



# Liquid desiccant lithium chloride regeneration by membrane distillation for air conditioning



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## ARTICLE INFO

### Article history:

Received 8 August 2016

Received in revised form 14 December 2016

Accepted 18 December 2016

Available online 23 December 2016

### Keywords:

Membrane distillation (MD)

Liquid desiccant air conditioning

Desiccant regeneration

Energy efficiency

## ABSTRACT

Liquid desiccant air conditioning (LDAC) has emerged as an attractive technology for improving indoor air quality and thermal comfort. Regeneration of liquid desiccants is critical to sustain the process efficiency of LDAC. This study explores membrane distillation (MD) for regeneration of lithium chloride (LiCl) desiccant solution commonly used in LDAC. The results demonstrate the viability of MD for LiCl regeneration. The MD process at the feed temperature of 65 °C could increase the LiCl concentration up to 29 wt.% without any observable LiCl loss. Given the high concentration of the LiCl solution feed, unlike traditional desalination applications, the impact of concentration polarisation on the process water flux was significant. Indeed, the calculated water flux obtained by excluding the concentration polarisation effect was more than twice the experimentally measured water flux from a concentrated LiCl solution (>20 wt.%). The regeneration process can be optimised in terms of regeneration capacity ( $\Delta C$ ) and specific thermal energy consumption ( $\alpha$ ) by regulating several operating conditions, including LiCl concentration, feed temperature, and circulation cross flow velocity. Increasing feed temperature and circulation cross flow velocity was beneficial to the process efficiency, enhancing water flux and  $\Delta C$  while reducing  $\alpha$ . On the other hand, increasing LiCl concentration resulted in a linear decrease in both water flux and  $\Delta C$ , but an increase in  $\alpha$  following a hyperbolic function.

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## 1. Introduction

Ongoing economic and environmental concerns together with the demand for thermal comfort have resulted in significant innovation in the air conditioning industry. Amongst the current technologies for improving indoor thermal comfort and air quality, liquid desiccant air conditioning (LDAC) has emerged as an attractive option in terms of humidity control and energy consumption [1–3]. LDAC can offer improved humidity control with significant energy savings particularly in applications where latent loads (moisture) are very high relative to sensible loads [1,2]. Examples include hot and humid climates as well as applications in commercial buildings that require low indoor humidity to avoid condensation on glass doors and building envelopes.

LDAC can simultaneously regulate the humidity and temperature of air by removing moisture using a liquid desiccant solution. The latent load of the process air is controlled by the absorption rate of moisture to the liquid desiccant. The liquid desiccant

solution can then be reconcentrated (i.e. regenerated) by removing excess water using a desalination process, most commonly thermal evaporation. When thermal evaporation is used, heat is the primary energy input to the LDAC process. Thus, electricity consumption by LDAC is only one-fourth of that of a vapour-compression air conditioning system for the same cooling output [2]. As a result, where waste heat (i.e. recovered from engines or industrial processes) or solar thermal energy are readily available, LDAC can be much more energy efficient compared to conventional air conditioning methods which are based on vapour-compression technology [3,4].

Liquid desiccant regeneration is a critical step in LDAC. Given their very high solubility in water, LiCl and LiBr have been widely used as desiccating agents for LDAC [4,5]. The solubilities of LiCl and LiBr in water at 25 °C are 45.4 and 60.7 wt.%, respectively. The dehumidification efficiency of LDAC using these solutions is strongly affected by salt concentration and solution temperature. In general, a more concentrated liquid desiccant solution at a lower temperature produces a higher moisture absorption rate [1,6]. When the liquid desiccant flows along a dehumidifier, it absorbs moisture from the air, resulting in a slight dilution. Thus, it is

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necessary to reconcentrate the weak (i.e. diluted) liquid desiccant before the next dehumidification cycle. Unlike desalination processes for drinking water production, the regeneration of a liquid desiccant involves the removal of only a small volume of water but from an extremely saline feed solution. It is also noteworthy that the regeneration of liquid desiccant solution accounts for over 75% of the total energy consumption of LDAC [3]. Therefore, optimising the regeneration step is crucial to the overall energy consumption of LDAC.

In most current LDAC applications, the weak liquid desiccant solution is reconcentrated by conventional thermal evaporation [2,3,7]. The weak desiccant solution is heated to about 70–90 °C [2]. The hot desiccant solution is then sprayed over a packed-bed contact media to allow for water evaporation. The heat source can be from the combustion of natural gas, waste heat, or solar thermal. When waste heat or solar thermal can be utilised, LDAC is a much more favourable option than vapour-compression air conditioning techniques that rely exclusively on electricity input. It is noteworthy that liquid desiccant regeneration by thermal packed-bed evaporation can result in considerable desiccant loss due to carryover. Desiccant carryover does not only result in the need to replenish desiccating agents (hence a cost increase), but also cause potential long-term health concerns [2,3]. To address the issue of desiccant carryover, several membrane separation processes, including reverse osmosis (RO) [8] and electro-dialysis (ED) [9], have recently been investigated for regenerating liquid desiccants. However, the high electricity demand of RO and ED renders them less attractive for LDAC applications.

Membrane distillation (MD) is a combination of thermal evaporation and membrane separation. MD has several notable attributes that are particularly suitable for desalination application of extreme saline solutions. Indeed, the technical viability of MD for the treatment of RO brine from seawater [10–12] and coal seam gas produced water [13,14], fracking fluid [15], and draw solution for forward osmosis [16,17] has been widely demonstrated in the literature. In MD, a microporous hydrophobic membrane is used as a physical barrier to prevent the penetration of liquid water while allowing for the transport of water vapour (gas) across the membrane. A variety of hydrophobic materials such as polyvinylidene fluoride (PVDF), polypropylene (PP), and polytetrafluoroethylene (PTFE) can be used as MD membranes [18,19]. Only water in vapour form can be transported through the membrane; thus, MD can theoretically offer complete salt rejection [18,20]. Therefore, desiccant loss due to carryover during liquid desiccant regeneration using MD is expected to be negligible. In addition, unlike the conventional thermal evaporation process, MD can be operated at a lower feed temperature (from 40 to 80 °C) that is more compatible with low-grade waste heat and solar thermal [18,20].

Unlike a typical desalination process for clean water production, MD regeneration of liquid desiccant encounters an extremely concentrated feed solution. Thus, in addition to the temperature polarisation effect, concentration polarisation is expected to be significant in the MD process for liquid desiccant regeneration. In MD, the water vapour pressure gradient induced by the temperature difference across the membrane is the driving force for the transport of water vapour. Temperature polarisation effect renders the temperature difference between the feed and the distillate membrane surfaces smaller than that between the bulk feed and distillate streams, thus reducing the actual driving force and hence water flux of the MD process [21,22]. Similarly, due to the concentration polarisation effect, salt concentration at the feed membrane surface can be higher than in the bulk solution, thus reducing water activity and hence water vapour pressure. Indeed, the significant influence of concentration polarisation effect has also been reported in the osmotic distillation process of hypersaline solutions [23,24]. Thus, it is essential to evaluate the impact of concen-

tration polarisation effect on the regeneration of liquid desiccant by MD [25]. It is also important to identify parameters that can be manipulated to alleviate the concentration polarisation effect.

This study aimed to assess the viability of MD for regenerating LiCl liquid desiccant for LDAC. The MD process was first characterised with ultrapure (Milli-Q) water to determine the significance of the temperature polarisation effect. Then, the effect of concentration polarisation on water flux during the MD process with the LiCl solution was examined. The influence of operating conditions, including feed temperature, LiCl concentration, and circulation cross flow velocity, on the process regeneration capacity and thermal energy consumption was also systematically investigated.

## 2. Materials and methods

### 2.1. Materials

A lab-scale direct contact membrane distillation (DCMD) system was used. The system (Fig. 1) consisted of a plate-and-frame membrane module with two acrylic semi-cells and a hydrophobic flat-sheet PTFE membrane. Detailed description of the acrylic semi-cells is available elsewhere [26]. The flat-sheet PTFE membrane was from Porous Membrane Technology (Ningbo, China). The thickness, nominal pore size, and porosity of this membrane were 60  $\mu\text{m}$ , 0.2  $\mu\text{m}$ , and 80%, respectively. The membrane module had an active membrane area of 138  $\text{cm}^2$  available for mass transfer.

The feed solution (2 L) from the feed tank was heated using stainless steel coils submerged in a hot water bath, and then fed into the feed channel of the membrane module. As the hot feed solution moved along the membrane in the feed channel, water evaporated and transferred in vapour phase through the membrane pores to the distillate stream, thus concentrating the feed solution. The reconcentrated solution leaving the membrane module was returned to the feed tank. On the other side of the membrane, 2 L of Milli-Q water (i.e. used as the initial distillate) was circulated through the distillate channel to condense the water vapour that permeated from the feed stream. The temperatures of the feed and distillate stream were controlled using a heating element with a temperature control unit and a chiller, respectively. The circulation flow rates of the feed and the distillate streams were regulated and monitored using two variable-speed gear pumps (Model 120/IEC71-B14, Micropump Inc., Vancouver, Washington, USA) and two rotameters. The feed solution was continuously weighed using a digital balance connected to a computer to determine the water flux.

Laboratory grade anhydrous lithium chloride (LiCl) and Milli-Q water were used to prepare the liquid desiccant solution.

### 2.2. 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 distillate LiCl concentration (i.e. in ppm) was then calculated from the distillate electrical conductivity (i.e. in  $\mu\text{S}/\text{cm}$ ) using the conversion coefficient of 0.64. The feed LiCl concentration was calculated based on the initial LiCl 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.

### 2.3. Experimental protocols

#### 2.3.1. Process characterisation experiments

Milli-Q water was first used as the feed to characterise the process and to quantify the temperature polarisation effect. Milli-Q

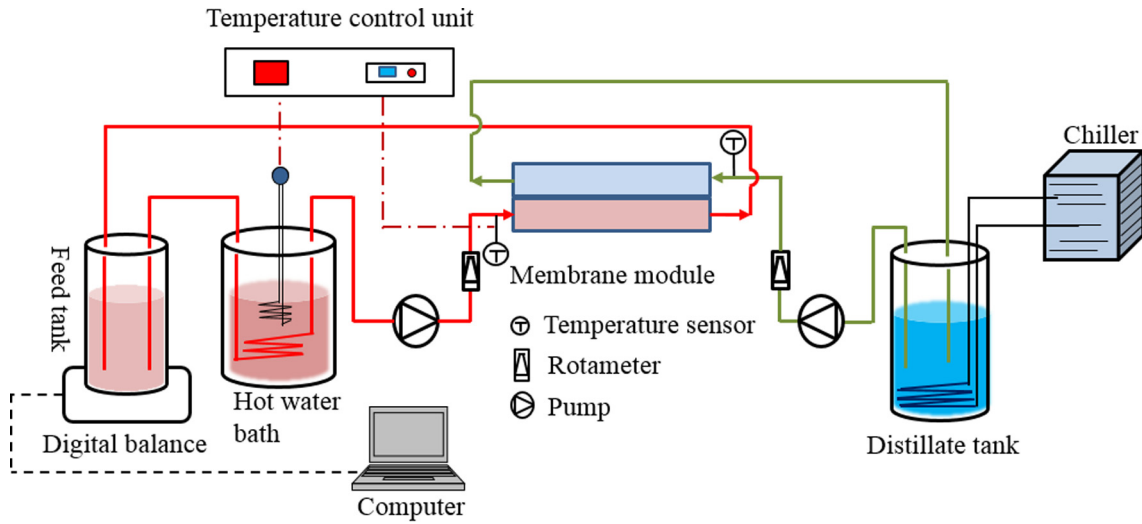


Fig. 1. The schematic diagram of the DCMD unit.

water feed at temperature of 55, 60, and 65 °C was introduced to the feed channel at a volumetric flow rate of 0.5, 0.75, and 1.0 L/min (i.e. equivalent to a cross flow velocity of 0.03, 0.045, 0.06 m/s, respectively). The distillate at a constant temperature of 25 °C was circulated through the distillate channel at the same flow rate to the feed. Water flux of the process at each set of operating conditions was measured for 1 h after the attainment of stable operation.

### 2.3.2. LiCl solution regeneration by MD

MD of the LiCl solution feed was tested to assess the significance of concentration polarisation effect, and to elucidate the influence of operating conditions on water flux, regeneration capacity, and specific thermal energy consumption of the process. The operating conditions were as described above. During the experiments, water flux and the distillate electrical conductivity were regularly measured.

### 2.4. Mass transfer coefficient of the MD system

Water flux of DCMD is proportional to the water vapour pressure difference between two sides of the membrane, and is expressed as [20]:

$$J = C_m \times (P_{m,feed} - P_{m,distillate}) \quad (1)$$

where  $J$  is water flux (L/m<sup>2</sup> h),  $C_m$  is the membrane mass transfer coefficient (L/m<sup>2</sup> h Pa), and  $P_{m,feed}$  and  $P_{m,distillate}$  are the water vapour pressure (Pa) at the feed and distillate membrane surfaces, respectively.  $C_m$  is a function of membrane properties and process operating conditions, and can be theoretically calculated [20,27]. However, the theoretical calculation of  $C_m$  can be excluded [27] because water flux calculation using  $C_m$  involves the water vapour pressure at the membrane surfaces. Indeed, it is more practical to use water vapour pressure of the feed and distillate streams for water flux calculation. Taking this approach, water flux of DCMD can be calculated as:

$$J = K_m \times (P_{feed} - P_{distillate}) \quad (2)$$

where  $K_m$  is the process mass transfer coefficient (L/m<sup>2</sup> h Pa), and  $P_{feed}$  and  $P_{distillate}$  are the water vapour pressure (Pa) of the feed and distillate streams, respectively. Water vapour pressure of the feed and distillate streams can be calculated as [27]:

$$P = x_{water} \times a_{water} \times P_0 \quad (3)$$

where  $x_{water}$  and  $a_{water}$  are the water molar fraction and water activity, and  $P_0$  is the vapour pressure (Pa) of pure water in the feed and distillate streams.  $P_0$  can be calculated using the Antoine Equation [28]:

$$P_0 = \exp\left(23.1964 - \frac{3816.44}{T - 46.13}\right) \quad (4)$$

where  $T$  is the temperature (K) of the feed and distillate streams, which can be readily measured using temperature sensors. For the DCMD process with LiCl solution feed,  $x_{water}$  can be calculated based on the weight concentration of the LiCl solution, whereas  $a_{water}$  can be estimated using the Pitzer model by the “PHREEQC” software. Additionally, the salt rejection ( $R$ ) of the DCMD process with LiCl solution feed is calculated as:

$$R = \left(\frac{C_{feed} - C_{distillate}}{C_{feed}}\right) \times 100\% \quad (5)$$

where  $C_{feed}$  and  $C_{distillate}$  are the LiCl concentration of the feed and distillate, respectively.

Due to polarisation effects, the water vapour pressure at membrane surfaces differs from that in the bulk feed and distillate streams. For the DCMD process with Milli-Q water, only temperature polarisation effect exists given the negligible concentration of salts. It is noteworthy that temperature polarisation effect has been incorporated in the value of  $K_m$  while concentration polarisation effect was excluded.

### 2.5. Regeneration capacity and energy consumption

The regeneration capacity of the MD process is evaluated based on the increase in LiCl concentration achieved by the process [29], and can be calculated as:

$$\Delta C = \frac{C_{feed} \times F_{distillate}}{F_{feed} - F_{distillate}} \quad (6)$$

where  $\Delta C$  is in wt.%,  $F_{feed}$  and  $F_{distillate}$  are the mass flow rate (kg/h) of the feed and distillate, respectively. Actually,  $\Delta C$  is the difference in LiCl concentration between the outlet and the inlet of the feed channel.

The process specific thermal energy consumption ( $\alpha$ ), which is the amount of heating required to increase LiCl weight concentration by 1%, can be calculated as:

$$\alpha = \frac{F_{\text{feed}} \times C_p \times (T_{\text{feed}} - 25)}{3.6 \times 10^3 \times \Delta C} \quad (7)$$

where  $\alpha$  is in kW/wt.%, and  $C_p$  is the specific heat capacity (kJ/kg.°C) of the feed solution.  $C_p$  is dependent on the concentration and temperature of the LiCl solution, and its calculation is given elsewhere [30].

### 3. Results and discussion

#### 3.1. MD process characterisation

The process water flux and mass transfer coefficient ( $K_m$ ) were first experimentally determined using Eqs. (2)–(4) and Milli-Q water as the feed solution (Fig. 2). As can be seen in Eqs. (2)–(4) (Section 2.4), the temperature polarisation effect was embedded in the experimentally determined  $K_m$  value. Because Milli-Q water was used as the feed solution, the concentration polarisation effect could be excluded. The temperature polarisation effect can be assessed by comparing  $K_m$  values at different feed solution temperatures and hydraulic conditions at the membrane surface (presented by the circulation cross flow velocity). As expected, the temperature polarisation effect was more severe at high feed temperature, reflected by a decrease in  $K_m$  as feed temperature increased from 55 to 65 °C (Fig. 2B). These results are consistent with the literature [31,32]. In contrast, increasing the circulation cross flow velocity improved the hydraulic condition at the membrane surface, hence mitigating the effect of temperature polarisation [31,33]. Indeed, both water flux and  $K_m$  increased as the circulation cross flow velocity was elevated (Fig. 2A and B). It is noteworthy that the influence of circulation cross flow velocity on water flux and  $K_m$  was more significant at high feed temperature (i.e. 65 °C) where the temperature polarisation effect was severe (Fig. 2A and B).

#### 3.2. Concentration polarisation during MD regeneration of LiCl solution

Based on the  $K_m$  value obtained from Milli-Q water as the feed solution, the water flux of the MD process with the LiCl solution feed was calculated using Eqs. (2)–(4) and then experimentally compared. The results demonstrated in Fig. 3 indicate a profound

influence of LiCl concentration and particularly the concentration polarisation effect on water flux during the MD process with the LiCl solution feed.

LiCl at high concentration in the feed solution significantly reduced MD water flux. The initial water flux of the MD process with the LiCl 20 wt.% solution feed was noticeably lower than that obtained during the process with Milli-Q water feed under the same operating conditions (Fig. 3). In addition, as the LiCl solution was concentrated, both the calculated and measured water flux decreased linearly (Fig. 3). For example, the calculated water flux at a feed temperature of 55 °C gradually decreased from 12.0 to 2.5 L/m<sup>2</sup> h as the LiCl solution concentration increased from 20 to 30 wt.%. The reduction in the calculated water flux was largely attributed to the decrease in the water activity and hence the water vapour pressure of the LiCl solution. Indeed, the estimated water activity of the LiCl solution at 55 °C (i.e. using the PHREEQC software) decreased from 0.68 to 0.21 as its concentration increased from 20 to 30 wt.%.

Compared to the calculated values, the experimentally measured MD water flux with the LiCl solution feed was much lower (Fig. 3). This reduction reveals the significance of the concentration polarisation effect during MD regeneration of the LiCl liquid desiccant. The  $K_m$  values used for the water flux calculation with the LiCl solution feed were obtained during the system characterisation with Milli-Q water, in which the concentration polarisation effect was excluded. For the process with the LiCl solution feed, the impact of feed concentration on water flux was discernible as discussed above. The concentration polarisation effect rendered the LiCl concentration at the membrane surface higher than that in the bulk feed solution [21,31,34], thus aggravating the negative impact of feed concentration on the process water flux. As a result, all experimentally measured water flux was less than half of the calculated values under the same operating conditions (Fig. 3). Significant deviation of experimentally measured water flux values from simulated data has also been reported during the concentration of cranberry juice by osmotic distillation due to severe concentration polarisation effect [24].

The impact of concentration polarisation on water flux is considered negligible compared to that of temperature polarisation for MD processes with seawater (i.e. with average salinity of 3.5 wt.%) or aqueous salt solutions with similar concentrations [31,35,36]. However, for the MD regeneration of LiCl liquid

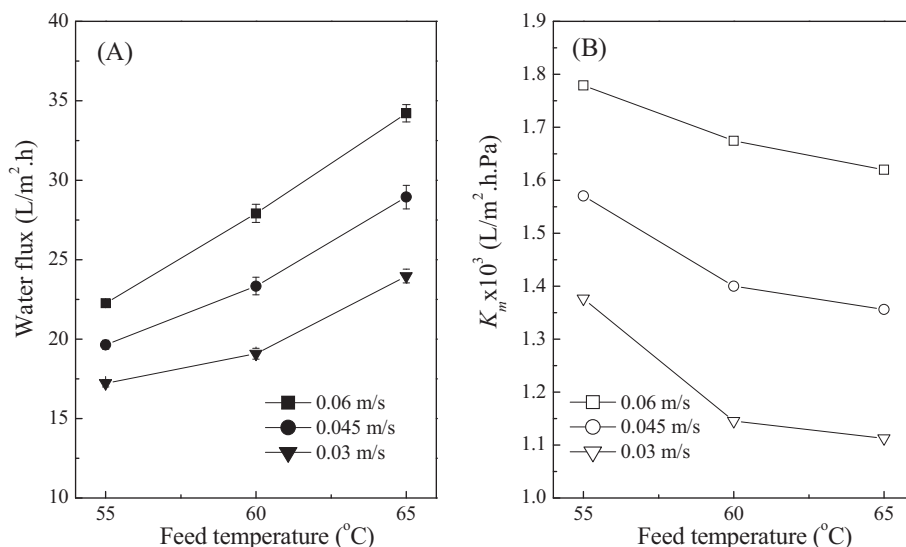
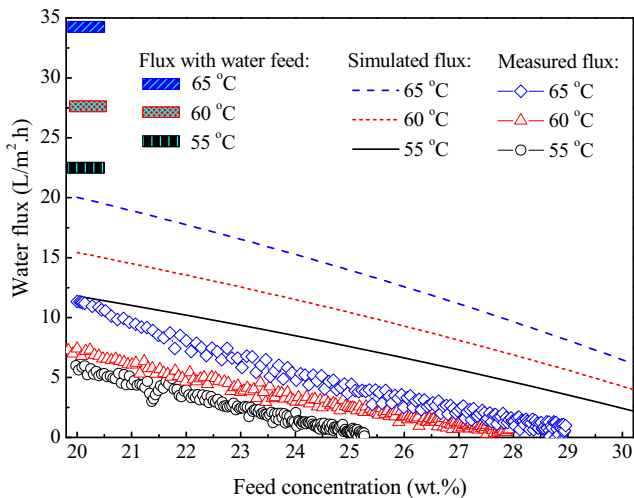


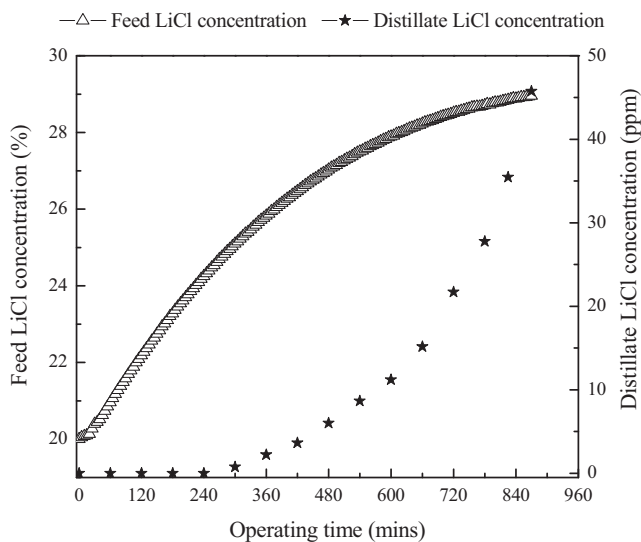
Fig. 2. (A) Water flux and (B) process mass transfer coefficient ( $K_m$ ) of the MD process with Milli-Q water at various feed temperature and circulation cross flow velocities, and a constant distillate temperature ( $T_{\text{distillate}}$ ) of 25 °C (Error bars represent the standard deviation of six measurements).



**Fig. 3.** Influence of LiCl concentration on the calculated and experimentally measured water flux during the MD process with the LiCl solution at various feed temperature. Operating conditions:  $T_{\text{distillate}} = 25\text{ }^{\circ}\text{C}$ , circulation cross flow velocity  $V_{\text{feed}} = V_{\text{distillate}} = 0.06\text{ m/s}$ . Water flux obtained during the process characterisation with Milli-Q water feed at the same operating conditions was incorporated for comparison.

desiccant, the feed concentration is significantly higher (i.e.  $>20\text{ wt.}\%$  for this study), and thus the concentration polarisation effect exerts a much stronger influence on water flux compared to that encountered in seawater desalination applications. Methods to increase flow turbulence, including gas bubbling [37,38], ultrasonic irradiation [39,40], microwave irradiation [41], and use of spacers [42,43], may help mitigate polarisation effects in MD regeneration of LiCl solution, but at the cost of increased process complexity and energy consumption. It is worth reiterating that unlike seawater desalination for fresh water production, MD regeneration of liquid desiccant requires the removal of only a small volume of water from the feed. Thus, low water flux can be more acceptable for MD regeneration of liquid desiccant compared to seawater desalination applications.

Of a particular note, the MD process demonstrated an excellent separation efficiency and a negligible LiCl leakage (i.e. LiCl loss into the distillate) (Fig. 4). Indeed, during the first 240 min of the exper-



**Fig. 4.** Feed and distillate LiCl concentration as functions of operating time during the MD process with the LiCl solution feed. Operating conditions:  $T_{\text{feed}} = 65\text{ }^{\circ}\text{C}$ ,  $T_{\text{distillate}} = 25\text{ }^{\circ}\text{C}$ ,  $V_{\text{feed}} = V_{\text{distillate}} = 0.06\text{ m/s}$ .

iment at feed temperature of  $60\text{ }^{\circ}\text{C}$ , LiCl remained undetectable in the distillate and a complete LiCl rejection was achieved despite the increased feed LiCl concentration (Fig. 4). LiCl at a trace level of 46 ppm (compared to the feed concentration of over 29 wt.%) was only detectable at the end of the experiment. Throughout the experiment, LiCl rejection was over 99.98%.

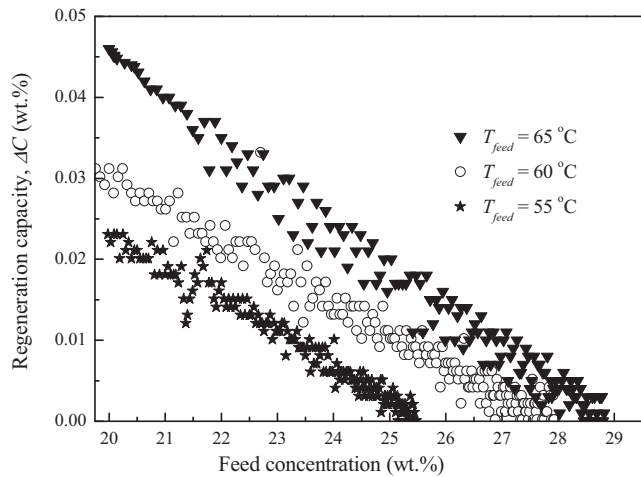
Similar to what observed during the experiments with Milli-Q water, feed temperature also exerted a great influence on the MD process with the LiCl solution feed. Increasing feed temperature raised the water vapour pressure of the LiCl feed stream, thus favouring a higher water flux. Indeed, the measured water flux of the process with LiCl solution was almost doubled when the feed temperature increased from  $55$  to  $65\text{ }^{\circ}\text{C}$  (Fig. 3). Elevating feed temperature also increased the ‘workability’ of the MD process with LiCl solution. As demonstrated in Fig. 3, the process at feed temperature of  $55\text{ }^{\circ}\text{C}$  could only concentrate the LiCl solution up to 25 wt.%, whereas a LiCl concentration of 29% could be achieved in the process at feed temperature of  $65\text{ }^{\circ}\text{C}$ . Feed temperature also strongly affected the regeneration capacity and thermal energy consumption of the process. This will be further discussed in the next section.

### 3.3. Regeneration capacity and energy consumption

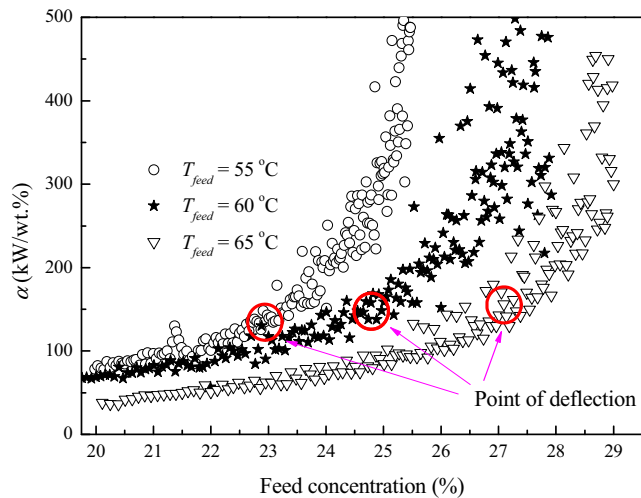
Both regeneration capacity and thermal efficiency are crucial process performance parameters for MD regeneration of liquid desiccants. The regeneration capacity of the MD process with LiCl solution was evaluated using the increase in LiCl concentration between the inlet and the outlet of the feed channel ( $\Delta C$ ). On the other hand, thermal efficiency of the MD process was assessed using the specific thermal energy consumption ( $\alpha$ ).

Feed temperature strongly affected the regeneration capacity and thermal efficiency during the MD regeneration of LiCl solution. Increasing feed temperature exponentially raised the driving force for water vapour transfer from the LiCl solution to the distillate, thus boosting both water flux and  $\Delta C$ . Indeed, similar to water flux,  $\Delta C$  was almost doubled when feed temperature increased from  $55$  to  $65\text{ }^{\circ}\text{C}$  (Fig. 5). Increasing feed temperature was also beneficial to the process with respect to  $\alpha$ . Elevating feed temperature resulted in increase in both  $\Delta C$  and the thermal energy input of system (Eq. (7)). However,  $\Delta C$  increased at a higher rate compared to the thermal energy input with increased feed temperature, thus leading to decrease in  $\alpha$  (Fig. 6).

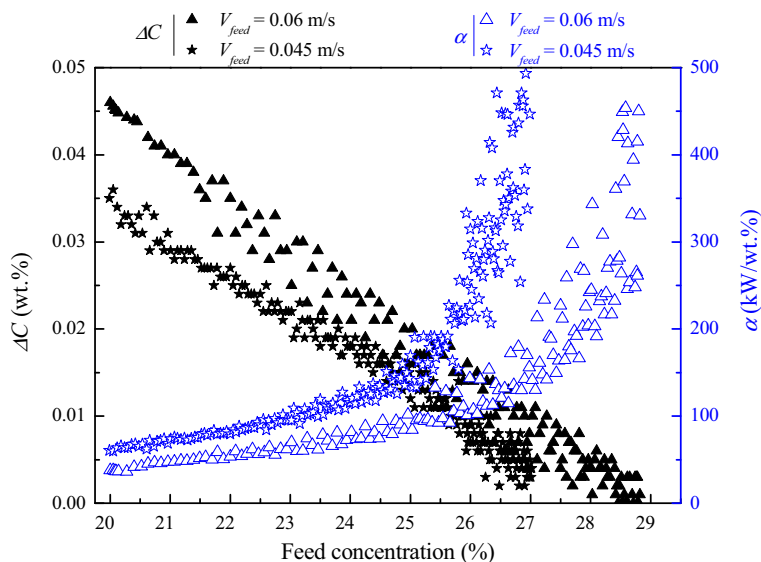
Unlike feed temperature, increasing feed concentration resulted in a linear reduction in  $\Delta C$  (Fig. 5). The increase in LiCl concentration in the feed also led to an increase in  $\alpha$  following a hyperbolic function (Fig. 6). As expressed in Eq. (6),  $\Delta C$  was dependent on both feed concentration ( $C_{\text{feed}}$ ) and the distillate flow rate ( $F_{\text{distillate}}$ ) at a constant feed flow rate. An increase in  $C_{\text{feed}}$  resulted in a decrease in  $F_{\text{distillate}}$  at a higher rate (Fig. 3). As a result,  $\Delta C$  linearly decreased with increased  $C_{\text{feed}}$ . In contrast, increasing  $C_{\text{feed}}$  slightly reduced the specific heat capacity ( $C_p$ ) of the feed solution, thus resulting in a small reduction in the thermal energy input. The rate of thermal energy input reduction was much smaller than that of  $\Delta C$ . As a result,  $\alpha$  increased as a hyperbolic function of  $C_{\text{feed}}$ . The increase in  $\alpha$  at below the deflection point of the hyperbola was small (Fig. 6). On the other hand, beyond the deflection point,  $\alpha$  increased sharply as LiCl concentration continued increasing (Fig. 6). Results in Fig. 6 suggest that LDAC should be operated at LiCl concentration below the deflection point of the hyperbola. In other words, the maximum LiCl concentrations at feed temperatures of  $55$ ,  $60$ , and  $65\text{ }^{\circ}\text{C}$  are approximately 23, 25, and 27 wt.%, respectively. The maximum LiCl concentration could be increased by operating the process at a higher feed temperature and thus alleviating the negative influence of increased feed concentration on  $\alpha$  (Fig. 6).



**Fig. 5.** Regeneration capacity ( $\Delta C$ ) as a function of feed concentration during the MD process of LiCl solution at different feed temperatures. Other operating conditions:  $T_{\text{distillate}} = 25\text{ }^{\circ}\text{C}$ ,  $V_{\text{feed}} = V_{\text{distillate}} = 0.06\text{ m/s}$ .



**Fig. 6.** Specific thermal energy consumption ( $\alpha$ ) as a function of feed concentration during the MD process of LiCl solution at different feed temperatures. Other operating conditions:  $T_{\text{distillate}} = 25\text{ }^{\circ}\text{C}$ ,  $V_{\text{feed}} = V_{\text{distillate}} = 0.06\text{ m/s}$ .



**Fig. 7.** Regeneration capacity ( $\Delta C$ ) and specific thermal energy consumption ( $\alpha$ ) as functions of feed concentration during the MD process of LiCl solution at two different water circulation cross flow velocities. Other operating conditions:  $T_{\text{feed}} = 65\text{ }^{\circ}\text{C}$ ,  $T_{\text{distillate}} = 25\text{ }^{\circ}\text{C}$ .

Circulation cross flow velocity also exerted discernible effects on both  $\Delta C$  and  $\alpha$  of the process. As demonstrated in the MD experiments with Milli-Q water feed, circulation cross flow velocity had a profound effect on water flux. This influence was even stronger for the MD process with the LiCl solution feed that encountered significant polarisation effects. Increasing circulation cross flow velocity helped promote water flux by mitigating both temperature and concentration polarisation effects, thus resulting in higher  $\Delta C$  (Fig. 7). Increasing circulation cross flow velocity also raised the thermal energy input of the system similarly to increasing feed temperature (Eq. (7)); however, the increase rate of thermal energy input was smaller than that of  $\Delta C$ . As a result,  $\alpha$  was reduced for the process at a higher circulation cross flow velocity (Fig. 7).

It is noteworthy that  $\Delta C$  and  $\alpha$  values obtained in this study were from a single-pass lab-scale MD system. The thermal efficiency and  $\Delta C$  of the MD regeneration of LiCl solution can be significantly improved for pilot or large-scale systems with a larger membrane area and more effective heat insulation [29]. In addition, MD can be operated in brine recycling mode to improve the process thermal efficiency and to increase LiCl concentration [44]. Heat exchangers can also be employed to utilise the sensible heat of the regenerated LiCl solution and distillate stream for pre-heating the feed stream [45]. The recovery of the sensible heat from the regenerated LiCl stream not only is beneficial to the MD process but also helps reduce the cooling load required for the regenerated stream before entering the dehumidifier. It is also noted that  $\alpha$  reported in this study was calculated for 1% increase in LiCl concentration (Eq. (7)). In practice, during the dehumidification process, the LiCl concentration difference between the inlet and the outlet the dehumidifier can be as low as 0.1% [46]. Therefore, the actual thermal energy consumption of MD regeneration of LiCl desiccant solution can be much lower than the reported  $\alpha$  values.

The results reported here reveal the importance of process optimisation when integrating MD with the dehumidifier in LDAC. A more concentrated LiCl solution at lower temperature is preferred for the dehumidifier to obtain higher air dehumidification efficiency [1,4]. In contrast, the MD process is more efficient (i.e. with respects to water flux,  $\Delta C$ , and  $\alpha$ ) with LiCl solution at lower concentration and higher temperature. On the other hand, increasing the circulation cross flow velocity is beneficial for both dehumidification and the subsequent MD regeneration of the LiCl solution.

Operating the integrated dehumidifier–MD at higher circulation cross flow velocity leads to increases in dehumidifier effectiveness [47] and in MD water flux and  $\Delta C$ , and a decrease in  $\alpha$ . It is noteworthy that increasing LiCl solution circulation cross flow velocity also increases the electricity consumption of LDAC and the risk of MD membrane wetting [20,27]. As a result, further studies on process optimisation, particularly at a pilot level, are necessary to realise the practical integration of MD with LDAC operation.

#### 4. Conclusions

The suitability of membrane distillation (MD) for regenerating LiCl liquid desiccant for air conditioning application was demonstrated in this study. At feed temperature of 65 °C, the process could increase LiCl concentration up to 29 wt.% without any significant LiCl loss. However, unlike traditional desalination application, the effect of concentration polarisation during the MD operation with the LiCl solution was significant. Operating parameters to optimise MD regeneration of LiCl solution include LiCl concentration, feed temperature, and circulation cross flow velocity. Increasing LiCl concentration led to a linear decrease in both water flux and regeneration capacity ( $\Delta C$ ). On the other hand, the increase in LiCl concentration in the feed resulted in an increase in the specific thermal energy consumption ( $\alpha$ ) following a hyperbolic function. By increasing feed temperature and circulation cross flow velocity of the MD process, an increase in water flux as well as  $\Delta C$  and a reduction in  $\alpha$  could be achieved.

#### Acknowledgements

The Vietnam International Education Development (VIED), under the Ministry of Education and Training (MoET), and the University of Wollongong (UOW) are acknowledged for PhD scholarship support to Hung C. Duong.

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