



Membrane distillation to regenerate different liquid desiccant solutions for air conditioning

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ABSTRACT

The capacity of membrane distillation (MD) to regenerate three commonly used liquid desiccant solutions (i.e. CaCl₂, LiCl, and a mixture of CaCl₂/LiCl) for liquid desiccant air-conditioners (LDAC) was evaluated. The results demonstrate considerable impact of the concentration polarisation effect on the process water flux during MD regeneration of these three desiccant solutions. For each of these liquid desiccant solutions, the experimentally measured water flux of the MD process was about half of the calculated value using the process mass transfer coefficient (K_m) obtained during the process characterisation without taking into account the concentration polarisation effect. The observed deviation between the experimentally measured and calculated process water flux indicates the need to include the concentration polarisation effect in the model for calculating water flux. Although Ca²⁺ concentration in the CaCl₂ and CaCl₂/LiCl liquid desiccant solutions exceeded the solubility limit for CaCO₃, membrane scaling was not observed. Nevertheless, there was evidence that membrane fouling might occur during extended MD regeneration of liquid desiccant solutions containing CaCl₂.

1. Introduction

Satisfying the desire for both thermal comfort and energy saving in buildings is a great challenge to the air-conditioning industry. Most air-conditioning systems are currently based on conventional mechanical vapour compression, in which the air is first cooled to below its dew point for dehumidification and then reheated to obtain the desired temperature [1–4]. In these systems, energy is wasted due to over cooling and the subsequent reheating of the air, particularly in areas with high humidity. As a result, there is a growing interest in alternative air-conditioning technologies to meet the thermal comfort requirement but with lower energy footprint [1,3].

Liquid desiccant air-conditioning (LDAC) is a promising alternative to conventional mechanical vapour compression air-conditioners [5–8]. LDAC systems control air humidity by absorbing moisture from the air into a liquid desiccant stream. The sensible heat load can then be achieved using a complementary evaporative cooler. This technique eliminates the risk of over cooling and the subsequent reheating, and hence is more energy efficient. Indeed, energy consumption by LDAC is about one fourth of that by a vapour compression system. In addition, LDAC can utilise solar thermal energy rather than electricity [2,7].

Aqueous solutions of halide salts (e.g. LiCl and CaCl₂) have been

used as liquid desiccants in LDAC. At the same weight concentration, LiCl solution has a high dehumidification capacity but is expensive and toxic if released into the environment. Compared to LiCl solution, CaCl₂ solution offers a lower dehumidification capability; however, it is more affordable and less toxic (i.e. indeed CaCl₂ is widely used as a domestic moisture absorbent). As a result, mixtures of CaCl₂ and LiCl have also been proposed for LDAC applications [2–4].

A core component of LDAC is liquid desiccant regeneration, in which excess water is removed to maintain the dehumidification capacity. Liquid desiccant regeneration accounts for over three-quarters of the total energy consumption of LDAC systems [9]. Most current LDAC systems use a thermal evaporator for liquid desiccant generation. During this process, the weak (i.e. diluted) liquid desiccant solution is heated up to about 90 °C and then sprayed over a packed-bed contact media. Hot air is blown counter-currently along the contact media to remove water vapour from the packed-bed, therefore reconcentrating the liquid desiccant solution. The reconcentrated liquid desiccant is then cooled down prior to re-entering the dehumidifier. Desiccant carry-over is a major issue associated with the current regeneration method due to the direct contact between liquid desiccant solution and the hot air stream. Desiccant carry-over inevitably results in desiccant loss (thus increasing chemical cost), corrosion risk to building

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equipment, and health concerns due to potential exposure to toxic desiccant chemicals [8,10,11].

Several processes have been explored to replace the thermal evaporator for liquid desiccant regeneration in LDAC [12–14]. One of them is membrane distillation (MD), a thermally-driven membrane separation process [6,15,16]. MD uses a microporous hydrophobic membrane to separate the liquid desiccant and the permeate streams. The hydrophobic membrane allows only water vapour to permeate through it while retaining all dissolved salts in the liquid desiccant stream [17,18], thus eliminating desiccant loss due to carry-over [6,16]. Moreover, MD utilises a transmembrane water vapour pressure gradient as the driving force for salt-water separation, and the liquid phase is discontinued across the membrane [17,19]. The MD process is not affected by the osmotic pressure of the feed solution. Thus, MD applications have been successfully demonstrated for a range of saline solutions including seawater [20,21], industrial wastewater [22,23], and even brines from seawater desalination [24–26] and natural gas exploration [27–30] as well as draw solutions for forward osmosis operation [31,32]. Finally, because the MD process can be efficiently operated at mild feed temperature [33,34], low-grade waste heat and solar thermal energy can be utilised to reduce the energy cost of liquid desiccant regeneration in LDAC systems.

To date, there have been only two attempts to explore the feasibility of MD for regeneration of liquid desiccant solution for LDAC, and only LiCl has been investigated in these studies. Duong et al. [6] systematically demonstrated the technical viability of MD regeneration of LiCl solutions. Rattner et al. [15] optimised the operating conditions of an MD regeneration process of LiCl solutions for LDAC applications using computer simulation. MD regeneration of CaCl₂ solutions and mixed CaCl₂/LiCl solutions used for LDAC systems remains a notable research gap in the literature. Given the difference in scaling propensity and kinetic properties between CaCl₂ and LiCl solutions, MD regeneration of CaCl₂ solutions and mixed CaCl₂/LiCl solutions might deviate from that of LiCl solutions.

This study aimed to demonstrate the viability of the MD process for regeneration of CaCl₂ solution and mixed CaCl₂/LiCl solution in comparison with LiCl solution. The MD process was first characterised with Milli-Q water to determine the baseline process water flux and mass transfer coefficient. Then, the influence of different liquid desiccants on the process water flux was then manifested in MD experiments with three liquid desiccant solutions (e.g. CaCl₂ and LiCl solutions and a mixed CaCl₂/LiCl solution). Finally, polarisation effects and membrane scaling behaviour of the MD process during a continuous concentration of the three liquid desiccant solutions were examined.

2. Materials and methods

2.1. Experimental system

A bench scale direct contact MD (DCMD) system was utilised (Fig. 1). The system comprised a plate-and-frame membrane module and hot- and cold-water cycles. The membrane module consisted of two acrylic semi-cells with engraved flow channels with depth, width, and length of 0.3, 9.5, and 14.5 cm, respectively. In the hot-water cycle, feed solution (1.8 L) from the feed tank was heated in a hot water bath using submerged stainless-steel coils prior to entering the feed channel. As the hot feed solution travelled along the feed channel, water evaporated at the membrane surface and permeated through the membrane in vapour form to the distillate channel; thus, the feed solution was concentrated. The concentrated feed solution was then returned to the feed tank. On the other side of the membrane, Milli-Q water (1.8 L) was used as the initial distillate, and was circulated through the distillate channel to condense the permeated water vapour. The temperatures of the feed solution and the distillate were regulated using a temperature control unit and a chiller, respectively. Temperature sensors were placed immediately before the inlets of the feed and distillate

channels. Two variable-speed gear pumps and rotameters were used to regulate the feed and distillate circulation rates.

2.2. Materials

A flat-sheet hydrophobic polytetrafluoroethylene (PTFE) membrane from Porous Membrane Technology (Ningbo, China) was selectively used in this study. The membrane had thickness, nominal pore size, and porosity of 60 μm, 0.2 μm, and 80%, respectively. The effects of different MD membrane materials including PTFE, polyvinylidene fluoride (PVDF), and polypropylene (PP) on regeneration of liquid desiccant solutions will be investigated in a future study.

Milli-Q water and three liquid desiccant solutions were used as the MD feed in this study. The liquid desiccant solutions contained a single CaCl₂ or LiCl salt, or a mixed CaCl₂/LiCl salts (1:1 in weight) with a concentration of 20 wt%. Milli-Q water and laboratory grade anhydrous CaCl₂ and LiCl were used to prepare the liquid desiccant solutions.

2.3. Analytical methods

The electrical conductivity of the distillate was measured using an Orion 4-Star Plus pH/conductivity meter (Thermo Scientific, Waltham, Massachusetts, USA). The salt concentration of the feed solution was calculated based on the initial concentration (i.e. 20 wt%) and the recorded weight of the feed solution with the assumption that the MD process provided a complete salt rejection. The MD process water flux was measured by continuously weighing the feed tank using a digital balance connected to a computer (Fig. 1).

The surface morphology of the virgin and fouled membranes was examined using a low vacuum scanning electron microscope (SEM) (JOEL JSM-6490LV, Japan). Membrane samples were air-dried and subsequently coated with a thin layer of gold before the SEM analysis.

2.4. Experimental protocols

2.4.1. Process characterisation

The MD process was characterised with Milli-Q water as the feed. The MD system was operated at constant distillate temperature (20 °C) as well as feed and distillate circulation cross flow velocity (0.045 m/s) while the feed temperature was varied from 45 to 65 °C. The MD system was operated for at least 1 h or until stable water flux had been achieved. Operation under steady state condition was extended further for 1 h for recording the water flux every 5 min.

2.4.2. MD regeneration of liquid desiccant solutions

MD experiments with the liquid desiccant solutions were conducted at feed temperature of 55, 60, and 65 °C with the same operating conditions as described in Section 2.4.1. During these experiments, the distillate obtained from the process was returned to the feed tank to maintain a constant feed salt concentration. Water flux and distillate conductivity were measured every 5 min for 1 h after the process had reached its stable operation.

Extended MD experiments were operated at feed temperature of 65 °C until the process water flux decreased to about 2 L/m²·h. During these experiments, the obtained distillate was not returned to the feed tank; therefore, the liquid desiccant concentration increased throughout the MD process. At the completion of the MD process, the membrane was either dismantled from the MD system and air dried for SEM analysis. To assess membrane reusability, the extended MD process was repeated, but when the water flux had decreased to 2 L/m²·h the process was terminated to rinse the system with Milli-Q water for 5 min before restarting it with fresh liquid desiccant solutions (i.e. 20 wt%).

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