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Design strategy for networking membrane module and heat exchanger for direct contact membrane distillation process in seawater desalination

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HIGHLIGHTS

- A numerical simulation is achieved to evaluate the performance of membrane distillation.
- Different membrane distillation coefficient was considered to verify the simulation.
- We suggest a design tool for selecting competitive technology for desalination.

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ABSTRACT

An energy-efficient design strategy for networking membrane modules and heat exchangers in membrane distillation (MD) process was developed in this work. A numerical simulation model was used to describe heat and mass transfer in direct contact type MD membrane module. Mass transfer coefficients were evaluated under different feed flow rates and feed temperatures. Feed flow rate had the predominant effect on the mass transfer coefficient, while feed temperature had a minimal effect. Thus, an empirical equation for the mass transfer coefficient relative to feed flow rate was employed in the simulation to estimate flux and outlet temperatures of membrane module. This approach was verified by two-stage module test results, which showed a good correlation with simulation results. After comparison of different unit process designs, a desired one including partial brine recycle scheme was selected due to the highest efficiency of energy utilization. Replications of a selected unit process will be useful for design of a large scale MD process.

1. Introduction

Membrane distillation (MD) is an emerging technology that holds interest in application of seawater desalination due to the minimal flux decline at high salt concentration and the availability of low-grade waste heat [1,2]. MD is a non-isothermal transport process of water vapor through a porous hydrophobic membrane while other membrane processes for water treatment are isothermal. This process involves simultaneous heat and mass transport across the membrane. Direct contact membrane distillation (DCMD) is a type of membrane distillation process in which condensing distillate is in contact with the membrane [3]. In this process, the vapor pressure difference between hot brine and cold distillate drives transport of vapor. Therefore, vapor flux of DCMD is often described by a mass transfer coefficient and a vapor pressure difference as follows [4],

$$N = C \times \Delta P = C \times \left(P_{fm} - P_{dm}\right) \tag{1}$$

where N is the vapor flux [kg/m^2.h], C is the mass transfer coefficient [kg/m^2.s.Pa], ΔP is the vapor pressure difference [Pa], P_{fm} is the vapor pressure at the membrane surface in the feed side, and P_{dm} is the vapor pressure at the membrane surface in the distillate side.

The mass transfer coefficient cannot be easily obtained because the temperature of the membrane surface cannot be directly measurable. For convenience, some researchers [5,6] used a different transfer coefficient relative to the measurable quantities as follows,

$$N = C' \times \left(P_f - P_d\right) \tag{2}$$

where C' is the global mass transfer coefficient [kg/(m^2.h)], P_f is the vapor pressure of the feed side [Pa], and P_d is the vapor pressure of the distillate side [Pa]. Bulk temperatures in feed side and in distillate side are often estimated by the average of inlet and outlet temperatures in each side. The vapor pressure difference is calculated from bulk temperatures in each side with Antoine equation. Zhang mentioned that this method could be used after constructing a set of database for outlet temperatures in a specific module with given operating conditions [6].

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Many researchers used numerical simulation method to predict flux and outlet temperatures of MD module [1,7,8]. In this method, heat and mass transfer of infinitesimal elements of membrane are described by theoretical equations based on film theory. If mass transfer coefficient is known, the vapor pressure at the membrane surface within an element can be calculated by the integration of differential equations with steady state approximation. The heat and mass transfer in each element are integrated with recurrence relationships to explain those in a membrane, which in turn are used to estimate those in a module. Therefore, estimation of mass transfer coefficient is the most important step before doing numerical simulation of MD module.

There is some literature mentioning the dependence of operating conditions on mass transfer coefficients. It is reported that temperature dependence of mass transfer coefficient was well approximated by Clausius–Clayperon equation in a temperature difference below 10 °C [9]. Schineider et al. observed that mass transfer coefficients increased exponentially as feed temperature increased from 70 to 90 °C [10]. Hwang et al. [11] noted that mass transfer coefficient increased with feed flow rate at feed temperature of 60 °C, while it was kept constant at feed temperature of 40 °C regardless of feed flow rates. It is worth investigating the effects of operating conditions on the mass transfer coefficient systematically, because these effects are not clearly understood with a limited number of literature.

In MD process design, a number of heat exchangers and membrane modules are connected in a series or in parallel for high distillate production with low energy consumption. Girlon et al. suggested a method similar to McCabe–Thiele diagram with empirical equations between brine temperature drop between stages and temperature differences across the membrane for design of multi-stage DCMD module [12]. Lu and Chen proposed the use of a superstructure model, which includes all possible routes of streams, for optimization of multi-stage AGMD (Air gap membrane distillation) module [13]. The energy efficiency of an MD system in terms of gained output ratio (GOR), defined as the ratio of distillate production to the external steam input (typically used in distillation processes), is 0.3–0.8 in one article [14] and are 2–9 in another [12]. The differences were caused not only by the different operating conditions, but also by the different arrangements of membrane modules and heat exchangers. The effects of different process designs on GOR have not been discussed much in the literature.

The objective of this work is to derive a design strategy for MD process. We assumed that mass transfer coefficient is a key factor to determine performance of membrane module. Thus, research efforts were made to correlate mass transfer coefficients with operating conditions. Numerical simulation method was used to evaluate the performance of membrane modules and energy utilization efficiency in different arrangements of membrane modules and heat exchangers for MD process.

2. Numerical simulation

Numerical simulation method was used to calculate mass transfer coefficients and to predict the performances of the module (flux, feed outlet temperature, and distillate outlet temperature). A crossflow type DCMD module [15] was considered in the simulation by stacking layers of many fibers as described Fig. 1. Numerical analysis of this type of module was performed in two directions, x and y. *x* is the location across the length of fibers and the y is the j^{th} layer of the fibers. We assumed that there was no lateral mixing in x-direction in this type of module.

2.1. Heat transfer in feed side

Heat transfer of the feed (shell) side was described by the following equation:

$$\left(\frac{dQ_f(x)}{dx}\right)_j = h_f A_{rf} \alpha \left(T_{f,j}(x) - T_{fm,j}(x)\right) \tag{3}$$

where $A_{rf} = \left(\frac{d_o}{d_i}\right)$, $\alpha = n_j \pi d_i$

Feed side heat transfer coefficient was calculated by the Zukauskas [16] correlations (Eqs. (4a) and (4b)). These correlations are used to describe shell side heat transfer of staggered tube bundle in crossflow type heat exchangers. Song et al. claimed that these equations described

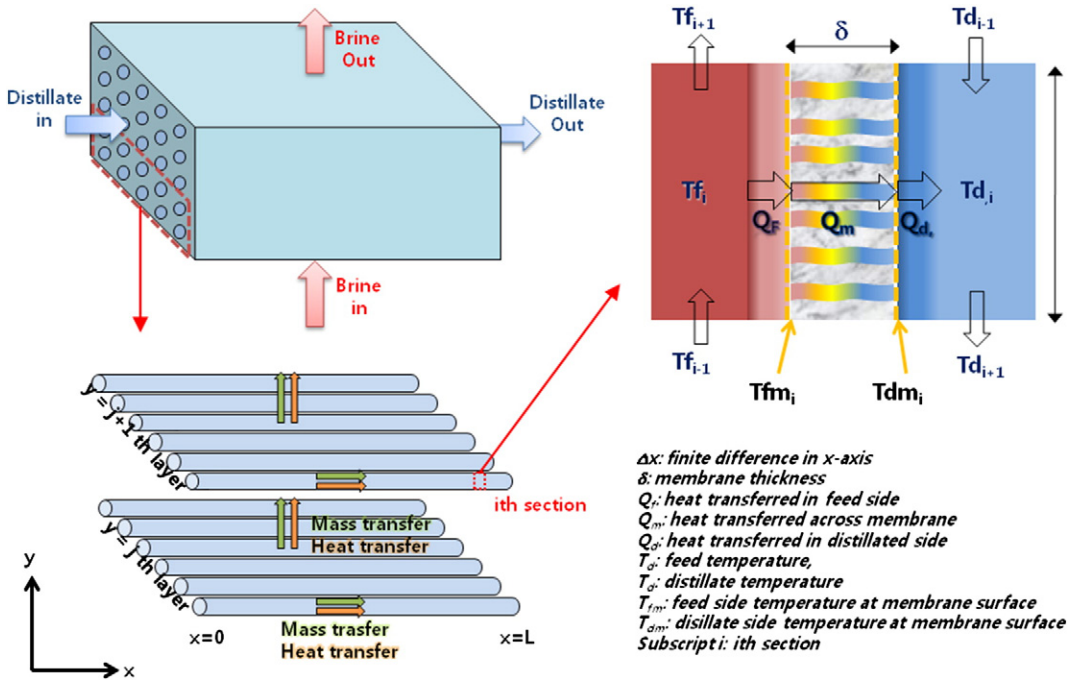

Fig. 1. Numerical Analysis model of membrane module.