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Heat and mass transfer in a quasi-counter flow parallel-plate membrane-based absorption heat pump (QPMAHP)

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ABSTRACT

A quasi-counter flow parallel-plate membrane-based absorption heat pump (QPMAHP) is proposed and used for fluid heating. The concept is like a combined counter/cross-flow parallel-plate membrane contactor, where the refrigerant (water) and the absorbent (salt solution) flows are separated by the semi-permeable membranes, which only guarantee the permeation of water vapor. The solution stream attracts the water vapor from the water stream across the membranes. Latent and mixing heats are then released on the solution side for upgrading low-temperature heat to high temperature useable heat. A mathematical model is established in a unit cell, containing two membranes with an air-gap in between and two neighboring channels, to study the coupled heat and mass transports in the QPMAHP. A finite difference method is employed to solve the normalized equations governing momentum, heat and mass transports. The solution temperature lift and efficiency are then obtained. A heat pump system based on the QPMAHP is designed and set up to validate the results. It can be found that the solution temperature lift and efficiency increase about 9.1% when the entrance ratio and aspect ratio are equal to 0.1 compared to those of a cross-flow one.

1. Introduction

Energy consumption for heating and domestic hot water is very high, especially in urban northern China accounting for as high as 25% of the total building energy consumption. Moreover, it increases continuously because of the rapid urbanization of China and obvious improvement in living standards [1–3]. Fossil fuel combustion in boilers is a common approach for heating and domestic hot water in China because of its coal-dominated energy structure. However fossil fuel is non-renewable energy on earth. Further, the serious problem of environment pollution restricts the development of the fossil fuel combustion method [4].

In order to realize energy conservation and environmental protection, the heating systems driven by renewable energy or industrial waste heat have been gained much attention [5–8]. Though none is perfect, of the various heating technologies, absorption heat pump system has its coherent advantages of easily driven by industrial waste heat, large heating capacity and low power consumption. However, low efficiency and huge device are its shortcomings. In recent years, the membrane-based absorption heat pump, which is operated at atmospheric pressure, has been proposed and investigated [9–12]. The concept is a membrane contactor, where the refrigerant (water) and the absorbent (salt solution) flows are separated by multiple selectively permeable membranes with air gaps between the neighboring membranes, which only permit the permeation of the water vapor, while preventing the liquid streams from permeating [13–15]. Therefore a net flux of the water vapor is generated across the membranes, which heats the solution stream and cools the water stream, creating a temperature lift of the solution stream. The air-gaps reduce sensible heat transferred from the solution stream back to the water stream. The operation is conducted at atmospheric pressure. Therefore the device weight, system complexity, and production cost are largely reduced compared to a conventional vacuum one. Further, it enables lossless energy storage for heating and cooling processes driven by renewable heat sources such as solar energy or waste heat [9–12].

A parallel-plate membrane-based absorption heat pump (contactor) has been proposed and used for heating, which has been designed to be the contactor with a pure counter flow arrangement [9]. It has been well-known that a pure counter flow contactor may have higher effectiveness than that of a pure cross-flow one. However a pure counter flow membrane contactor with multiple channels is difficult in sealing and separation between the water and the solution streams [16,17]. Therefore a quasi-counter flow parallel-plate membrane-based heat pump

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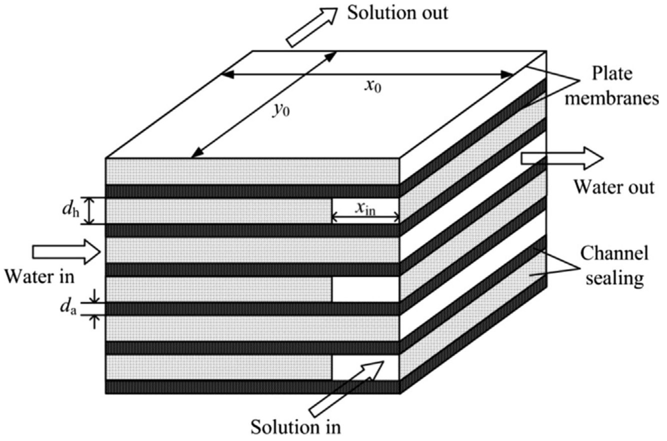

Fig.1. Structure of a quasi-counter flow parallel-plate membrane-based absorption heat pump (QPMAHP) used for fluid heating.

(QPMAHP), as shown in Fig.1, is proposed and used for heating. As seen, parallel-plate channels are formed by plate membranes stacked together. Each neighboring channels are separated by two membranes with an air-gap in between. The water and the solution streams flow alternatively through the channels. The water stream flows from the left inlet to the right outlet straightly to have a relatively high velocity, while the solution stream enters from the right header into the duct and leaves it from the left header in a S-shaped path. It is obvious that the water and the solution streams are in a quasi-counter flow arrangement.

The heat and mass transports in the QPMAHP employed for fluid temperature upgrade are vital important in engineering applications for performance analysis. Regretfully, these issues have not been mentioned up until now. It should be noted that the heat and mass transports in a similar membrane contactor employed for liquid desiccant air dehumidification have been investigated [18]. However the processes are different since the large heat transfer resistance between the two streams with an air-gap. Further, their performance evaluation parameters are different. One is solution temperature lift, while another one is air dehumidification effectiveness. The novelties in this study are that a mathematical model is developed to investigate the heat and mass transfer in the QPMAHP used for fluid heating. Effects of the flowing arrangements, entrance ratios, and aspect ratios on the heat and mass transfer in the QPMAHP are analyzed. The results are useful for structure and performance optimizations of the QPMAHP.

2. Mathematical model

2.1. Governing equations

As seen from Fig.1, the water and the solution streams flow alternately through the channels in a quasi-counter flow arrangement in the QPMAHP, which is consisted of a series of identical elements. Each element is comprised of two neighboring ducts, two membranes, and their sandwiched air-gap. An element is selected as the calculating domain due to its simplicity in calculation. The coordinate system of the element is depicted in Fig.2. As seen, the water stream flows straightly along x-axis with a uniform velocity $u_{w,in}$ in the upper channel, while the solution stream flows from the right corner with a uniform velocity $u_{s,in}$ into the bottom channel and out from the left corner. Heat and moisture are exchanged between the two streams. The water stream is served as the evaporation source, while the solution stream is used as the heating fluid. Water vapor is absorbed by the solution stream from the water stream across the membranes and the air-gap. Latent and mixing heats are then released on the solution side for upgrading low-temperature heat to high temperature useable heat. Sensible heat transferred from the heated solution back to the water is largely reduced because of the large heat transfer resistance in the air-gap.

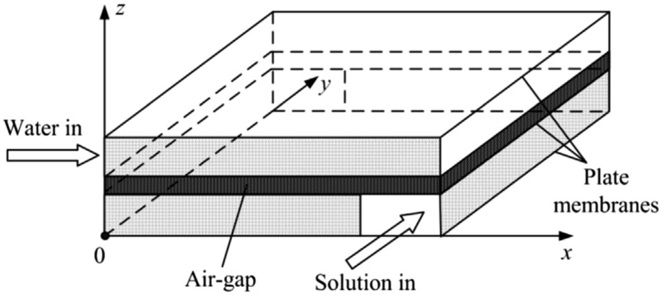

Fig.2. Coordinate system of the unit cell showing the water and the solution channels, two membranes and their sandwiched air-gap.

The established mathematical model is two-dimensional and steady-state. Heat and mass transfer are estimated by the bulk average velocity, temperature, equilibrium humidity and mass fraction in the water and the solution channels. Both the water and the solution streams are laminar ($Re < 2000$) and Newtonian with constant thermo-physical properties. Other assumptions are as follows:

(1) Heat and moisture transports with the surroundings are neglected since the outer walls of the contactor are adequately insulated and hydrophobic.
(2) Heat conduction and moisture diffusion of the fluids along their mainly flowing directions are neglected compared to energy transport and vapor convection by the bulk flows. It is since the Peclet numbers (Pe) of the fluids are larger than 10 in the practical applications [12,19,20].
(3) Heat and moisture transports are transferred only normal to the membrane plate (z-direction) because of the rather small membrane thickness (around 100 μm) and air-gap distance (about 1.0 mm).
(4) Heat loss and gain from the water vapor phase change are occurred only in the water and the solution sides, respectively.

For the water stream, the evaporation heat is extracted from the water. On the other hand, sensible heat is transferred from the solution stream to the water stream. Therefore the normalized equation for heat conservation is

$$\frac{\partial T_w^*}{\partial x^*} = NTU_{sen}(T_s^* - T_w^*) + H_{evap}^* \cdot NTU_{Lat}(\omega_s^* - \omega_w^*) \tag{1}$$

where T and ω are temperature (K) and humidity ratio (kg/kg), respectively; Superscript "*" represents dimensionless form; Subscript "w" and "s" mean the water and the solution streams, respectively; NTU is number of transfer units, which is defined by

$$NTU_{sen} = \frac{h_{tot} n_{mem} x_0 y_0}{2 m_w c_w} \tag{2}$$

$$NTU_{Lat} = \frac{\rho_a k_{tot} n_{mem} x_0 y_0}{2 m_w} \tag{3}$$

where x_0 and y_0 are contactor length and width (m), respectively; n_{mem} is number of the membrane plates; c is specific heat (kJ kg^{-1} K^{-1}); m is total mass flow rate (kg/s); h_{tot} and k_{tot} are total