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Laminar flow and heat transfer in plate membrane channels: Effects of the deformation heights

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A B S T R A C T

Membrane channels have been extensively used for air humidity control and energy recovery. The membranes are commonly parallel-plate type. However they probably are deformed because of their weak mechanical strengths and fluid pressure. Effects of the deformation heights (Δh) on the laminar flow and heat transfer in the plate membrane channels are studied based on two unit cells. Each one of them includes two neighboring membranes and a channel sandwiched by the membranes. The equations governing the momentum and heat transports are established together with a uniform wall temperature boundary condition and numerically solved by a finite volume approach. The mean (fRe) and Nusselt number (Nu_m) are obtained. The influences of the deformation heights (Δh), aspect ratios (b/a), and Reynolds numbers (Re) on the $(fRe)_m$ and Nu_m are calculated. It can be found that when the b/a is less than or equal to 25, the Nu_m rises with the Δh increasing for the air channel. However the Nu_m firstly rises, and then decreases with the Δh increasing when the b/a ranging from 30 to 40. For the water/LiCl solution channels, the Nu_m for the LiCl solution is about 40%–56% larger than that for the water stream.

1. Introduction

In the past few years, plate membrane contactors have been widely used for air humidification/dehumidification [1–6] and air/liquid total heat recovery [7–13], which is the new developments in HVAC systems because of the applications of semi-permeable membranes for both sensible heat and moisture transports. The former one is focused on air humidity control, while the latter one is for energy recovery from the exhaust air stream. Compared to conventional direct-contact devices for air humidification/dehumidification (e.g. packed towers or beds [14,15]), the membrane-based contactors can eliminate the entrainments of liquid water or liquid desiccant aerosols in the air stream sent into indoor environment [1–13]. 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 between the air and the liquid streams [1–13].

In the plate membrane contactor, as shown in Fig. 1(a), a series of plate membranes are stacked together to form the channels. The air and the liquid streams, which flow alternately through the channels, are usually in a cross-flow arrangement because of convenient channel sealing and efficient heat and mass exchanges [1–4]. In the contactor, the membranes are parallel-plate in the making process at the first time. However deformations of the membranes are probably occurred when the fluid flows in the channels [16–18]. Further, it can be observed that the deflections features of the membranes in the channels for the air and the liquid streams are different [1,2]. For the air channel, as shown in Fig. 1(b), the upper plate membrane is concave downward due to the pressure of the liquid fluid (water/desiccant) in the above neighboring channel. However the bottom membrane is almost unchanged due to the relatively less incompressibility of the liquid water/desiccant and its larger pressure [18]. For the liquid channel, as shown in Fig. 1(c), the above and the bottom membranes are nearly undeformed and sunken, respectively. It is just opposite to that for the air channel. The sealings are conducted around the channels. Therefore the deformation membrane can be approximated as a segment of a sphere surface. The membrane concavities are described by the maximum deformation heights (Δh) in the membrane surface, as shown in Fig. 1(b) and (c).

It has been known that the basic data of friction factor and heat mass transfer coefficients in the plate membrane channels are necessary for the performance evaluation and optimization of the

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Nomenclature

A	area (m^2)
a	channel height (m)
b	channel length or width (m)
c_p	specific heat ($Jkg^{-1}K^{-1}$)
d_p	pore diameter (m)
D	diffusivity (m^2/s)
D_h	hydrodynamic diameter (m)
f	friction factor
fRe	Poiseuille number (*Po*), which is a product of friction factor (*f*) and Reynolds number (*Re*)
Δh	deformation height (m)
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
x, y, z	coordinates (m)
X_s	mass fraction of solution (kg water/kg solution)

Greek letters

ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
δ	membrane thickness (m)
λ	heat conductivity (Wm^{-1} K^{-1})
ω	humidity ratio (kg water vapor/kg dry air)

Superscript

*	dimensionless

Subscripts

a	air
b	bulk
log	logarithmic mean
in	inlet
m	average (mean)
mem	membrane
out	outlet
s	solution
w	water
x, y, z	x-axial, y-axial and z-axial directions, respectively

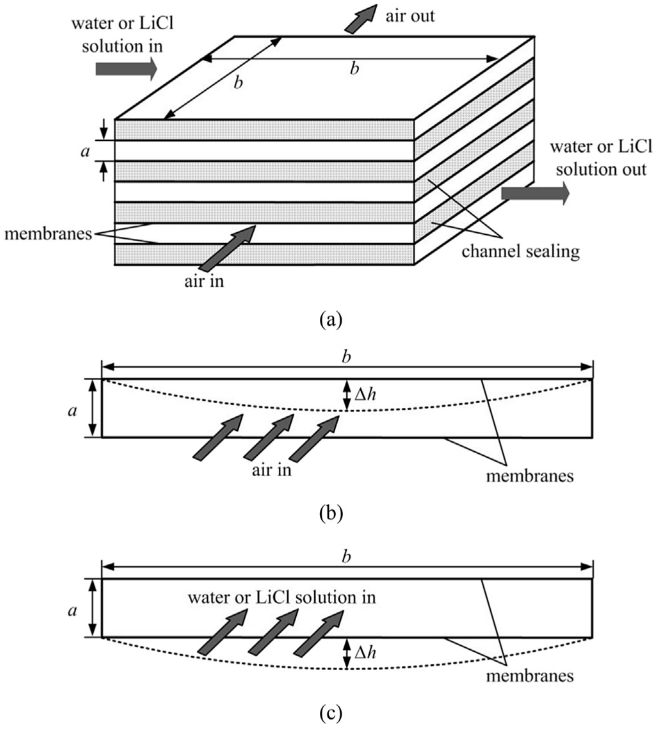

Fig. 1. Structure of the plate membrane contactor used for air humidity control. (a) Structure of the plate membrane contactor; (b) Cross-section of the single channel of the air stream; (c) Cross-section of the single channel of the water or LiCl solution streams.

plate membrane contactors used for air humidity control and energy recovery. Although the transport data in the parallel-plate membrane channels have been investigated [19,20], they are not suitable for the plate membrane channels with membrane deflections due to the different channel structure.

The novelties in this study are the investigations of the laminar flow and heat transfer in the plate membrane channels employed for air humidity control and energy recovery. The equations governing the momentum and heat transports are established and numerically solved. A uniform temperature boundary condition is imposed on the membrane surfaces. The friction factors and Nusselt numbers under different structural dimensions and fluid properties are obtained. The Sherwood numbers can be calculated by the heat and mass transfer analogy. The influences of the membrane deformations on the transport phenomena in the channels are disclosed. The results are useful for the structural design and energy analysis in the plate membrane channels.

2. Mathematical model

2.1. Governing equations

In the membrane contactor, as shown in Fig. 1(a), it is comprised of many identical and individual elements (channels). The air and the liquid (water/LiCl solution) streams flow through the neighboring channels in a cross-flow arrangement. For reasons of the symmetry and simplicity in calculation, two typical unit cells, as shown in Fig. 2(b) and (c), one for the air stream and the other one for the liquid stream, are selected as the calculated domains. Both of them contain two membranes and their sandwiched channel. They are the main regions. In the practical applications, flow homogenizers are commonly stalled at the inlets of the unit cells to make the velocities uniform. To eliminate the effect of the outlet outflow boundary condition, downstream extended regions are set in the unit cells. Their lengths are equal to 4*b*, which are four times of the membrane channel length (*b*). The coordinate systems of the unit cells are depicted in Fig. 2. As seen, the lower plane is a parallel-plate membrane, while the upper one is a concaved downward membrane, which can be approximated as a segment of a sphere surface. It is valid since the deformation height (Δh) is rather small (less than 2 mm) compared to that of the channel length or width (100 mm). Further, they can be obviously observed and verified from our previous experiments based on the parallel-plate membrane channels [1–3]. The left and the right planes are adiabatic sealing strips. The air stream flows perpendicularly from the front