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Laminar flow and heat transfer in a quasi-counter flow parallel-plate membrane channel in the solution side with cooling tubes

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ABSTRACT

An internally-cooled parallel-plate membrane contactor has been proposed, designed, and used for liquid desiccant air dehumidification. It is comprised of a series of side in and out parallel-plate membrane channels (QCPMC). The processing air and the liquid desiccant (solution) streams are separated by the membranes. Cooling tubes are installed in the solution channel to take away the absorption heat. The friction factors and heat transfer coefficients in the complex QCPMC with the cooling tubes in the solution side (QCPMCC) are necessary for the structural design and energy analysis. Therefore the laminar flow and heat transfer in the solution channel are studied based on a unit cell containing the sandwiched domain outside the cooling tubes between two neighboring membranes. The momentum and thermal transport governing equations are built up together with a uniform wall temperature boundary condition and solved by a finite volume approach. The mean (fRe) and Nusselt numbers (Nu_m) are then calculated. Influences of the Reynolds numbers (Re), tube number (N_{tube}), tube outer diameters (d_{outer}), tube arrangements, and connection types of tubes on the $(fRe)_m$ and Nu_m are analyzed. It can be found that when $d_{outer} = 0.003$ m, the $(fRe)_m$ rises with an increase in the N_{tube}. However the Nu_m decrease with the N_{tube} increasing. When $N_{tube} = 4$, the $(fRe)_m$ rise with an increase in the d_{outer}. However the larger the d_{outer} are, the smaller the Nu_m are.

1. Introduction

In past twenty years, membrane contactors have been extensively employed for energy recovery or liquid desiccant air dehumidification [1–7]. For these indirectly contacted technologies, one critical drawback of liquid desiccant droplet entrainments encountered in the directly contacted desiccant energy exchangers or the packed bed type liquid desiccant dehumidifiers [1–7]. The processing air stream and the liquid desiccant (solution) stream are separated by the semi-permeable membranes, which only allow the transports of sensible heat and water vapor between the two streams through the membranes [1–7]. Therefore the solution droplets escaped into the air can be prevented.

Parallel-plate membrane contactors are commonly used for liquid desiccant air dehumidification because of their simple structure, low pressure loss, low cost, etc [8–10], where a series of plate-type membranes are stacked together to form the channels. The processing air stream and the solution stream flow in the neighboring channels. To improve the performances of the membrane contactors, a quasi-counter flow arrangement of the two streams are proposed and used for the HVAC applications [9,10]. For the liquid desiccant air dehumidification process, the solution temperature is lifted due to the absorption heat, which will largely reduce the moisture absorption ability of the solution stream. A novel internally-cooled quasi-counter flow parallel-plate membrane contactor, as shown in Fig. 1, was firstly proposed, designed and tested by Abdel-Salam et al. [11]. As seen, the contactor is comprised of a number of quasi-counter flow parallel-plate membrane channels (QCPMC) with side inlets and side outlets. The air and the solution streams flow from the side inlets into the contactor and out from the side outlets, which forms a quasi-counter flow arrangement. Several Z-shaped cooling tubes are installed in the solution channel to form the QCPMC with the cooling tubes in the solution side (QCPMCC). Cooling water flows inside the tubes to take away the absorption heat swiftly. The cooling water and the solution streams flow in a counter flow arrangement. The solution temperature can be effectively controlled.

The novel internally-cooled quasi-counter flow parallel-plate membrane contactors are similar to three-fluid (air, solution, and refrigerant) heat and mass exchangers [11–14], which are to enhance the performances. Compared to a two-fluid energy exchanger with the same design parameters, the sensible, latent,

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Nomenclature

c_p	specific heat (J kg^{-1} K^{-1})
d_{outer}	tube outer diameter (m)
D_h	hydrodynamic diameter (m)
f	friction factor
fRe	product of friction factor (f) and Reynolds number (Re)
H	channel spacing height (m)
N_{tube}	cooling tube number
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
T	temperature (K)
u, v, w	velocities in x-axial, y-axial, and z-axial directions (m/s), respectively
x_0	channel length (m)
x_{in}	entrance length (m)
x, y, z	coordinates (m)
y_0	channel width (m)

Greek letters

ρ	density (kg/m^3)
μ	dynamic viscosity (Pa·s)
λ	heat conductivity (W m^{-1} K^{-1})

Superscripts

*	dimensionless

Subscripts

a	air
b	bulk
ext	extended region
log	logarithmic mean
in	inlet
m	average (mean)
mem	membrane
out	outlet
tube	cooling tubes
v	water vapor
x, y, z	x-axial, y-axial and z-axial directions, respectively

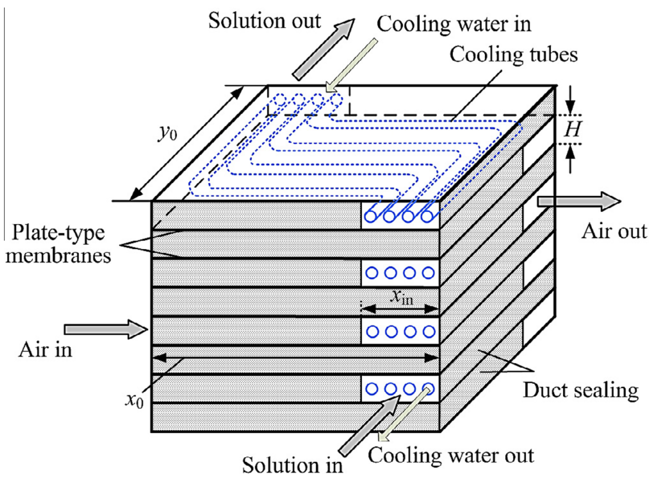

Fig. 1. Structure of the quasi-counter flow parallel-plate membrane contactor with Z-shaped cooling tubes in the solution side used for liquid desiccant air dehumidification.

and total effectivenesses of the three-fluid one can be improved by about 69%, 28%, and 39%, respectively [11]. Under the diluted desiccant solution regeneration operating conditions, the sensible, latent, and total effectivenesses of the three-fluid one can be increased by 38%, 40%, and 39%, respectively [12]. The influences of the phase change energy released in liquid desiccant energy exchangers on the temperatures of the air and desiccant solution streams under air-cooling and dehumidification operating conditions have been experimentally investigated [13]. Also studied are the influences of inlet air humidity and solution flow rate on the performances of the energy exchangers [13]. Besides the effects of the structures and operating conditions, the effects of flow maldistributions caused by membrane deflections on the performances have been investigated [14]. The performances were deteriorated due to the flow maldistributions, which could be reduced by membrane pre-tension [14].

The performance evaluation of the internally-cooled quasi-counter flow parallel-plate membrane contactor is of vital importance in the practical application of liquid desiccant air dehumidification. The friction factor and heat mass transfer coefficients in the channels are necessary. The fundamental data in the QCPMC for the solution stream have been calculated in the adiabatic membrane contactor [8]. However the basic data in the QCPMCC for the solution stream are still not available from the open literatures. The transport phenomena in the QCPMCC are neither similar to those in the QCPMC, nor similar to those in the rectangular channels [15,16] because of their different structures.

The novelties in this study are that laminar flow and heat transfer in the QCPMCC used for liquid desiccant air dehumidification are studied. LiCl solution is used as the liquid absorbent in this study. Cooling water is used as the refrigerant in the cooling tubes. The equations governing the momentum and heat transports are established and numerical solved. The friction factors and Nusselt numbers in the channels under a uniform temperature boundary condition are then numerically obtained. Further, the influences of the structural parameters of the channels on the basic data are disclosed. The results provide fundamentals for the structural design and energy analysis in the internally-cooled membrane contactors formed by the QCPMCC employed for liquid desiccant air dehumidification.

2. Mathematical model

2.1. Governing equations

In the aforementioned internally-cooled quasi-counter flow parallel-plate membrane contactor, as shown in Fig. 1, it is comprised of a series of QCPMC and QCPMCC for the air and the solution streams, respectively. The two streams flow in the neighboring channels in a quasi-counter flow arrangement. Due to the simplicity in modeling and calculation, a unit cell including the sandwiched zone outside the cooling tubes between the neighboring membranes are 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 membrane surfaces of the neighboring parallel-plate membranes. Several Z-shaped cooling tubes are populated inside the unit cell. An extended region is added at the outlet to eliminate the influence of the outlet boundary condition,