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Fluid flow and heat transfer across a curved hollow fiber membrane tube bank (CHFMTB): Effects of the tube deformations

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A B S T R A C T

A cross-flow hollow fiber membrane tube bank (HFMTB) is commonly employed for air humidification or dehumidification. The tubes in the HFMTB are easily deformed due to the gravity of the water/liquid desiccant stream inside the tubes and the scour of the air stream flowing across the tube bank. Fluid flow and heat transfer across a curved hollow fiber membrane tube bank (CHFMTB) with a regularly populated arrangement are investigated. Two unit cells containing two columns of the curved tubes are selected as the computational domains, which include 12 tubes both for the in-line and staggered arrangements. The equations governing the fluid flow and heat transfer are established via a renormalization group k-ε (RNG KE) turbulent model. The mean friction factors (f_m) and Nusselt numbers (Nu_m) for the air flowing across the CHFMTB under various tube arrangements (in-line, staggered), Reynolds numbers (Re), tube deformed heights (Δh) and angles (θ) are calculated and analyzed. It can be found that the mean friction factors and Nusselt numbers for the staggered arrangement are about 2.1–2.7 and 1.4–2.2 times of those for the in-line arrangement, respectively. For most of the Reynolds numbers ranging from 68.42 to 342.30, both the mean friction factors and Nusselt numbers for the HFMTB are almost larger than those for the CHFMTB. Further, the larger the Reynolds numbers are, the larger the differences are.

1. Introduction

Recently, hollow fiber membrane contactors have been extensively used for air humidification [1–5] or dehumidification [6–11]. The hollow fiber membrane contactor is formed by a hollow fiber membrane tube bank (HFMTB) placed in a plastic shell space, which is similar to a shell-and-tube heat exchanger [1–11]. The inner tubes form the tube side, while the voids between the outer shell and the tubes form the shell side. The processing air and the water/liquid desiccant streams are separated from each other by the semi-permeable membranes, which only permit the permeation of water vapor but prohibit the transports of the water and liquid desiccant [12,13]. Therefore the liquid droplets, which are rather harmful in the air humidification and dehumidification applications, can be completely prevented.

The processing air and the liquid streams can be in a counter flow arrangement [6–8] or in a cross-flow arrangement [9–11] in the membrane contactors. The latter one has a higher effectiveness because of its larger packing density (as large as 1500 m^2/m^3) and smaller pressure drop in the shell side [14–16]. Therefore a cross-flow hollow fiber membrane contactor, as shown in Fig. 1, is commonly employed for the air humidity adjusting processes, where the larger air flow rates can be handled. The liquid stream flows in the tube side (inside the tubes), while the air stream flows in the shell side (across the tube bank) in a cross-flow arrangement. It can be found that the hollow fiber membrane tubes are easily deformed due to the gravity of the liquid stream inside the tubes and the scour of the air stream, which are depicted in Fig. 1(b). Therefore a curved hollow fiber membrane tube bank (CHFMTB) is formed and employed for air humidification/dehumidification.

The fluid flow and heat mass transfer in the CHFMTB are of vital importance in the practical applications. It is noteworthy that the transport phenomena inside the curved circular channels (tubes) have been fully investigated [17–20]. Regretfully, the fluid flow and heat transfer across the CHFMTB have not been studied enough because of its complex structure, which is different with those across a straight hollow fiber membrane tube bank or a cylinder bundle [21–23]. The fundamental data such as friction factor and Nusselt number across the CHFMTB are necessary for the design and optimization of the tube bank. However these values under various tube deformations cannot be taken from open literatures up until now. Further, the Reynolds numbers for the air stream are usually in the range of 50–350 in the air humidification/dehumidification processes [24]. It has been known that the

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Nomenclature

A	area (m^2)
c_p	specific heat of air ($kJ\ kg^{-1}\ K^{-1}$)
D_h	hydraulic diameter (m)
f	friction factor
h	convective heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$)
k	turbulent kinetic energy ($m^2\ s^{-2}$)
N	tube number
Nu	Nusselt number
P	time-averaged pressure (Pa)
Pr	Prandtl number
r	radius (m)
Re	Reynolds number
S_T	transverse distance between the neighboring tubes (m)
T	time-averaged temperature (K)
U	time-averaged velocity ($m\ s^{-1}$)
u	velocity ($m\ s^{-1}$)
x, y, z	coordinates in the unit cells
x_0, y_0, z_0	wide, length, and height in the unit cells, respectively

Greek letters

ε	turbulent energy dissipation rate ($m^2\ s^{-3}$)
μ	molecular dynamic viscosity (Pa·s)
ρ	density ($kg\ m^{-3}$)
τ	shear stress (N/m^2)
φ	packing fraction

Superscripts

$*$	dimensionless form
$'$	fluctuation value

Subscripts

a	air
b	mass-averaged value (bulk value)
eff	effective
i	inlet
m	total mean
max	maximum value
mem	membrane
o	outlet, outer
t	turbulent
v	vapor
w	wall
x, y, z	x, y, and z axis directions, respectively

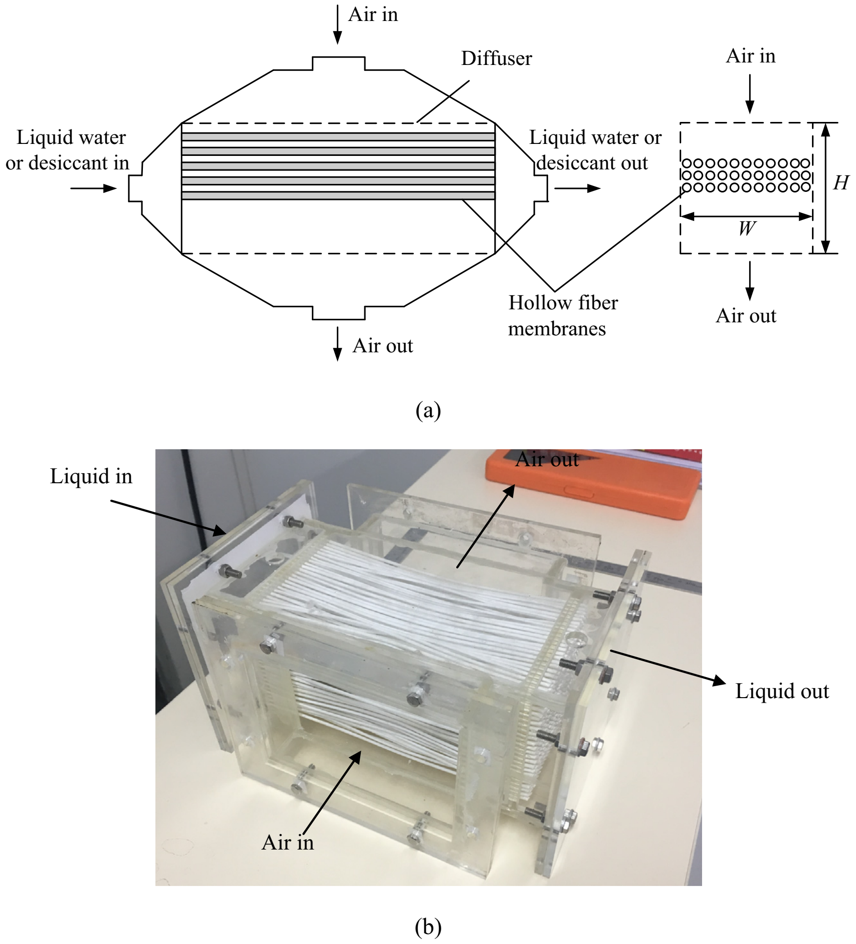

Fig. 1. Structure of a hollow fiber membrane contactor used for air humidification/dehumidification. (a) Schematic diagram; (b) Real picture of the membrane contactor.