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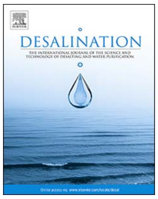

Energy efficiency of direct contact membrane distillation

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ABSTRACT

Membrane distillation (MD) is a promising technology due to its ability to function using low temperature differences and low-quality heat sources, thus allowing it to operate on solar or waste heat. The flux and energy efficiency of MD are influenced by temperature and concentration polarization, process conditions, and membrane-related parameters like thickness, tortuosity, thermal conductivity, pore size, and porosity. To date, a comprehensive review of membrane and distillation parameters on energy consumption has not yet been conducted. Accordingly, this review introduces the central energy parameters for MD (e.g., energy efficiency, gained output ratio, etc.) and discusses the reported impacts of membrane properties, mass and heat transfer, feed water properties, and system parameters on the energy parameters. The application of solar energy to direct contact MD (DCMD) is also discussed. A critical analysis of the energy efficiency of DCMD processes will help to establish its strengths and limitations and provide a road map for the development of this technology for both large-scale and portable applications.

1. Introduction

The large-scale desalination industry is currently dominated by multi-stage flash distillation, multiple effect distillation, and reverse osmosis (RO) techniques [1,2]. Although reverse osmosis has lower energy requirements relative to the other leading technologies, the method is known to be expensive for small-scale water purification purposes. Membrane distillation (MD) is a promising technology that operates based on the partial vapor pressure difference developed across a membrane. This technique utilizes a porous hydrophobic filter that is capable of preventing feed liquid entry into the pores while allowing the volatile vapors to cross to the distillate side. This characteristic makes MD unique among common water purification technologies as it can completely separate inorganic and non-volatile compounds without the use of traditional distillation techniques. However, the fabrication of a purely hydrophobic membrane that resists internal wetting while maintaining high vapor throughput is a continuing challenge.

In terms of energy efficiency, MD is an attractive technology due to its ability to function using low temperature differences and low-quality heat sources. Thus, it is an economically viable large-scale purification technology because it can utilize either solar thermal energy [3], waste heat, or natural temperature gradients. In fact, the heat requirement for MD is so low that Baghbanzadeh et al. [4] have recently suggested the notion of zero thermal energy input membrane distillation (ZTIMD), where the natural temperature difference between the sea surface water (at 30 °C) and the sea bottom water (at 10 °C) can be used as the process driving force without the need for preheating and zero waste production, which contrasts the seawater reverse osmosis (SWRO) process. Further, a simulation study has suggested that the specific energy consumption of ZTIMD would be in the range of 0.45 kW h/m^3, which is comparable to commercial SWRO processes [4].

The low energy requirement of MD techniques makes it competitive with RO; moreover, it can also be applied to high temperature applications where RO is not suitable. In fact, direct contact MD (DCMD) is a thermally driven process that can operate at temperature above 100 °C, making it a more energetically efficient method for use in onsite wastewater desalination [5]. The US oil and gas industry generates approximately 3.3 billion m^3 of wastewater annually, with salinity concentrations almost 7 times higher than seawater. Onsite desalination using steam assisted gravity drainage (SAGD) systems that produce wastewater have been proven to be more environmentally friendly and economically viable than disposal through deep well injection technology. The energy consumption of wastewater desalination has been

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evaluated using various models to provide a baseline to develop this technology [6]. The minimum energy required for seawater desalination with a recovery ratio of 50% is 1 kWh/m^3; however, this energy consumption rises to 9 kWh/m^3 for the removal of various salt ions from wastewater produced by SAGD. The study suggested that while RO is still more energy efficient, multistage membrane distillation can be utilized for better heat recovery higher recovery rate [6].

Small-scale and portable water distillation units are highly advantageous for use in remote areas and underdeveloped countries that lack appropriate water and electrical infrastructure. Renewable energy assisted MD strategies may serve as an alternative to replace the current expensive water purification approaches to improve the quality of life in such regions without increasing the demand for scarce and expensive electricity. To this end, extensive research has been conducted to utilize solar power in membrane distillation systems [7–16]; however, the cost of this process remains higher than that of photovoltaic-powered RO. Therefore, solar powered membrane distillation (SPMD) requires more research and development to make it an economically viable option in both industrial and small-scale applications. A detailed review on the energy analysis, energy consumption, and water production costs from a system engineering standpoint was conducted in 2012 and noted significant differences in the bench scale and large scale energy consumption of MD technology. Comparisons with commercial water purification processes such as multistage flash (MSF) and RO have concluded that MD is still in the early stages of development and requires parameter standardization for accurate capital cost calculations, particularly for large scale applications [12].

The relationships between the operating conditions such as water recovery, feed temperature, water circulation rate, and membrane scaling and the thermal efficiency of MD have been critically evaluated for seawater distillation using the brine re-cycling technique [17]. Detailed reviews of MD technology for water desalination have evaluated the materials, preparation techniques, and properties of various membrane types and compared the four main types of MD: Air Gap MD (AGMD), DCMD, Gas Sweeping MD (GSMD), and Vacuum MD (VMD) [18,19]. These reviews also discussed the hybridization of MD techniques with RO, forward osmosis (FO), and photocatalysis and concluded that the higher energy consumption of MD is a major challenge that hinders its large-scale application [18,19]. Therefore, the relationship between energy efficiency and process parameters needs to be more deeply explored to help guide improvements towards making MD a more competitive technology.

Compared of other MD technologies such as, GSMD, VMD, and AGMD, DCMD is advantageous due to design and process simplicity, applicability to various types of feed water, and functionality at a wide range of operating energies/temperatures relative [20]. As illustrated in Fig. 1, GSMD, VMD, and AGMD demand extra pressure, inert gas, pumping, and condensers for operation, which make these techniques comparatively more challenging than DCMD [21,22]. Despite the possibilities of membrane scaling, fouling, and wetting in DCMD it has been proposed as the most appropriate technology for wastewater treatment in the oil and gas industry in part because of its addition to 100% salt and organic removal rate [21,23,24].

The overall efficiency of membrane desalination systems is highly dependent on the properties of the membrane itself such as, material selection (e.g., polypropylene (PP), polytetrafluoroethylene (PTFE), and polyvinylidene fluoride (PVDF)) and fiber shape (i.e., flat sheet, hollow, and fibrous). Synthesis routes also have a significant influence on the performance of the membranes and the overall DCMD technology. Recently, much attention has been given to membrane preparation using electrospinning synthesis because of its versatility and simplicity, which allows optimized membrane design through control of the fibers' material, shape, and deposition pattern. A recent review on the application of electrospinning technology for the fabrication of nanofibrous membranes and their property–function relationships has been published. The review critically and technically highlighted the advantages and disadvantages of this technology and suggested further actions that can develop the electrospinning technique for use in large-scale membrane synthesis [19].

Flux and energy efficiency in DCMD are inter-related and strongly influenced by polarization (temperature and concentration), process conditions (such as flow velocities and salinity), and membrane-related parameters like thickness, tortuosity, thermal conductivity, pore size, and porosity [25,26]. A few technical reviews have extensively covered the design and development of membranes and their impacts on the DCMD mechanism, as well as the influence of fabrication techniques on the performance of DMCD desalination technology [11,27–31]. Numerous efforts have been made to reduce the energy consumption of DCMD to make it more energy efficient [6,7,17,32]. As of today, however, a comprehensive review of membranes and distillation parameters on energy consumption has not yet been conducted.

Given all of the above, the need to accumulate and evaluate the updated research is obvious. A critical analysis of the energy efficiency of DCMD processes will help to establish its strengths and limitations and provide a road map for the development of this technology for both large-scale and portable applications. Many technical challenges must still be addressed at the forefront of MD development, including its high energy consumption, low thermal efficiency, membrane wetting, membrane scaling, low water flux, and membrane structure and design [19,25]. The objective of this review is to discuss the recent developments in direct contact membrane distillation, specifically for the improvement of DCMD energy consumption as a function of mechanistic properties.

2. Energy efficiency and desirable energy requirements ($< 1\ kWh/m^3$)

More than 11,000 desalination plants are in operation globally, producing > 26 million m^3/day; approximately 63% of this capacity originates from West Asia and the Middle East, North America accounts for ~11%, while North Africa and Europe account for ~7% each [33]. Desalination plants in Qatar produce over 1 million m^3/day of fresh water alone and by 2030 the country is expected to be nearly 96% urbanized, increasing the demand. Desalinating water on these scales can be restrictively expensive due to the high energy demands of current technologies.

Currently the top three methods of desalination are: multi-stage flash distillation (MSF), multiple effect distillation (MED), and RO [34]. As seen in Table 1, MSF is the primary desalination method currently being used in Qatar and throughout the region. Because it relies on boiling water, however, MSF is one of the most energy intensive techniques, requiring up to 75 kWh/m^3. This energy is generated through combustion of fossil fuels, and two-thirds of the energy is ultimately rejected as waste heat [35]. MED is another thermal technique that uses a sequence of vessels (or "effects") of decreasing pressure and boiling water. Although MED is more efficient than MSF, it still requires up to 55 kWh/m^3 to produce fresh water. RO operates using high pressure applied to a semipermeable membrane, and for this reason it uses less energy than the MSF and MED thermal methods. However, the membrane can become clogged with minerals.

Given the high-energy costs associated with existing desalination methods, there is a great demand for technologies that can utilize low-temperature sources such as waste heat or solar energy. DCMD is one such technology. Energy efficiency, with respect to DCMD, is commonly defined as "the ratio of the heat transfer due to flux Q_N [convection] to the total heat transported through the membrane Q_m [convection + conduction]" and is given by Eq. (1) [26]:

$$\varepsilon_T = \frac{Q_N}{Q_m} = \frac{Q_N}{Q_N + Q_C} \tag{1}$$

where Q_N is the heat transfer due to convection by the vapor flux, Q_m is the total heat transported through the membrane, and Q_c is the heat