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Simple method for balancing direct contact membrane distillation

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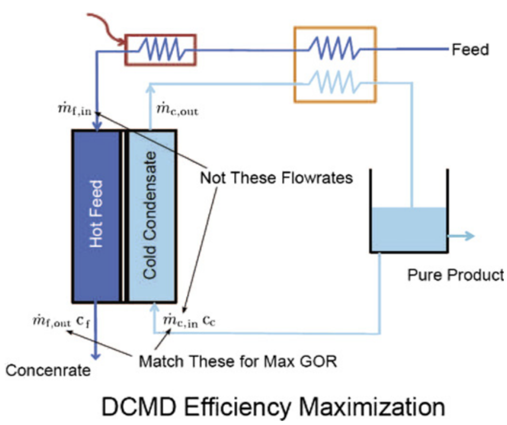
HIGHLIGHTS

- Balancing leads to 50% higher GOR than equal inlet flow rates in DCMD.
- DCMD balancing achieved by setting heat capacity rate ratio to one at end
- Proposed method deviates by about 5% from absolute maximum GOR at high salinity.
- Real-time balancing most useful for variations in inlet salinity

GRAPHICAL ABSTRACT



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ABSTRACT

A simple theoretical method for maximizing efficiency via real-time balancing of direct contact membrane distillation (DCMD) systems is presented. The method is applicable under variable operating conditions. Balancing involves measuring only the flow rates of feed stream out of the module and the cold water flow into the module, as well as the salinity of the feed. A valve or variable frequency drive is used to set the condensate water flow into the module so that the heat capacity rates of the hot and cold streams are equal. This method is much simpler and more general than what is proposed in the literature, which generally requires more measurements and a complicated expression. Balancing leads to 20–50% improvement in efficiency (GOR) compared to equal inflow of both feed and pure water streams, which is the common practice. Real-time balancing is particularly useful for variations in feed salinity, whereas the improvement by real-time balancing is low for changes in system top or bottom temperatures.

1. Introduction

Membrane distillation (MD) systems are capable of treating highly concentrated water streams and are considered to be more fouling resistant than other membrane based desalination technologies [1]. MD can be configured as a single stage or a multi-stage system. In single stage MD, the pure water vapor leaving the membrane pores can either be condensed within the module or outside. MD configurations such as direct contact (DCMD) and air gap (AGMD) which involve condensation within the module have been found to be more suitable for achieving higher energy efficiency than systems like sweeping gas and vacuum MD with external condensation [2].

Thermal energy consumption constitutes the major portion of the cost of water from membrane distillation and for solar-driven MD systems energy efficiency governs the required capital investment in

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Nomenclature

Roman symbols

B	membrane permeability, kg/m^2·s·Pa
BPE	boiling point elevation, °C
c_p	specific heat capacity, J/kg-K
d	depth or thickness, m
DCMD	direct contact membrane distillation
GOR	gained output ratio
h_{fg}	enthalpy of vaporization, J/kg
HX	heat exchanger
k	thermal conductivity, W/m·K
L	length of module, m
m	molality, mol/kg
$\dot{m}$	mass flow rate, kg/s
MD	membrane distillation
MR	mass flow ratio of condensate stream to feed stream inflow
$\dot{Q}$	heat transfer rate, W
p^{vap}	vapor pressure, Pa
s	salt concentration, g/kg
T	temperature, °C

Greek symbols

δ	membrane thickness, m
η	thermal efficiency
ϕ	porosity

Subscripts/superscripts

amb	ambient
c	condensate
f	feed
h	heater
HX	heat exchanger
in	inlet
m	membrane interface
out	outlet
p	product

solar panels [3]. As a result, improving energy efficiency, measured here in the form of gained output ratio (or GOR), is of significant interest. While energy efficiency can be increased by increasing top temperature or system size, methods to increase energy efficiency without increasing capital cost, such as by optimizing system operating conditions are more advantageous:

$$\mathrm{GOR} = \frac{\dot{m}_p h_{fg}}{\dot{Q}_h}. \quad (1)$$

DCMD is the oldest configuration of MD and the most commonly studied configuration due to its relatively simple design [4]. Optimizing DCMD operation to improve energy efficiency is the focus of this work. In DCMD, hot saline water flows across one side of a microporous hydrophobic membrane. Cooler pure water is passed on the other side of the membrane. Due to the vapor pressure difference established by the temperature difference between the two streams, water vapor passes from the hot side to the cold side and condenses into the pure water stream. In addition, heat is also transferred from the hot side to the cold side in the form of conduction, which is a loss mechanism in MD. As a result of these two processes, the temperature of the hot stream decreases as it flows through the system and the temperature of the cold stream increases. In order to reuse energy and achieve gained output ratio (GOR) greater than 1, the energy in the warm distillate stream would have to be recovered. To do this, a counterflow external heat exchanger is used as shown in Fig. 1a that preheats the feed water before further heat is added in the feed top heater [5].

The pure water stream is recirculated after the fresh water produced within the MD module is removed. The feed may also be recirculated in a closed loop to increase the overall recovery ratio. Additional external cooling is necessary if both streams are recirculated, to prevent temperature rise of the feed and cold water loops. Heat recovery from the permeate stream can be achieved only when $T_{c,out} > T_{f,out}$ if the feed is recirculated. This condition may not be satisfied for very short length systems.

Some studies use an optional additional heat exchanger to reduce the pure water inflow temperature down to ambient temperature [6, 7]. This increases the temperature difference for desalination within the MD module, leading to higher flux. Fig. 1b shows the difference in performance between using an additional heat exchanger and not using the additional heat exchanger based on numerical modeling. The system with an additional heat exchanger performs better especially when the MD area is small, and hence overall energy efficiency is low. For systems with larger membrane area, the difference in performance between the two systems is smaller. This computation was performed using the model described by Summers et al. [2], by setting $T_{c,in} = T_{c,HX,out}$ (for the case of no additional heat exchanger) or $T_{c,in} = T_{amb}$ (for the case of using a large additional HX). This study will focus on a system with no additional heat exchanger because of its relative simplicity and lower cost.

The hot and cold water streams are usually set up in counterflow configuration in order to distribute the flux uniformly within the system and achieve higher energy efficiency.

Swaminathan et al. [8] showed that the energy efficiency of permeate gap (PGMD) and conductive gap (CGMD) MD systems was maximized when the pure water in the gap flows countercurrent to the cold water stream, as opposed to parallel or crossflow conditions. When the pure water flows in the same direction as the hot stream and countercurrent to the cool stream, at any local position along the MD module, the total flow in either direction is equal. This leads to a more uniform driving temperature difference across the module length and higher energy efficiency by about 40% compared to a case with pure water flow co-current to the cold stream. Thermodynamically, this increased efficiency is attributed to lower specific entropy generation within the module.

Unlike in the case of AGMD and other configurations, in DCMD, the flow rate of the cold water stream can be varied independently of the warm water flow rate. Several studies in the past used an equal input flow rate of hot and cold water into the module. Guan et al. [7] performed DCMD simulations and found that the GOR was maximized when the feed and cold water inlet flow rates are approximately equal. Winter [9] experimentally showed that flux and GOR are both maximized under a symmetric operating condition where the mass flow rates of the hot and cold streams are equal at the hot end of the module.

Lin et al. [6] showed through numerical modeling of a coupled DCMD-Heat Exchanger (DCMD-HX) system, that the optimal value of cold pure water mass flow rate is not equal to that of the hot inflow, but about 90–92% of this value. They developed an analytical expression for this critical mass flow ratio, $\mathrm{MR_{Lin}}$ as a function of T_{top}, T_{bottom}, $\mathrm{BPE_{f,in}}$, $\mathrm{BPE_{f,out}}$, c_p^f and c_p^c (Eq. (4)) where mass flow rate ratio MR is defined as $\mathrm{MR} \equiv \frac{\dot{m}_{c,in}}{\dot{m}_{f,in}}$. Temperature and salinity are combined in the form of T^*, defined as:

$$T^*_{f,in} = T_{sat}\left(P_{vap}\left(T_{f,in}, s_f\right)\right) \quad (2)$$

$$T^*_{c,in} = T_{sat}\left(P_{vap}\left(T_{c,in}, s_f\right)\right) \quad (3)$$

where P_{vap} is the vapor pressure of salt water and is a function of temperature and salinity (s_f). A higher salinity results in a lower T^* through an increase in boiling point elevation (BPE), since $T^* \approx T - \mathrm{BPE}$.