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Factors governing mass transfer during membrane electrodialysis regeneration of LiCl solution for liquid desiccant dehumidification systems

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ABSTRACT

This study investigates the mass transfer mechanisms and the performance of membrane electrodialysis (ED) for regenerating lithium chloride (LiCl) solution commonly used in liquid desiccant dehumidification systems. Experiments were conducted using an ED experimental system while numerical simulation was performed using COMSOL Multiphysics. The results showed that the water flux transfer due to osmosis and electro-osmosis during ED regeneration of LiCl liquid desiccant was significant and could not be ignored. The water flux due to osmosis and electro-osmosis is directly associated with the osmotic gradient and the applied current between the cathode and anode, respectively. The average flux of water from the spent solution to the regenerated solution decreased from 0.292 to 0.161 g/s m^2 when the initial concentration of the solutions in the spent and regenerated tanks increased from 18 to 30% (wt/wt) with the same applied current of 12 A and the same solution flow rate of 100 L/h. On the other hand, the salt flux due to osmosis was insignificant. The average salt flux transfer was 0.0053 g/s m^2 when the initial concentration difference between the regenerated and the spent channels was 25% (wt/wt). Simulations were conducted to elucidate the relationship between the concentration profile of LiCl solution along the membrane surface and the concentration polarization in the ED channel with respect to the circulation flow rate and applied current. Overall, the results suggest that the concentration difference between the regenerated and spent LiCl solutions should be minimized for an optimum ED performance.

1. Introduction

The increase in energy demand for air conditioning and climate changes are some of the most significant challenges facing the building sector (Pérez-Lombard, Ortiz, & Pout, 2008). The building sector accounts for around 40% of total world energy usage, of which about 50% is attributed to heating, ventilation and air-conditioning (HVAC) systems (Duan et al., 2012; Lin, Ma, Sohel, & Cooper, 2014). Building energy efficiency is therefore essential to reduce global energy usage and greenhouse gas emissions.

Over the last few decades, many energy efficient technologies have been proposed for improving the performance of building HVAC systems (Chua, Chou, Yang, & Yan, 2013; Marszal et al., 2011; Wang, Ma, & Gao, 2010). Among them, desiccant cooling has emerged as an attractive approach (Daou, Wang, & Xia, 2006; Niu, Xiao, & Ma, 2012). Desiccants are hygroscopic or dehumidified substances with the ability to attract moisture from air based on their affinity to water (Daou et al., 2006; Waugaman, Kini, & Kettleborough, 1993). To maintain the dehumidification capability, it is necessary to continuously regenerate the desiccant to remove water molecules from the system (Mohammad, Mat, Sulaiman, Sopian, & Al-abidi, 2013).

Regeneration of liquid desiccants is therefore a key process in a desiccant dehumidification system. Solar thermal regeneration has been commonly considered since solar energy availability usually coincides with the high demand of building cooling demand (Misha, Mat, Ruslan, & Sopian, 2012). Nevertheless, the high temperature of liquid desiccants after the regeneration process can impede the overall performance of desiccant dehumidification systems. Therefore, several non-thermal regeneration techniques have also been studied. Al-Sulaiman, Gandhidasan, & Zubair (2007) proposed a liquid desiccant cooling system using a reverse osmosis (RO) process

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Nomenclature

A	Membrane surface area (m^2)
B	Membrane water permeability (mol.m^{-2} s^{-1} bar^{-1})
C	Weight per weight concentration (% (wt/wt))
c	Molar concentration (mol m^{-3})
D	Diffusion coefficient (m^2 s^{-1})
F	Faraday's constant (96485C mol^{-1})
i	Current density (A m^{-2})
J	Molar flux (mol s^{-1} m^{-2}) or mass flux (g s^{-1} m^{-2})
m	Number of the independently measured variables
N	Number of cells
n	Mole number
R	Gas constant (m^3bar K^{-1} mol^{-1})
T	Temperature (K)
t	Time (s)
t_w	Water transport number
u	Ions mobility (s mol kg^{-1})
V	Volume (m^3)
$\dot{V}$	Volumetric flow rate (m^3 s^{-1})
v	Velocity (m s^{-1})
x	Independently measured variable
y	Calculated variable
z	Charge number of ions
Greek symbol	
ρ	Solution density (g m^{-3})
ϕ	Solution potential (volt)
π	Osmotic pressure (bar)
Superscript	
j	Initial condition
t	Time (s)
Subscript	
Dif	Diffusion
eos	Electro-osmosis
G	Regenerated
GT	Regenerated tank
in	Inlet
I	Applied current
M	Membrane
os	Osmosis
S	Spent
ST	Spent tank
s	Species in solution
tot	Total
w	Water

for desiccant regeneration. However, a pump with high pressure was required to overcome the high osmotic pressure of the liquid desiccant. Another approach is to use an electrodialysis (ED) process to regenerate liquid desiccants (Li & Zhang, 2009). ED is an ion-exchange membrane separation process. In ED, ions can be transported through selective cation or anion membranes under an electric potential gradient (Strathmann, 2004). Owing to the selectivity of ion-exchange membranes, cations and anions can only migrate through cation-exchange membranes (CEMs) and anion-exchange membranes (AEMs), respectively.

The use of ED for liquid desiccant regeneration was first proposed by (Li & Zhang, 2009), who used a single stage photovoltaic-electrodialysis (PV-ED) system. A double stage PV-ED system was subsequently developed by Li, Zhang, & Quan (2011), leading to 50% energy savings in comparison to their first single stage PV-ED system. Cheng, Zhang, & Li (2013) further developed a hybrid ED regeneration system, in which the heat generated by solar photovoltaic thermal collectors was used to pre-treat the liquid desiccant solution before entering the ED stack. The results from these studies have demonstrated the potential practicality of ED technology for liquid desiccant regeneration. However, the remaining technical challenge is to determine the operating envelope and optimize ED operation specifically for liquid desiccant regeneration.

Mass transfer of ions and water in ion-exchange membranes has been extensively investigated both theoretically and experimentally (Casas, Aladjem, Cortina, Larrotcha, & Cremades, 2012; Casas et al., 2011; Fidaleo & Moresi, 2005; Nikonenko, Lebedev, Manzanares, & Pourcelly, 2003; Ortiz et al., 2005; Sadrzadeh, Kaviani, & Mohammadi, 2007; Tanaka, 2003, 2006; Zourmand, Faridirad, Kasiri, & Mohammadi, 2015). However, most previous studies were in the context of sea or brackish water desalination in which salt concentrations in the feed were much lower than that in liquid desiccant regeneration. Tanaka (2003) developed an experimental and theoretical procedure to investigate the mass transport and energy consumption of ED for seawater desalination. Nikonenko et al. (2003) developed a model which considered two chemical species in the external diffusion boundary. The mechanism of the competitive transport of anions through AEMs was described using Nernst-Plank and Donnan equations (Nikonenko et al., 2003). A mathematical model based on Nernst-Plank equation was also used by Casas et al. (2012); Casas et al. (2011) to predict the performance of an ED system for concentrating the brine of the reverse osmosis of the seawater desalination process.

To date, there have been very few attempts to experimentally examine the performance of ED specifically for liquid desiccant regeneration. An experimental setup was developed by Cheng, Xu, & Zhang (2013) to examine the effect of the solution flow rate on the mass transfer and current utilization of the ED stack. Guo, Ma, Al-Jubainawi, Cooper, & Nghiem (2016) experimentally investigated the effects of four operating parameters of ED on the concentration increase of the lithium chloride (LiCl) liquid desiccant solution. The four operating parameters considered were the initial concentration of the regenerated solution, the initial concentration difference between the regenerated and spent solutions, the applied current density and the solution flow rate. The results from the experimental tests showed that ED technology can be potentially useful for liquid desiccant regeneration if the operating conditions of ED are properly selected. However, the mechanisms governing the mass transfer inside the ED stack for liquid desiccant regeneration have not been examined.

A key distinction between ED for desalination and liquid desiccant regeneration is the mass transfer induced by osmotic, electro-osmotic, ion migration, and diffusion. This study aims to elucidate the mass transfer mechanisms of ED for regenerating LiCl liquid desiccant commonly used in desiccant cooling systems. The originality of this work is to employ a combination of both numerical simulation and experimental evaluation to examine the behaviors and concentration profile of the ED stack under different operating conditions to understand the fundamental mechanisms governing the mass transfer of the ED for liquid desiccant regeneration.

2. Theory and research methods

2.1. Mass transfer mechanisms

There are four major mass transfer mechanisms in ED, namely electro-osmosis, osmosis, ion migration and diffusion. Electro-osmosis and osmosis are responsible for water transport. Ion