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A predictive model for the assessment of the temperature polarization effect in direct contact membrane distillation desalination of high salinity feed

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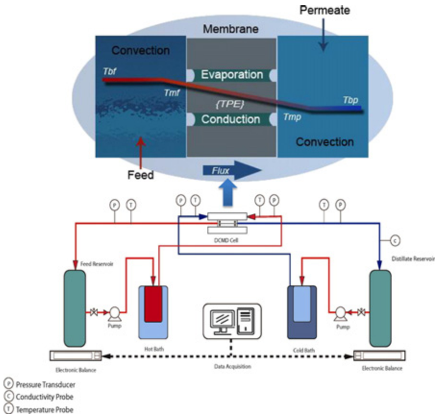
HIGHLIGHTS

- Predictive DCMD model for the assessment of temperature polarization effect
- Insight into local and global temperature polarization in DCMD
- Model prediction of flux and temperature profiles in the axial direction of flow
- Comparison of model predicted axially averaged flux and experimental flux
- Accurate prediction of temperature profiles under a wide range of conditions

GRAPHICAL ABSTRACT



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ABSTRACT

Temperature polarization is one of the major sources responsible for flux drop in membrane distillation systems due to the reduction in the driving force across the membrane. The present study offers a predictive model developed for the estimation of the temperature polarization coefficient across the membrane taking into consideration the simultaneous heat and mass transfer phenomena. The uniqueness of the developed model is its ability to predict the intermediate temperatures (temperatures along the flow path of the membrane sheet) which can be used to estimate the local flux and local temperature polarization coefficients as opposed to the methods used by others which estimate the TPC, using the average bulk temperatures, resulting in a tool that enables the estimation of the temperature polarization coefficient (TPC) at different operating conditions. It was found that higher feed temperatures result in higher temperature polarization effect and hence a lower TPC. It was also observed that TPC increases with feed flow rate. The highest TPC value of 0.82 was achieved for a flow rate of 3 L/min and a feed–permeate temperature system of 60–20. The use of flow promoters further enhances the performance of the DCMD system and was reflected on increasing the TPC values (0.66 for a spacer filled channel compared to 0.47 for a spacer free operation) at 1.5 L/min flow condition with 70–30 temperature system. The axially integrated local flux values predicted by the model were in good agreement with the experimentally measured fluxes.

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1. Introduction

Although nearly 71% of Earth is covered with water less than 3% is suitable for human consumption. Around the world, water is not evenly distributed among the nations and many arid countries are classified below the world's water-poverty line [1]. The Arabian Gulf region is considered as one of the most water-stressed zones in the world with less than 1% of the world's available freshwater and around 6% of its population. In the Gulf Cooperation Countries (GCC), an average water consumption of 400 L per capita was recorded in 1980 compared to 700 L per capita in 2013; an increase due mainly to the change in life standards and industrial advancements [2]. This increase in the water demand was not consistent with the population growth during the same period; the water consumption has increased by four fold while the population growth has increased by only two fold. Due to the water scarcity in the GCC, most of the freshwater supplies come from desalination plants (via thermal or membrane desalination).

Desalination is an energy intensive process that removes dissolved salt and other minerals from saline water in order to produce higher quality water fit for industry, agriculture or human consumption. The energy required for desalination is generated by combusting fossil fuels, thus adding to the footprint of this industry and its environmental impacts. In addition, more than two-thirds of the energy supplied to thermal desalination plants is wasted [3] in the form of cooling water or flue gases. In fact the amount of energy consumed in desalination plants largely depends upon the technology used. In order to produce 1 m^3 of distilled water using multi-stage flash distillation (MSF), 12 kWh thermal energy, 3.5 kWh electrical energy and a maximum temperature of 120 °C are required compared to 6 kWh thermal energy, 1.5 kWh electrical energy and a maximum temperature of 70 °C to produce the same amount of distilled water using MED process. In contrast, Reverse Osmosis (RO) technology has the lowest energy consumption. RO requires between 4 and 7 kWh of energy to produce 1 m^3 of water and this value depends on the size of the plant and the extent of energy integration of the process [3]. With this in mind, technologies lending themselves for the use of reject, waste or solar energy to produce or augment the production of drinking water are desirable. Membrane distillation (MD) desalination is one such emerging technology. The most distinctive feature of MD is its driving force. The driving force for MD is the water vapor pressure difference across the membrane while the driving force for other membrane technologies is the difference in the total pressure. The membranes used for MD are hydrophobic allowing water vapor to pass but not liquid water. To evaporate the water, there has to be a pressure gradient, which is obtained by heating up the water to increase its vapor pressure. Low-grade waste heat or solar energy can be used to heat up the hot side that will increase its vapor pressure before being introduced into the membrane module. The heat of condensation is sometimes recovered and utilized to preheat the incoming feed water, which will further reduce the amount of energy used in such multi-stage membrane operations.

Several arrangements have been identified to set the vapor pressure difference across the two sides of the membrane: direct contact membrane distillation (DCMC), air gap membrane distillation (AGMD), sweep gas membrane distillation (SGMD) and vacuum membrane distillation (VMD). In fact all of the previous techniques share the same principle; contacting the feed water with the hot side of the membrane, which allows the water vapor to penetrate through the membrane pores but not the solution. DCMD is the most studied configuration due to its inherent simplicity and setup involved. There are several factors affecting flux from the MD process including feed temperature, inlet concentra\tions, circulation velocity and stirring rate as well as permeate inlet temperature, velocity, vapor pressure difference and membrane properties. Each one of the above factors directly, or indirectly, affects the performance of the membrane thermal (heat transfer) and flux performance (mass transfer) [4]. The retained solutes accumulate at the membrane surface where their concentrations gradually increase at the interface and decrease at the bulk. Concentration build-up generates a diffusive flow back to the bulk of the feed. At steady state, the flow of the convective solute to the membrane surface is balanced by the diffusive flux flow of the solute from the membrane neighborhood to the bulk. In summary, the solute concentration is higher at the interface of the membrane compared to that in the bulk solution; a phenomenon referred to as *concentration polarization* (CP). CP tends to reduce the transport rates across the membrane because, for a given pressure difference and since the transport rates are inversely proportional to the concentration difference across the membrane, this tends to reduce the permeate flux [5–7]. With simultaneous heat and mass transfer taking place across the membrane (Fig. 1(a)) the thermal boundary layer, located just adjacent to the membrane surface, creates a heat resistance and makes the temperature at the liquid–membrane interface lower than that at the bulk of the feed; reducing the driving force as a result. This is considered as one of the most important factors responsible for flux reduction in the MD which also has a higher effect on reduction of flux in comparison to the CP effect. In fact, it has been reported that up to around 80% drop in the driving force can be attributed to the so-called *temperature polarization effect* (TPE), expressed mathematically using the term temperature polarization coefficient (TPC) in Eq. (1) [5,8]. TPC is the ratio of the trans-membrane temperature difference to the bulk temperature difference or the ratio of the temperature difference across the membrane element (on the feed and permeate liquid/vapor interface) to the difference between the feed and permeate bulk temperatures.

$$TPC = \frac{T_{fm-T_{pm}}}{T_{fb}-T_{pb}} \tag{1}$$

Temperature polarization effect is one of the largest sources of flux drop in MD systems [8,9]. The estimation of temperature polarization coefficients helps in further understanding the heat and mass transport phenomena in the MD. Schofield et al. [9] have developed basic equations in order to model the simultaneous mass and heat transfer in membrane distillation and were among the first to introduce the term *temperature polarization* and attract considerable attention to these phenomena. However, much of the body of the literature in membrane distillation was experimental and the few modeling contributions reported were limited in scope while recognizing the importance of temperature and concentration polarization in membrane distillation.

In the literature, reported mathematical formulations were mostly developed using a two-dimensional heat and mass transfer equation to simulate a particular application more accurately [7]. The main predictions were related to estimating water productivity from DCMD processes and used the experimental data to correlate the membrane-based parameters (such as the membrane coefficient) to the system-based parameters including the vapor pressure difference. Many researchers used bulk temperature to represent interfacial temperature with the heat transfer correlation in order to estimate the heat transfer coefficients at restricted boundary conditions resulting in deviations from real data due to the temperature polarization effect. Accordingly detailed models to predict the temperature polarization coefficient with respect to the system's intermediate temperatures are needed. Once intermediate temperatures and membrane surface temperatures are predicted, temperature flux mechanisms can be evaluated. This leads to accurate estimations of the mass flux and heat transfer coefficients and ultimately proper prediction and optimization of design and operational parameters.

In this work, a DCMD multi-dimensional model has been formulated and solved to provide local information such as hot and cold side temperatures and flux and temperature polarization coefficients. The intermediate temperatures will be estimated and used to predict the local temperature polarization coefficients at various axial positions along the flow in a direct contact membrane distillation cell specially designed