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Longitudinal fluid flow and heat transfer between an elliptical hollow fiber membrane tube bank used for air humidification

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HIGHLIGHTS

- An elliptical hollow fiber membrane tube bank (EHFMTB) is employed for air humidification.
- Longitudinal fluid flow and heat transfer between the HFMTB are investigated.
- Friction factor and Nusselt number between the EHFMTB are obtained.
- The results are useful for performance evaluations of the EHFMTB for air humidification.

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ABSTRACT

The longitudinal fluid flow and heat transfer between an elliptical hollow fiber membrane tube bank (EHFMTB) used for air humidification are investigated. In the tube bank, the water stream flows inside the fibers, while the air stream flows axially between the fibers. The air and the water streams, in a counter flow arrangement, are exchanging heat and moisture effectively through the membranes. Two regularly populated arrangements of the tube bank, in-line and staggered, are considered. Two representative unit cells consisting of two fibers and the air stream flowing longitudinally between the fibers are selected as the calculation 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 friction factor and Nusselt number in the unit cells are then obtained, analyzed, and experimentally validated. They are compared with the data obtained for a hollow fiber membrane tube bank (HFMTB). The results are useful for structural optimization and performance evaluations of the EHFMTB employed for air humidification.

1. Introduction

Recently, a hollow fiber membrane tube bank (HFMTB) has been employed extensively for air humidification in fuel cell [1–3] and heating, ventilation, and air conditioning (HVAC) applications [4–6]. The process air and the water streams are separated from each other by the semi-permeable membranes, which only allow the permeation of water vapor but prohibit the transports of liquid water and other gases [7,8]. Therefore liquid water droplet crossover, which is rather harmful to these applications, can be completely prevented.

It has been known that circular cross-sectional hollow fiber tubes in the HFMTB are probably transformed to elliptical ones in practical engineering applications [9,10]. It is because the membranes are not enough in mechanical strength and easily squeezed during the manufacturing process. To evaluate the effects of shape transformations on fluid flow and heat transfer, an elliptical hollow fiber membrane tube bank (EHFMTB), as shown in Fig. 1, are fabricated and used for air humidification. The regularly populated tube bank is comprised of a bundle of elliptical cross-sectional fibers, which can be in-line and staggered arrangements. The process air flows axially between the EHFMTB, while the water stream flows inside the fibers. The two streams are 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 fibers) have been well-studied [11–13]. Therefore the transport phenomena between the EHFMTB are the focus in present study. Regretfully, the longitudinal fluid flow and heat transfer between the EHFMTB have not been mentioned in literature up until now.

The novelties in this study are the axial fluid flow and heat transfer between the EHFMTB used for air humidification are investigated. The equations governing the momentum and heat transfer for the air flowing longitudinally between the EHFMTB are established and solved via a boundary-fitted coordinate

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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)
D_h	hydrodynamic diameter (m)
d	equivalent circular diameter of a ellipse (m)
f	friction factor
L	effective length of the tube bank (m)
n_{fiber}	number of fibers
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
r	radius (m)
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood 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)
δ	membrane thickness (m)
θ	dimensionless temperature
ω	humidity ratio (kg water vapor/kg dry air)
ξ, η	transversal coordinates in computational plane
Superscripts	
*	dimensionless
Subscripts	
a	air
h	heat
i	inlet
L	local
m	mean, membrane
o	outlet
s	saturated
T	values calculated under uniform temperature boundary condition
tot	total
v	vapor
w	wall, wall mean, water vapor

system. The friction factor and Nusselt number are obtained and analyzed. An experiment is performed to validate the results. The results can provide fundamentals for structural design and performance evaluations in the EHFMTB used for air humidification.

2. Mathematical model

2.1. Governing equations

The EHFMTB, as shown in Fig. 1, is used for air humidification. The air and the water streams flow axially outside and inside the fibers, respectively, in a counter flow configuration. For reasons of symmetry and simplicity in calculations, two unit cells shown in Fig. 1a and b for the in-line and the staggered arrangements, respectively, are selected as the calculation domains.

The geometric constructions of the unit cells are complex. Therefore a boundary-fitted coordinate transformation method is employed. The physical planes shown in Fig. 2a and b are transformed to the computational plane shown in Fig. 2c. The air stream flows along the z axis between the fibers.

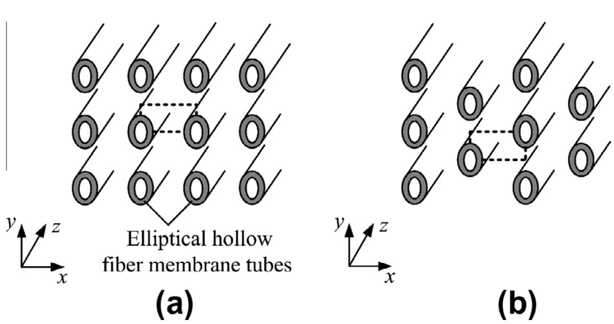

Fig. 1. Schematic of an elliptical hollow fiber membrane tube bank (EHFMTB). (a) In-line; and (b) staggered. The area surrounded by the dash line is the representative unit cell.

In practical engineering applications, Reynolds number for the air stream is much less than 2000. Therefore the air stream is laminar. Other assumptions are made:

(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 assumed hydrodynamically fully developed, but developing both thermally and in concentration [14–16].
(3) The temperature on the fiber surface is constant.

For the two-dimensional fully developed laminar flow (fluid has only longitudinal velocity), the Navier–Stokes equations reduce to [14,15]

$$\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)=\frac{dp}{dz} \tag{1}$$

where u is velocity (m/s); μ is dynamic viscosity (Pa s); p is pressure (Pa); x, y and z are coordinates in the physical plane (m).

Energy conservation equation can be expressed as [14,15]

$$\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=\rho c_p u\frac{\partial T}{\partial z} \tag{2}$$

where T is temperature (K); λ is heat conductivity (W m^{-1} K^{-1}); ρ is density (kg/m^3); c_p is specific heat (kJ kg^{-1} K^{-1}).

The above two equations governing momentum and heat transfer can be normalized to [17,18]

$$\frac{\partial^2 u^*}{\partial x^{*2}}+\frac{\partial^2 u^*}{\partial y^{*2}}=-\frac{S_L^2}{D_h^2} \tag{3}$$

$$\frac{\partial^2 \theta}{\partial x^{*2}}+\frac{\partial^2 \theta}{\partial y^{*2}}=U\frac{\partial \theta}{\partial z_h^*} \tag{4}$$