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Research Paper

# Fluid flow and heat transfer in hexagonal parallel-plate membrane channels (HPMC): Effects of the channel heights and fluid parameters

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## HIGHLIGHTS

- Hexagon-like parallel-plate membrane channels (HPMC) are used for air humidity control.
- Fluid flow and heat transfer in the HPMC are investigated.
- The larger the channel heights (2*H*) are, the smaller the mean friction factors ($f_m$) are.
- $Nu_m$ for the LiCl solution are larger than those for the water and the air streams, respectively.

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## ABSTRACT

Membrane-based air humidity control technology offers a potential alternative for addressing the vital problem of liquid droplet entrainments encountered in a traditionally direct-contacting approach. A parallel-plate membrane contactor has been extensively used for this application. It is comprised of a series of plate-type membranes to form the channels. The processing air and the liquid (water/liquid desiccant) streams flow in a pure cross-flow arrangement. To improve the performances, hexagonal parallel-plate membrane channels (HPMC) are proposed. Effects of the deformation heights (2*H*) and fluid parameters on fluid flow and heat transfer in the HPMC are investigated based on a unit cell, which includes one piece of membrane and half a channel. The equations governing the fluid flow and heat transfer are established together with a uniform temperature boundary condition and solved by a finite volume method. The mean friction factors ($f_m$) and Nusselt numbers ($Nu_m$) in the channels under various channel heights (2*H*) and fluid varieties are obtained. It has been found that when the fluids and *Re* are fixed, the larger the 2*H* are, the smaller the $f_m$ are. For the fixed 2*H* and *Re*, the $Nu_m$ for the LiCl solution stream are about 1.21–1.38 and 1.51–2.85 times of those for the water and the air streams, respectively.


## 1. Introduction

In recent years, the requirements of air humidity condition for product manufacture and resident lives are more and more stringent with the rapid development of economy and society, especially the manufacturing environments of specific medical and precise instruments. The traditional air humidity control technologies are more and more difficult to meet the increasing demands because of its high energy consumption or the droplets entrained in the processed air. Fortunately, the membrane-based air humidity control approach would be a good choice [1–8]. The air and the liquid (water/liquid desiccant) streams are separated by the semi-permeable membranes, which only guarantee the transports of heat and water vapor between the air and the liquid streams [1–8]. Therefore the air stream is humidified or dehumidified in an indirect contact way which can effectively address the problem of the small liquid droplets entrained in the processed air. As a result, the quality of the air stream is greatly improved.

To realize air humidity control, a parallel-plate membrane contactor has been designed employed [1–4]. A series of plate membranes are stacked together to form the channels. The air and the liquid streams, which flow through respective channels, are separated by the membranes. Furthermore, the streams are in a cross-flow arrangement [1–4]. It is desired to be a counter flow arrangement with better performances in the heat and mass exchangers [9,10]. However the pure counter flow configuration is difficult to be conducted because of the inconvenient separation between the air and the liquid streams. Therefore a hexagonal parallel-plate membrane contactor, as shown in Fig. 1, is designed and used for air humidity control. As seen, the contactor is

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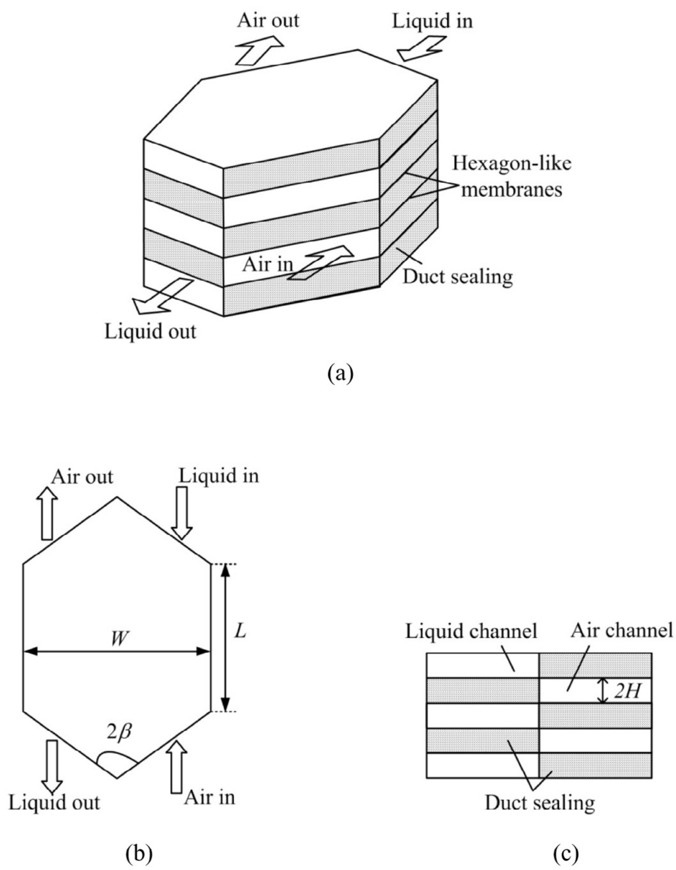


**Fig. 1.** Structure of a hexagonal parallel-plate membrane contactor (HPMC) used for liquid dehumidification. (a) Three-dimensional space diagram; (b) Planform; (c) Lateral view.

comprised of many hexagonal parallel-plate membrane channels (HPMC). The air and the liquid streams flow alternatively through the HPMC with a combination arrangement of the pure cross-flow and the pure counter flow arrangements. Although the heat and mass transfer in the HPMC have been modeled [11–13], the detailed influences of the channel heights ($2H$) and fluid varieties (air, water, or desiccant) on the fundamental data have not been disclosed. However they are necessary for structural design and energy analysis in the HPMC. This is the objective of present study.

## 2. Mathematical model

### 2.1. Governing equations

The membrane contactor, as shown in Fig. 1, is comprised of a series of identical and individual elements (channels). The air and the liquid streams (water/liquid desiccant) flow through the channels alternately. In present study, the water and LiCl solution streams are employed for air humidification and dehumidification, respectively. For reasons of the symmetry and simplicity in calculation, a unit cell including one piece of plate-type membrane and half of the channel is selected as the calculating domain. The coordinate system of the unit cell is depicted in Fig. 2. As seen, the upper and lower planes are the symmetric mid-plane and the plate-type membrane, respectively. The fluids (air, water, or desiccant) flow from the right hand plane with a uniform velocity $u_{in}$ and a uniform temperature $T_{in}$ into the channel and out from the opposite plane. The inlet velocity ($u_{in}$) is in the $y$-axis direction. There is not velocity component in $x$-axis direction. The velocity distribution is realized by the flow homogenizer installed at the inlet. The channel length ($L$) and width ($W$) are fixed. They are both equal to 10 cm. The apex angle ($2\beta$), as shown in Fig. 1(b) is fixed at 90°. However the channel heights ($2H$) are varied to establish the physical models.

In the practical applications, both the air and the liquid streams are laminar and incompressible since the Reynolds numbers for the flows are much less than 2000. The fluids are Newtonian with constant thermo-physical properties. Body forces and viscous dissipations are ignored. The membrane surfaces are assumed to be impermeable. Then the research focus is turned to the effects of the channel structure and fluid property on the fluid flow and heat transfer in the channels. Additionally, a uniform temperature boundary condition is imposed on the membrane surface. It is reasonable because the temperature difference across the membrane surface is relatively small compared to that between the channel inlet and outlet [1–4]. Furthermore, the model and the fundamental data are also suitable for those in the hexagonal parallel-plate metal-formed channels.

Based on above assumptions, the fluid flows in the channels are governed by continuity equation, Navier–Stokes equations and energy equation. In Cartesian coordinates, their normalized expressions can be described as follows [14–17]:

$$\frac{\partial u_i^*}{\partial x_i^*} = 0 \tag{1}$$

$$u_i^* \frac{\partial u_j^*}{\partial x_i^*} = -\frac{\partial p^*}{\partial x_i^*} + \frac{\partial^2 u_i^*}{\partial x_j^{*2}} \tag{2}$$

$$u_i^* \frac{\partial T^*}{\partial x_i^*} = \frac{1}{Pr} \cdot \frac{\partial^2 T^*}{\partial x_i^{*2}} \tag{3}$$

where superscript "*" is dimensionless form; $u$ is velocity (m/s); $p$ is pressure (Pa); $T$ is temperature (K); $Pr$ is Prandtl number.

The dimensionless coordinates are defined by

$$x_i^* = \frac{x_i}{L} \tag{4}$$

where $L$ is channel length (m), as shown in Fig. 1(b).

The dimensionless velocities are defined by

$$u_i^* = \frac{\rho u_i D_h}{\mu} \tag{5}$$

where $\rho$ is density (kg/m$^3$); $\mu$ is dynamic viscosity (Pa·s); $D_h$ is the hydraulic diameter of the channel, which can be calculated by

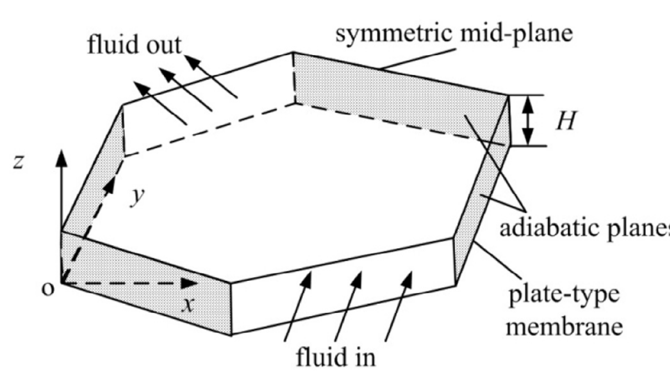


**Fig. 2.** The calculating domain of the hexagonal parallel-plate membrane channel.