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Solution-side effectiveness for a liquid-to-air membrane energy exchanger used as a dehumidifier/regenerator

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HIGHLIGHTS

- Liquid-to-air membrane energy exchangers are called LAMEEs in this paper.
- For the first time, the solution-side (SS) effectiveness are introduced for LAMEEs.
- The SS effectiveness is very important when a LAMEE is used as a regenerator.
- Both the air-side and solution-side effectiveness of the LAMEE increase with Cr*.
- The air-side and solution-side effectiveness values are different in most cases.

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ABSTRACT

A liquid-to-air membrane energy exchanger (LAMEE) is an energy exchange device that transfers heat and moisture between air and salt solution streams through a semi-permeable membrane which is permeable for water vapor but impermeable for liquid water. LAMEEs have been used as a dehumidifier/regenerator in air-conditioning systems. In this paper, the solution-side effectiveness are presented for a small-scale single-panel LAMEE when it is used to regenerate the solution flow. The solution-side effectiveness are very important in regenerators where the main focus is on the salt solution, and the solution properties (i.e. solution outlet concentration) are important. The small-scale LAMEE is tested under air dehumidification and solution regeneration test conditions using a LiCl solution at one NTU (i.e. NTU = 5) and three different Cr* values (Cr* = 2, 4 and 6). The results show that both the air-side and solution-side effectiveness of the LAMEE increase with Cr*. The solution-side latent effectiveness is lower for the regenerator in comparison to the dehumidifier (e.g. 43% lower at Cr* = 6). Also, the numerical results for a small-scale LAMEE which were presented in literature are used in this paper to evaluate the solution-side effectiveness of the LAMEE under different test conditions. The numerical results show that the difference between the air-side and solution-side latent effectiveness are negligible. Therefore, the air-side latent effectiveness can be used to evaluate the solution-side latent effectiveness of LAMEEs.

1. Introduction

There are three types of energy recovery (ER) devices available to recover both heat and moisture from an exhaust air stream in buildings; these are: air-to-air membrane energy exchangers (AAMEE), energy wheels and liquid-to-air energy exchangers used in run-around liquid desiccant coupled systems [1,2]. In AAMEEs the heat and moisture transfer between supply and exhaust air streams through a semi-permeable membrane. The effectiveness of the AAMEE have been calculated for both supply and exhaust air streams using ANSI/AHRI Standard 1060 [3]. This standard can be used to calculate the effectiveness of energy wheels for the supply and exhaust air streams. Also, the effectiveness-NTU method, which was developed for heat exchangers [4], can be used to predict the performance of the AAMEEs and energy wheels. Simonson and Besant [5] introduced an operating condition factor (H^*) parameter for energy wheels to calculate the total performance of the energy wheels directly from sensible and latent effectiveness. This method can be used to calculate the total effectiveness of liquid-to-air energy exchangers [6].

Liquid-to-air energy exchangers have been used to transfer heat and moisture in liquid-desiccant (LD) air-conditioning systems. In liquid-to-air energy exchangers, a salt solution and air can be in direct contact, such as packed beds [7], or indirect contact, such as hollow fiber membrane contactors [8] and liquid-to-air membrane energy exchangers (LAMEEs) [6]. In LAMEEs, the heat and moisture transfer between the salt solution and the air stream occurs through a semi-permeable membrane. This membrane is permeable for water vapor but impermeable for liquid water. The

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Nomenclature

A	energy transfer area (m^2)
C	salt solution concentration (%)
c_p	specific heat capacity at constant pressure (J/kg K)
Cr^*	heat capacity ratio
H	enthalpy (J/kg)
H^*	operating condition factor
H_{ex}	exchanger height (m)
h	convective heat transfer coefficient (W/m^2 K)
h_{fg}	enthalpy of phase change (J/kg)
k	thermal conductivity (W/m K)
L_{ex}	exchanger length (m)
L_s	exchanger solution inlet length (m)
$\dot{m}$	mass flow rate (kg/s)
NTU	number of heat transfer units
Nu	Nusselt number
q	transferred energy in heat or energy exchangers (W)
R	membrane resistance (s/m)
RH	relative humidity
T	temperature (°C or K)
U	overall heat transfer coefficient (W/m^2 K)
W	humidity ratio (kg_{water}/kg_{air})
X	solution mass fraction (kg_{water}/kg_{salt})

Greek symbols

δ	thickness (m)
ε	exchanger effectiveness
Δ	differential between two quantities

Subscripts

air	air
in	inlet
lat	latent
max	maximum
mem	membrane
min	minimum
out	outlet
salt	pure salt
sen	sensible
sol	salt solution
tot	total

membrane is an important part in membrane based energy exchangers, and it is important to evaluate its properties in terms of health issues. Refs. [9,10] did a comprehensive review on membrane fouling and bio-fouling which have been used in membrane-based desalination systems. The properties of those membranes is similar to membranes which have been used in LD systems. Alkhudhiri et al. [9] presented a few strategies for pre-treatment and membrane cleaning due to membrane fouling in the liquid side of the membrane such as solution pretreatment by microfiltration, ultrasonic irradiation technique and fouling control by operating at low temperature and high flow rate. Ref. [10] reviewed previous works on membrane fouling and bio-fouling, and it concluded that problems resulting from bio-fouling such as bacterial and microbial growth were significantly lower than fouling encountered in other membrane processes.

Liquid-to-air energy exchangers have been used as a dehumidifier and regenerator in LD air-conditioning systems [11–13]. Fig. 1 shows a schematic of a run-around membrane energy exchanger (RAMEE) system as a LD air-conditioning system. The RAMEE consists of two LAMEEs, one in the supply and another in the exhaust air streams where the heat and moisture transfers between these two air streams using a closed solution loop [14]. In humid climates, the supply LAMEE acts as a dehumidifier to dehumidify the supply air and the exhaust LAMEE acts as a regenerator to regenerate the salt solution. The dehumidifier conditions the supply air to a building and thus the focus is on the air side (i.e. the air outlet conditions are the control variable that must be satisfied). The regenerator is used in the exhaust air stream to recover waste energy form the building's exhaust air, and regenerate the salt solution concentration to reuse it in the dehumidifier. In the regenerator, the main focus is on the solution side since the solution properties are very important [15]. The solution properties (i.e. solution concentration) must be regenerated (dried) in the regenerator to adequately remove moisture from the supply air in the dehumidifier.

There are few papers in the literature on the economic and environmental performances of membrane liquid desiccant air conditioning (M-LDAC) systems [16,17]. Abdel-Salam and Simonson [16] evaluated the economic performance and emissions production of a M-LDAC system using the TRNSYS software program, and compared the M-LDAC system with a conventional air conditioning (CAC) system. The M-LDAC system consists of two LAMEEs, which were used as a dehumidifier and a regenerator. A cooling coil was used in the CAC system to dehumidify the supply air. The results showed that the annual energy consumption and life cycle cost of the M-LDAC system are 19% and 12% lower than the CAC system, respectively. The annual emission of CO_2 decreased by 19% when the M-LDAC system was used in comparison with the CAC system. Also, Patel et al. [17] studied volatile organic compounds (VOCs) transfer in RAMEE systems between supply and exhaust air streams through a salt solution loop, which are an important class of indoor air contaminants which can cause severe health damage. Toluene (C_7H_8) and formaldehyde (HCHO) were used as the VOCs in their study. The results showed that transfer of VOCs in a RAMEE system is negligible for VOCs with low solubility in water and small for VOCs with high solubility in water.

In the literature and practice, liquid-desiccant packed beds are the most common air dehumidifiers and the solution regenerators, and the air-side effectiveness is exclusively used to evaluate the dehumidification and regeneration performance of the packed beds [18–21]. Liu et al. [22] tested a cross flow packed bed with a LiBr salt solution in an LD air-conditioning system as a regenerator. They investigated the impact of the air and solution inlet parameters on the regeneration performance of the bed using air-side effectiveness definitions. In another paper [11], they analytically investigated the coupled heat and mass transfer in dehumidifier/regenerator packed beds with parallel, cross and counter flow configurations for the air and salt solution using the air-side effectiveness. This analytical model can be used for the optimal design of dehumidifier and regenerator packed beds. Yin et al. [12] developed a model to evaluate the performance (based on air-side effectiveness) of a dehumidifier/regenerator packed bed which is equipped with an internal cooling/heating water loop. The results showed that the internally cooled/heated equipment, which is added to the traditional packed bed, improves the dehumidification and regeneration performance of the packed bed. In these papers on packed beds, the air-side effectiveness definitions were used to evaluate the regeneration performance of liquid