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Effects of the random distributions on the longitudinal transport phenomena between an elliptical hollow fiber membrane bundle

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ABSTRACT

An elliptical hollow fiber membrane bundle (EHFMB), which is installed in a shell to form a counter flow tube-and-shell heat exchanger like hollow fiber membrane contactor, is commonly used for air humidity control. EHFMB is usually randomly packed in practical applications because of the randomness in the assembly process. The longitudinal transport phenomena between a randomly distributed elliptical hollow fiber membrane bundle (REHFMB) are studied. To disclose the effects of the random distributions on the transport phenomena, a unit cell containing 20 fibers based on Voronoi tessellation technology and the air flowing axially between the REHFMB is selected as the calculating domains. The governing equations governing the fluid flow and heat transfer between the REHFMB are established and numerically solved. The friction factor and Nusselt number in the unit cell under various fiber distributions, packing fractions (φ), rotation angles (β) and semiaxis ratios (b/a) are then obtained, analyzed, and experimentally validated. It can be found that the elliptical semiaxis ratios, the random distribution in positions, and rotation angles all have effects on the axial transport phenomena between the REHFMB. Further, the random distribution in positions is the dominant factor.

1. Introduction

Recently, membranes have been extensively employed for the processing air humidity control in heating, ventilation, and air conditioning (HVAC) applications [1–10]. Among them, a representative structure of an elliptical hollow fiber membrane bundle (EHFMB) has been proposed and used [7–10]. It is because a membrane contactor formed by the EHFMB has some obvious advantages compared to a conventional gas/liquid directly contacting device, including no entrainment of solution droplets, a large packing density, a promising effectiveness and an independent control of tube and shell side flow rates [11–13].

In a tube-and-shell heat exchanger like counter flow membrane contactor formed by EHFMB, the liquid stream flows inside the elliptical fibers (tube side), while the air stream flows between the fibers (shell side) in a pure counter flow arrangement. The fundamental data such as friction factor and Nusselt number in the contactor are of vital importance for its design. It has been known that the fluid flow and heat transfer inside the elliptical fibers (tube side) have many thorough investigations [14,15]. Therefore this study is focused on the shell side. In the shell side, the air stream flows axially between the fibers, which are probably randomly distributed because of its convenience in the manufacturing process. However, the longitudinal transport phenomena between the randomly distributed elliptical hollow fiber membrane bundle (REHFMB) have not been mentioned in literatures up until now. It should be noted that the axial fluid flow and heat transfer between a circular hollow fiber membrane tube bank have been experimentally and numerically investigated [16–22]. However the results are not suitable for the REHFMB. It is because their cross-sectional shapes are different. One is circular, and another one is elliptical. Therefore the influences of the elliptical semiaxis ratios and fiber distributions in positions and rotation angles on the axial momentum and thermal transports between the REHFMB should be disclosed.

The novelties in present study are the effects of the randomly distributed features on the purely axial transport phenomena between the REHFMB employed for air humidity control are investigated. The equations governing the momentum and heat transports for the air flowing longitudinally between the REHFMB are established and numerically solved by a commercial software FLUENT. The friction factor and Nusselt number are then numerically obtained, experimentally validated and analyzed. The results can provide basic data for structural design of the contactor formed by the REHFMB used for air humidity control.

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2. Mathematical model

2.1. Unit cell

As mentioned, the air stream flows axially between the REHFMB, which is comprised of a bundle of elliptical fibers. They are randomly distributed in the cross-section. In order to disclose the influences of the randomly populated features on the longitudinal fluid flow and heat transfer between the elliptical fibers, Voronoi tessellation is employed [23,24]. The concept is a mathematical modeling technology used to describe the subdivision of space between randomly packed points. It provides a method to calculate the geometric features of random spacing. Based on this technology, the randomly distributed elliptical fibers are divided into a series of polygonal cells, as depicted in Fig. 1. Each cell is consisted of one elliptical fiber and an air fluid around it, which is formed by straight boundaries equidistant between neighboring fibers. Therefore the overall transport properties for the whole random fibers can be approximated by the contributions of the individual cells [23,24]. It has been known that the elliptical fibers are numerous, usually 50–400 in a shell with a cross-sectional diameter of 4 cm [25,26]. Therefore a direct modeling of the whole fiber bundle is difficult to perform. To address this problem, a unit cell, which is the polygon encompassed by the bold line shown in Fig. 1, is selected as the calculating domain. As seen, the unit cell contains 20 elliptical fibers and the surrounding air fluid between the fibers. It should be noted that the fiber number used for numerical test is up to 50 in the unit cell. Further, the influences of the fiber number on the basic data of friction factor and Nusselt number will be evaluated to ensure that the results are independent of the fiber number. In the determined unit cell, the effects of the randomly packed features and the fiber-to-fiber interactions on the longitudinal transport properties between the whole REHFMB can be described.

In the unit cell, the central location and rotation angle (β) of each elliptical fiber in the REHFMB is random and mutually independent, which fit normally distributed nature [27]. Therefore a normally distributed random model [27] is employed to predict the random distributions of the elliptical fibers.

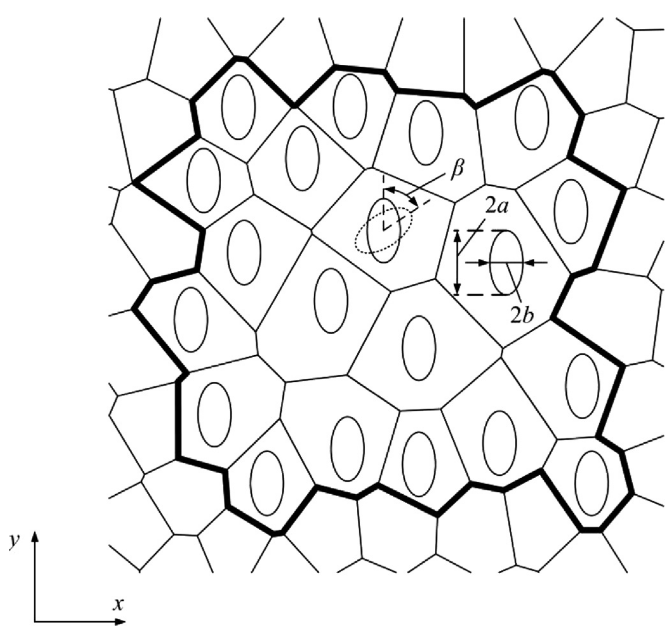

Fig. 1. The local cross-section of the randomly distributed hollow fiber membrane bundle (REHFMB). The area between the fibers surrounded by the bold line is the calculating unit cell containing 20 fibers showing various randomly distributed features of fibers.

The Box–Muller transform [28,29] is a pseudo-random number sampling method for generating pairs of independent, standard, normally distributed (zero expectation, unit variance) random numbers. The basic form given by Box and Muller takes two samples from the uniform distribution on the interval (0, 1) and maps them to two standard, normally distributed samples. Suppose U_1 and U_2 are two independent random variables which are uniformly distributed in the interval (0, 1). Let

$$Z_1 = \sqrt{-2\ln U_1}\ \cos(2\pi U_2) \tag{1}$$

$$Z_2 = \sqrt{-2\ln U_1}\ \sin(2\pi U_2) \tag{2}$$

where Z_1 and Z_2 are independent random variables with standard normal distributions; E and S are mean value and square deviation, respectively, which can be manually adjusted [28,29]. Therefore two groups of random numbers can be obtained by [28,29]

$$Z_3 = E + Z_1 S \tag{3}$$

$$Z_4 = E + Z_2 S \tag{4}$$

Then the geometric center coordinates and rotation angles of the elliptical fibers in the unit cell can be given by Z_3 and Z_4. Therefore the unit cell with the randomly distributed elliptical fibers is determined. Six unit cells are generated for each specific fiber packing fraction, elliptical semiaxis and ratio rotation angle. Further, the friction factors and Nusselt numbers are obtained for each cell. Their average values are obtained as the last results, which will be listed in the following.

2.2. Governing equations

In the unit cell, as shown in Fig. 1, the air stream flows longitudinally between the elliptical fibers along z-axis. The z-axial length of the unit cell is 0.4 m, which is accordance with the actual REHFMB. A three-dimensional mathematical model containing momentum and heat transports are established. The governing equations are given based on the following assumptions:

(1) The air stream is assumed Newtonian with constant thermal-physical properties (specific heat capacity density, thermal conductivity, and viscosity).
(2) The air stream is laminar owing to the low Reynolds number for the air stream (<2000) in practical applications.
(3) The temperature on the fiber surface is considered to be a constant. It is valid because the Biot number for heat transfer in the channel is much less than 0.1 [14,15].

For the three-dimensional laminar air stream flowing longitudinally between the REHFMB, the equations governing the momentum and thermal transports are [30,31]:

Conservation of mass

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} + \frac{\partial w^*}{\partial z^*} = 0 \tag{5}$$

where x, y and z are spanwise, normal and streamwise coordinates, respectively; u, v and w are velocities in x, y and z directions (m/s), respectively; Superscript "*" means dimensionless form.

Conservation of momentum in the three coordinates

$$u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*} + w^*\frac{\partial u^*}{\partial z^*} = -\frac{1}{2}\frac{\partial p^*}{\partial x^*} + \frac{D_h}{W}\cdot\frac{1}{Re}\cdot\left(\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}} + \frac{\partial^2 u^*}{\partial z^{*2}}\right) \tag{6}$$

$$u^*\frac{\partial v^*}{\partial x^*} + v^*\frac{\partial v^*}{\partial y^*} + w^*\frac{\partial v^*}{\partial z^*} = -\frac{1}{2}\frac{\partial p^*}{\partial y^*} + \frac{D_h}{W}\cdot\frac{1}{Re}\cdot\left(\frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}} + \frac{\partial^2 v^*}{\partial z^{*2}}\right) \tag{7}$$