Desalination 378 (2016) 14–27

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

A stepwise model of direct contact membrane distillation for application to large-scale systems: Experimental results and model predictions

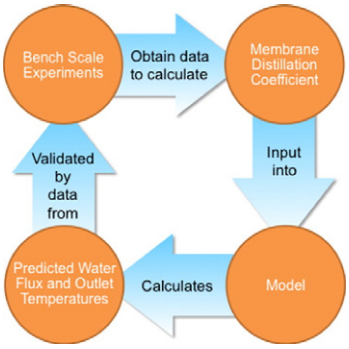
Ryan D. Gustafson [a], Joanna R. Murphy [b], Andrea Achilli [b,*]

[a] Sonny, Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089, USA
[b] Environmental Resources Engineering Department, Humboldt State University, Arcata, CA 95521, USA

HIGHLIGHTS

- A simplified membrane distillation coefficient calculation method is validated.
- A stepwise modeling approach is shown to accurately model large-scale DCMD membrane modules.
- A new spacer modeling method accounts for woven spacers with complex geometries.
- Distribution of water flux, temperature and concentration along the membrane are modeled.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form 15 September 2015
Accepted 21 September 2015
Available online 30 September 2015

Keywords:
Membrane distillation
Direct contact membrane distillation
Desalination
Membrane distillation coefficient
Heat and mass transfer modeling, Spacers

ABSTRACT

A model of mass and heat transfer in direct contact membrane distillation (DCMD) is presented. The distributions of water flux, temperature, and concentration in membrane module channels are modeled to provide cumulative water flux and outlet temperatures and concentrations. The membrane distillation coefficient (MDC)—a membrane-specific mass transfer coefficient—for a well-characterized PTFE membrane was shown to be accurately modeled as a constant value. The MDC was used with a stepwise modeling approach, in which the membrane area is discretized into multiple steps, to provide the distribution of process variables parallel to the membrane surface. A new generalized spacer modeling method was used to account for the presence of complex woven spacers in the flow channels, addressing a significant gap in the DCMD modeling literature. Model predictions showed good agreement with experiments in co-current and counter-current flow modes for different operating conditions and membrane sizes. The stepwise modeling approach was shown to be necessary for providing accurate mass and heat transfer predictions for large-scale DCMD modules, providing a useful tool for the design of large-scale DCMD systems.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Membrane distillation (MD) is a thermally driven liquid separation process that is used to distill water from an impaired feed water source [1]. Interest in MD has grown steadily in recent years due to the

* Corresponding author.
E-mail address: aa2767@humboldt.edu (A. Achilli).

http://dx.doi.org/10.1016/j.desal.2015.09.022
0011-9164/© 2015 Elsevier B.V. All rights reserved.

increased demand for clean water around the world [2]. MD is an attractive option for treatment and reuse of impaired water sources because of its high rejection and high compatibility with renewable energy and low-grade waste heat sources [3]. MD provides nearly 100% rejection of non-volatile feed solutes [4–8] and it has been investigated for application to a variety of feed water sources including seawater [6, 9–11], brackish water [12], produced water [13–15], and various wastewater streams [16–19]. The benefits of MD make it an ideal candidate for water separation applications where renewable energy or low-grade waste-heat sources are available.

In direct contact membrane distillation (DCMD), a microporous hydrophobic membrane separates a warm feed water stream from a cool distillate water stream, both of which are in direct contact with the membrane surface. Water flux in DCMD is a function of the transmembrane vapor pressure difference, which is induced by the difference in solution temperatures and—to a lesser degree—salinities on either side of the membrane. The vapor pressure difference across the membrane causes water at the feed membrane surface to enter the vapor phase, travel through the membrane pores, and condense upon contact with the distillate stream. The transfer of mass and heat across the membrane causes the formation of thermal boundary layers, in a phenomenon known as temperature polarization [8]. The transfer of mass across the membrane, combined with the nearly 100% rejection of feed solutes, causes the formation of a concentration boundary layer on the feed side of the membrane in a phenomenon known as concentration polarization [8]. The polarization effects result in the creation of thermal and concentration boundary layers [20,21] that reduce the vapor pressure driving force in DCMD, as shown in Fig. 1.

To calculate the water flux across the membrane, the transmembrane vapor pressure difference is multiplied by a membrane-specific mass transfer coefficient, known as the membrane distillation coefficient (MDC) [22]. The MDC is often modeled by either Knudsen diffusion, molecular diffusion, Poiseuille flow, or a transition between two or more of these mass transfer mechanisms [23]. These mechanisms are viewed as mass transfer resistances that can be arranged in different combinations of series and parallel resistances, by employing the electrical circuit analogy [4,24]. The Dusty Gas Model [25–27] is the most frequently used arrangement of these mass transfer resistances [3,28]. Poiseuille flow is typically neglected in DCMD because these systems are typically operated with a negligible total pressure difference across the membrane [3,28], though some researchers have demonstrated Poiseuille flow to be a relevant mechanism of mass transfer in DCMD [29–32]. Ding et al. [23] explained this type of behavior by demonstrating that the dominant mass transfer mechanism in DCMD may change from one membrane to another, depending on membrane characteristics. For example, they indicated that two different mechanisms can provide almost identical results for a membrane with a smaller average pore size, but provide very different results for a membrane with a larger average pore size. To account for differences in mass transfer mechanism dominance for different membranes, many researchers have begun to use the ratio of the mean free path of water vapor in air to the membrane pore diameter, or Knudsen number, to select the appropriate arrangement of mass transfer resistances [3,33]. While use of the Knudsen number does increase the viability of the mass transfer resistance models, the large number of unknowns within these models requires extensive independent experiments to be performed [34], and the complexity of these equations leads to long computation times. The uncertainty associated with calculation of membrane characteristics, which are heavily used in the mass transfer resistance models, adds to the difficulties associated with using these models [31,33,35].

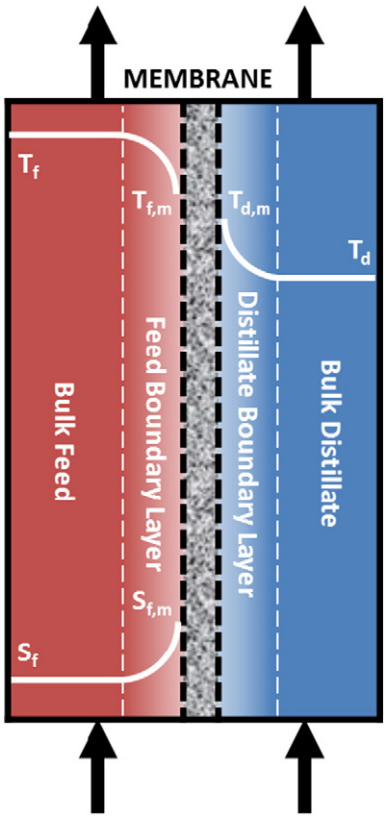


Fig. 1. Temperature and concentration polarization cause the formation of boundary layers that reduce the driving force of the DCMD process. T_f and T_d are the bulk feed and distillate temperatures, respectively; $T_{f,m}$ and $T_{d,m}$ are the membrane surface temperatures in the feed and distillate, respectively; and S_f and $S_{f,m}$ are the feed salinities of the bulk solution and the solution at the membrane surface, respectively.

The results of some researchers have indicated that the MDC can be assumed to be constant for some membranes [13,22,36]—indicating the possibility of a much simpler modeling alternative to the mass transfer resistance models. The mass transfer resistance models are functions of membrane characteristics, operating pressures, and the average membrane temperature [22]. Membrane characteristics are constant and no total pressure gradient exists in DCMD, as the feed and distillate streams are both maintained near atmospheric pressure [3,4,28]. The average membrane temperature can vary greatly due to the range of feed and distillate temperatures that can be employed in DCMD. However, Phattaranawik et al. [22,36] showed that the MDC can be assumed to be constant with feed temperatures ranging from 40 to 70 °C and a 20 °C distillate temperature, for the three membranes tested. Sirkar et al. [13] showed that a constant MDC can also be assumed for produced water temperatures between 110 and 125 °C for the PTFE membrane tested. If the MDC can be assumed to be constant, with negligible error in model predictions, then modeling of DCMD becomes much more accessible and therefore much more practical.

Another factor that strongly defines the practicality of a DCMD model is the ability to provide accurate predictions for large-scale systems. For a model of DCMD to be applicable to large-scale systems, it must account for changes in operational variable values—such as temperature, flow rate, and salinity—along the length of the membrane. Most of the earlier models of DCMD neglected the changing nature of operational variables from inlet to outlet, instead relying on inlet or average conditions for calculation across the entire membrane area [22,23, 28,33,37,38]. Neglecting the changing nature of operational variable values along the length of the membrane may produce little error at the bench-scale, but is likely to introduce significant error in more realistic, large-scale membrane modules. More recent models of DCMD have attempted to account for the variation of operational variable values along the length of the membrane by employing stepwise modeling approaches. Manawi et al. [37,39] used a stepwise approach and iterative solution method with Microsoft Excel's Solver to develop flux and temperature profiles along the length of the membrane.

Download English Version:

https://daneshyari.com/en/article/622948

Download Persian Version:

https://daneshyari.com/article/622948

Daneshyari.com