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Performance analysis of a membrane liquid desiccant air-conditioning system

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ABSTRACT

A new membrane liquid desiccant air-conditioning (LDAC) system is proposed and investigated in this paper. Liquid-to-air membrane energy exchangers (LAMEEs) are used as a dehumidifier and a regenerator in the proposed membrane LDAC system, which can eliminate the desiccant droplets carryover problem occurring in most direct-contact LDAC systems. A parametric study on steady-state performance of the membrane LDAC system is performed using the TRNSYS energy simulation platform. The impacts of various climatic conditions and key system parameters on the system performance are evaluated. Results show that the proposed membrane LDAC system is capable of achieving recommended supply air conditions for productive, comfort and healthy environments if the key system parameters are effectively controlled. The system coefficient of performance (COP) at the design condition is 0.68, and the sensible heat ratio (SHR) for the dehumidifier lies in the range between 0.3 and 0.5 under different climatic, operating and design conditions. The proposed membrane LDAC system is able to effectively remove latent load in applications that require efficient humidity control.

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1. Introduction

The world energy consumption has increased significantly in past decades, due to population growth and economic development. Since air-conditioning (AC) systems make up 50% of building energy consumption [1], there should be energy efficient AC systems that are able to provide healthy environments with acceptable indoor air quality (IAQ) in order to improve the health and productivity of building occupants. Desiccant dehumidification AC systems show promise as energy efficient AC systems [2].

Although there are several advantages for the widely used conventional AC systems and they are able to effectively remove sensible loads within conditioned spaces, they are inefficient in terms of conditioning latent loads. When indoor humidity control is required in some cases, the cooling coil temperature in conventional AC systems must be lower than the dew point temperature of the process air stream in order to remove moisture by condensation. This results in wet cooling coil surfaces that may lead to the growth of mold and bacteria; consequently lead to undesirable health issues and poor IAQ within conditioned spaces [3]. Moreover, after moisture is removed from the process air stream, the overcooled air often needs to be reheated before it is supplied to the occupied spaces. A large amount of energy consumed in the overcooling and reheating processes makes conventional AC systems energy intensive [4]. It is clear that the latent load treatment is a challenge for conventional AC systems. Since latent load is dominant over sensible load in ventilation air in hot and humid regions, according to the ventilation cooling load index developed by Harriman et al. [5], efficient AC systems that can handle the latent load effectively are required.

The aforementioned drawbacks of conventional AC systems can be avoided by using liquid desiccant air-conditioning (LDAC) systems. LDAC systems are considered as a promising alternative to other AC systems especially in the applications that require efficient humidity control such as: supermarkets, green buildings and greenhouses [6–8]. Although many studies have been performed on this topic since the 1950s, most of them focused on direct-contact liquid-to-air conditioners [9–19]. These systems have been found to be more energy efficient than conventional AC systems, but entrainment of desiccant droplets in the air streams is a significant drawback of the direct-contact LDAC systems. The carryover of liquid desiccant by the supply air stream can lead to the corrosion of downstream ducting and equipment which results in high maintenance requirements, short life cycles and high costs. In addition, desiccant carryover may affect IAQ within the conditioned space and health of occupants. These drawbacks have limited the widespread use of LDAC systems in civil/domestic applications [20].

Different liquid desiccant dehumidifiers that are able to overcome the droplets carryover problem have been designed and developed recently [21]. One design uses an internally

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Nomenclature

A	surface area of membrane (m^2)
CC	cooling capacity (kW)
Cr^*	thermal capacity ratio
C_{sol}	solution concentration
c_p	specific heat capacity(kJ/kg K)
COP	coefficient of performance
$COP_{chiller}$	chilling system coefficient of performance
D_h	hydraulic diameter (m)
E	rate of energy consumption (kW)
E_T	slope of equilibrium humidity to temperature of solution (g/kg K)
ECOP	electrical coefficient of performance
h	specific enthalpy (kJ/kg)
h_c	convective heat transfer coefficient (W/m^2 K)
h_m	convective mass transfer coefficient (kg/m^2 s)
H^*	operating condition factor
k	thermal conductivity of the membrane (W/m K)
k_f	thermal conductivity of the fluid (W/m K)
k_m	permeability of the membrane (kg/m s)
L	Length of the LAMEE (m)
Le	Lewis number
$\dot{m}$	mass flow rate (kg/s)
MRR	moisture removal rate (g/s)
NTU	number of heat transfer units
NTU_m	number of mass transfer units
Nu	Nusselt number
Q	rate of heat transfer (kW)
RH	relative humidity (%)
SHR	sensible heat ratio
T	temperature (°C)
TCOP	thermal coefficient of performance
U	overall heat transfer coefficient (W/m^2 K)
U_m	overall mass transfer coefficient (kg/m^2 s)
W	humidity ratio (g/kg)

Greek letters

δ	thickness of the membrane
η	efficiency
ε	effectiveness

Subscripts

air	air flow
amb	ambient
cool	cooling
deh	dehumidifier
ev	evaporator
in	inlet
lat	latent
min	minimum
out	outlet
p	pumping
reg	regenerator
sen	sensible
sol	solution flow
SHX	sensible heat exchanger
th	thermal
w	water

cooled/heated (isothermal) low flow rate flat-plate exchanger that is able to significantly reduce or eliminate the carryover of droplets by the low-speed air stream [22–25]. Another design is the indirect-contact liquid-to-air energy exchanger, where the liquid desiccant and air stream are separated by semi-permeable membranes which eliminate the liquid desiccant carryover problem. The energy performance of using these membrane energy exchangers in a hybrid membrane LDAC system was studied by Bergero and Chiari [20,26], and it was found that energy savings may exceed 60% in humid climates compared to a conventional AC system. However, the characteristics of the membrane LDAC systems have not been extensively studied.

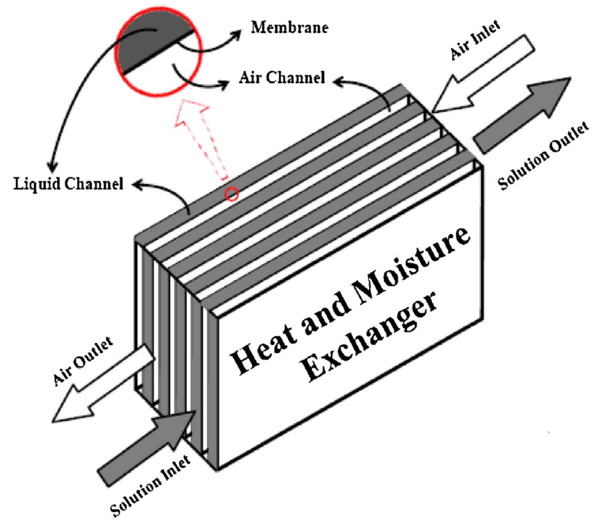

Fig. 1. Schematic of a counter-flow LAMEE [30].

The aim of the present study is to analyze the characteristics of a membrane LDAC system that uses flat-plate liquid-to-air membrane energy exchangers (LAMEEs) to serve as the dehumidifier and regenerator [27–30]. The proposed system is modeled using TRNSYS [31,32]. The performance of the system is investigated under different climate conditions (i.e. outdoor temperature and relative humidity), design conditions (i.e. number of transfer units and solution heat exchanger effectiveness) and operating conditions (i.e. liquid desiccant flow rate and temperature of solution entering the regenerator/dehumidifier).

2. Membrane LDAC system

2.1. Liquid-to-air membrane energy exchanger (LAMEE)

In the proposed membrane LDAC system, the dehumidifier and regenerator are liquid-to-air membrane energy exchangers (LAMEEs) with counter-flow configuration as shown in Fig. 1. The specifications of the LAMEEs at design conditions are shown in Table 1.

The air and desiccant solution streams in the LAMEEs are separated by semi-permeable membrane (e.g. polyethylene,

Table 1
The LAMEEs specifications and the membrane properties.

Parameter	Value	Unit
LAMEE height	1	m
LAMEE length	2	m
Number of solution channels	250	–
Air channel thickness	6.35	mm
Solution channel thickness	3.17	mm
Membrane type	AY Tech. ePTFE	–
Membrane thickness	0.54	mm
Membrane vapor diffusion resistance	97	s/m
Membrane modulus of elasticity	387	MPa
Membrane liquid penetration pressure	82	kPa
Membrane thermal conductivity	0.334	W/m K

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