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Research Paper

Performance testing of a cross-flow membrane-based liquid desiccant dehumidification system

Hongyu Bai [a], Jie Zhu [a,*], Ziwei Chen [a], Lina Ma [a], Ruzhu Wang [b], Tingxian Li [b]

[a] *Department of Architecture and Built Environment, The University of Nottingham, University Park, Nottingham NG7 2RD, UK*
[b] *Institute of Refrigeration and Cryogenics, Key Laboratory for Power Machinery and Engineering of M.O.E, Dongchuan Rd. 800#, Shanghai Jiao Tong University, Shanghai 200240, China*

HIGHLIGHTS

- The performance of a membrane-based dehumidifier is investigated experimentally.
- A full map of the dehumidifier main operating parameters is presented.
- Effectiveness increases with solution to air mass flow rate ratio and *NTU*.
- Effectiveness can be improved by decreasing solution temperature.

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ABSTRACT

A membrane-based liquid desiccant dehumidification system is one of high energy efficient dehumidification approaches, which allows heat and moisture transfers between air stream and desiccant solution without carryover problem. The system performance is investigated experimentally with calcium chloride, and the impacts of main operating parameters on dehumidification effectiveness (i.e. sensible, latent and total effectiveness) are evaluated, which include dimensionless parameters (i.e. solution to air mass flow rate ratio m^* and number of heat transfer units *NTU*) and solution properties (i.e. concentration C_{sol} and inlet temperature $T_{sol,in}$). The sensible, latent and total effectiveness reach the maximum values of 0.49, 0.55, and 0.53 respectively at $m^* = 3.5$ and $NTU = 12$, and these effectiveness are not limited by m^* and *NTU* when $m^* > 2$ and $NTU > 10$. Both the latent and total effectiveness increase with C_{sol}, while almost no variation is observed in the sensible effectiveness. All effectiveness can be improved by decreasing $T_{sol,in}$. The experimental data provide a full map of main design parameters for the membrane-based liquid desiccant air conditioning technology.

1. Introduction

Buildings consume a significant part of the global total energy, particularly heating, ventilation and air-conditioning (HVAC) systems are responsible for around 50% of the energy consumed in buildings [1]. As a matter of fact, the energy consumption for dehumidification process accounts for 20–40% of the total energy used in HVAC systems, and it can be higher when 100% fresh air ventilation is required for better indoor environment [2]. Without proper air dehumidification, occupants would feel uncomfortable and mildew would grow on building interior walls in the humid region. Furthermore, production safety and quality would be seriously affected by high humidity level [2]. It has been shown that the building energy consumption could be decreased by 20–64% with efficient dehumidification technologies [3].

Currently, cooling coil is mostly preferred for dehumidification [4], which adopts cooled water as the cold medium generated from vapour compression system (VCS). The conventional VCS has advantages of good stability in performance, long life and a reasonable electrical COP (between 2 and 4) [5]. However, the working fluids used in VCS such as R-22, R-410A and R-134A with the high global warming potential are harmful to the environment. Furthermore, VCS consumes substantial amount of electrical energy [6]. In the traditional cooling coil, air dehumidification is undertaken simply by cooling air below its dew point for condensation in order to reduce its moisture content. Normally, this type of dehumidification is followed by reheating the dehumidified air to a desired temperature. Consequently, this combined process consumes a

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* Corresponding author.
E-mail address: jie.zhu@nottingham.ac.uk (J. Zhu).

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Nomenclature

A	membrane surface area (m^2)
AH	absolute humidity (kg/m^3)
c_p	specific heat capacity (J/kg K)
C	concentration (%)
C_r^*	capacitance ratio
d	width of the rectangular channel (m)
h	convective heat transfer coefficient (W/m^2 K)
H	height of the rectangular channel (m)
H^*	operating factor
k	thermal conductivity (W/m K)
L	characteristic length of the rectangular channel (m)
m^*	solution to air mass flow rate ratio
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
NTU	number of heat transfer units
NTU_m	number of mass transfer units
P	atmospheric pressure (Pa)
P_v	equilibrium vapour pressure of desiccant solution (Pa)
RH	relative humidity (%)
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
$\dot{V}$	volumetric flow rate (l/min)
W	humidity ratio (kg/kg)

Greeks

ε	effectiveness
δ	thickness of membrane (m)
ρ	density (kg/m^3)

Subscripts

air	air flow
crit	critical value
in	inlet
lat	latent
mem	membrane
min	minimum value
out	outlet
sen	sensible
sol	solution flow
tol	total

considerable amount of energy to cool (typically using a VCS) and heat (using hot water or electricity) the supply air [7].

In the traditional desiccant system, the vapour pressure gradient between humid air and desiccant results in heat and moisture transfers [8,9]. The system operates using either solid or liquid desiccant. Solid desiccant system is compact, simple and less subject to desiccant carryover and corrosion problems, while liquid desiccant system has lower regeneration temperature, higher dehumidification capacity and lower air side pressure drop [10]. Liquid desiccants can be regenerated using low-grade heat sources such as solar energy, and the regenerated solution can be used as energy storage medium as well [11]. In such way, the liquid desiccant system has been well developed recently.

The traditional liquid desiccant system commonly adopts the packed bed, where air and desiccant are in direct contact. Comprehensive researches have been conducted on the direct contact system [12–15], and it has been found that air conditioning energy consumption reduces by up to 26–80% in the hot and humid climate. However, in the direct contact system, small desiccant droplets are carried over by the supply air to the indoor environment, which badly affects the occupant health, building structure and furniture [2].

Recently, selectively permeable membrane has been used to replace the packed bed as the heat and mass transfer medium to overcome the desiccant droplet carryover problem. Semi-permeable membrane is able to prevent the solution from carrying over into the supply air, while selectively permitting heat and moisture transfers between the liquid desiccant and supply air [2,16–20]. The selectively permeable membrane can be classified into two types: parallel plate [21–33] and hollow fiber [34–38]. Several researches have been carried out to investigate the membrane-based dehumidifier performance. For example, Moghaddam et al. [21] experimentally and numerically studied different parameter influences on the steady state performance of a small-scale counter-flow liquid-to-air membrane energy exchanger (LAMEE), these parameters include thermal capacity ratio (Cr^*), number of heat transfer units (NTU) and number of mass transfer units (NTU_m). Hemingson et al. [22,23] developed a model of moisture transfer resistance between the membrane and solution for a counter-flow LAMEE, and conducted experimental tests under a range of outdoor weather conditions. Fan et al. [24,25] built a mathematical model for a single cross-flow LAMEE, which is applied to a run-around LAMEE system consisting of both dehumidifier and regenerator. The impacts of Cr^*, NTU and NTU_m on both sensible and latent effectiveness of the run-around system are evaluated. Seyed-Ahmadi et al. [26,27] developed a mathematical model to simulate the transient behaviours of a single cross-flow LAMEE and a run-around LAMEE, which is also compared with Fan's steady state model. Apart from counter and cross flows, an innovative flow configuration, counter-cross flow, has been investigated. Vali et al. [28,29] modelled a run-around LAMEE system using the counter-cross flow exchangers as dehumidifier and regenerator, and assessed the steady state system performance. Moghaddam et al. [30] studied the effect of the direction of heat and mass transfer inside the counter-cross flow LAMEE through experiment and numerical simulation. However, in the above researches, the fundamental data required for mathematical modelling such as Nusselt number (Nu) and Sherwood number (Sh) are simply borrowed from well-known books, which are generally obtained under uniform temperature or heat flux boundary condition. Thus they are unable to reflect the real heat and mass transfer properties. To solve this problem, Huang et al. [31] proposed a mathematical model for the cross-flow parallel-plate membrane module to conjugate heat and mass transfer in a cross-flow LAMEE under a fully developed flow condition. The fundamental data of Nu and Sh under various aspect ratios are calculated. However, the assumption of a fully developed flow is not reasonable in this model. Accordingly, they [32] improved this model by considering the effect of the developing entrance length on the fluid flow pattern.

Most of the researches in literatures focus on numerical modelling of heat and mass transfer in LAMEE. Some of them experimentally assess the LAMEE performance for different heat and mass transfer directions or liquid desiccant types [3,30]. Researchers also analyse the impacts of NTU, solution to air mass flow rate ratio (m^*), and solution inlet temperature ($T_{sol,in}$) on the liquid desiccant air-conditioning system [39]. However a few studies investigate the LAMEE performance by considering the operating parameters: NTU, solution to air mass flow rate ratio (m^*), solution inlet temperature ($T_{sol,in}$) and concentration (C_{sol}) [21–25,40]. Thus in order to get a full map of the operating characteristics of a LAMEE, a series of experimental tests are carried out in this study to evaluate the performance of a full-scale membrane-based cross-