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Performance analysis of a quasi-counter flow parallel-plate membrane contactor used for liquid desiccant air dehumidification

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HIGHLIGHTS

- A quasi-counter flow parallel-plate membrane contactor (QFPMC) is used for liquid desiccant air dehumidification.
- A two-dimensional steady-state heat and mass transfer mathematical model is developed.
- Compared to a cross-flow parallel-plate membrane contactor (CFPMC), the performances in the QFPMC are deteriorated.
- The solution channel pressure drop is increased.

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ABSTRACT

A quasi-counter flow (combined counter/cross-flow) parallel-plate membrane contactor (QFPMC) is proposed and employed for liquid desiccant air dehumidification. The air and the liquid desiccant streams, in a quasi-counter flow arrangement, are separated by the selectively permeable membranes, which only allow the permeations of heat and water vapor while preventing other gases and liquid desiccant from permeating. A two-dimensional steady-state mathematical model is developed to study the performances in the QFPMC used for liquid desiccant air dehumidification. A finite difference method is employed to solve the equations governing momentum, heat and mass transports. The pressure drop, sensible cooling and dehumidification effectiveness are then obtained. An experimental work is conducted to validate the results. It can be found that compared to a cross-flow parallel-plate membrane contactor (CFPMC), the cooling and the dehumidification effectiveness of the QFPMC used for liquid desiccant air dehumidification are deteriorated by approximately 5–29% and 2–13%, respectively. Further, the solution channel pressure drop is increased by about 0.15–4.84 times.

1. Introduction

Recently, membrane-based liquid desiccant air dehumidification technology has been employed to overcome the substantial drawback of liquid desiccant droplet crossover encountered in the traditional direct-contacting liquid dehumidification method [1–7]. For the novel technology, the air and the liquid desiccant streams are separated from each other by selectively permeable membranes, which prevent the liquid droplets from escaping into the processing air while permitting the transports of heat and water vapor between the air and the solution streams [1–7].

A cross-flow parallel-plate membrane contactor (CFPMC) is a typical heat and mass exchanger, which has been employed for liquid desiccant air dehumidification [3–7]. It has been well known that a counter flow contactor may have higher effectiveness compared to the cross-flow one. Therefore it is desirable to have a counter flow membrane contactor used for liquid desiccant air dehumidification to improve the performances. However, a contactor with a pure counter flow arrangement is difficult in duct sealing between the air and the solution streams. Further, it is hard to construct in a limited space available in the HVAC system [4,8]. Therefore a quasi-counter flow parallel-plate membrane contactor (QFPMC), as schematically depicted in Fig. 1, is proposed and employed for realizing liquid desiccant air dehumidification. As seen, parallel-plate channels are formed by plate-type membranes stacked together. Equal spacing is kept between the neighboring membranes. The air and the solution streams flow alternatively through the parallel channels. The air stream flows uniformly in a straight path from left to right to control pressure drop and noise. However, the solution stream enters from the right header at the

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Nomenclature

c_p	specific heat (kJ kg^{-1} K^{-1})
c_s	specific heat of solution (kJ kg^{-1} K^{-1})
d_h	channel spacing height (m)
D_f	diffusivity (m^2/s)
D_h	hydrodynamic diameter (m)
f	friction factor
h	convective heat transfer coefficient (kW m^{-2} K^{-1})
h_{abs}	absorption heat (kJ/kg)
k	convective mass transfer coefficient (m/s)
Le	Lewis number
m	mass flow rate (kg/s)
n_{mem}	membrane plate number
NTU	number of transfer units
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
u	velocity (m/s)
x_0	contactor length (m)
x_i	channel inlet width (m)
x, y, z	coordinates (m)
X_s	mass fraction of solution (kg water/kg solution)
y_0	contactor width (m)

Greek letters

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

Superscripts

*	dimensionless

Subscripts

a	air
cal	calculated
cool	cooling effectiveness
deh	dehumidification effectiveness
e	equilibrium
exp	experimental
in	inlet
Lat	latent
mem	membrane
out	outlet
s	solution
sen	sensible
surf	surface
tot	total
v	water vapor
x, y	x-axial and y-axial directions, respectively

right hand corner of the contactor and leaves it from the left header at the left hand corner. The solution stream may travel along an S-shaped path line through the solution channel. It is obvious that the flowing arrangement between the air and the solution streams is similar to a combination of counter and cross-flow, which can also be called quasi-counter flow.

The performance analysis and evaluation of the QFPMC used for liquid dehumidification are of vital importance in engineering applications. Regretfully, these issues have not been mentioned up until now. It is noteworthy that the performances in a similar quasi-counter flow metal-formed parallel-plate exchanger employed for sensible heat recovery have been investigated [4]. However, the results are not applicable for membrane contactor. It is because there are simultaneous heat and mass transfer between the air and the solution fluids. Further, phase change heats are generated on the membrane surfaces because of water vapor absorbed by liquid desiccant. The coupling between the air and the solution streams through the membranes should be taken into account seriously.

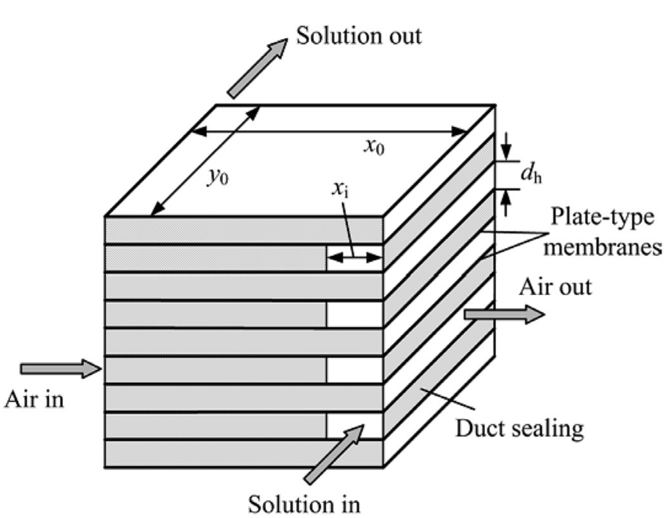

Fig. 1. Structure of a quasi-counter flow parallel-plate membrane contactor (QFPMC) used for liquid desiccant air dehumidification.

The novelties in the present study are that the performances of the QFPMC used for liquid desiccant air dehumidification are investigated based on a two-dimensional steady-state mathematical model. A finite difference method is employed to solve the equations governing momentum, heat and mass transports. The pressure drops, sensible cooling and latent dehumidification effectiveness are then numerically obtained and experimentally validated. The results can provide fundamentals for future contactor design, structural optimization and performance evaluation.

2. Mathematical model

2.1. Governing equations

In the above-mentioned membrane-formed contactor, as shown in Fig. 1, the air and the solution stream flow alternately through the parallel-plate channels in a quasi-counter flow arrangement. The contactor is comprised of several individual and identical elements. Further, for reasons of symmetry and simplicity in calculation, one membrane and two neighboring fluid flowing channels are selected as the calculating domain. The coordinate system of the element is depicted in Fig. 2. As seen, the air stream flows straightly along x-axis with a uniform velocity $u_{a,in}$ in the bottom channel. The solution stream flows from the right hand corner (inlet header) with a uniform velocity $u_{s,in}$ into the upper channel and out from the left hand corner (outlet header). Both the inlet and the outlet headers have a length of x_i, which is less than the contactor length (x_0), as shown in Fig. 1. Heat and moisture are exchanged through the