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Membrane Distillation and its Integration with Conventional Desalination Technologies

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Abstract: Desalination technologies suffer from two major limitations namely their low energy efficiency and the environmental impacts associated with brine discharge. Hybrid desalination seems to be a trend in the new plants offering several advantages including more flexibility and lower specific energy consumption. This work reviewsfirst a variety ofhybrid desalination configurations emphasizing on their advantages and limitations. A special focus was on membrane distillation (MD) process, an emerging hybrid thermal-membrane process for desalination and water treatment. Several studies on integrating MD with other conventional desalination technologies have been reviewed and commented. The work illustrates the capability of MD to be coupled with a large number of desalination processes. It highlights the capability of MD to be used as a complimentary process to one of the conventional technologies to further concentrate its discharged brines.It is believed that hybrid configurations with MD could solve several issues related to this process such as its low energy efficiency and its low recovery ratio.

Key words: Hybrid Desalination · Membrane distillation · Recovery ratio · Specific energy consumption

INTRODUCTION

Desalination of saline waters is the main source for supplying potable water to several countries worldwide. The total desalination capacity in those countries is expected to grow significantly during the next few years. New constructed and commissioned plants are either based on Reverse Osmosis (RO) technology or on hybrid thermal and RO processes. However, the specific energy consumption associated with these conventional desalination technologies which rely heavily on fossil fuels is still high. The energy consumed in modern desalination plants is estimated to be more than the third of total operating cost of desalinated water. Besides, it is estimated that average power-equivalent demand for all desalination worldwide is around 23 GWe [1]. Actual sea water Reverse Osmosis (RO) plants may consume approximately 3.5 kWh/m^3 as electrical energy [1]. This rate is much higher for major conventional thermal desalination plants namely the Multi-Stage Flash (MSF) and the Multiple Effect Distillation (MED) where in addition to the electrical energy required to drive electrical components such as various types of pumps, thermal energy can be as high as 78 and 64 kWh/m^3 respectively for MSF and MEDas shown in Table 1.

On the other side, energy use in desalination technologies results in major environmental impacts. The direct greenhouse gas (GHG) footprint for RO and MSF ranges between 2.1-3.6 and 10-20 kg of CO_2 per m^3 of fresh water [1]. In addition, Desalination technologies suffer from the negative environmental impacts associated with the concentrated brine discharged back to sea. In fact, large quantities of warmer and more concentrated brine are disposed to the nearby water environment. Missimer *et al*. [3] discussed the major environmental impacts of desalination. They focused specifically on concentrated brines discharged from sea water reverse osmosis (SWRO) desalination plants by addressing two important aspects namely the design of intakes and outfalls and the assessment and reduction of environmental impacts.

Therefore, hugeattention and efforts are being invested to reduce the aforementioned limitations of conventional desalination plants. The main directions of such efforts and attempts are to develop advanced components of the existing technologies such as developing new RO membranes, to integrate clean energy sources such as renewable and waste heat sources, to optimize hybrid desalination technologies and to develop new desalination techniques such as Forward Osmosis (FO), Capacitive Deionization (CDI) Membrane Distillation (MD) [1, 5].

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Table 1: Energy consumption of major conventional desalination technologies (adapted from[2])

Desalination technology	MSF	MED	RO
Method	Distillation	Distillation	Filtration
Specific thermal energy consumption (kWh/m^3)	52-78.3	40.3-63.9	0
Specific electrical energy consumption (kWh/m^3)	2.5-5	2-2.5	2.5-7

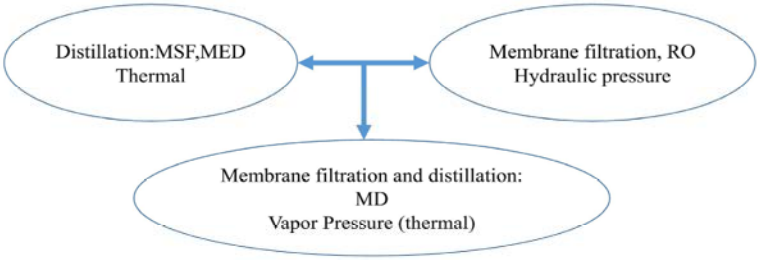

Fig. 1: Overview on the driving forces for the main desalination technologies in addition to MD (MSF: Multi stage flash, MED: Multiple effect distillation, RO: reverse osmosis)

Membrane Distillation (MD)

General description of MD

Membrane Distillation (MD) is anemerging and rapidly developing membrane technology for desalination and water treatment and several other applications. MD process can be considered as hybrid (thermal-membrane) process since it involves liquid vapor phase change and transport of water vapor through porous hydrophobic membranes. Membrane distillation differs from other thermal and membrane processes in that the driving force is the difference in vapor pressure of water caused by an existing temperature difference across the membrane rather than total pressure difference like for RO. Thus, vapor molecules are transported from the high vapor pressure (high temperature) side to the low vapor pressure (low temperature) side of a hydrophobic membrane through which only the generated vapor can pass.

Figure 1 shows the general principle of the main desalination processes in addition to MD.

Membrane distillation is a non-isothermal membrane separation process that was introduced in 1963. During the last five decades, important actions on research and development have been deployed in different regions worldwide which resulted in exponential growth in MD related publications including technical reports, journal and conference papers and patents [2,4,5,6].For instance, the specific term “membrane distillation” appears in Science direct (*www.sciencedirect.com*) 117, 295 and 634 times between 1980-2000, 2001-2010 and 2011-2016 respectively [6]. The published works concern various topics varying from the development of novel MD membranes, transport phenomena in MD, renewable energy and MD integration to economic analyses. A good number of those published studies have been performed theoretically or in lab scale conditions while the pilot and commercial MD projects are very few. Only 20 pilot and commercial projects have been reported recently between 1999 and 2016 [6]. The capacity of MD units in these projects shows an exponential increase from 0.12 m^3/day to more than 400 m^3/day and the use of waste heat and solar energy as heat supply is almost in all the reported projects.

Despite of all these research and development activities, the practical implementation and commercialization of the MD technology appear to face serious barriers and critical limitations.

Advantages and Limitations of MD: MD has several important advantages when compared with other desalination processes. The main ones can be summarized as follows:

- It is simple to use and operate. Compared to RO systems, MD ones have better operation behavior. Therefore lower maintenance is required [5].
- It requires low levels of pressure and temperature. There are almost no requirements on membrane mechanical properties. Besides, low-grade thermal energy including solar and geothermal energy and waste heat can be used to drive MD process.
- The integration of solar energy and MD is particularly very attractive. MD systems operate at temperatures between 60 to 90°C for which the solar thermal collectors have high efficiency [7-9]. For detailed and critical review on solar desalination by MD, the following references are recommended [10-12].

- Theoretically, the process operates at liquid –vapor equilibrium. It has 100% theoretical rejection of non-volatile components [2, 13]. Therefore, the produced water has a very high quality from any feed concentration. Contrary to RO systems, chemical pretreatment of the feed water is not necessary [8]. Several studies have shown that the feed salinity has almost no influence on the water quality [13-15]. This characteristic of the MD process suggests to use it in some applications where the feed concentration is high. Safavi and Mohammadi [13], for instance, conducted an experimental analysis on desalination using Vacuum Membrane Distillation (VMD) of high salinity water with concentrations ranging from 100 to 300 g/L.
- Several works investigated the performance of hybrid desalination where MD units are used to desalinate the brine out of a main desalination process such as RO or MED [16]. Some attempts have been conducted to use of MD for brine concentration and salts production in the frame of zero liquid discharge (ZLD) approach [17].

However, MD performance remains unsatisfactory due to several limitations associated with its very low production rate per unit membrane area and its high specific energy consumption. Gonzalez *et al*. [2] reported that the thermal energy consumption of MD systems ranges from 120 to 1700 kWh/m^3 of distilled water while the electric energy consumed is between 0.6 to 1.8 kWh/m^3. Khayet [12] conducted a comprehensive and critical review on energy consumption and water cost for solar desalination using membrane distillation. The estimated specific energy consumption from various MD systems was found to vary from 1 to about 9000 kWh/m^3 which indicates a real concern on the actual energy management within these desalination systems. Besides, the MD membranes appear to be sensitive to the type of feed water which affects their hydrophobic behavior and production rate consequently.

Several experimental and theoretical investigations have been conducted to develop methods and evaluate concepts for enhancing the performance of MD systems. [5, 7, 11, 14] among others, reviewed the status of the MD process and proposed approaches for improvements. Recently, Thomas *et al*. [6] reported revived attention for MD during the last few decades.

Several concepts and methods have been used to enhance the efficiency of the MD process by improving the recovery ratio and the product flux. These methods are based for example on appropriate energy management within the MD units by recovering the heat contained in permeate and brine streams and multi-staging. Brine recycling and integration of energy recovery devices as well as hybridization with other conventional desalination technologies are few examples to enhance the overall efficiency of the MD process.

Hybridization in Desalination: Hybrid desalination concept refers to the integration of two or more processes in order to provide better performance, lower environmental impacts and lower water cost as compared to the standalone configurations. Although the concept is not new, its implementation is becoming larger the last period. Hybridization is also used in other applications such as in renewable energy systems. Thus, solar photovoltaic can be integrated with wind to adjust the intermediate operation of each system and reduce the storage.

Hybrid desalination couples in general thermal and membrane technologies. The main advantages can be as follows:

- The hybrid configuration provides more flexibility in operation;
- Larger capacities can be reached.
- Lesser specific energy consumption is expected to be recorded as well as lesser gas emissions
- Smaller intake and outfalls structures: lower environmental impacts (brine discharge)
- Low construction cost
- High plant availability
- Better water and power matching for dual purpose power and desalination plants.

Hybrid desalination can deal with the integration of distillation and membrane processes with power generation. There exit numerous options of hybrid desalination systems. They can be very simple but also more complicated. Earlier and in order to eliminate the use of a second pass to the RO process, hybrid configurations were proposed so that RO product with higher concentration is combined with the low salinity product from thermal process (MED or MSF).

There exit several examples of hybrid conventional desalination plants integrating thermal (MSF or MED) and membrane (RO) processes.The main examples are the plants of AlFujairah2 (UAE) and RasAlkhair-1 (KSA). AlFujairahplant with a total capacity of 595 000 m^3/day combines MED-TVC (Thermal vapor compression) and

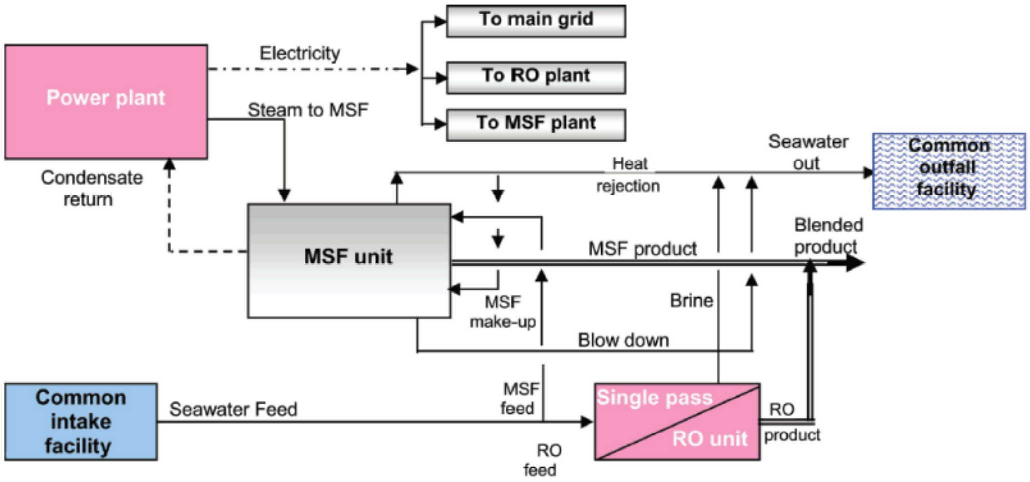

Fig. 2: Schematic diagram of a hybrid MSF-RO desalination plant [21].

RO [18] while RasAlkhair plant integrates MSF and RO. The total capacity of RasAlkhair reaches 1037 million of m^3/day (MSF - around 727 Million of m^3/day and RO - around 310) [19]. Helal [20] presented an overview on main desalination technologies and discussed about several hybrid structures integrating two or more processes. He also outlined the main advantages and limitations of each structure.Hamed [21] reviewed up to 2004 the status of hybrid desalting systems. He presented some commercially available hybrid desalination plants. Figure 2 depicts an example of such plants where power and water from MSF and a single pass RO are produced simultaneously. The coupling between MSF and RO units is weak since they operate in parallel and are entirely independent.Besides, the produced waters from RO and MSF are blended. Zak and Mistos [22] proposed several hybrid thermal-thermal desalination structures and assessed their performance in terms of performance ratio (PR), recovery ratio (RR) and specific surface area (SA). The results of their simulations show that MSF-MED concept exhibits larger PR and RR compared to the standard MSF-Once through (OT) system for the same operating conditions and same number of stages and effects.

Examples of Hybrid Desalination Systems Including MD: The use of MD integrated with other processes particularly RO has been the subject of some recent studies. Suchan integration of MD with other desalination technologies can improve the overall performance of the whole combined system. Macedonio and Drioli [23] designed and studied the performance of a Reverse Osmosis system followed by a Membrane Distillation unit. The results are encouraging due to the possibility of overcoming the limits of the single units. Criscuoli and Drioli [24]conducted an energy and exergy analysis of an integrated system coupling RO, MD and Nanofiltration (NF) modules where the MD unit operates on the RO brine while the NF unit was used for the RO feed pretreatment. They concluded that such integrated systems represent an attractive alternative to RO and to conventional thermal desalination processes. Mericq *et al.*[25] proposed an integrated Vacuum Membrane Distillation (VMD) and Reverse Osmosis (RO) unit in which the VMD was considered as complimentary process to the RO to further concentrate the RO discharged brines and then increase the overall recovery of the plant. El-Zanati and El-Khatib [26] proposed an integrated system composed of nano-filtration (NF), RO and VMD. The overall recovery for sea water was increased from 30-35 % to 76.2 % respectively when using RO and the hybrid system. Pangarkar *et al.* [27] presented a review on combining RO and MD processes for desalinating groundwater. The use of MD as a process for crystallization of RO brines has been considered by Ji *et al.* [28].The authors reported that a water recovery ratio of 90 % was reached.

MD-RO Hybrid: Orfi *et al.* [29] proposed a theoretical study on the integration of geothermal energy with MD followed by RO unit. This work was motivated by the use of the available energy contained in the geothermal waters to drive the MD unit. The brine exiting from the MD still with moderate concentration is directed to the RO modules. Figure 3 depicts a schematic diagram on such a combined system. Several simulations showing the

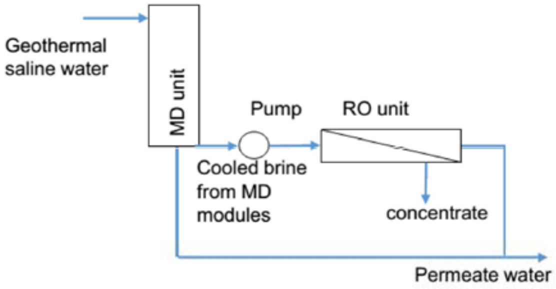

Fig. 3: A schematic for an integrated MD and RO units using geothermal source [29]

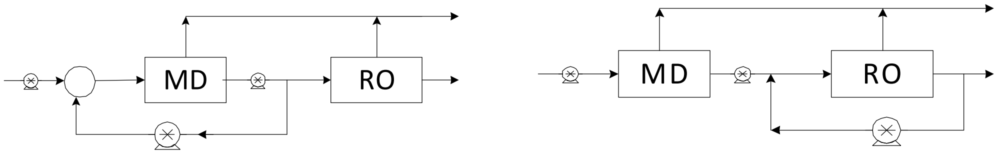

Fig. 4: MD-RO in series with brine recycle (BR) on the MD unit (left)and MD/RO in series with brine recycle on the RO unit (right)

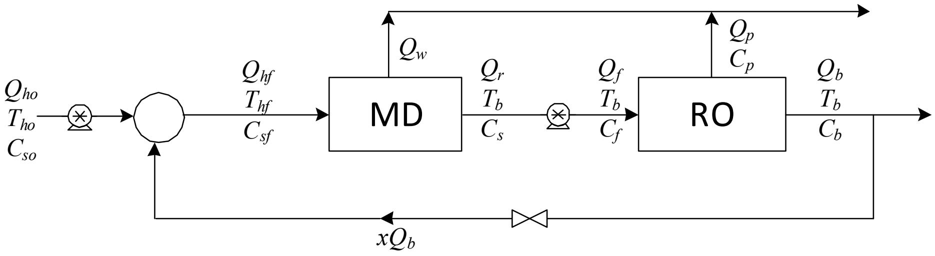

Fig. 5: MD/RO in series with BR on both units [30]

Table 2: Feed salinity effect on recovery ratio of the overall MD-RO (feed temperature 70 °C)

Feed Salinity [ppm]	MD brine (ppm)	MD Recovery ratio (%)	RO brine (ppm)	RO Recovery ratio (%)	MD-RO recovery ratio	MD-RO Concentration factor
2000	2802	28.62	6065	53.93	67.12	3.03
10000	13708	27.05	14557	5.86	31.32	1.46

influence of feed salinity on the overall system performance were conducted using a developed numerical model for MD process and ROSA software for RO calculations.

Table 2 shows examples of the obtained results. For feed salinity of 2000 ppm, the MD recovery ratio is about 29% while it is about 54 % for RO. The overall MD-RO recovery ratio increases to 67 %. Similar trends are observed for higher feed salinity i.e. 10000 ppm except that the overall recovery falls to 31.3 % compared to 67 % for brackish water of 2000 ppm.

Further analyses using more performance criteria such as energy consumption and cost would give clearer picture on such a combined geothermal-MD-RO configuration.

RO-MD Hybrid: In order to overcome the low MD recovery ratio, Ali *et al.* [30] investigated various design configurations of MD-RO hybrid system including brine recycling and cascading structure. The study included also a cost analysis. Process integration results inan increased recovery rate and reduced specific energy consumption. Brine recycling is found to considerably improve the recovery rate to 40% at energy cost of 0.9$/m^3. However, this improvement is limited to the case when the final brine is recycled to the RO feed. Figures 4 and 5 shows examples of coupling MD and RO with brine recycling.

MVC-MD Hybrid: In the objective of increasing the energy efficiency of MD process, Swaminathan *et al.* [31] proposed to combine it with mechanical vapor

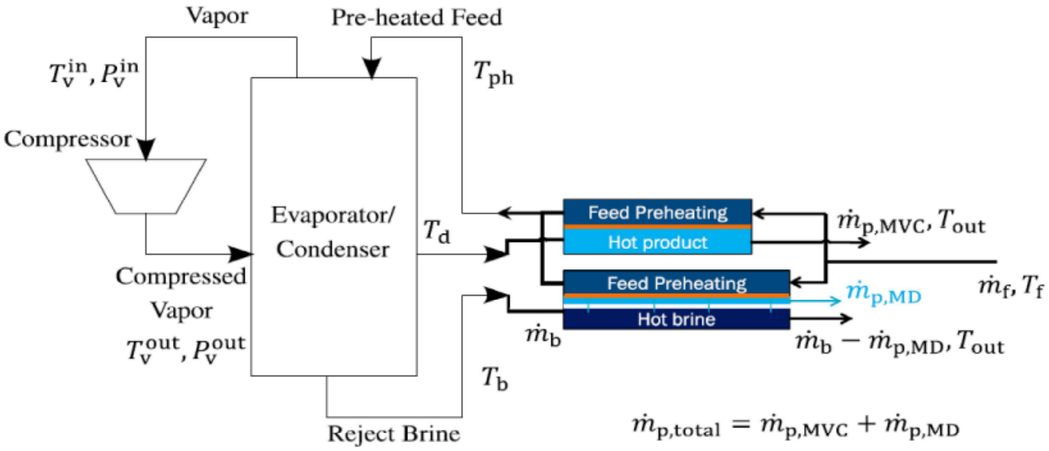

Fig. 5: MVC–MD hybrid system [31]

compression system (MVC) by replacing the preheater heat exchangers by MD systems. Such an integration allows additional pure water from MD and performing as preheating of the MVC feed water by recovering the thermal energy contained in permeate and brine streams. The results show that the hybrid MVC-MD can lead to 6% of decrease of the water cost compared to a simple MVC system for same operating conditions. Figure 5 depicts a representation of the integrated MVC-MD system. The work was focused on the cost analysis. A more comprehensive technical/thermodynamic investigation would be important.

CONCLUSION

This work presents an overview on hybridization in desalination by discussing the advantages and limitations of hybrid systems. It focusses also on Membrane Distillation (MD), an emerging desalination and water treatment process. Several studies on integrating MD with other conventional desalination technologies have been reviewed and commented. The benefits of such integration are highlighted and discussed. In particular, Membrane Distillation is often used to desalinate the brine exiting from a main desalination process, thermal or membrane process. The work suggests developing more studies on the appropriate and optimum integration of MD and other desalination technologies.

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