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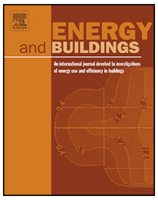

Experimental study and analysis of heat and mass transfer ability of counter-flow packing tower and liquid desiccant dehumidification system

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ABSTRACT

The purpose of air-conditioning systems is to provide a suitable indoor environment with respect to temperature, humidity and fresh air. Liquid desiccant dehumidification constitutes an effective method for extracting moisture from humid air with less energy consumption. Current studies mainly focus on dehumidification system under certain heat and mass transfer ability (number of mass transfer units NTU_m). This paper will investigate NTU_m of counter-flow packing tower and its influence on system performance. An experiment including a counter-flow packing tower was conducted. When the height of tower was 0.7 m, the volumetric mass transfer coefficient was between 1–4 kg/(m^3·s) and NTU_m presented a range between 0.9–1.4, when air flow rate changes from 1 kg/(m^2 s) to 2.5 kg/(m^2 s). When the height changed to 2.1 m, the NTU_m of the tower presented a variation from 3.3 to 4.3. Furthermore, a simulation model is developed, which is validated by experimental data and past research results. The influence of NTU_m on total circulation flow path is mainly caused by heat and cold offset and an NTU_m value approximately of 4 constitutes a suitable value of increasing heat and mass transfer ability. Comparing three typical flow paths, when NTU_m is lower than 3.5, inter-stage circulation presents improved performance in system COP. When NTU_m is large, total circulation is efficient. The system *COP* cross points of flow paths are caused by heat and cold offset and concentration difference of the solution circulation between the dehumidifier and the regenerator, which can be quantified by loss coefficient ε and χ respectively. The heat and mass transfer ability of the system should be considered in the designing process of flow path configuration to obtain an efficient performance for different range of NTU_m.

1. Introduction

Air-conditioning systems are designed to provide a suitable indoor environment with respect to temperature, humidity and fresh air. Liquid desiccant dehumidification proved an effective method for moisture extraction from humid air with reduced energy consumption compared to traditional methods like conventional vapor compression systems [1]. Moreover, liquid desiccant dehumidification offers the possibility of efficient utilization of solar energy, waste heat and other energy-saving sources.

Liquid desiccant dehumidification establishes an energy efficient way to dehumidify air, which attracts increasing research attention. Relevant studies include the basic physical property of the desiccant, heat and mass transfer performance of dehumidifier or regenerator and novel design of air handling system. The dehumidifier and regenerator establish the key components of the liquid desiccant dehumidification systems with ordinary two flow patterns between air and solution as counter-flow type and cross-flow type. Many researchers studied the heat and mass transfer between humid air and liquid desiccant. Jain et al. [2], conducted an experimental study on a falling film tubular absorber and a falling film plate regenerator and compared the experimental results with theoretical model predictions. Yin et al. [3], experimentally examined the performance of a packed tower regenerator and dehumidifier. Liu et al. [4], developed a heat and mass transfer process theoretical model in a cross flow dehumidifier/regenerator.

Past experimental results include a variety of solutions (LiBr, LiCl, $CaCl_2$ and TEG), different flow path (counter-flow and cross-flow), air –solution flow rate and inlet states. This paper mainly focuses on heat and mass transfer ability of the packing tower, therefore the relevant studies in literatures [5–16] are summarized in Table 1. The influencing factors of heat and mass transfer ability of packing tower consist of air flow rate (G), air inlet temperature

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Nomenclature

A	Heat and mass transfer area (m^2)
COP	Coefficient of performance
c_p	Specific heat (J/(kg K))
h	Specific enthalpy (kJ/kg)
Le	Lewis number (dimensionless)
m	Mass flow rate(kg/s)
NTU_m	Number of mass transfer units (dimensionless)
Q	Heat (kJ)
r	Latent heat of vaporization (kJ/kg)
T	Temperature (°C)
V	Heat and mass transfer volume (m^3)
X	Concentration (%)
ω	Humidity ratio (g/kg)
α	Convective heat transfer coefficient (W/m^2 K)
α_m	Volumetric mass transfer coefficient (kg/m^3 s)

Subscripts

a	Air
c	Condenser
e	Evaporator
in	Inlet condition
out	Outlet condition
s	Solution

($T_{a,in}$) and humidity ratio ($\omega_{a,in}$), solution flow rate (L), solution inlet temperature ($T_{s,in}$) and concentration (X_{in}). Researchers modify the above factors during the experimental procedure to obtain the relationship fitting formula among heat-mass transfer coefficient and the above influencing factors. Chung et al. [5], presented a fitting formula of heat and mass transfer coefficient including the flow rate ratio and concentration as variables and Elsarrag et al. [6] demonstrated a fitting formula by adopting flow rate ratio and water vapor pressure as variables. Liu et al. [7] and Moon et al. [8], also indicated fitting formulas of heat and mass transfer efficiency. Abdul-Wahab et al. [9], obtained statistical prediction models for the water condensation rate and the dehumidification effectiveness for structured liquid desiccant air dehumidifier.

In the research field of liquid desiccant dehumidification system, many researchers proposed different flow paths. According to cooling and heating method, different flow paths can be classified into cooling/heating solution, cooling/heating air and cooling/heating of both solution and air. For cooling/heating solution, Niu et al. [17] proposed a liquid desiccant and heat pump hybrid air-conditioning system. Zhang et al. [18] presented a frost-free air source heat pump system with integrated liquid desiccant dehumidification. Solution is cooled in the evaporator to enhance its dehumidification ability and heated in the condenser to be regenerated. The corrosion problems of heat exchanger should be solved to achieve an efficient cooling/heating solution. For cooling/heating air, Mohan et al. [19] and Yin et al. [20] cooled or heated the air prior entering the dehumidifier and regenerator. By cooling/heating air, the direct contact of liquid desiccant solution with metallic heat exchanger was avoided, but the system performance was limited due to the heat capacity of air, which reduces evaporating temperature and increases condensing temperature [21]. Dai et al. [22] and Lazzarin et al. [13], proposed a flow path to cool and heat both solution and air. Additionally, several researchers demonstrated multi-stages dehumidification systems to improve the heat and mass transfer between air and solution [18,23]. The flow paths can be driven by heat pump, for which evaporator of heat pump is exploited as cooling source and condenser is operated as heating source. Oth-

Table 1
Review of past experimental results of heat and mass transfer of the packing tower.

Reference	Solution	Flow pattern	Air flow rate	Solution flow rate	Flow rate ratio R	Height of tower	Packing type
			(kg/(m^2 s))	(kg/(m^2 s))	(G/L)	m	
Patnaik et al. [10]	LiBr	counter[a,b]	1.26–1.94	0.58–0.95	2.0–2.2	0.4/0.28	randomly packed polypropylene Tri-Packs
Factor et al. [11]	LiBr	counter [a,b]	2.04–2.72	0.41–2.45	5.0–1.1	1.0	randomly packed Intalox
Lazzarin et al. [12]	LiBr	counter [a]	0.58	0.14–1.03	4.1–0.56	0.725	randomly packed 25 mm plastic Pall Rings
Flaherty et al. [13]	LiBr	counter [a]	1.51	1.28–2.83	1.2–0.5	0.4/0.28	polypropylene Tri-Packs No. 1/2
Chung et al. [5]	LiCl	counter [a]	0.83–1.70	9.82–20.6	0.1–0.2	0.4	2 random packings, 2 structured packings [c]
Fumo et al. [14]	LiCl	counter [a,b]	0.89–1.18	5.02–7.42	0.15–0.21	0.6	2.54 cm polypropylene Rauschert Hiflow rings
Longo et al. [15]	LiCl	counter [a,b]	0.43–0.47	0.10–1.17	0.23–2.6	0.725	randomly packed 25 mm plastic Pall Rings
Sultan et al. [16]	$CaCl_2$	counter [b]	0.36–1.61	0.11–0.53	1.4–2.7	0.5	structured packed column
Abdul-Wahab et al. [9]	TEG	counter [a]	1.49–2.65	0.18–1.1	8.3–2.4	0.48	structured packing consisted of arrays of plates
Liu et al. [7]	LiBr	cross[a,b]	1.59–2.43	2.15–4.55	0.44–1.12	0.55	Celdek structured packing
Moon et al. [8]	$CaCl_2$	cross[a]	0.51–3.32	0.84–2.05	0.39–2.38	0.3	cross-corrugated cellulose paper structured packing

[a] Dehumidification.

[b] Regeneration.

[c] Random Packings: 5/8 in. polypropylene Flexi rings, 1/2 in. ceramic Berl saddles, Structured Packings: cross corrugated cellulose, PVC.