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An analytical solution of heat and mass transfer in a counter/parallel flow plate membrane module used in an absorption heat pump

Si-Min Huang*, Minlin Yang, Wei-Hao Huang, Shi Tao, Bing Hu, Frank G.F. Qin**

Key Laboratory of Distributed Energy Systems of Guangdong Province, Dongguan University of Technology, Dongguan 523808, China

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ABSTRACT

A plate membrane module is applied in an absorption heat pump for heating to provide domestic hot water. In the membrane module, water and salt solution are used as refrigerant and absorbent, respectively. The water and the solution streams, in a counter flow or a parallel flow arrangement, are separated by the membranes, which only allow transmission of water vapor, while prevent the water and the solution from permeating. The water vapor evaporated from the water stream is transferred across the membranes and the air-gaps and then absorbed by the solution stream. Absorption heat is then generated to heat the solution stream. In the membrane module, an element, including two plate membranes, an air-gap, and two neighboring channels, is selected as the calculation zone. A heat and mass transfer model is established in an element to study the coupled heat and mass transfer. An analytical solution is obtained and experimentally validated for the normalized equations governing the momentum, heat and mass transports, which provides a fast, accurate, and convenient tool for the structural design and optimization of the module. Influences of the dimensionless parameters on the solution temperature lift are studied. It is concluded that the solution temperature lift first increases and then decreases with a decrease in the solution mass flow rate. The solution inlet mass fraction ($X_{s,in}$) of 0.55, the solution inlet temperature ($T_{s,in}$) of about 25 °C, and the aspect ratios of the air-gaps (W/d_a) of about 50 may have the best performances of the membrane modules. Both the sensible and latent heat transfer parameters are the dominate factors affecting the solution temperature lift.

1. Introduction

With the rapid development of the society, the building energy conservation should be focused on the energy consumptions of air conditioning, heating, and domestic water since they account for more than 60% of the total building energy consumption [1]. The heat sources required in buildings have the features of low grade energy, narrow temperature range, and being close to environment temperature [2]. Heat pumps can absorb heats from the natural or industrial waste heats to improve the grade of the low temperature heat source, which can meet the needs of the air conditioning, heating, and domestic water [2]. Based on operation principles, heat pumps contain injection, adsorption, compression, and absorption types, etc [3]. Among them, the absorption heat pumps can be directly driven by heats to transform the heats from the low-temperature heat source to the high-temperature one, which is an effective technology for recycling the low-temperature heats. Further, the environmentally-friendly working mediums are used in the absorption heat pumps, which have the features of environmental protection and energy conservation [3–9]. With rapid developments and utilizations of the distributed energy systems, the applications of the absorption heat pumps gain much attention [3–9]. However, the conventional absorption heat pumps have two distinct shortcomings: low efficiency and huge devices.

Recently, with the development of the membrane technology, the atmospheric membrane-based absorption heat pumps have been proposed and studied [10–15]. The liquid/liquid membrane modules are used as the absorbers, where the water and the salt solution streams are separated by a number of air-gap membranes. The membranes only permit the transmission of the water vapor, while preventing the water and the salt solution from permeating [16–26]. The water vapor evaporated from the water stream is transferred across the membranes and the air-gaps and then absorbed by the solution stream, which is presented in Fig. 1. The salt solution, which has strong moisture absorption ability, is commonly employed here. The water vapor transferred across the membranes and the air-gaps is driven by the differences of the water vapor partial pressures between the water and the solution surfaces. The solution is heated because of the absorption of the water vapor. At the same time, sensible heat is largely reduced by the air-gaps to

* Corresponding author.
** Corresponding author.
E-mail addresses: huangsm@dgut.edu.cn (S.-M. Huang), qingf@dgut.edu.cn (F.G.F. Qin).

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Nomenclature

CF	counter flow
c	specific heat ($kJkg^{-1}K^{-1}$)
d	channel height (m)
d_p	membrane pore size (μm)
D	diffusivity (m^2/s)
H_{evap}	evaporation heat (kJ/kg)
H_{mix}	mixing heat (kJ/kg)
h	heat transfer coefficient ($kWm^{-2}K^{-1}$)
k	mass transfer coefficient (m/s)
L	module length (m)
m	mass flow rate (kg/h)
n_{mem}	membrane number
NTU	Number of Transfer Units
PF	parallel flow
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
W	module width (m)
x	x axial coordinate (m)
X_s	mass fraction of water mass in solution mass (kg water/kg solution)

Greek symbols

ρ	density (kg/m^3)
δ	membrane thickness (m)
λ	heat conductivity ($Wm^{-1}K^{-1}$)
ω	humidity ratio (kg water vapor/kg dry air)
τ	membrane pore tortuosity
ξ	membrane porosity
σ	flow direction controller, "+1" for counter flow and "–1" for parallel flow arrangement

Superscripts

*	dimensionless

Subscripts

a	air
e	equilibrium
in	inlet
Lat	latent
mem	membrane
out	outlet
R	mass flow rate ratio
s	solution
sen	sensible
va	water vapor in air
ws	water in solution

transfer from the heated solution stream back to the water stream because of the large heat transfer resistances in the air-gaps [10–15]. Compared to a conventional vacuum absorption heat pump, the novel membrane-based one is performed at atmospheric pressure. Therefore the device weight is small and the production cost is relatively low. Further, the stored salt solution can be used for air dehumidification in the hot and humid seasons [10–15].

The membrane modules are commonly flat-plate [10,11] or hollow fiber membrane types [12–15]. The former one, as shown in Fig. 1, is easily realized and manufactured because of its simple structure. As seen, rectangular channels are formed by flat-plate membranes populated and installed together. Each air-gap is sandwiched by two neighboring plate membranes. The water flows from the left inlet into the water channels and out from the right outlet straightly, while the salt solution enters from the right/left inlet into the solution channels and leaves from the left/right outlet in a counter or a parallel flow arrangement. In order to improve the performances of the membrane modules, a counter flow plate membrane modules are desired. However for reasons of channel sealings between the neighboring fluids, the side in and side out (quasi-counter flow) membrane module has been proposed and applied in the absorption heat pump [10], which was referenced from the quasi-counter flow membrane-based membrane dehumidifiers proposed by Simonson et al. [18–23]. In these quasi-counter flow membrane modules, the module length is commonly much larger than its width. Further, the entrance ratio is as smaller as 0.1. It has been found that about 90% of the module length is in a counter flow arrangement [10,18–23]. Therefore the quasi-counter flow plate membrane module can also be approximated as a pure counter flow one, which can also be evaluated by the mathematical model developed here.

The performance analysis and evaluation of the plate membrane modules applied in the absorption heat pumps are of vital importance in practical applications. It has been known that the heat and mass transports inside the plate membranes are strongly coupled between the water and the solution streams [9–11]. Further, the classical heat and mass analogies between the fluids are not suitable here because of the rather large mass transfer Biot number (≫0.1) [10]. The overall heat and mass transfer resistances are also influenced by inlet operation conditions, transport properties of the membranes, module structures, etc. Therefore the classical correlations of sensible effectiveness-Number of Transfer Unit (ε-NTU) developed in metal-formed sensible heat exchangers are not suitable for the performance evaluations of the membrane modules employed in the absorption heat pumps. The correlations between the module performances and the Number of Transfer Units for the sensible heat and moisture transports should be derived for the performance optimizations of the plate membrane modules employed in the absorption heat pumps.

In present study, a lumped parameter mathematical model is established in a unit cell containing two neighboring channels, two plate membranes, and an air-gap in the counter/parallel flow plate membranes module applied in the absorption heat pumps. An analytical solution to the normalized equations governing the coupled heat and mass transports are derived by some simply algebraic transformations. The algebraic expressions of solution temperature lift (ΔT_{lift}), energy transfer rate of the solution stream (*ETR*), and heat transfer effectiveness of the solution stream (ε) are obtained and validated experimentally. Effects of the inlet operation conditions, the module dimensions, and the dimensionless governing parameters on the module performances are studied. The analytical solution provides an effective tool for the performance evaluations of the plate membrane modules, which is convenient and accurate.

2. Mathematical model

2.1. Heat and mass conservation equations

The plate membrane module, as shown in Fig. 1, is comprised of a number of the same elements. Each element includes two neighboring channels, two plate membranes, and an air-gap. An element is selected as the calculation zone because of its simplicity, which is shown in Fig. 2. As seen, the water flows along x-axis in the upper channel, while the solution flows from the right/left inlet into the bottom channel and