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Electrical equivalent thermal network for direct contact membrane distillation modeling and analysis

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ABSTRACT

Membrane distillation (MD) is an emerging water desalination technology that offers several advantages compared to conventional desalination methods. Although progress has been made to model the physics of the process, there are two common limitations of existing models. Firstly, many of the models are based on the steady-state analysis of the process and secondly, some of the models are based on partial differential equations, which when discretized introduce many states which are not accessible in practice. This paper presents the derivation of a novel dynamic model, based on the analogy between electrical and thermal systems, for direct contact membrane distillation (DCMD). An analogous electrical thermal network is constructed and its elements are parameterized such that the response of the network models the DCMD process. The proposed model captures the spatial and temporal responses of the temperature distribution along the flow direction and is able to accurately predict the distilled water flux output. To demonstrate the adequacy of the proposed model, validation with time varying and steady-state experimental data is presented.

1. Introduction

Membrane distillation (MD) is a thermally driven distillation process combined with a membrane separation technique. In this process, a hot feed stream is passed along one side of a hydrophobic membrane, which is only permeable to water vapor and retains liquid water, whereas the other side is kept at a lower (cooler) temperature. Due to this temperature difference across the membrane, water evaporates at the feed-membrane interface and the induced partial vapor pressure difference drives only water vapor through the membrane where the vapor condenses at the cold permeate side of the membrane. MD has three main configurations each with its strengths and weaknesses. A schematic diagram of direct contact membrane distillation (DCMD) is shown in Fig. 1, where both the hot feed and cold permeate streams are in direct contact with the membrane. Another configuration is the air gap membrane distillation (AGMD), in which the permeate stream is separated from the membrane by a stagnant air gap. The third setup is vacuum membrane distillation (VMD), where a vacuum is applied at the permeate side in order to enhance flux transfer [1].

MD requires low-grade heat which can be harvested from solar thermal energy and other renewable or waste heat sources [2]. Also, unlike the well-known reverse osmosis (RO), MD operates at a lower water pressure which in turns reduces the capital and operational costs. All these advantages make MD ideal for remote area desalination plants installations with minimal infrastructure and less demanding membrane characteristics [3]. However, MD is faced with challenges that are yet to be addressed in order for this technology to be competitive with conventional desalination techniques.

In recent years, renewable energy has been integrated into many water desalination technologies, such as RO and MD. However, the unsteady nature of renewable energy sources poses a challenge which requires special attention when coupled with a desalination process. This effect has to be considered when modeling the process and designing control strategies. While several model-based control techniques have been successively applied on the RO process [4–7], MD still lacks dynamical models that can be adopted for control applications. Therefore, to ensure successful and economical operation of solar-powered membrane distillation (SPMD), the development of a dynamical model for MD that can be used for control purposes is essential.

As a result of spatial and temporal dependency of MD processes, modeling such systems can be quite complicated. Previous studies on MD modeling fall into three main approaches. The first approach

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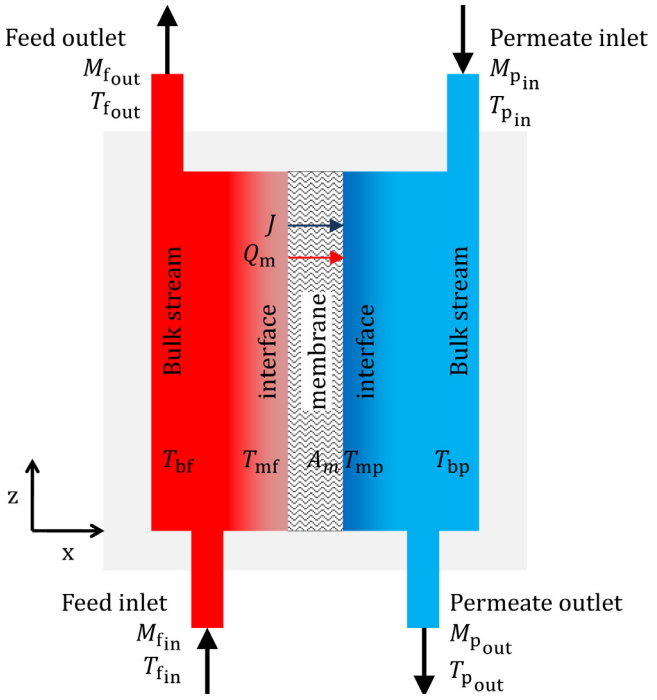

Fig. 1. Schematic diagram of DCMD module showing across sectional view of the setup and the relevant variables of the process.

is based on empirical models that are dimensionless in space and steady in time [8,9]. The second approach accounts for the spatial variations of the process but it's steady in time, e.g. in [10] mass and energy conservation laws were used to develop models for DCMD, AGMD, and VMD. Whereas in [11] the steady-state laminar Navier–Stokes equation was used for momentum balance coupled with energy and mass balance equations to study DCMD. The third approach considers the time response of the MD process, e.g. in [12] a black box model based on artificial neural networks was identified for SPMD. Few studies have proposed dynamic models based on partial differential equations (PDEs), like [13] where the AGMD configuration was considered and in [14] where the advection–diffusion equation was used to model DCMD process.

There are two common limitations of reported models. Firstly, models that are based on steady-state analysis lack the temporal dimension. Secondly, having a PDE based model poses some challenges the control design and the computational requirements. The lacking of dynamic models for MD that can be adopted in control design and applications is the main motivation for this study. Unlike black box models, this work aims at developing a dynamic physical model that gives more insight into the intrinsic variables of the MD process. Using analogy between electrical and thermal systems, an electrical thermal network (ETN) model is derived and parameterized for DCMD. The proposed model captures the distributed nature of heat and mass transfer processes in DCMD. In this paper, DCMD configuration was chosen because of its simplicity and the availability of a DCMD experimental setup in our laboratory at the Water Desalination and Reuse Center (WDRC) at KAUST. Also, DCMD has the largest number of paper published in refereed journals, according to [1]. Moreover, the proposed model can easily be adapted for other MD configurations.

The proposed model accounts for the temperature gradient and calculates the local water vapor flux values along the flow direction in both feed and permeate channels. It also considers the thermal boundary layers formed at the membrane interfaces. In general, lumped-parameter models offer simplicity to study complex systems and facilitate simulations, at the same time they are reduced order versions of somewhat an equivalent PDE models. These models also preserve the controllability and observability properties of the system, which could be lost when discretizing the PDE models due to the introduction of many states that are not observable in practice. Indeed, electrical-analogy based models have been used to describe the dynamic behavior of many industrial and biological systems such as heat exchangers [15], and the human cardiovascular system [16]. Moreover, it was shown that the transient diffusion phenomena and the heat transfer due to non-steady fluid flow can be described by an electrical analogue model, see [17,18] respectively. Literature above motivated the method presented in this paper.

This paper is organized as follows. In Section 2, the underlying concepts of mass transfer are given followed by a presentation of the general idea of the proposed approach to model heat transfer. Then, an electrical thermal network analog to DCMD system is designed in Section 3. The final equations for the DCMD system based on the electrical analogy are derived in Section 3.3. The proposed model is validated against experimental data in Section 4. Section 5 summarizes the obtained results.

2. Direct contact membrane distillation

2.1. System description

A schematic diagram of the direct contact membrane distillation is shown in Fig. 1, (refer to Appendix A for the nomenclature description). In this configuration, hot water is passed along a hydrophobic membrane from one side, called the feed, and cold water flows in the counter direction along the other side, which is called the permeate. Water vapor is driven from the feed side across the membrane and into the permeate side by the induced partial vapor pressure difference. Both heat and mass transfer processes occur simultaneously as water evaporates at the feed-membrane interface and condenses at the permeate–membrane interface. As a result, the temperature at the membrane boundary layers differs from the bulk temperature of the feed and permeate streams, this is known as the temperature polarization effect. This effect reduces the mass transfer driving force, and as a result lowers the production rate of the system. The mass and heat transfer processes are described in more details in the following subsections.

2.2. Mass transfer in DCMD

The transport phenomena are described by the classic gas permeation and heat transfer theories. The mass flux (J) in DCMD is related to the saturated vapor pressure difference across the membrane ΔP through the membrane mass transfer coefficient B_m as follows [19]

$$J = B_m \Delta P = B_m(P_{mf} - P_{mp}). \tag{1}$$

The mechanism dominating the mass transfer through the porous membranes depends on the pore radius (r) and the mean free path of the vapor molecules (λ). For membranes with pore radius in the range of $0.5\lambda < r < 50\lambda$, the membrane mass transfer coefficient is expressed as a parallel combination of Knudsen diffusion (B_{Kn}) and molecular diffusion (B_D) coefficients [8] given by

$$B_m = \frac{1}{1/B_{Kn} + 1/B_D}, \tag{2}$$

where (T in K):

$$B_{Kn} = \frac{4}{3}\frac{\varepsilon r}{\chi\delta}\sqrt{\frac{2m_w}{\pi\bar{R}T}},$$

$$B_D = \frac{\varepsilon r}{\chi\delta}\frac{PD}{P_a}\frac{m_w}{\bar{R}T}.$$