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Fluid flow and heat transfer across an elliptical hollow fiber membrane tube bank with randomly distributed features

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ABSTRACT

An elliptical hollow fiber membrane tube bank (EHFMTB) has better performances while being employed for air humidification. The EHFMTB is populated in a plastic shell to form a shell-and-tube heat exchanger like membrane contactor. The tube bank is always randomly populated in practical applications because of convenience and randomness in the manufacturing process. The fluid flow and heat transfer across a randomly distributed elliptical hollow fiber membrane tube bank (REHFMTB) are investigated. To disclose the influences of the fiber arrangements on the performances, three unit cells containing 20 fibers with different randomly distributions are selected as the calculating domains. A renormalization group k–ε (RNG KE) turbulence model with enhanced wall treatment is used for solving the equations governing the momentum and heat transports. The friction factor and Nusselt number across the REHFMTB under various fiber distributions, Reynolds numbers (Re), packing fractions (φ) and elliptical semiaxis ratios (b/a) are numerically obtained and experimentally validated. It is found that the comprehensive heat transfer performance is deteriorated for the fluid flow across the REHFMTB.

1. Introduction

A hollow fiber membrane tube bank (HFMTB) has been extensively used for air humidity control in recent years [1–5]. It is because a membrane contactor formed by the HFMTB has some obvious advantages compared to a conventional gas/liquid directly contacting device, including no entrainment of liquid droplets, a large transport area, and an independent control of tube and shell side flow rates [6]. The liquid stream flows inside the fibers (tube side), while the processing air stream flows across the fibers (shell side). They are separated from each other by the semi-permeable membranes, which only allow the permeation of water vapor but prohibit the transports of liquid and other gases [1–6].

The fluid flow and heat transfer across an elliptical hollow fiber membrane tube bank (EHFMTB) with regular arrangements (in-line and staggered) have been comprehensively studied by Huang et al. [7]. It has been found that the EHFMTB has better heat and mass transfer performances than those in the HFMTB [7]. However the fiber arrangement in the EHFMTB is probable randomly populated because of the randomness and convenience in the making. Further, the fibers are numerous in the EHFMTB (about 100–2000). Therefore even a small deviation in positioning an elliptical fiber would lead to a large irregularity in the whole tube bank arrangement [8]. The random distributions of the fibers would have great influences on the transport phenomena across the randomly distributed elliptical hollow fiber membrane tube bank (REHFMTB), which is populated in a plastic shell to form a cross-flow membrane contactor, as shown in Fig. 1. The liquid and the processing air streams flow inside and across the fiber tubes, respectively. The basic data of friction factor and Nusselt number across the REHFMTB are of importance for engineers. Unfortunately, they are still unknown up until now. Further, the fluid flow across the REHFMTB is neither pure laminar nor fully turbulent, but transitional flow [9]. It is because the Reynolds number of the fluid flow ranges from 50 to 550 in the practical applications [10,11]. Though there are some studies focused on the transport phenomena across the regular elliptical tube banks [12–15], no such investigations have been conducted across the REHFMTB. Therefore the transport features of the fluid flow and heat transfer across the REHFMTB under the transitional flow region should be disclosed, which are useful for structural design and performance evaluation of the REHFMTB employed for air humidity control.

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Nomenclature

A	area (m^2)
a	elliptical semiaxis in y axis (m)
b	elliptical semiaxis in x axis (m)
c_p	specific heat (kJ kg^{-1} K^{-1})
D	diffusivity (m^2 s^{-1})
d_h	hydraulic diameter (m)
E	mean value of a normal distribution
f	friction factor
H	transverse length (m)
h	convective heat transfer coefficient (k W m^{-2} K^{-1})
j	Colburn j-factor
k	turbulent kinetic energy (m^2 s^{-2}), mass transfer coefficient (m/s)
L	longitudinal length (m)
Le	Lewis number
m	mass flow rate (kg s^{-1})
n_{fiber}	number of fibers
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
S	square deviation of a normal distribution, modulus of the mean rate of strain sensor
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
u	random variable that is uniformly distributed in the interval (0, 1]
u	velocity (m s^{-1})
x, y	coordinates in physical plane (m)
Z	random variable of a normal distribution

Greek letters

Γ	diffusion coefficient
ε	turbulent energy dissipation rate (m^2 s^{-3})
μ	dynamic viscosity (Pa s)
λ	thermal conductivity (k W m^{-1} K^{-1})
ρ	density (kg m^{-3})
δ	membrane thickness (m)
ω	humidity (kg/kg)

Superscripts

*	dimensionless form

Subscripts

a	air
b	bulk
in	inlet
log	logarithmic mean
m	total mean, mass
mem	membrane
out	outlet
s	saturated
shell	shell side of tube bank
t	turbulent
tot	total
unit	unit cell
v	vapor
w	wall
x, y	x and y axis directions, respectively

2. Mathematical model

2.1. Unit cells

The location of each fiber centre in the REHFMTB is random and mutually independent, which fit normally distributed nature [16]. Therefore a normally distributed random error model is employed to describe the random distribution of the fibers.

The Box–Muller transform [17,18] 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

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

and

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

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 [17,18]. Therefore two groups of random numbers can be obtained by [17,18]

$$Z_3 = E + Z_1 \cdot S \quad (3)$$

$$Z_4 = E + Z_2 \cdot S \quad (4)$$

Then the geometric center coordinates of the elliptical fibers in the REHFMTB can be given by Z_3 and Z_4.

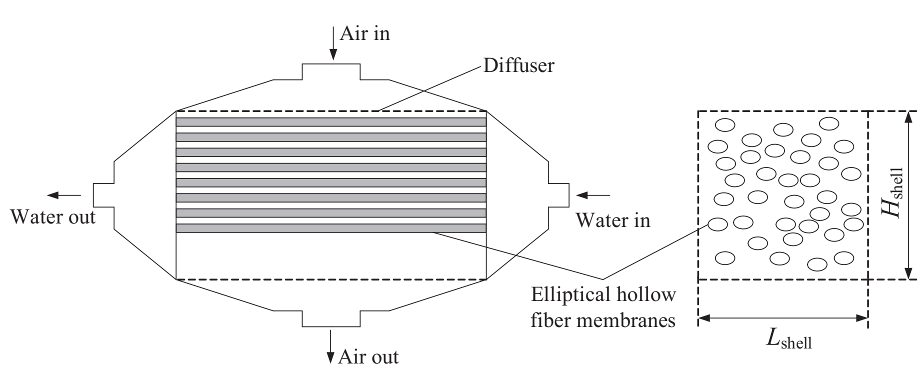

Fig. 1. Schematic of a cross-flow hollow fiber membrane contactor with randomly distributed elliptical fibers.