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Laminar flow and heat transfer between a regularly distributed elliptical hollow fiber membrane tube bank

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Effects of the various semiaxis ratios (b_{le}/a_{le}, b_{ri}/a_{ri}), longitudinal and transverse pitch-to-diameter ratios (S_L/d, S_T/d) on the longitudinal fluid flow and heat transfer between a regularly distributed elliptical hollow fiber membrane tube bank (EHFMTB) employed for air humidity control are investigated. In the tube bank, the liquid stream flows inside the fibers, while the air stream flows axially between the fibers in a counter flow arrangement. Two regularly populated arrangements of the tube bank, in-line and staggered, are considered. Two representative elements containing two fibers and the air stream flowing axially between the fibers are selected as the calculating domains. The governing equations for the fluid flow and the heat transfer between the EHFMTB are established and numerically solved via a boundary-fitted coordinate transformation method. The fully developed Poiseuille numbers (fRe) and local Nusselt numbers under a uniform temperature condition (Nu_T) under various semiaxis ratios, longitudinal and transverse pitch-to-diameter ratios are then obtained. It can be found that the fRe and Nu_T have their largest values when the b_{le}/a_{le} and b_{ri}/a_{ri} both are equal to 1.0 and 1.5 for the in-line and the staggered arrangements, respectively. The S_L/d and S_T/d have larger influences than the b_{le}/a_{le} and b_{ri}/a_{ri} on the fRe and Nu_T.

1. Introduction

In the past few years, a hollow fiber membrane tube bank (HFMTB) has been widely used for air humidity control (humidification/dehumidification) [1–6], which are the new developments in HVAC systems because of the applications of semi-permeable membranes for both sensible heat and moisture transports. Compared to conventional direct-contact devices for air humidity control (e.g. packed towers or beds [7,8]), the membranes can eliminate the entrainment of liquid water or liquid desiccant aerosols in the processing air sent into indoor environment [9–12]. It is because the air stream and the liquid water/desiccant stream are separated from each other by the semi-permeable membranes, which only allow the transports of heat and water vapor [9–12].

It has been known that circular cross-sectional hollow fiber tubes in the HFMTB are probably transformed to elliptical ones in practical applications [4,5,13,14]. It is because the membranes are not enough in mechanical strength and easily squeezed during the manufacturing process. Effects of the random distributions on the longitudinal laminar flow and heat transfer between an elliptical hollow fiber membrane tube bank (EHFMTB) have been studied [4]. It has been found that the heat transfer coefficients for the randomly distributed EHFMTB are approximately 19.5–91.8% less than those for the regularly distributed ones (in-line and staggered arrangements). To evaluate the influences of shape transformations on the fluid flow and heat transfer in the tube bank, an EHFMTB, as shown in Fig. 1, are fabricated and used for air humidification [5]. The regularly populated tube bank is comprised of a bundle of elliptical cross-sectional fibers, which are in-line and staggered arrangements. The air flows axially between the EHFMTB, while the water flows inside the fibers in a counter flow arrangement.

The fundamental data such as friction factor and Nusselt number in the EHFMTB are of vital importance. The transport phenomena in the elliptical channels (inside the tubes) have been studied enough [15,16]. Therefore this study is focused on the transport phenomena between the EHFMTB. The fluid flow and heat transfer across the EHFMTB have been investigated [17]. However it is a cross-flow one with an air stream flowing over the tube bank. Though the longitudinal fluid flow and heat transfer between the regularly distributed EHFMTB have been investigated [5]. The friction factors and Nusselt numbers under various semiaxis ratios (b/a) have been obtained. However the semiaxis ratios for the elliptical tubes in the calculating elements are the same. Further,

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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 ($Jkg^{-1} K^{-1}$)
D_h	hydrodynamic diameter (m)
d	equivalent circular diameter of a ellipse (m)
f	friction factor
fRe	Poiseuille number
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
S_L	longitudinal pitch (m)
S_T	transverse pitch (m)
T	temperature (K)
u	velocity (m/s)
U	dimensionless velocity coefficient
x, y, z	coordinates in physical plane (m)

Greek letters

ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)

Superscript

$*$	dimensionless

Subscripts

h	heat
i	inlet
le	left
m	mean
ri	right
T	values calculated under a uniform temperature boundary condition
w	wall, wall mean

the longitudinal pitch (S_L) and the transverse pitch (S_T) are set as the same values. However they have evident effects on the friction factors and Nusselt numbers between the regularly distributed EHFMTB. A mathematical model containing the equations governing the momentum and heat transports for the air flowing longitudinally between the EHFMTB are established and solved via a boundary-fitted coordinate transformation approach. The friction factor and Nusselt number are then obtained. The influences of the various semiaxis ratios, longitudinal and transverse pitch-to-diameter ratios on the axially laminar flow and heat transfer between the regularly distributed EHFMTB are investigated. This is the novelty in present study.

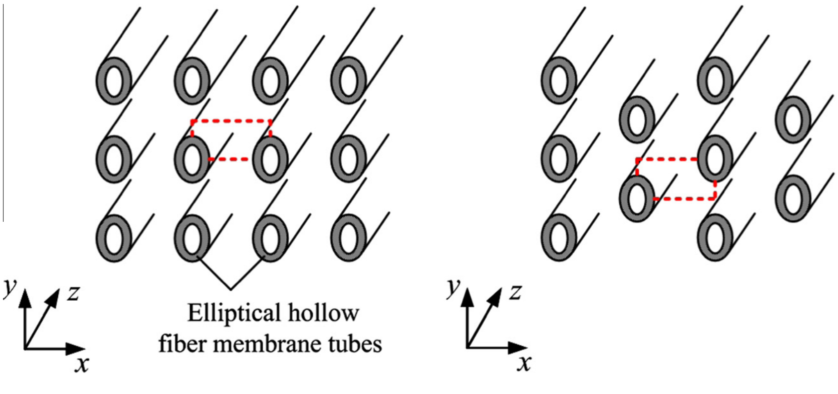
2. Mathematical model

2.1. Governing equations

The regularly distributed EHFMTB, as shown in Fig. 1, is employed for air humidity control. The air stream flows axially between the tube bank. For reasons of symmetry and simplicity in calculations, two elements depicted in Fig. 1 are selected as the calculation domains. A boundary-fitted coordinate transformation method is employed for transforming the complex physical planes shown in Fig. 2(a) and (b) to the computational plane shown in Fig. 2(c). The air stream flows along the z axis between the elliptical fibers.

The mathematical model is established based on the following assumptions:

(1) The air stream is laminar because of the relatively small Reynolds number for the air stream in the practical applications (<2000).
(2) The air stream is assumed Newtonian with constant thermal-physical properties.
(3) The air stream is assumed hydrodynamically fully developed, but developing both thermally and in concentration [18–20].
(4) The temperature on the fiber surface is constant. It is reasonable since this study is focused on the effects of the channel structures on the friction factor and Nusselt number in the channels, not on the coupled heat and mass transports. Further, the results will be also appropriate for the metal-formed channels.



(a) (b)

Fig. 1. Schematic of a regularly distributed elliptical hollow fiber membrane tube bank (EHFMTB). (a) In-line arrangement; (b) staggered arrangement. The area surrounded by the red and dash line is the representative element.