that in DCMD

Main AGMD drawback

AGMD still suffers from producing low flux compared to DCMD.

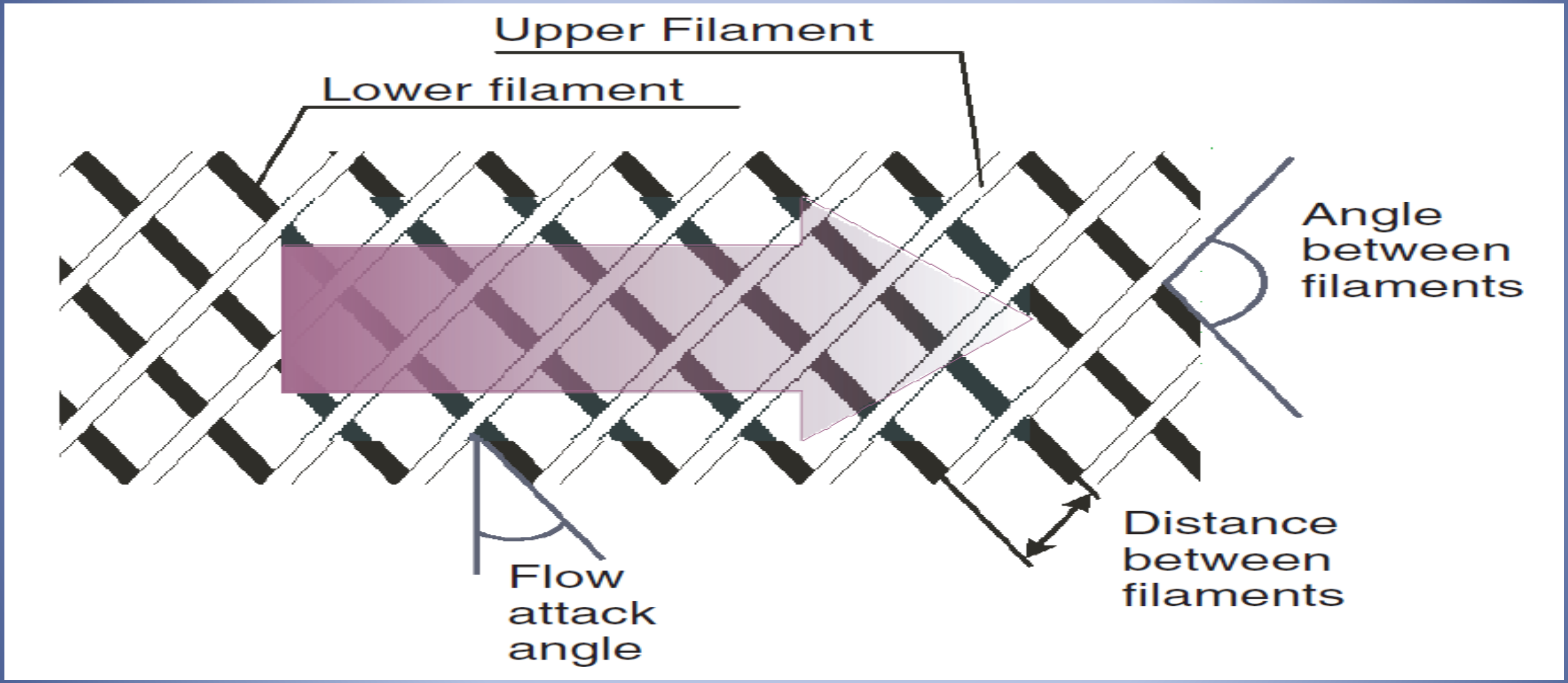


Desalination 422 (2017) 91–100

Therefore, many studies interested to overcome this problem by modifying AGMD configuration.

Modified AGMD configuration

1- spacers inside the feed chamber



The results showed that the maximum flux with spacers was about 2.5 times higher, compared to an empty channel.

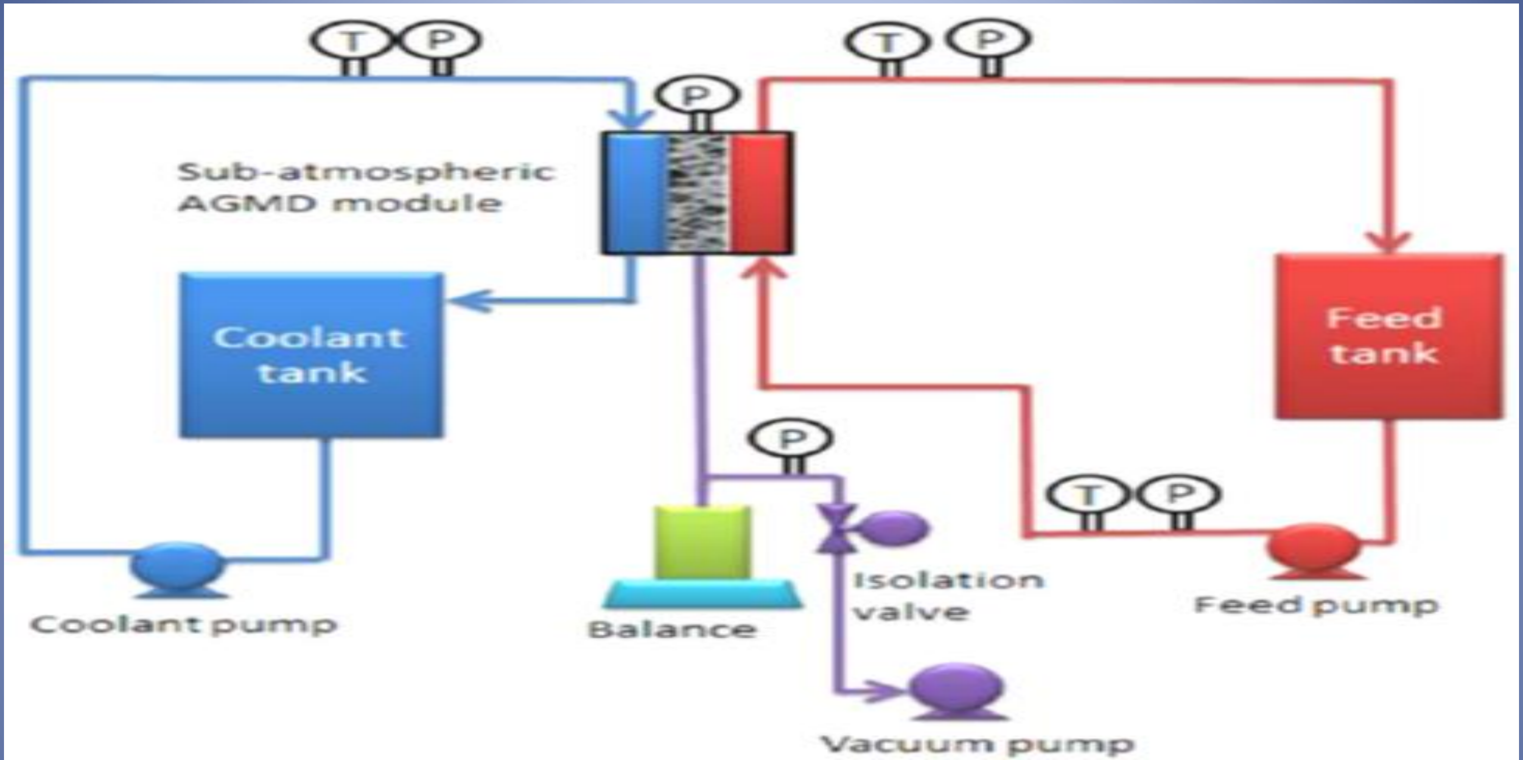
" *Desalination,* vol. 183, no. 1-3, pp. 363-374, 2005.

2- channeled coolant plate consisted of different types of fins over the condensation plate

The flux enhanced maximum up to 50% compared to a flat coolant plate.

Desalination, 359, 71-81, 2015.

3 -An integrated vacuum system with AGMD



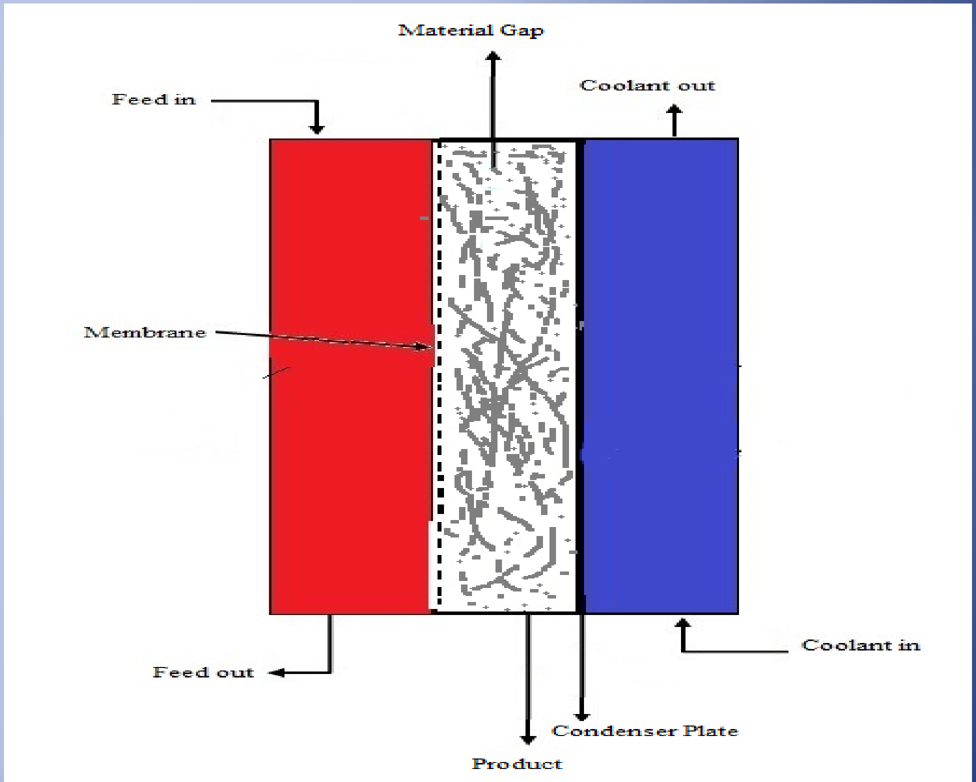
The Flux of V-AGMD module is measured to be 3 times the flux of single stage AGMD

Journal of Membrane Science, 489, 73-80, 2015

4-Material gap membrane distillation to fill the gap between the membrane and the condensation. The proposed materials were DI water, Sand, polypropylene, and sponge (polyurethane).

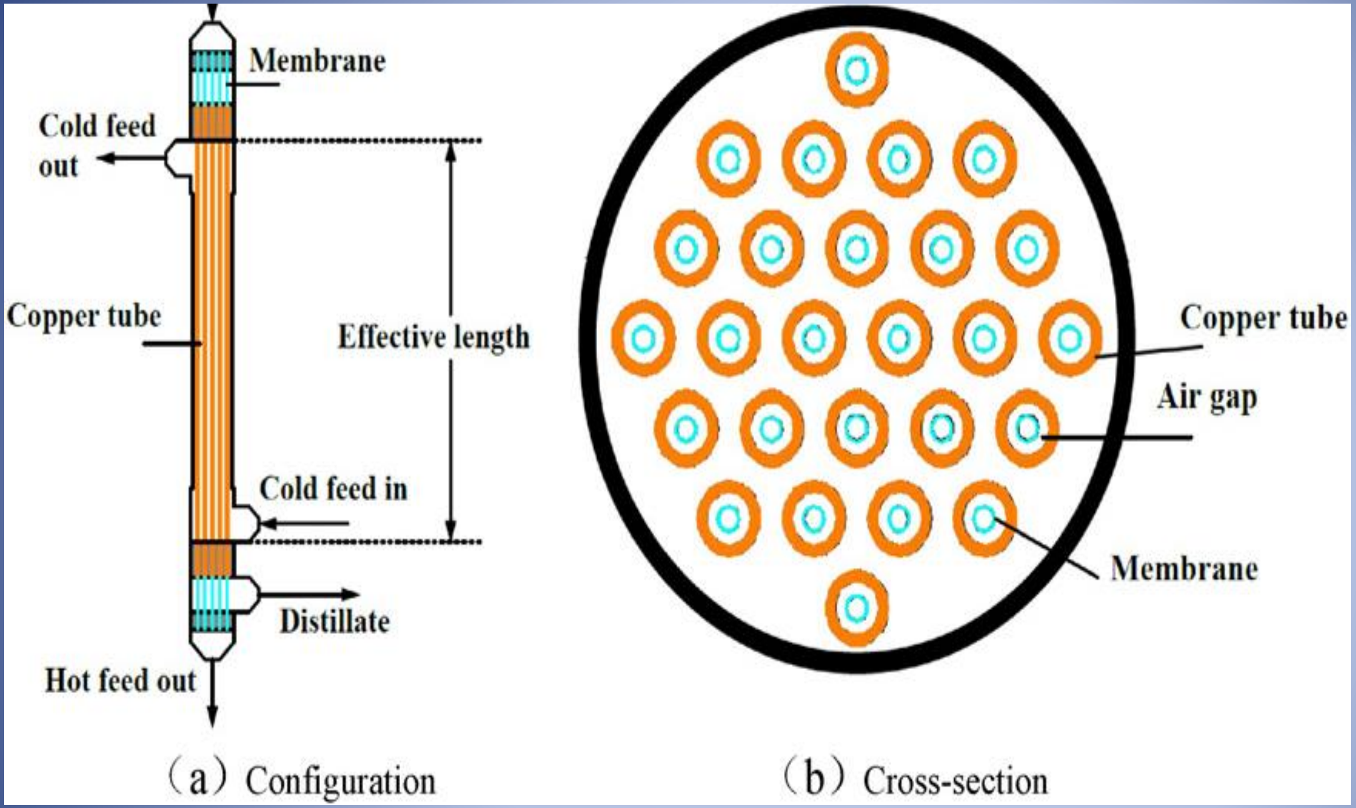
-very high flux was obtained in the range of 200–800% by filling the gap with sand and DI water

- No effect for polypropylene and polyurethane



Journal of Membrane Science, 448, 240-247, 2013.

5- double-pipe AGMD module (DP-AGMD-M)



The Flux of DP-AGMD is measured to be 3 times the flux of single stage AGMD

Desalination, 396, 48-56, 2016.

6- coating condensing surface with a nano-structured copper oxide.

It was found that there were improvements in flux in excess of 60% over original AGMD

Journal of Membrane Science, 492, pp. 578-587, 2015.

7- multi-effect air gap membrane distillation process (ME-AGMD).

The Flux of ME-AGMD module is measured to be 3.5 times the flux of single stage AGMD.

Journal of Environmental Chemical Engineering, 3, no. 3, 2127-2135, 2015.

8- multistage AGMD (MS-AGMD) with parallel and series flow stage connections for the feed stream and coolant stream.

The Flux of MS-AGMD is measured to be 2.6 and 3 times the flux of single stage AGMD.

Desalination, 417, pp. 69-76, 2017

Membranes in AGMD

- The most popular polymers used in MD membranes are:

1. polytetrafluoroethylene (PTFE)
2. polypropylene (PP)
3. and polyvinylidene fluoride (PVDF)

- Both Ceramic and Glass membranes have rarely used in AGMD process

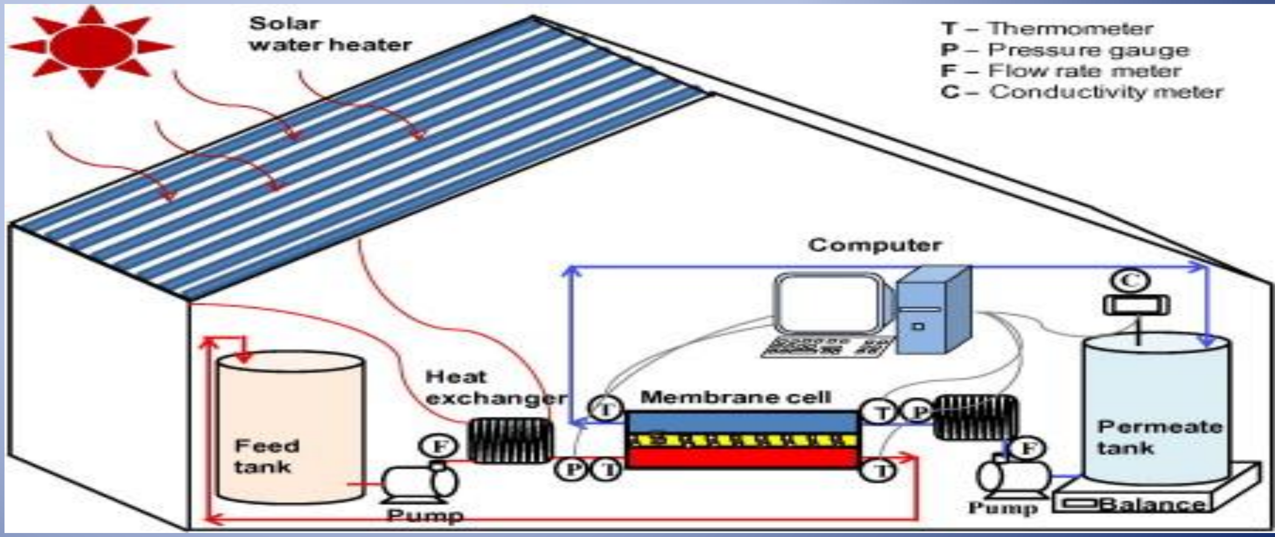
Modified membrane for AGMD

Modified Membrane Type	Thickness (µm)	Pore size (µm)	Feed Solution With its observations	Flux kg/m².h
PVDF/LiCl/DMA 8/3/89	-*	0.35	1-2% aqueous NaCl solution, T_f = 59.85 °C, T_p = 19.85 °C	23.4
G/PVDF-HFP	100	0.86	3.5 wt% NaCl, T_f = 60 °C, T_p = 20 °C Salt rejection 99.99%	22.9
G/PVDF-0.5	88	0.11	RO brine from CSG produced water, salt rejection 99.99%, T_f = 60 ±1.5 °C, T_p = 20 ±1.5 °C	20.5
iPP (M-1)	67.2	0.25	6 wt% NaCl	6.6
Dual-layer nonwoven nanofiber membranes PH/PAN, N6; or PVA	92.7	0.18	3.5 wt% NaCl, T_f = 60 °C, T_p = 20 °C	15.5
Clay–alumina	-	1.43	solution, salt rejection 99.96%, temperature difference 60°C	4.1
FAS grafted ceramic membranes	-	0.05 and 0.2	NaCl, T_f = 90 °C, T_p = 5 °C, salt rejection close to 100%	6.7
Electro-spun PVDF membranes	-	0.2	1 wt% NaCl, temperature difference 60 °C	12.0
Polyvinylidene fluoride	-	0.1	1 g/l NaCl, T_f = 60 °C	13.0
Triple layer membrane: Layer1: PET support Layer2: PVDF casted Layer3: PVDF nanofiber	175	0.1	3.5 wt% NaCl, T_f = 80 °C	15.2

Grafted ceramic membranes: **Z1** **Z2** **A1**	-	0.05 0.2 0.2	NaCl molarity is 0.1 M, T_p = 5 °C, T_f (Z2 and A1)= 95 °C , T_f (Z1) = 90 °C	3.97 8.43 6.8
Grafted ceramic membranes using Tunisian clay	-	0.18 µm	NaCl molarity is 1 M, T_f= 95 °C, T_p= 5 °C Flow velocity= 2.6 m/s	6.5
Grafted ceramic membranes using Tunisian olive oil molecules.	9 µm	11 nm	99% salt rejection	7.0
Modified ceramic membranes using Zr, Al and AlSi	-	0.05	1 mol/L NaCl, ΔT = 70 °C	4.6
Modified ceramic membranes using: **Zr50** **Ti5**	-	0.05 0.005	0.5 M NaCl solution, T_f = 95 °C	4.7 0.83
Modified nanospiked glass membrane	500	4	5 wt% NaCl, T_f = 95 °C	11.1
Plazma coating using Perflourohexane (PFB) and Hexafluorobenzene (HFB) on PET	-	<0.3	Juice	4.0
Surface modifying macromolecules on PEI	64.7	0.027	30 g/L NaCl, T_f = 60°C, Tp=20°C, salt rejection 99.94%	5.4
Modified PVDF by electrospinning and CF4 plasma	150	0.81	RO brine, salt rejection 100%, T_f = 60 ±1.5 °C, T_p = 20 ±1.5 °C	15.3

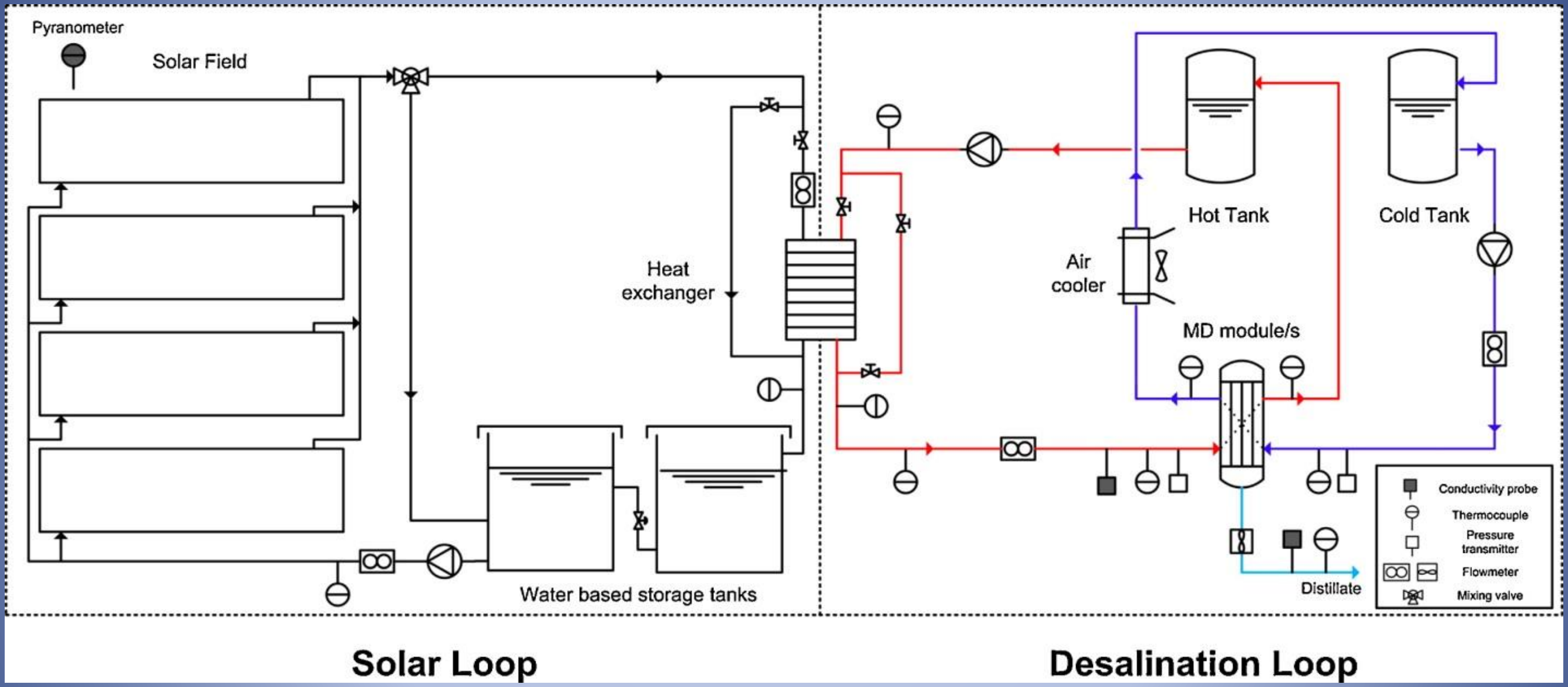
Integration of AGMD with renewable energy for desalination

- Utilization of solar thermal energy for the solar MD desalination system (SMDDS) comes out to be the green technology for solving the water resources problem and energy cost.
- The components of a SMDDS system are a solar collector, heat storage tank, heat exchanger, and MD module.



*Separation and Purification Technology,*143, 94-104, 2015

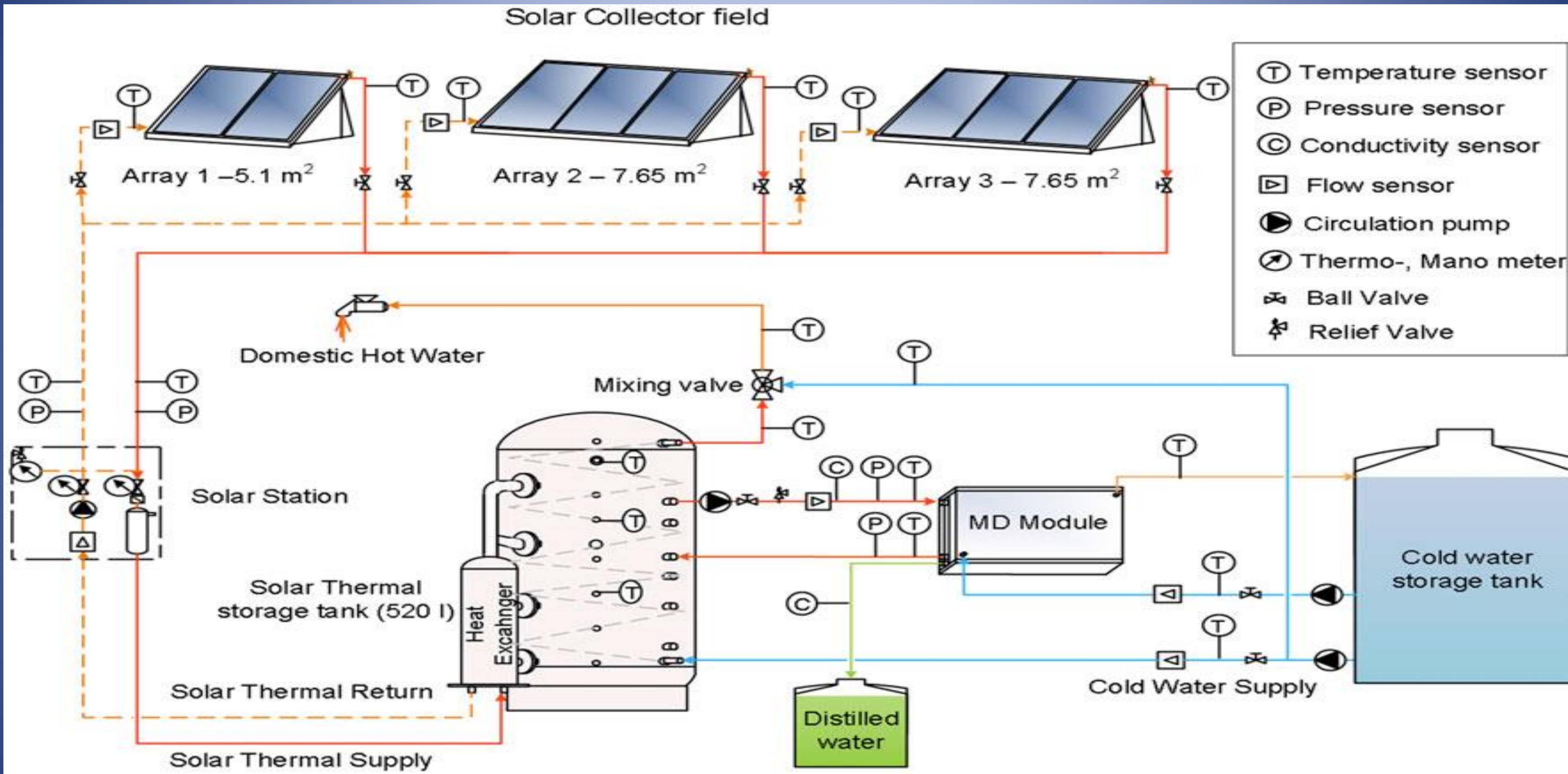
solar powered AGMD modules



The obtained Flux values was 7 Kg/h m^2

Journal of Membrane Science, 379, 1-2, 386-396, 2011

integration of solar domestic hot water (SDHW) and MD symbolic as SDHW-MD

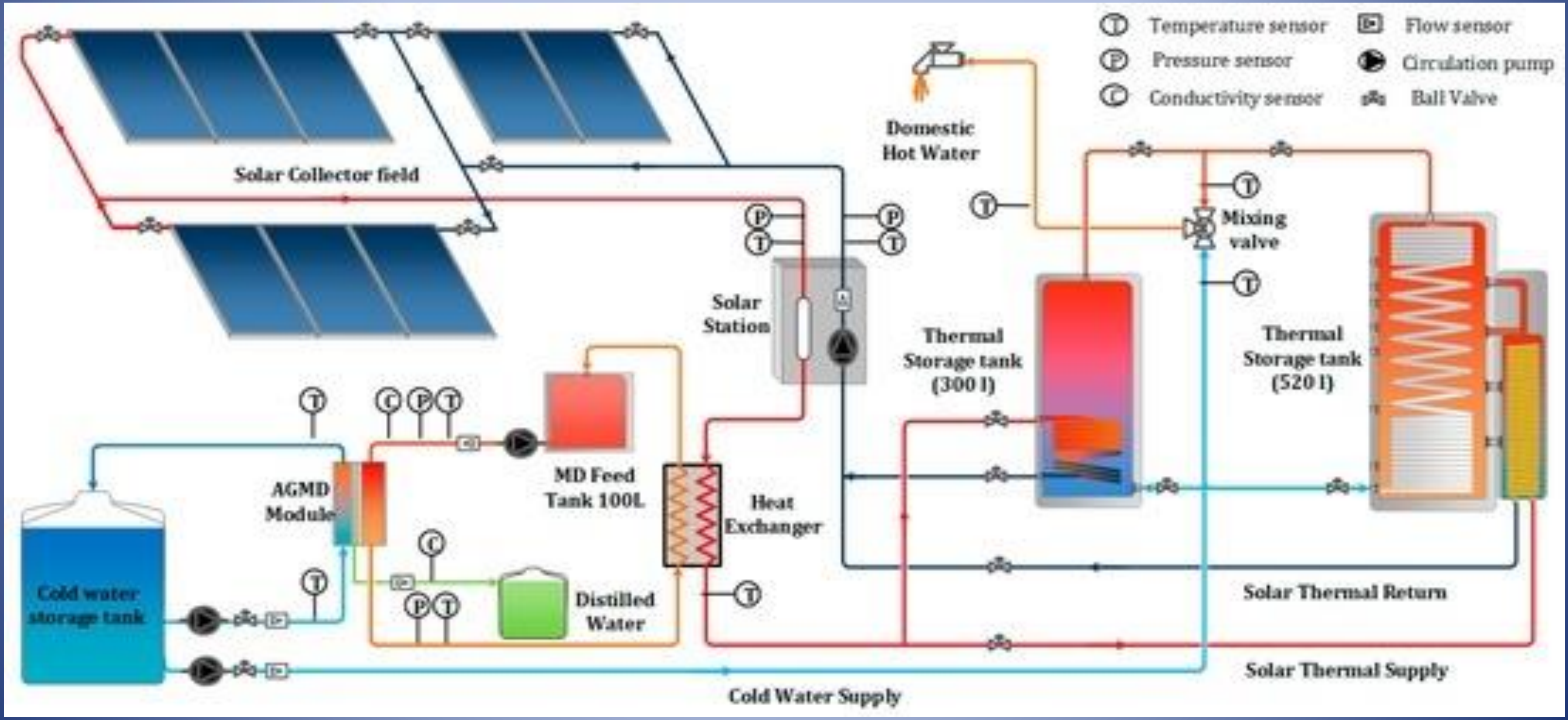


The demand of 15–25 L/d of pure drinking water and 250 L/d of domestic hot water.

Desalination and Water Treatment, 57, no. 46, 21674-21684, 2016.

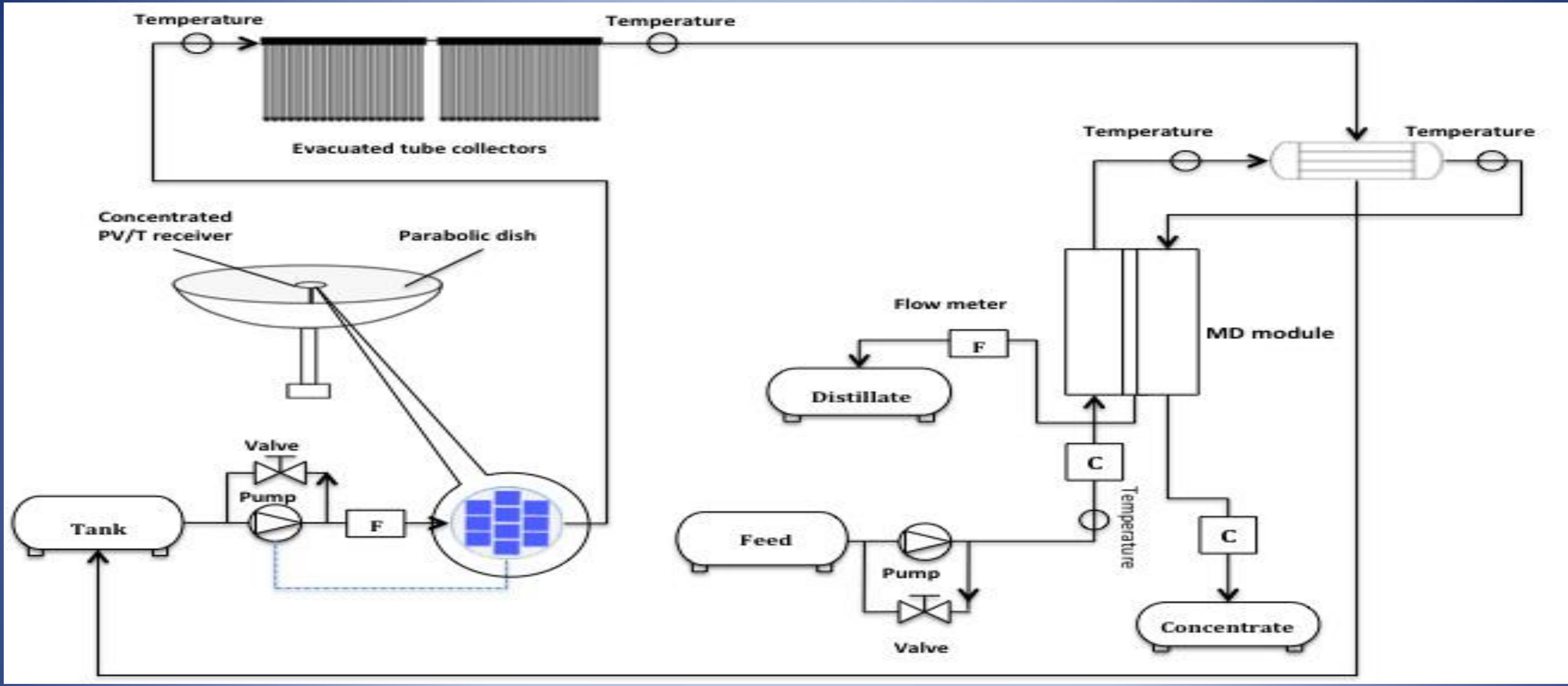
Integrated solar and AGMD
Direct Solar Combined MD (SCMD)

This system experimentally tested for single household application for production 20 L/day of pure water (< 10 µS/cm) and 250 L/day of hot water simultaneously without any auxiliary heating device



Energies, vol. 10, no. 4, 2017.

integration of evacuated tube and concentrated photovoltaic/thermal (CPV/T) solar collectors with AGMD

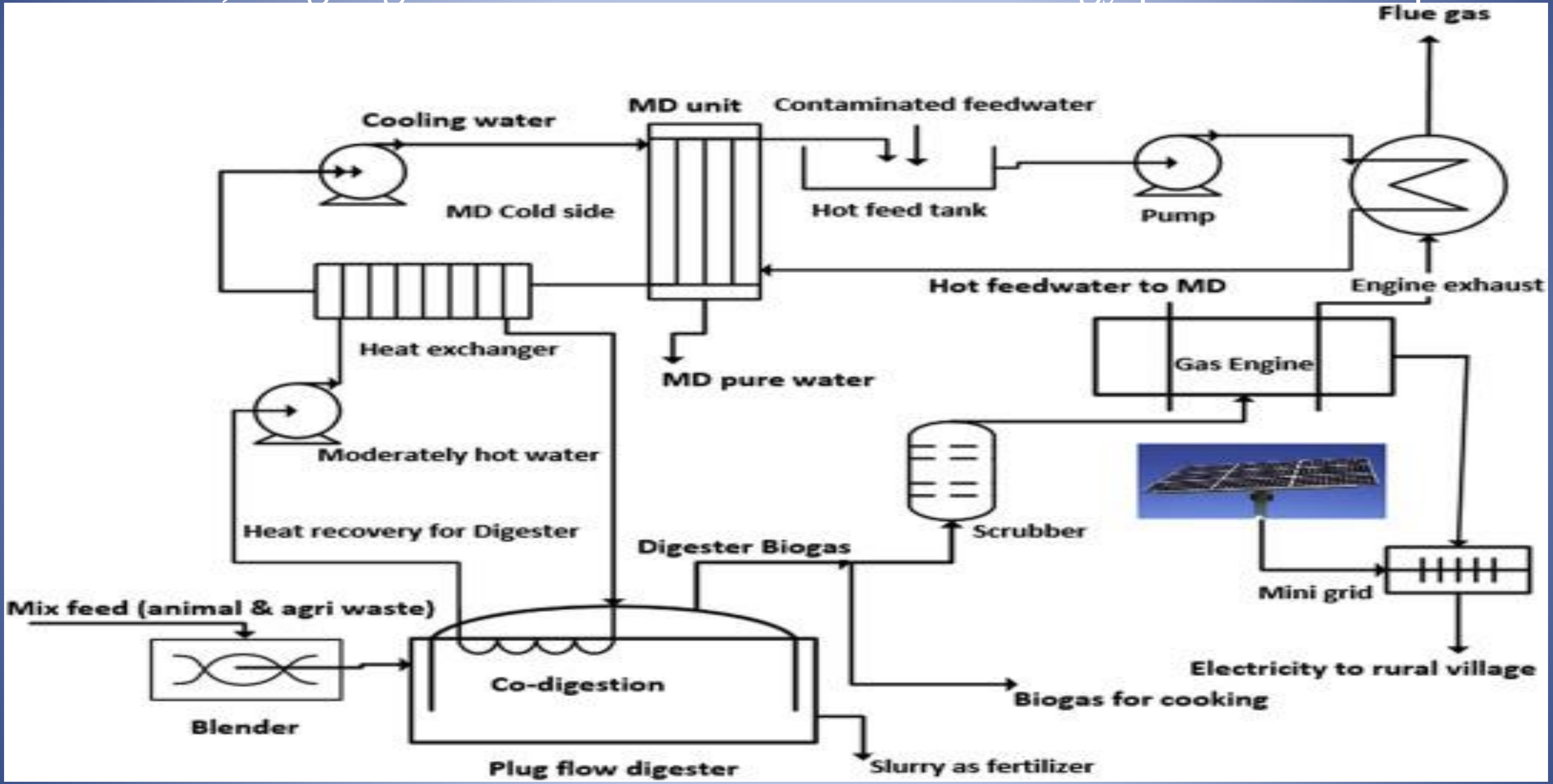


This integration provides two types of energy; (1) a thermal energy which is required to drive the AGMD unit, and (2) an electrical energy which is required to power the pump and tracking devices. Flux of 3.4 Kg/m^2h and a conductivity of 35 µs/cm

International Conference on Advances in Energy Research, vol. 54, P. C. Ghosh, Ed. (Energy Procedia, Amsterdam: Elsevier Science Bv, 2014, pp. 725-733.

polygeneration AGMD pilot plan

It consists of biogas digester, solar panel, storage battery, inverter, charge controller, biogas generator and AGMD for clean energy provision and pure



Excess digester gas is employed for cooking and lighting, while waste heat from the process derived a AGMD unit for desalination

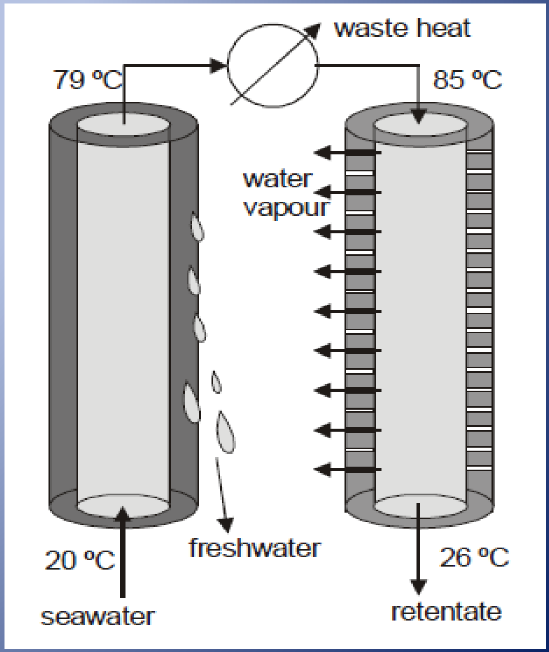
Energy, vol. 93, pp. 1116-1127, Dec 2015.

The Memstill® module

- It was developed by a scientific institution in the Netherlands, for desalination of seawater by AGMD carried out in a counter current flow configuration.
- cold seawater flows through a tubular condenser with non-permeable well-wettable walls via a heat exchanger into the membrane evaporator which consists of a microporous hydrophobic membrane through which water vapor can diffuse. The condenser and evaporator tubes are separated by an air gap.

It produced pure water with a flow rate of 100 m^3/day

Desalination, 187, no. 1-3, pp. 291-301, 2006.



Conclusions and Future remarks

- AGMD has high thermal efficiency due to air insulation between the heated feed stream and the coolant stream.
- AGMD provides the freedom of using any coolant fluid since the coolant does not mix with the condensate.
- AGMD can deal easily with membrane leakage and in case of membrane damage, and the distillate does not have the chance to get contaminated like that in DCMD.
- AGMD suffers from producing low flux compared to other MD configurations.
- Therefore, many studies were conducted to overcome this problem by modifying AGMD configuration, modifying and casting new membranes, and decreasing the required energy by using a renewable energy and energy recovery systems.

Conclusions and Future remarks, continue….

- More attention is given recently to the integration of AGMD with solar energy and poly-generation systems to provide electricity, potable water and domestic hot water from salty water in remote areas.
- It is expected that this integration will dominate the conventional desalination process in future.
- Further research is required in modification of this solar AGMD hybrid process to reduce the water production cost and the energy consumption by studying suitable modules, renewable energy systems, waste energy, hybrid systems and types of used membranes.
- In general, different scenarios and techniques is needed to enhance the permeate flux of AGMD at low cost of energy.

Acknowledgement

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Publication

- This work is based on paper titled:

A Comprehensive Review of Air Gap Membrane Distillation Process

Sent to journal of membrane science.