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Flashed-feed VMD configuration as a novel method for eliminating temperature polarization effect and enhancing water vapor flux

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ABSTRACT

The coupling of heat and mass transfer in membrane distillation (MD) process makes enhancing water vapor flux and determining MD membrane mass transfer coefficient (MTC) fairly challenging due to the development of temperature gradient near the membrane surface, referred to as temperature polarization (TP). As a result, the change in feed temperature at the membrane surface will be difficult to measure accurately. In this paper, the effect of TP was decoupled from the membrane MTC by preventing the liquid feed stream from contacting the membrane surface through the use of a novel custom-made vacuum MD (VMD) module design. Results showed that a temperature difference of 10 °C between the feed bulk and feed temperatures at the membrane surface/interface is estimated to take place in the typical VMD configuration, while the proposed flashed-feed VMD configuration eliminates TP effect and gives a flux 3.5-fold higher (200 kg/m^2 h) under similar operating conditions. Therefore, it can be concluded that heat transfer coefficient is considered to be the main factor controlling resistance of water vapor flux in the typical VMD configuration. The measured MTC of the tested commercial membrane was found to be more accurate and the highest among all reported MTCs in the MD literature (2.44×10^{-6} kg/m^2 s Pa). Additionally, a transmembrane temperature difference of 5 °C and 10 °C in the novel configuration can produce water vapor fluxes of about 9 kg/m^2 h and 40 kg/m^2 h, respectively, at a feed temperature of 70 °C, which is very attractive for scaling-up the process.

1. Introduction

Membrane distillation (MD) is one of the promising sustainable desalination technologies that received wide interest in academia but not yet in industry. MD holds high potential for developing new seawater desalination processes that can be driven by solar, geothermal or waste heat energy [1–3]. MD applies a micro-porous hydrophobic membrane as a physical interface between two aqueous mediums where the difference in temperature between these mediums drives the separation process. At a relatively low operating pressure, capillary forces of the hydrophobic micro-porous membrane prevent the hydrophilic liquid phase from wetting the membrane pores while water vapor phase can pass through. However, unlike the reverse osmosis (RO) process, MD process development is still facing some challenges that prevent it from reaching industrial scale level. Below are just few facts about MD and RO processes:

- Both separation techniques were invented in the same decade (RO in 1962 and MD in 1963).
- For typical seawater quality, MD membrane requires zero or few bars of hydraulic pressure only to drive the fluids across the module relative to more than 60 bars applied on RO membranes. This means no specific pressure vessels and pipes are needed for MD membrane modules to resist the high applied pressure.
- The low interaction between the process fluid and membrane, and the larger average pore sizes of MD membranes make them less vulnerable to fouling as compared to dense RO membranes [4]. Additionally, MD membrane can be easily cleaned through backwash with air or wetting solution [5].
- The MD process is much safer since it can be operated at atmospheric pressure and more efficient in rejecting ionic components (about 100%) compared to the RO process [4].
- Even though the operating temperatures of the MD process are higher than those of RO process, they are still considered as mild (< 80 °C) and most of the available polymeric materials meet this requirement [6].

MD is also not different from the conventional thermal desalination

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Nomenclature

C_m	Mass transfer coefficient (kg/m^2 h)
h	Heat transfer coefficient (kJ/m^2 h)
J	Water vapor flux (kg/m^2 h)
J_p	Water vapor flux in viscous flow regime (kg/m^2 h)
k_g	Air thermal conductivity (W/m K)
k_m	Membrane thermal conductivity (W/m K)
k_s	Polymer thermal conductivity (W/m K)
M	Water vapor molecular weight (kg/mol)
ΔP	Water vapor pressure difference (kPa)
P_i	Water vapor at the membrane pore interface (kPa)
P_v	Water vapor of the membrane vacuum side (kPa)
R	Universal gas constant (m^3 kPa/k mol)
ρ	Water vapor density (kg/m^3)
r	Average membrane pore radius (m)
ε	Average membrane porosity
τ	Membrane pore tortuosity
η	Water vapor viscosity (kg/m s)
δ	Membrane thickness (m)
Q	Heat flux (W/m^2)
T_b	Bulk feed temperature (K)
T_i	Feed temperature at the membrane surface (K)
T_{avg}	Average temperature inside membrane pores (K)
P_{avg}	Average pressure at membrane pores (kPa)

technologies that were deployed earlier in industry. The heat recovery system design in these conventional thermal units is very essential for improving their thermal efficiency. Therefore, they operate at low ΔT (5–10 °C) between the evaporation and condensation surfaces and at the same time produce large quantity of distillate. However, even though installing heat recovery systems in MD processes increase their thermal efficiency, the recovered heat always results in a lower distillate flux through the reduction of the driving force across the membrane which makes the improvement of MD flux very challenging. For example, in a multi-stage flash (MSF) plant, the water vapor flux is usually more than 800 kg/m^2 h and is only driven by 5–7 °C temperature difference [7,8]. On the other hand, MD flux is far less than this value even at higher temperature difference across the membrane. The maximum flux in all direct contact membrane distillation (DCMD) studies is reported to be less than100 kg/m^2 h even though the temperature difference between the hot and cold fluids is as high as 60 °C, which is not practical for large scale modules [9]. Given these considerations, two fundamental questions are being raised:

(1) Why the MD flux is so low as compared to MSF?
(2) Is it the membrane structure itself that restricts the vapor flow, or it is originating from the reduction in driving force caused by temperature polarization (TP)?

In this paper, we comprehensively addressed these issues by developing a new experimental method in which the effect of TP on MD water vapor flux has been decoupled from the mass transfer effect. To achieve this, we conducted MD experiments in a custom-made module offering a novel MD configuration design to the feed side, which we refer to as flashed-feed configuration. Briefly, the new method implies conducting two sets of vacuum membrane distillation (VMD) experiments. In the first set of experiments, the feed was flashed before it physically contacted the surface of the hydrophobic membrane in order to eliminate the TP effect. Although the hydrophobic membrane used in this study was not in direct contact with the feed water when the system was run in the feed-flashed mode, it still separated the feed side from the permeate side similar to any other MD processes due to inherent ability of hydrophobic membrane to prevent pores wettability as the flashed vapor is a kind of moisture, thus ensuring high purity of produced water vapor. With this concept, water vapor is produced and transported through the membrane in a relatively very small volume (a few millimeters separate the feed liquid level and the membrane surface) compared to the huge volume required in MSF distillers, as an example (the distance between the brine level and the condensation surface is about 2 m). By measuring the water vapor flux and the pressure drop across the membrane, the mass transfer coefficient (MTC) has been calculated. In the second set of experiments, the feed was allowed to contact the membrane as in a typical VMD configuration. By comparing the water vapor fluxes from these two sets of experiments, the TP effect has been determined.

2. Theory

Beside its hydrophobic property, MD membranes should have some other important properties that are expected to extend their life time and boost their thermal and production performance, including:

- High liquid entry pressure
- Chemical and mechanical stability at process operating conditions
- Low thermal conductivity
- High porosity
- Optimal membrane thickness
- Low tortuosity

Most of these required properties (if not all) have been already met by currently available commercial PTFE and PVDF membranes. However, it seems that MD researchers are not yet agreeing on whether the available membranes are good enough for the MD process development. This fact might be inferred from 2016 year MD publications where one can still see some researchers working on developing new MD membranes without seeing net improvements in flux compared to commercially available membranes under the same operating conditions, e.g. [10–18] while other researchers still use the commercial MF membranes, especially in studies focused on pilot plant testing, e.g. [19–23]. Even though the MD researchers' disagreement on the appropriateness of the available MF membranes for MD process might be a good driver for further membrane development, the main reason in our opinion for this disagreement stems from the difficulty in accurately estimating the MD membrane performance. A number of factors, including absence of standard test method for evaluating MD membrane performance; complexity and irregularity of the membrane pore structure; the coupled heat and mass transfer mechanisms, and the development of interfacial gradient of temperature and salt concentration (referred to as temperature and concentration polarization, respectively) are all contributing to the difficulty in estimating MD membrane performance.

In the MD-specific research, the membrane performance has been estimated by a range of different techniques, which can be divided into two main categories. The first category includes all techniques used to estimate individual membrane parameters such as average pore size, porosity, tortuosity, thickness, etc. The second category includes techniques that estimate the overall performance of the MD membrane without paying attention to the individual characteristics of the membrane structure. Both categories have their own advantages and disadvantages. For example, determining membrane performance through their individual characteristics is considered fairly cumbersome and subject to high percentage of errors in their measurements, which are expected to increase when the individual parameters are applied in the mass transfer mechanistic equations (viscous, Knudsen and diffusion flow equations) to determine membrane mass transfer performance. On the other hand, the first category techniques are essential for finding