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Heat and mass transfer enhancement in a cross-flow elliptical hollow fiber membrane contactor used for liquid desiccant air dehumidification

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ABSTRACT

To improve the performances of a hollow fiber membrane contactor (HFMC) employed for liquid desiccant air dehumidification, an elliptical hollow fiber membrane contactor (EHFMC) is proposed. The contactor is assembled by a collection of elliptical hollow fibers populated in a shell. The liquid desiccant and the processing air streams flow inside and across the elliptical fibers, respectively. They are in a cross-flow configuration. The momentum and the conjugate heat and mass transports in the EHFMC are investigated based on Happel's free surface model. In this approach, a single elliptical fiber, an air stream across the fiber, and a liquid desiccant stream inside the fiber are selected as the calculating element. The air stream in the element is encompassed by a hypothetical outer free surface with an elliptical shape. The equations governing the momentum, heat and mass transports in the air and the solution streams are established and solved together with the conjugate heat and mass transfer boundary conditions. The fundamental data of the friction factor, Nusselt and Sherwood numbers in the element are then numerically calculated, experimentally validated, and analyzed. These basic data are compared with those obtained in the HFMC.

1. Introduction

It has been known that there is a substantial shortcoming of liquid desiccant droplet entrainment encountered in the traditionally direct-contacting liquid desiccant air dehumidification technology, which has limited its development in a large extent. To address this problem, a hollow fiber membrane contactor (HFMC) has been employed extensively for realizing liquid desiccant air dehumidification [1–6]. The air and the liquid desiccant streams are separated from each other by the semi-permeable membranes, which only guarantee the permeation of water vapor but prohibit the transports of liquid solution and other unwanted gases [7,8]. So the liquid desiccant droplets, which are rather harmful to indoor environment, can be completely prevented.

The HFMC is designed and assembled by a collection of elliptical hollow fiber tubes populated in a plastic shell. The concept is similar to a traditional metal-formed shell-and-tube heat exchanger. The inner tubes form the tube side, and the voids between the fiber tubes form the shell side. The liquid desiccant stream flows in the tube side (inside the tubes), while the air stream flows in the shell side (outside the tubes) in a cross-flow configuration. To save energy and control economic cost, enhancing the heat and mass transfer in the HFMC is an efficient method. Further, transformations of the circular cross-sectional hollow fibers to elliptical cross-sectional ones may be a good alternative without any other additions of enhanced fins and components [9]. Therefore an elliptical hollow fiber membrane contactor (EHFMC), as shown in Fig. 1, is designed for liquid desiccant air dehumidification. An elliptical hollow fiber membrane tube bank is placed in the shell space. The processing air stream flows across the elliptical fibers, while the solution stream flows inside the fibers.

It is obvious that the structure of the EHFMC is like a cross-flow shell-and-tube heat exchanger with elliptical tubes. Heat and mass transfer in the EHFMC is the focus in present study. The transport phenomena in the EHFMC have not been sufficiently studied. It is because the air and the solution streams are conjugated together through the membrane. The membrane surface boundary conditions are neither uniform values (temperature or concentration) nor uniform fluxes (heat flux or mass flux) conditions. It is a conjugate problem which has not been taken into account seriously. Further, the features of the heat and mass transfer intensification under the conjugate boundary conditions have not been mentioned before.

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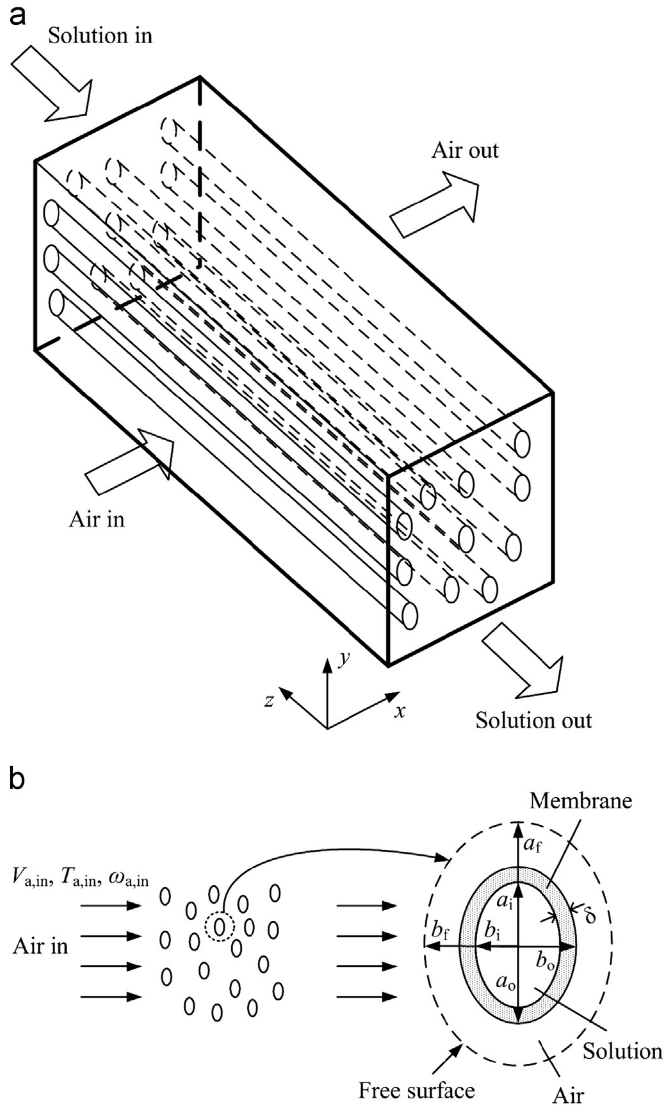

Fig. 1. Schematic of a cross-flow elliptical hollow fiber membrane contactor (EHFMC). (a) The shell and the tube structure of the contactor and (b) the free surface unit cell.

The novelties in present study are that the fluid flow and the conjugate heat mass transfer in the EHFMC are investigated. Happel's free surface model is adopted to establish the calculating element. The equations governing the momentum, heat and mass transports in the element are proposed and numerically solved together with the conjugate heat mass transfer boundary conditions. The friction factor, Nusselt and Sherwood numbers are calculated and experimentally validated. The basic data are compared to those in the HFMC. Heat and mass transfer enhancement in the EHFMC for liquid desiccant air dehumidification are disclosed and analyzed. Further, the results provide fundamentals for performance improvement and structural design of the EHFMC.

2. Mathematical model

2.1. Governing equations

The cross-flow EHFMC, as shown in Fig. 1(a), is used for liquid desiccant air dehumidification. The air and the solution streams flow in the tube side (inside the elliptical fibers) and in the shell side (outside the fibers), respectively. They are in a cross-flow configuration. To disclose the transport phenomena in the EHFMC, the whole elliptical tube bank selected as the calculating domain may be the most accurate approach. However, there are commonly 500–3000 elliptical fibers in a $10 \times 10\,\text{cm}^2$ cross-sectional contactor. Therefore the direct prediction based on the whole tube bank is difficult to conduct. Further, this method is rather computation-intensive and time-consuming. In order to address this problem and for reasons of easiness, Happel's free surface model [10,11] is employed. Although this approach is ideal and coarse, it has been commonly used to predict the fluid flow and heat mass transfer across the tube bank [10,11]. According to this approach, the tube bank is considered to be formed by a collection of elements with frictionless free surfaces. There is a single elliptical fiber in the middle and is encompassed by a hypothetical air fluid envelope with an elliptical shape. The packing fraction of the element, which ranges from 0.0 to 1.0, is equal to that of the whole tube bank in the contactor. In the element with an outer free surface, the elliptical semiaxis of the outer free surface in the y-axis and x-axis can be obtained by [10,11]

$$a_f = a_o \left(\frac{1}{\varphi}\right)^{1/2}, \quad b_f = a_f \frac{b_o}{a_o} \tag{1}$$

where a_o and b_o are elliptical semiaxis of fiber outer surface in the y-axis and x-axis (m), respectively, φ is packing fraction of the contactor, which can be calculated by

$$\varphi = \frac{n_{fiber}\pi\, a_o b_o}{WH} \tag{2}$$

where n_{fiber} is number of fibers, W is contactor shell width (m), and H is contactor shell height (m).

In the EHFMC, the air and the solution streams are in a cross-flow configuration. Due to the symmetry of the selected element and simplicity in simulations, only half of the element is selected as the calculating domain. The coordinate system of the element is presented schematically in Fig. 2(a). As seen, the solution flows along the z-axis inside the elliptical channel, while the air flows along the x-axis across the elliptical fiber. The air stream is approaching the elliptical fiber with a constant and uniform velocity $V_{a,in}$, at a uniform temperature $T_{a,in}$ and a uniform humidity ratio $\omega_{a,in}$ [1–3].

The air and the solution flows are assumed laminar. It is valid since the Reynolds numbers for the two flows are relatively small (<300) in most practical applications [1]. Other assumptions are made:

(1) The thermal–physical properties of the fluids such as density, viscosity, thermal conductivity, and specific heat capacity are assumed constant [12].
(2) The air flow is assumed two-dimensional because of the relatively large fiber length ($L = 30$ cm) compared with the elliptical semiaxis (around 600 μm). In other words, this assumption means that the variables of the air flow (velocity, temperature and humidity) are only the functions of x and y, and are independent of z [10,11].
(3) The solution flow is considered to be hydrodynamically fully developed, thermodynamically and concentrationally developing [13,14].
(4) Heat conduction and mass diffusion for the air and the solution flows are negligible compared to energy transport and mass convection by bulk flows since the Peclet numbers for the two flows are larger than 10 [15,16].

For the air stream over the single elliptical fiber (air side), the governing equations are comprised of the continuity equation, Navier–Stokes equations, energy and species mass conservation