Efficiency of Membrane Distillation to Produce Fresh Water

Sabri Mrayed, David Maccioni, Greg Leslie

Abstract**—**Seawater desalination has been accepted as one of the most effective solutions to the growing problem of a diminishing clean drinking water supply. Currently two desalination technologies dominate the market – the thermally driven multi-stage flash distillation (MSF) and the membrane based reverse osmosis (RO). However, in recent years membrane distillation (MD) has emerged as a potential alternative to the established means of desalination. This research project intended to determine the viability of MD as an alternative process to MSF and RO for seawater desalination. Specifically the project involves conducting thermodynamic analysis of the process based on the second law of thermodynamics to determine the efficiency of the MD. Data was obtained from experiments carried out on a laboratory rig. To determine exergy values required for the exergy analysis, two separate models were built in *Engineering Equation Solver* – the 'Minimum Separation Work Model' and the 'Stream Exergy Model'. The efficiency of MD process was found to be 17.3 % and the energy consumption was determined to be 4.5 kWh to produce one cubic meter of fresh water. The results indicate MD has potential as a technique for seawater desalination compared to RO and MSF. However it was shown that this was only the case if an alternate energy source such as green or waste energy was available to provide the thermal energy input to the process. If the process was required to power itself, it was shown to be highly inefficient and in no way thermodynamically viable as a commercial desalination process.

Keywords**—**Desalination, Exergy, Membrane distillation, Second law efficiency.

I. Introduction

POTABLE water supply has become a critical issue facing the ongoing well-being and development of society. Once considered plentiful, the supply of clean drinking water is commonly regarded as rapidly diminishing. Coupled with ever expanding populations, higher living standards and growing industry and irrigation throughout the world, the demand for sources of reliable and cheap potable water has never been greater. As such, in recent years governments have been searching for viable fresh water alternatives. One such method for potable water generation is desalination. Desalination has long been a source of potable water throughout the world. The desire to enhance sources of clean and cheap drinking water has resulted in the increased research and development of desalination technologies. Many of these efforts have focused on thermally-driven and membrane-based processes and technologies such as multi stage flash distillation (MSF) and reverse osmosis (RO). However the desire for techniques which are easier to use, more cost effective and requiring less energy has led to the development of membrane distillation (MD). Membrane distillation (MD) is a currently developing technology for desalination, first discovered by Weyl [1] in 1966. MD is a process to remove a volatile solute or solvent from a solution by a combination of evaporation and differences in partial pressure. It is being investigated as a low cost, energy saving alternative to conventional separation processes such as distillation and RO. The term 'membrane distillation' arises from the similarity of the process to regular distillation. As with distillation, MD performs separation based on the premise of vapor-liquid equilibrium, and as such requires the supply of the latent heat of vaporization to bring about a phase change [2]. The membrane aspect of MD stems from the hydrophobic microporous membrane (one which allows water vapor, but not liquid water to pass) to support the vapor-liquid interface. But the technology differs from other membrane technologies from the fact that the force driving the desalination process is the difference in partial pressure, as opposed to total pressure, across the membrane [3]. This research project has aimed to aid in the development of a more efficient means to desalination. In order for this goal to be achieved, an exergy analysis of MD was carried out to determine both how thermodynamically efficient the process currently is, and to identify areas within the process that contribute to the greatest amount of exergy destruction. These areas indicated the most inefficient stages of the process and hence where improvements can be made.

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II. Laboratory Procedure

A. Rig Setup

The MD rig has a DCMD configuration, meaning that the feed and permeate streams are in direct contact with the membrane. A heated aqueous feed stream and permeate stream are pumped into the rig from opposite ends of a hydrophobic membrane (see Figs. 1-3). Water vapor from the warmer feed side diffuses across the porous membrane where it then condenses on the cooler permeate side. The method employed for calculation of exergy values in MD will be to use the transmembrane flux. When the flux is multiplied by the feed flow rate, the exergy input to the system can be determined, hence allowing calculation of second law efficiency.

Data from the rig was collected from numerous sources throughout the process. These include:

- 5 x temperature probes
- 2 x pressure sensors

- 2 x flow meters
- 1 x mass balance
- 1 x conductivity meter

The temperature probes and pressure sensors are each connected to a data acquisition board, which allows for all data collected from the rig to be simultaneously logged onto the rig computer. This data along with the mass balance and electrical conductivity meter (measuring permeate conductivity), are programmed into a data logging interface, *LabVIEW*, to display and record live data.

Fig. 1 Polypropylene hollow-fibre membranes set in membrane fittings

Fig. 2 Water contact area of polypropylene hollow-fibre membranes

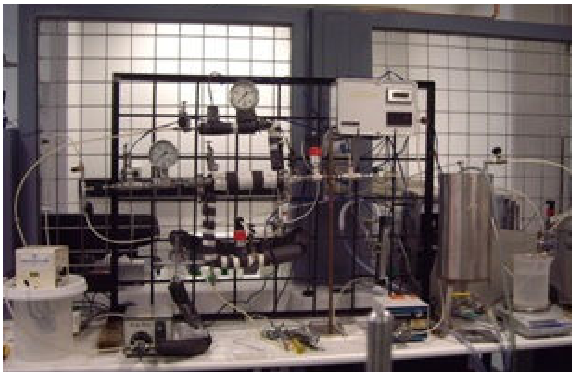

Fig. 3 MD rig setup

B. Leak Testing

Before starting any experiments it was essential to make sure there were no leaks at any point within the system. This is because the transmembrane flux calculation is based on a mass balance assuming the system to be a closed batch process. Leaks were also prevented to preserve the clean and safe working area. To identify leaks, cold water was pumped around both sides of the rig at high pressure while the membrane module was empty. No leaks were present, but if leaks were present, they should have been stopped by tightening the screwed connection of the joint from where the leak was emerging. Should this not stop the flow, the pipe or fitting may need to be replaced.

C. Membranes

Polypropylene (PP) membranes with the properties presented in Table I should be used as they have been found to be the most effective with the MD rig to be used [4].The standard operating procedures (SOP) were based on the work by Tom Denslow [4] to optimize and develop a standard method for use of the MD rig.

TABLE I
POLYPROPYLENE HOLLOW-FIBER MEMBRANE PROPERTIES

Membrane	Polypropylene
Pore Size (μm)	0.2
Inner Diameter (mm)	0.39
Outer Diameter (mm)	0.65

III. EXERGY MODEL DEVELOPMENT

In order to conduct an exergy analysis on a desalination processes, it was necessary to develop an appropriate exergy model. The method of Cerci and et al. [5] was adopted and modified to accommodate for its perceived shortcomings. The common issue with Cerci's model is the neglect for the dissociation of NaCl in solution. When incorporating the NaCl dissociation and including a term to account for the recovery ratio, the exergy analysis values generated from Cerci's model were able to favorably compare with those from literature. The minimum separation work of a process is an essential component in exergy analysis as it is used to calculate its second law efficiency using (1):

$$\eta_{II} = \frac{\dot{W}_{min}}{\dot{X}_{in,total}} \quad (1)$$

And minimum separation work W_{min} is calculated as:

$$\dot{W}_{\min} = RT_0\left(N_{s,brine}\ln\left(\frac{x_{s,brine}}{x_{s,SW}}\right) + N_{s,permeate}\ln\left(\frac{x_{s,permeate}}{x_{s,SW}}\right) + N_{w,brine}\ln\left(\frac{x_{w,brine}}{x_{w,SW}}\right) + N_{w,permeate}\ln\left(\frac{x_{w,permeate}}{x_{w,SW}}\right)\right) \quad (2)$$

where N_s molar flow rate of NaCl, N_w molar flow rate of water, and x is the mole fraction, T is the absolute temperature, and R is the gas law constant.

An exergy model was required to determine the exergy values for each stream in a desalination process. The model required inputs for an environmental reference state from which to make exergy calculations [6]-[8]. Any difference between the temperature, pressure or salinity of a stream in relation to the reference indicates that three exergy factors must be calculated for each stream – the thermal, physical and chemical exergy. The specific exergy for a stream is given by the sum of its exergy components:

$$\psi = \varepsilon_{th} + \varepsilon_{ph} + \varepsilon_{ch} \quad (3)$$

where, ψ is the total specific exergy of a stream (kJ/kg) $\varepsilon_{th}$is the thermal exergy component (kJ/kg) ε_{ph} is the physical exergy component (kJ/kg) $\varepsilon_{ch}$is the chemical exergy component (kJ/kg). A stream will only contribute thermal exergy if it has a temperature different to that of the reference state. Similar logic follows for physical exergy with pressure differences and for chemical exergy with changes in salinity. The equations required for each exergy component are as follows:

$$\varepsilon_{th} = \frac{C_{P,i}}{MW_i}\left[(T_i - T_0) - T_0\left(ln\frac{T_i}{T_0}\right)\right] \quad (4)$$

where, $C_{p,I}$ is the specific heat capacity of stream i MW_i is the molecular weight of stream i T_i and T_0 are the temperatures of stream i and the reference stream (stream 0).

$$\varepsilon_{ph} = \frac{|P_i\_P_0|}{\rho_i} \quad (5)$$

where, P_i and $P_0$are the pressures of stream i and the reference stream ρ_i is the density of the stream.

$$\varepsilon_{ch} = \frac{RT_0}{MW_i}[(x_s lnx_s + x_w lnx_w)_i - (x_s lnx_s + x_w lnx_w)_0] \quad (6)$$

IV. Results

A. Minimum Separation Work

Application of the feed flow rate, recovery ratio, and feed and product salinity the value of the minimum required work for MD process was found to be 0.78 kWh/m^3. This value is used to determine the second law efficiency once the total exergy input has been determined.

B. Experimental results

Experiments were conducted with 30 hydrophobic membranes in the membrane module, giving a greater membrane area than available in the other tests. The experiment was run with a feed temperature of 65°C and values for the change in permeate volume had been recorded every thirty seconds. The change in volume was plotted against time to determine the average transmembrane flux as shown in Fig. 4.

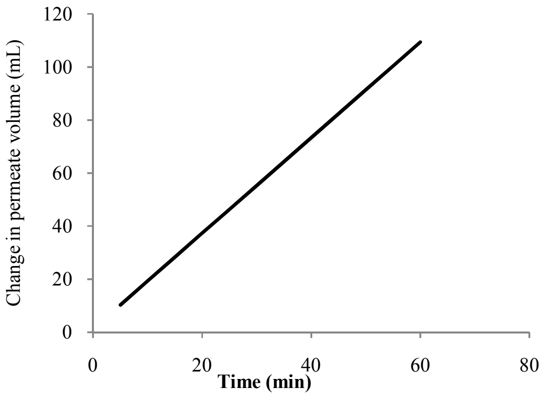

Fig. 4 Change in permeate volume over time for hot 3% saline feed/cold MilliQ permeate

The linear relationship shows that the average volume change was 1.8 mL/min. This was used to determine the average transmembrane flux across the membranes. To do so require knowledge of the total membrane area, this was calculated as follows:

Total membrane Area = No. of membranes × Membrane area

For 30 membranes with 0.65mm outside diameter and a length of 315mm, the total membrane area was 0.02m^2.

Flux (Liter/(m^{2}h)) was calculated according to the equation:

$$Flux = \frac{\Delta V_{permeate} \times 60}{A_{membrane} \times 1000} \quad (7)$$

where, $\Delta V_{permeate}$ is the change in permeate volume (mL/min) $A_{membrane}$ is the total membrane (m^2). Thus for the hot MilliQ feed with a salinity of 3% NaCl, cold MilliQ permeate at 65°C, the flux was 5.4 L/m^{2}h.

C. Exergy analysis

After having calculated the total flux across the membrane on the MD rig for the hot saline feed (to model seawater desalination via MD), it was now possible to calculate the total power requirement per cubic meter of clean water produced. Performing such a calculation requires the total exergy input to the system. For this MD process, there are two sources of exergy input – thermal exergy from heating the feed and physical exergy from driving the pumps. The exergy input from heating the feed stream was found by first determining the enthalpy of the feed stream and then dividing it by the flux rate. This produced a value for thermal exergy input in kJ/kg, which was then converted to the desired kWh/m^3. Summary of the stream flow rates and exergy data are presented in Table II.

TABLE II
STREAM EXERGY DATA AND CONDITIONS

Stream	T (K)	P (bar)	Sal (ppm)	$\dot{m}$ (kg/s)	ψ (kJ/kg)	$\dot{m}$ (kW)
Feed In	338.15	135.8	30000	0.012	10.09	0.121
Feed Out	331.65	101.3	30075	0.012	7.13	0.085
Permeate In	295.15	135.8	50	0.002	7.42	0.012
Permeate Out	308.15	101.3	50	0.002	8.01	0.014
Cooler	296.15	101.3	50	0.002	7.35	0.012

An exergy balance was then performed using the exergy flow rates. The data is presented both in Table III and by the exergy flow diagram in Fig. 5.

TABLE III
EXERGY DISTRIBUTION WITHIN MD PROCESS

Component	Exergy (kW)	% of Total
	Input	
Feed In	0.121	90.73%
Permeate In	0.012	9.27%
Total	0.133	100%
	Output Exergy	
Feed Out	0.085	63.97%
Cooler/Product	0.012	9.34%
Total	0.098	73.31%
	Exergy Destruction	
Around Membrane	0.034	25.85%
Around Cooler	0.001	0.84%
Total	0.036	26.69%

Knowing the total exergy input and recalling the minimum separation work of MD, W_{min}= 0.78 kWh/m^3, the exergy efficiency of the MD process was found to be, η_{II} = 0.03%

This value is very small and would instinctively be assumed to be grossly incorrect. However there are several reasons explaining the value: 99% of the power requirement for MD was found to be as a result of thermal exergy, which is anticipated to be provided by green or waste energy in commercial plants; and problems and inefficiencies concerning the MD rig. An important factor to consider when investigating the results of the exergy analysis of MD is that MD is understood to be a process which requires large amounts of thermal energy for a relatively small amount of product water. On its own, MD is an inefficient method for removing salt from water, a fact reinforced by the results obtained for the second law efficiency. However the relatively low feed temperature compared with other thermal desalination technologies (e.g. MSF) provides MD with a unique opportunity. Intuitively it is anticipated that not needing to raise the feed temperature to as great a level as that in MSF would result in a lower thermal energy requirement. As such it has been proposed that energy needed by MD for heating be provided by an alternate, environmentally friendly source. Two sources have been suggested: waste energy from other nearby operations (e.g. a coal fired power plant would be ideal); and green energy provided by either a solar, wind or wave power generating facility. Should MD be used in this way then the thermal exergy input used in the exergy analysis must be removed. This would leave the total exergy input to the MD process as being due to the physical exergy input from the pumps at the feed and permeate sides. An exergy analysis should therefore be performed for MD without the thermal input as this is what is proposed would be operating should a large scale MD desalination facility be constructed. The results for MD powered by either waste or green energy can be seen to be much more comparable and thus the efficiency of the process when supplied with waste energy to heat the feed should be calculated by using the total exergy input as being solely due to the pumps, therefore η_{II}= 17.33%.

Fig. 5 Exergy flow diagram for MD process

V. CONCLUSIONS

Having examined the results generated from this study it can be determined that MD has potential as an alternative for seawater desalination. However this appears subject to a waste or green energy source being available to provide the energy to account for the thermal exergy input to the system. The exergy efficiency of MD in this case was found to be 17%. Although acceptable for a desalination process, which rarely rise above 20% for thermodynamic efficiency, MD has been shown to be less efficient in exergy terms than RO. Thus the study has shown that although it appears to have potential as an alternate desalination process, MD still requires more development before it can be considered as a viable replacement for established desalination technologies, in particular RO.

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