



Using electrodialysis for regeneration of aqueous lithium chloride solution in liquid desiccant air conditioning systems



Yi Guo^a, Zhenjun Ma^{a,*}, Ali Al-Jubainawi^a, Paul Cooper^a, Long D. Nghiem^b

^a Sustainable Buildings Research Centre, University of Wollongong, Wollongong, NSW 2500, Australia

^b School of Civil, Mining & Environmental Engineering, University of Wollongong, Australia

ARTICLE INFO

Article history:

Received 22 September 2015

Received in revised form 13 January 2016

Accepted 15 January 2016

Available online 18 January 2016

Keywords:

Lithium chloride

Liquid desiccant

Regeneration

Electrodialysis

ABSTRACT

This study evaluates the potential of using electrodialysis (ED) technology to regenerate the aqueous lithium chloride (LiCl) solution, a commonly used liquid desiccant in liquid desiccant air conditioning (LDAC) systems. Experiments were performed using an ED system with ten cell pairs of ion-exchange membranes. A range of tests were carried out to examine the effects of the circulation flow rate, supplied current density, solution initial concentration and the concentration difference between the regenerated and spent solutions on the performance of ED for regenerating LiCl liquid desiccant solutions. The results showed that the regeneration capability of the ED stack decreased with the increase of the circulation flow rate. Regeneration performance in terms of the concentration enrichment increased as the supplied current density increased and the solution initial concentration decreased. It is also shown that the concentration difference between the regenerated and spent solutions is critical for the regeneration performance of ED. The ED stack can continuously increase the concentration of the regenerated solution when the concentration difference between the regenerated and spent solutions is below 5.86% (wt/wt), under the supplied current density of 57.1 mA/cm², circulation flow rate of 100 L/h, and the initial concentrations of the solutions in the regenerated and spent tanks of 28.77% and 23.96% (wt/wt), respectively. The current efficiency of the ED in two hours running for all experiments was in the range of 55.17–73.54%. The results obtained from this study would be useful for the ED regenerator design and system integration.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Significant energy is consumed for building heating, cooling and dehumidification. Thus, building energy efficiency is essential to reduce global energy usage and greenhouse gas emissions. Over the last several decades, many efforts have been made on the development and application of various sustainable and low energy technologies for promoting building energy efficiency [1–3]. Among different technologies, liquid desiccant dehumidification has gained significant scientific attention due to a high energy saving potential [4–8]. Liquid desiccant technologies have started to find practical applications for cooling and dehumidification [9].

In a liquid desiccant air conditioning (LDAC) system, the regeneration of the liquid desiccant is a key process to maintain the capacity of the liquid desiccant for continuous dehumidification. Different regeneration methods have been studied for LDAC

systems, including but not limited to thermal regeneration, ultrasonic regeneration, reverse osmosis regeneration and electrodialysis regeneration [10,11]. Thermal regeneration using solar energy, waste heat and heat pumps has been extensively studied. For instance, Elsarrag [12] examined a solar liquid desiccant regeneration system in terms of the liquid to air flow rate ratio, temperature and concentration of the liquid desiccant, and humidity ratio of the inlet air on the evaporation rate. Niu et al. [13] investigated the possibility to match liquid desiccant and heat pump in hybrid LDAC systems. The results showed that dynamic capacity matching among the dehumidifier, regenerator, evaporator and condenser can be achieved only through regulating the circulation flow rate, revolution of the compressor and air flow rate in the air cooled condenser simultaneously. Yamaguchi et al. [14] presented a hybrid liquid desiccant system, in which the absorber and regenerator were integrated with the evaporator and condenser of the heat pump, respectively. Their system could achieve a higher coefficient of performance by improving the isentropic efficiency of the compressor and the temperature efficiency of the solution heat exchanger. In thermal regeneration, the liquid desiccant is reactivated through a

* Corresponding author.

E-mail address: zhenjun@uow.edu.au (Z. Ma).

Nomenclature

a_0 – a_5	coefficients
F	Faraday number (96,485 C/mol)
I	supplied current (A)
M	molar mass (g/mol)
m	mass (kg)
N	number of membrane pairs
n	number of independent measured variables
t	temperature ($^{\circ}\text{C}$)
V	volume (L)
x	independent measured variable
y	calculated variable
z	charge of ions

Greek symbols

η	current efficiency (%)
ξ	concentration [% (wt/wt)]
ρ	density (g/cm^3)

Superscript

k	time (s)
0	initial condition

Subscript

r	regenerated
s	salt

process in which the moisture is transferred to the scavenging air through heating the solution to a high temperature (e.g. 65°C or higher). The desiccant must then be cooled down before entering the dehumidifier to achieve desirable dehumidification performance. Therefore, the efficiency of thermal regeneration is limited.

Yao [15] described the basic idea of a ultrasonic dehydrator for liquid desiccant regeneration. This non-thermal regeneration method can potentially improve the energy efficiency of the liquid desiccant dehumidification system due to the lower regeneration temperature. However, Yao [15] also acknowledged that the ultrasonic regeneration may bring environmental hazard issue and the energy savings due to the use of the ultrasonic regenerator for liquid desiccant were not reported. Al-Sulaiman et al. [16] studied the reverse osmosis (RO) process for regenerating calcium chloride liquid desiccant in a cooling system with two-stage evaporative coolers. It was pointed out that currently available RO membranes are not able to handle the high concentration of calcium chloride required in liquid desiccant applications.

Although the use of electro dialysis (ED) for liquid desiccant regeneration has only been recently explored [17–23], the benefits of integration of ED with LDAC systems have been demonstrated in the literature. ED has been primarily used for desalination, wastewater treatment, and ion separation applications in the chemical, food, and pharmaceutical industries [24–27]. Liquid desiccant regeneration by ED provides an opportunity to allow the system to operate at a low temperature and therefore reduce the need for cooling the desiccant. Using ED as a regeneration method was first proposed by Li and Zhang [17]. Through theoretical analysis, it was concluded that ED operation is more stable as the weather condition has limited impacts on the performance of the ED stack, as compared to thermal regeneration [28]. Single stage and double stage photovoltaics and ED driven regeneration for LDAC systems were proposed and the performance of the systems was evaluated through theoretical analysis [19,20]. It was concluded that the double-stage regeneration system can save more energy under the optimised working conditions than that of the single stage

regeneration system. In order to improve the reliability and the performance of ED for liquid desiccant regeneration, a desiccant pre-treatment ED regeneration system was proposed in [18]. It was shown that this new system was more energy efficient than the photovoltaics and ED driven regeneration system. Cheng et al. [21] experimentally examined the effect of the flow rates of the regenerated and spent desiccant solutions on the current utilisation and mass transfer rate of the ED regenerator. However, the effects of other key operating parameters such as supplied current and solution initial concentrations on the ED regeneration performance have not been evaluated. Li et al. [29] investigated the salt mass transfer of ED for liquid desiccant regeneration and it was found that the current intensity is the key factor influencing the ED regeneration performance.

Literature data to date showed that ED is a promising technology for liquid desiccant regeneration in LDAC systems. Nevertheless, previous ED investigations for other applications (e.g. desalination and wastewater treatment) indicated that ED performance can be influenced by many parameters, such as the construction of the ED stack, the characteristics of the membranes used, the concentrations of the feed and product solutions, solution flow rate, and current density or electric potential [30–32]. As the concentration of liquid desiccants used in LDAC systems is much higher than that of the solutions used in other fields such as water desalination, the behaviour of ED working with liquid desiccants is expected to differ from that in other fields. Thus, it is essential to substantiate the effects of the above mentioned parameters on ED performance specific for liquid desiccant regeneration.

This study aims to elucidate the effects of the operating conditions including the circulation flow rate, supplied current density, initial concentrations of the regenerated and spent solutions, and the concentration difference between the regenerated and spent solutions on the performance of the ED for regeneration of liquid desiccant solutions. As LiCl is one of the widely used liquid desiccants and has a low equilibrium humidity ratio under wide operating conditions [33], LiCl is considered as the working solution in this study.

2. ED working principle, experimental setup and experimental protocol

2.1. Working principle of electro dialysis

ED is a separation process used to transport cations and anions through cation and anion exchange membranes respectively, under the influence of a supplied electric field [34,35]. In an ED stack, a set of cation and anion exchange membranes are arranged alternately between the anode and the cathode. An example of the ED stack with two cell pairs is illustrated in Fig. 1. When the solution (i.e. liquid desiccant) is fed into the main cells of the ED stack, due to different permeability of cation and anion exchange membranes, the cations (Li^+) can only pass through the cation exchange membranes and the anions (Cl^-) can only pass through the anion exchange membranes. As a consequence, the concentration of the liquid desiccant in some cell spaces will increase, while the concentration of the liquid desiccant in the adjacent cell spaces will decrease due to the ions movement. The concentrated liquid desiccant can then be used for dehumidification. In this process, the electrical rinsing solution (i.e. Li_2SO_4 used in this study) is used to support the electrical conductivity in the two electrode cells.

In the ED regeneration process, osmosis appears if there is a difference between the concentrations of the spent and regenerated solutions, which can lead to the water transfer from the spent to the regenerated solutions. In the meanwhile, the salt diffuses from the regenerated to the spent solutions due to the concentration

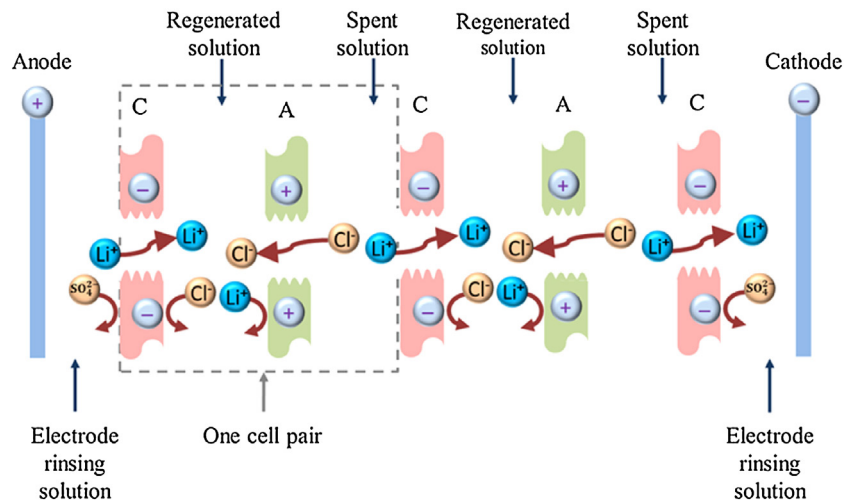


Fig. 1. Illustration of an ED stack with two cell pairs.

difference. When an electric current is applied to the ED electrodes, ions will migrate from the spent to the regenerated solutions. At the same time, water molecules will transport along with the migrated ions, which is called electro-osmosis phenomena [36].

2.2. Electrodialysis experimental setup

A lab-scale ED system was used in the experimental tests. The experimental setup and its simplified schematics are shown in Fig. 2. The ED system mainly consists of an ED stack, a rectifier, and a power transformer. The system also consists of three circulation pumps, three reservoirs, and three flow metres for the regenerated, spent, and electrolyte rinsing solutions, respectively.

The ED stack was equipped with an infrared coated titanium anode electrode, a stainless steel SUS316 cathode electrode and 10 cell pairs of cation and anion exchange membranes (Table 1). Na cation-(CMV) and Cl anion-(AMV) exchange membranes from Asahi Glass Co. Ltd. (Tokyo, Japan) were used. As aqueous lithium sulphate was used as the electrode rinsing solution in the ED stack, two extra cation exchange membranes were used at the electrical nodes to avoid sulphate radical anions migrating into the regenerated and spent solutions. The regenerated, spent, and electrode rinsing solutions were circulated through three 3.5 L transparent PVC tanks, respectively. During the experimental tests, the solutions were pumped to the ED stack by three magnetic drive pumps with a flow rate in the range of 60–140 L/h. The circulation flow rate in each loop was controlled by a globe valve.

The regenerated and spent solutions were prepared by dissolving the analytical grade lithium chloride into deionized water with different mass concentrations. The electrode rinsing solution was prepared by dissolving the analytical grade lithium sulphate into deionized water with a mass concentration of 3.00% (wt/wt) as suggested by the membrane manufacturer. Both lithium chloride and

lithium sulphate had a purity of 99.0% or higher. The three tanks worked as the reservoirs for the solutions and were scaled by the volumetric flask with a 0.1 L increment.

The rectifier used in the experimental tests was PowerTech MP3090. A portable density metre (30PX Densito) was used to measure the density and temperature of the aqueous lithium chloride solutions in both regenerated and spent tanks. The measured density and temperature were then used to calculate the concentrations of the LiCl solutions and the details can be found in Appendix. Three direct indication type variable area flow metres were used to measure the circulation flow rates in each individual flow stream. The volume of the solutions in the transparent PVC tanks was obtained directly through the scale on the tanks. The major measuring instruments used and their claimed measurement accuracies are summarised in Table 2.

For calculated concentration, the basic root-sum-square method can be used to determine its relative uncertainty [37]. The relative uncertainty $\frac{\delta y}{y}$ for a calculated variable y with a set of independent measured variables x_i can be determined by Eq. (1).

$$\frac{\delta y}{y} = \frac{\sqrt{\sum_{i=1}^n \left(\frac{\partial y}{\partial x_i} \delta x_i \right)^2}}{y} \quad (1)$$

where n is the number of the independent measured variables.

Based on Eq. (1), it was determined that the maximum compositional relative uncertainty for the concentration of the liquid desiccant in all experiments was 0.90%.

Table 1
Specification of the electrodialysis stack used.

Anion exchange membrane type	AMV
Cation exchange membrane type	CMV
Anode side separation membrane type	CMV
Cathode side separation membrane type	CMV
Number of pairs of membranes	10
Thickness of AMV and CMV membranes (μm)	120
Burst strength of AMV and CMV membranes (kPa)	200
Space of membrane cells (mm)	0.75
Effective area of the membrane (cm^2)	210
Geometrical surface area of the membrane (cm^2)	448

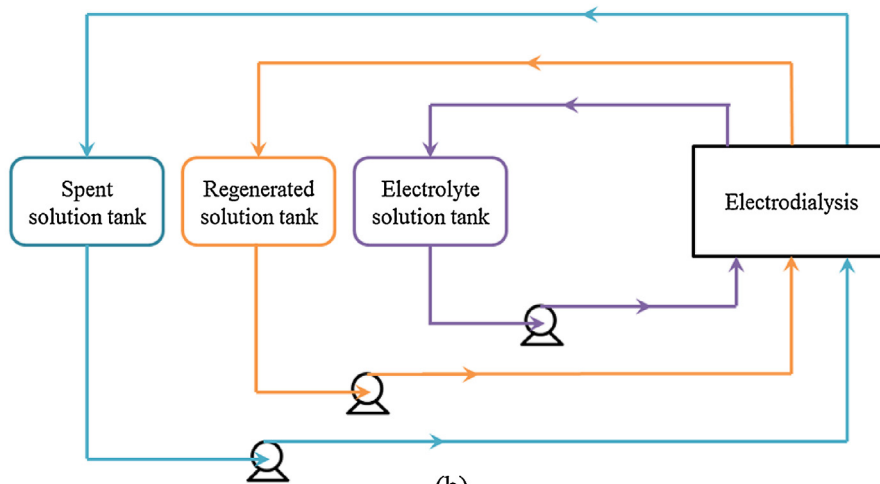
Table 2
Measuring instruments and measurement accuracies.

Name	Mode	Measurement range	Accuracy
Rectifier	PowerTech MP3090	40 A/15V DC	$\pm 1.0\%$
Density metre and temperature measurement	30PX Densito	2.0000 g/cm ³	± 0.001 g/cm ³
Flow metre	TOKYO KEISO AC-1510-4/6	40.0 °C	± 0.2 °C
		600 L/h	$\pm 3\%$ F.S.
Volumetric flask	–	100 mL	± 0.08 mL
Analytical balance	Mettler Toledo TLE104	120 g	± 0.25 mg



- 1- ED stack
- 2- Pump
- 3- Flow meter
- 4- Rectifier
- 5- Transformer
- 6- Tanks
- 7- Fume cupboard

(a)



(b)

Fig. 2. (a) Electrodesorption experimental setup employed in this study; (b) simplified schematic of the experimental setup.

2.3. Experimental protocol

It is noteworthy that the regenerated solution in this study refers to the stream of LiCl solution whose concentration increases through the ED stack and is the working solution to be used for dehumidification. The spent solution is the solution in the other stream whose concentration decreases through the ED process.

A total of 13 experiments categorised into 4 groups, as summarised in Table 3, were selected and used to illustrate the effects of the operating parameters on the performance of the ED stack for regenerating LiCl liquid desiccant solutions used in LDAC systems. These experiments were selected based on the possible operating conditions of ED for LiCl liquid desiccant regeneration. Each test was performed for 120 min. All experiments were operated by continuously recirculating the solutions in the regenerated and spent tanks through the ED stack under ambient conditions.

During the experiments, the three solution tanks were placed in a fume cupboard in order to extract the gases generated through the electrode reactions. The density and temperature of the solutions in both regenerated and spent tanks were measured by the density metre every 5 min. The volumes of the solutions in the regenerated and spent tanks and the voltage corresponding to the current supplied were recorded at the same time. For each experiment, the same circulation flow rates of the regenerated and spent streams were used in order to minimise the hydrodynamic pressure difference between the regenerated and spent cells of the ED stack. Most experiments were conducted in duplicate to validate the experimental reproducibility. Fig. 3 provides an example of the experimental reproducibility of experiment 1. It is shown that the largest variations between the two tests were 0.71% and 1.26% for the concentration and volume change of the regenerated solution, respectively.

Table 3
Summary of the experiments.

Test group	Experiment	Initial concentration of the solution in the regenerated tank [% (wt/wt)]	Initial concentration of the solution in the spent tank [% (wt/wt)]	Circulation flow rate (L/h)	Supplied current density (mA/cm ²)
Varying circulation flow rate	1	27.71	27.71	60	38.1
	2	27.71	27.71	100	38.1
	3	27.77	27.72	140	38.1
Varying current density	4	27.50	27.48	100	28.6
	5	27.57	27.48	100	38.1
	6	27.51	27.46	100	47.6
	7	27.40	27.39	100	57.1
Varying initial concentration	8	28.90	29.00	100	57.1
	9	24.93	24.92	100	57.1
	10	18.78	18.78	100	57.1
Varying concentration difference	11	28.90	29.00	100	57.1
	12	28.83	25.86	100	57.1
	13	28.77	23.96	100	57.1

The first group of the tests was to examine the effects of the circulation flow rate on the performance of the ED for liquid desiccant regeneration. The tests were carried out with three different circulation flow rates under the same supplied current density. The initial concentrations of the solutions in both regenerated and spent tanks were almost the same.

The second group of the experimental tests was to investigate the effects of the supplied current density on the performance of the ED for regenerating LiCl liquid desiccant solutions. The tests were performed with four different current densities under the same circulation flow rate and initial concentration. It is worthwhile to note that there was a slight difference among the initial solution concentrations of the four experiments as the initial concentrations of the solutions were hard to adjust because of the residuals in the system.

The third group of the tests was to study the effects of the initial concentrations of the regenerated and spent solutions on the regeneration capability of the ED for the LiCl liquid desiccant solution. The tests were carried out with three different initial concentrations of the solutions in the regenerated and spent tanks. In this group of the tests, the same supplied current density and the same circulation flow rate were applied.

The fourth group of the tests was designed to investigate the influence of the concentration difference between the regenerated and spent solutions fed to the ED stack on the ED regeneration

capability. All the tests were performed with the same circulation flow rate and the same supplied current density.

3. Data analysis methods

As the key focus of this study is to investigate the performance and capability of using ED for regenerating LiCl liquid desiccant solutions, the concentration and volume increase of the solution in the regenerated tank, and current efficiency of the ED stack were used as the performance indicators.

The concentration increase of the solution in the regenerated tank at the time k is the difference between the concentration of the solution at the time k and that of the solution at the beginning of the experimental test (i.e. initial concentration), as shown in Eq. (2). Similarly, the volume change of the solution in the regenerated tank at the time k can be determined by Eq. (3).

$$\Delta \xi_r^k = \xi_r^k - \xi_r^0 \quad (2)$$

$$\Delta V_r^k = V_r^k - V_r^0 \quad (3)$$

where $\Delta \xi_r^k$ and ΔV_r^k are the concentration increase and the volume increase of the solution in the regenerated tank at the time k respectively, ξ_r^k and V_r^k are the concentration and volume of the solution in the regenerated tank at the time k respectively, and ξ_r^0 and V_r^0 are the initial concentration and initial volume of the solution in the regenerated tank, respectively.

Current efficiency is the ratio of the electric charge transported by ions to the total amount of the electric charge applied to the ED stack [38] and is calculated by Eq. (4), in which the salt mass transfer is determined by Eq. (5).

$$\eta = \frac{zF \frac{\Delta m_s^k \cdot 1000}{M_s}}{NIk} \times 100\% \quad (4)$$

$$\Delta m_s^k = V_r^k \cdot \rho_r^k \cdot \xi_r^k - V_r^0 \cdot \rho_r^0 \cdot \xi_r^0 \quad (5)$$

where z is the charge of ions, F is the Faraday constant, Δm_s^k is the salt mass transfer from the spent solution to the regenerated solution at the time k , I is the supplied current, M_s is the salt molar mass, N is the number of membrane pairs, ρ_r^k is the density of the regenerated solution at the time k , and ρ_r^0 is the initial density of the regenerated solution.

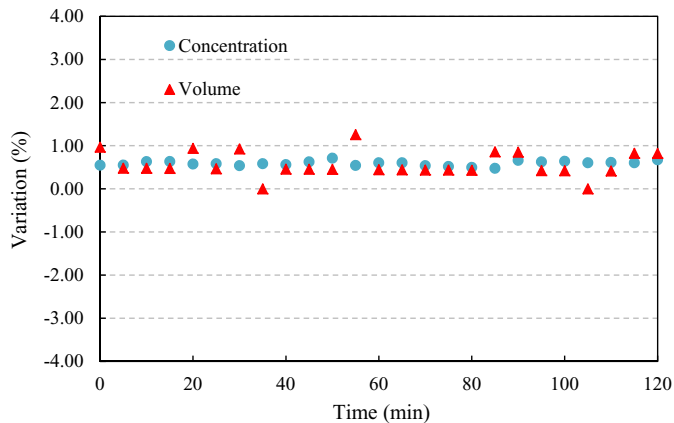


Fig. 3. Relative variation between the two tests of experiment 1 in terms of the concentration and volume variation of the regenerated solution – initial concentration of the solutions in regenerated and spent tanks of 27.71% (wt/wt), supplied current density of 38.1 mA/cm² and circulation flow rate of 60 L/h.

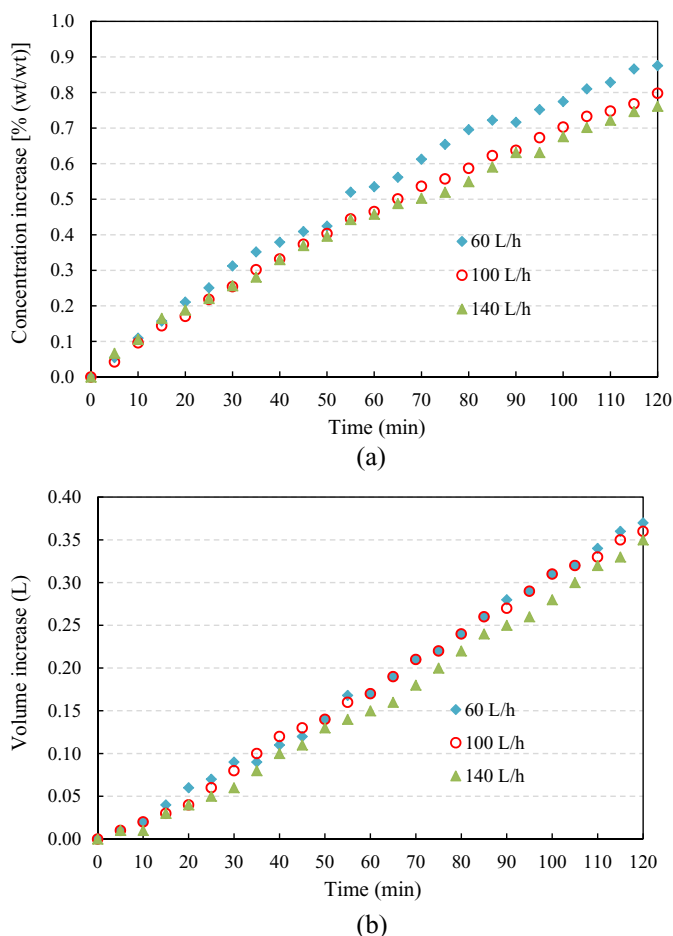


Fig. 4. (a) Concentration increase and (b) volume increase of the solution in the regenerated tank with circulation flow rates of 60, 100 and 140 L/h – initial concentration of the solutions in the regenerated and spent tanks of around 27.70% (wt/wt) and supplied current density of 38.1 mA/cm².

4. Results and discussions

4.1. Effect of circulation flow rate

Fig. 4 shows the concentration increases and volume changes of the regenerated solution as a function of the operating time under different tank circulation flow rates. LiCl concentration in the regenerated tank increased as the experiment progressed. For all three circulation flow rates investigated here, the concentration increase increased slightly faster at the beginning of the experiment and then slowed down with the operating time. This is mainly because the concentration difference between the regenerated and spent solutions continuously increased with the operating time. The increase in the concentration difference resulted in increased ion diffusion from the regenerated solution to the spent solution and increased water penetration from the spent solution to the regenerated solution due to osmosis [39,40], which negatively affected the regeneration of the liquid desiccant solution.

Fig. 4(a) also shows that the concentration increase under the higher circulation flow rate was slightly smaller than that under the lower circulation flow rate. This is because the circulation flow rate directly affected the ion residence time in the ED stack. A low circulation flow rate ensures that the ions have enough time to reach the membrane and penetrate through the membrane [41–45]. This conclusion is consistent with the results obtained when using ED in other fields [43,46–48]. Among the

three different circulation flow rates, the largest concentration increase achieved at the end of 2 h test was 0.88% (wt/wt) when the circulation flow rate was 60 L/h. The concentration increase at the end of 2 h test with the circulation flow rates of 100 L/h and 140 L/h were 0.80% (wt/wt) and 0.76% (wt/wt), respectively. As shown in Fig. 4(b), the volume increase of the solution in the regenerated tank almost linearly increased with the operating time, indicating that water in the spent solution stream was transferred into the regenerated solution stream due to electro-osmosis and osmosis. However, there was no significant difference in the volume increase when different circulation flow rates were applied.

The results from Fig. 4 indicated that the average concentration of the solution transferred from the spent stream to the regenerated stream was higher than the concentration of the solution in the regenerated tank. As a consequence, the concentration of the solution in the regenerated tank increased. The results from this group of experimental tests showed that the regeneration capability of the ED decreased with the increase of the circulation flow rate. However, the difference among the three experiments with different circulation flow rates was not significant.

4.2. Effect of current density

The variations of the concentration increases and the volume changes of the solution in the regenerated tank under four different supplied current densities with the operating time are shown in Fig. 5. The concentration increases of the solution in the regenerated tank during the experimental period of 120 min were 1.08%, 1.02%, 0.82% and 0.57% (wt/wt) when the current densities supplied to the ED stack were 57.1, 47.6, 38.1 and 28.6 mA/cm², respectively. The ED regeneration performance increased with the increase of the current density supplied. However, the increase became smaller when the supplied current density was above 47.6 mA/cm² compared to that with a low supplied current density. Similar to the test results with different circulation flow rates, a faster change in the concentration increase was observed at the beginning of each test. The rate of change decreased over time due to the continuous increase of the concentration difference between the regenerated and spent solutions.

Fig. 5(b) shows an almost linear increase in the volume of the LiCl solution in the regenerated tank over time. A faster change in the volume of the regenerated solution can be observed when a higher current density was applied. During the experiment of 120 min, the maximum volume increase of the solution in the regenerated tank was 0.57 L when the current density supplied to the ED stack was 57.1 mA/cm² while the minimum volume increase was 0.29 L when the supplied current density was 28.6 mA/cm². The observed changes in the volume of the regenerated solution indicate that more water was transferred from the spent solution to the regenerated solution when a higher current density was supplied.

The increase in the current density also increased the transport of LiCl from the spent solution to the regenerated solution. As a result, a larger concentration increase of the solution in the regenerated tank was achieved at a higher current density. It is, however, noteworthy that a higher supplied current density means more energy consumption. Thus, current density is a key variable that should be optimised when using ED for liquid desiccant regeneration.

4.3. Effect of initial LiCl concentration

Fig. 6(a) shows the concentration increase of the LiCl solution in the regenerated tank when varying the initial concentrations of the regenerated and spent LiCl solutions.

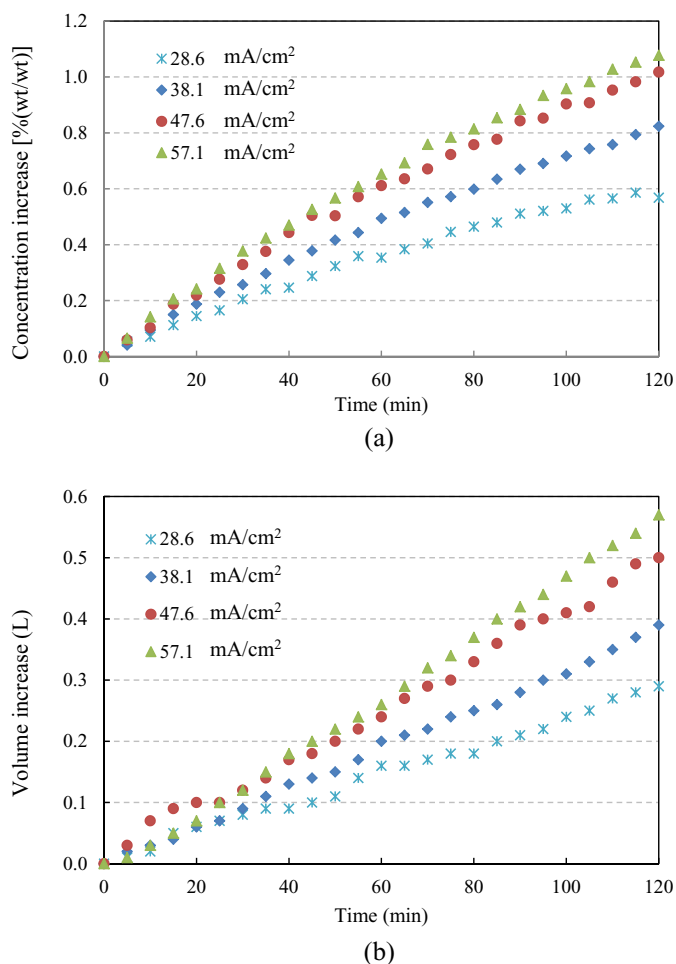


Fig. 5. (a) Concentration increase and (b) volume increase of the solution in the regenerated tank with current densities of 28.6, 38.1, 47.6 and 57.1 mA/cm² – initial concentrations of the solutions in the regenerated and spent tanks of around 27.50% (wt/wt) and circulation flow rate of 100 L/h.

Among the three experiments, the concentration increase of the regenerated solution was very similar when the initial solution concentrations were around 28.95% (wt/wt) and 24.92% (wt/wt). However, a higher concentration increase of the solution in the regenerated tank was observed when the initial solution concentration was around 18.78% (wt/wt). At the end of 120 min test, the LiCl solutions were enriched by 2.03%, 1.32% and 1.20% (wt/wt) when the initial solution concentrations were around 18.78%, 24.92% and 28.95% (wt/wt), respectively. This phenomenon could be attributed to different viscosities of the LiCl solution associated with different concentrations [49].

Fig. 6(b) shows that volume increase in the regenerated solution was faster with lower initial solution concentrations. The volume increase over the 120 min test period was 1.00, 0.69 and 0.54 L when the initial solution concentrations were around 18.78%, 24.92% and 28.95% (wt/wt), respectively. This illustrates that water can be readily transferred from the spent solution to the regenerated solution due to electro-osmosis and osmosis at lower concentrations, as compared to that at higher concentrations. The results also suggest that the regeneration capacity of ED for LiCl solutions decreases when increasing initial solution concentration. Therefore, an appropriate solution concentration should be used when using ED for liquid desiccant regeneration to enable both ED and dehumidifier has desirable performance.

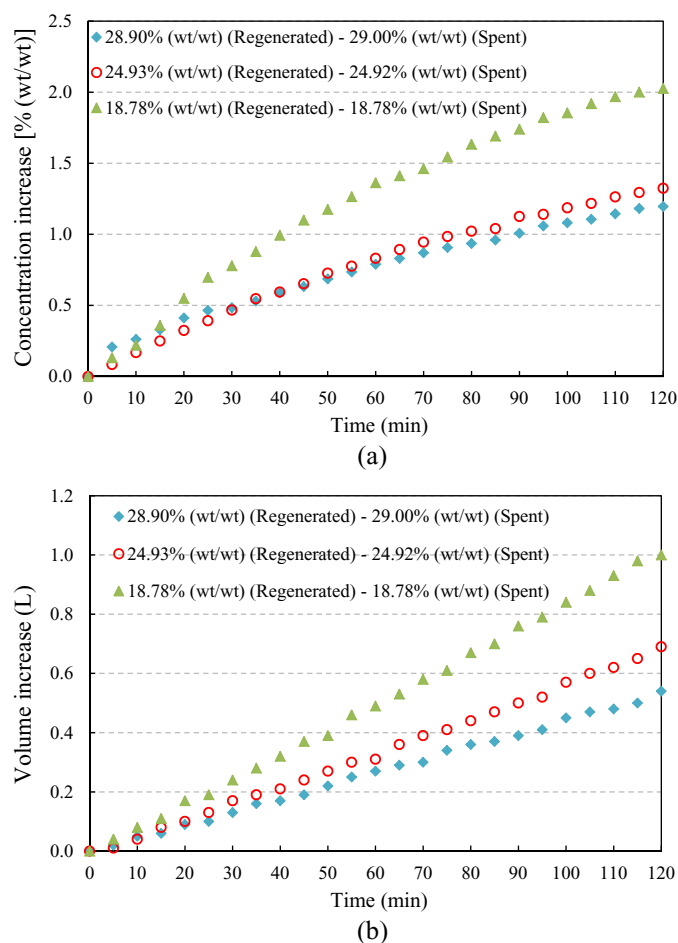


Fig. 6. (a) Concentration increase and (b) volume increase of the solution in the regenerated tank with initial solution concentrations of around 28.95%, 24.92% and 18.78% (wt/wt) – supplied current density of 57.1 mA/cm² and circulation flow rate of 100 L/h.

4.4. Effect of concentration difference between spent and regenerated solutions

Fig. 7(a) shows the variations of the concentration increase of the regenerated solution as a function of time under three different concentration differences between the regenerated and spent solutions. LiCl solution was continuously enriched during the entire experimental period if there was no difference in the initial concentration between the regenerated and spent solutions. However, the concentration of the regenerated solution slowly increased during the first hour and was then almost constant during the rest test when the initial concentration difference between the spent and regenerated solutions was around 3.0% (wt/wt). At the end of the experiment, the concentration increase of the regenerated solution was only 0.35% (wt/wt) while a value of 1.20% (wt/wt) was obtained when there was no difference in the initial concentrations between the regenerated and spent solutions. This means that under a large concentration difference, the osmosis and back diffusion greatly affected the ED performance as previous reported by Luo et al. [39] and Meng et al. [40].

When the initial concentration difference between the regenerated and spent solutions was around 5.0% (wt/wt), the concentration of the solution in the regenerated tank first slightly increased and reached to the peak when the system operated for around 40 min. From this point on, it kept almost constant for around 30 min and then started to decrease. This is mainly because the concentration difference between the regenerated solution and

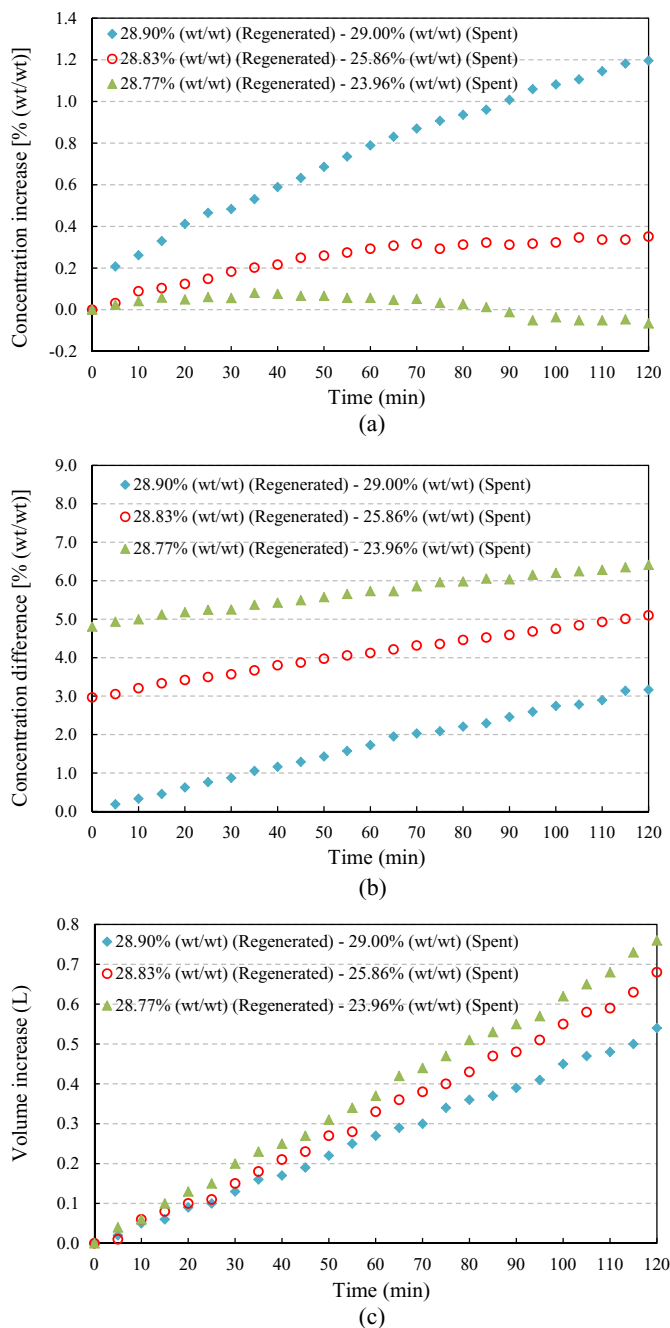


Fig. 7. (a) Concentration increase, (b) concentration difference between the regenerated and spent solutions and (c) volume increase of the regenerated solution with concentration differences around 0%, 3% and 5% (wt/wt) – initial concentration of the solution in the regenerated tank of around 29.00% (wt/wt), supplied current density of 57.1 mA/cm² and circulation flow rate of 100 L/h.

the spent solution continuously increased during the experimental test, as shown in Fig. 7(b). When the concentration difference reached to a certain value, it is then hard to further increase the concentration of the solution in the regenerated tank because of the effects of the osmosis and back diffusion. In this experiment, with a supplied current density of 57.1 mA/cm², the concentration of the solution in the regenerated tank started to decrease when the concentration difference between the regenerated and spent solutions was 5.86% (wt/wt). The above results demonstrated that the concentration difference between the regenerated and spent solutions should be controlled within a certain range in order to

maintain a good regeneration performance of the ED stack for liquid desiccants.

The volume increase of the regenerated solution is shown in Fig. 7(c). Similar to the results from previous experiments, the volume of the regenerated solution increased almost linearly with the operating time. A higher concentration difference resulted in a larger volume increase of the solution in the regenerated tank. The maximum volume increase was 0.76 L when the initial concentration difference between the regenerated and spent solutions was around 5.0% (wt/wt), followed by the initial concentration difference of around 3.0% (wt/wt) (0.68 L) and around 0.0% (wt/wt) (0.54 L).

The results from the above experiments with different initial concentration differences of the solutions in the regenerated and spent tanks illustrate that the concentration difference negatively affected the ED regeneration capacity due to the significant influences of the back diffusion and osmosis. The ED stack studied was not able to work as a regenerator when the concentration difference between the regenerated and the spent solutions was over 5.86% (wt/wt) under the test conditions specified in the experiment 13.

For all experiments, the concentration increase and the volume increase of the solution in the regenerated tank and the concentration difference between the solutions in the regenerated and spent tanks when the system operated for 60 min and 120 min are summarised in Table 4. Among all experiments, the experiment 10 with the initial concentrations of the regenerated and spent solutions of 18.78% (wt/wt), circulation flow rate of 100 L/h and supplied current density of 57.1 mA/cm² obtained the largest concentration increase (i.e. 1.36% and 2.03% (wt/wt)) and the volume increase (i.e. 0.49 and 1.00 L) after 60 and 120 min tests, respectively. The smallest concentration increases after 60 and 120 min tests were 0.06% and -0.07% (wt/wt) respectively, when the initial concentrations of the regenerated and spent solutions were 28.77% and 23.96% (wt/wt), the circulation flow rate was 100 L/h and the supplied current density was 57.1 mA/cm² (i.e. experiment 13). The smallest volume increases after 60 and 120 min test were 0.15 and 0.29 L under the conditions specified in the experiments 3 and 4, respectively. It can be concluded that a lower initial solution concentration benefited the ion migration. However, it also increased the migration of water from the spent to regenerated solutions due to electro-osmosis.

4.5. Current efficiency of ED for liquid desiccant regeneration

The current efficiency of ED for liquid desiccant regeneration of each experiment in two hours test is summarised in Table 5. It can be seen that, among all experiments, the current efficiency of the ED stack varied between 55.17% and 73.54%. A higher supplied current efficiency was obtained when a lower solution concentration was used. Experiment 10 obtained the highest value of 73.54% while experiment 3 provided the lowest value of 55.17%.

However, for the experiment 13, at the end of the 2 h test, even the concentration of the regenerated solution was lower than the initial concentration, the current efficiency was 66.04%. This means that current efficiency of the ED stack cannot be used alone to evaluate the performance of ED for liquid desiccant regeneration as it does not consider the water transfer from the spent solution to the regenerated solution, which is important when evaluating the performance of ED for liquid desiccant regeneration. Therefore, in the design and optimisation of ED for liquid desiccant regeneration, current efficiency and the concentration increase of the regenerated solution should be used together to estimate the ED regeneration performance.

Table 4
Experimental results for all experiments.

Experiment	60 min operation			120 min operation		
	Concentration increase ^a [% (wt/wt)]	Volume increase ^a (L)	Concentration difference ^b [% (wt/wt)]	Concentration increase [% (wt/wt)]	Volume increase (L)	Concentration difference [% (wt/wt)]
1	0.53	0.17	1.11	0.88	0.37	2.05
2	0.47	0.17	1.13	0.80	0.36	2.06
3	0.46	0.15	1.29	0.76	0.35	2.30
4	0.35	0.16	1.05	0.57	0.29	2.00
5	0.49	0.20	1.17	0.82	0.39	2.11
6	0.61	0.24	1.45	1.02	0.50	2.62
7	0.65	0.26	1.58	1.08	0.57	2.87
8	0.79	0.27	1.73	1.20	0.54	3.16
9	0.83	0.31	1.94	1.32	0.69	3.58
10	1.36	0.49	2.92	2.03	1.00	5.29
11	0.79	0.27	1.73	1.20	0.54	3.16
12	0.29	0.33	4.12	0.35	0.68	5.10
13	0.06	0.37	5.73	-0.07	0.76	6.41

^a The concentration and volume increases of the solution in the regenerated tank.

^b The concentration difference between the solutions in the regenerated and spent tanks.

Table 5
Current efficiency of the ED in each experiment.

Experiment No.	Current efficiency (%)
1	57.94
2	56.77
3	55.17
4	60.19
5	60.52
6	60.90
7	58.29
8	60.11
9	64.95
10	73.54
11	60.11
12	63.43
13	66.04

4.6. Temperature variation of the solution in the regenerated tank

Fig. 8 shows the temperature variation of the solution in the regenerated tank and supplied voltage to the ED stack corresponding to the current supplied under the test conditions of the experiment 2 presented in Table 3. It can be seen that, during the whole test period, the solution temperature continuously increased from 25.6 to 28.5 °C while the voltage supplied to the ED stack

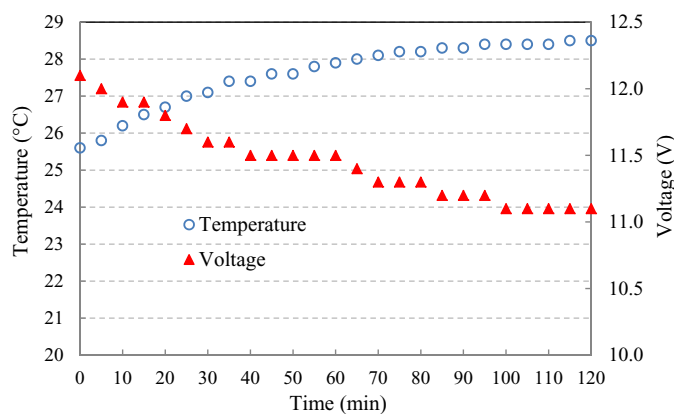


Fig. 8. Temperature and voltage variations of the solution in the regenerated tank – initial concentration of the solutions in regenerated and spent tanks of 27.71% (wt/wt), supplied current density of 38.1 mA/cm² and circulation flow rate of 100 L/h.

decreased from 12.1 to 11.1 V. The temperature increase was probably resulted from the heat absorbed from the solution pumps and the heat generated because of the Joule effect [50,51]. Due to the increased temperature, the electrical resistance of the solution therefore consequently reduced, which further decreased the electrical potential as a constant current was supplied to the ED stack.

4.7. Concentration and volume variation of the solution in the spent tank

The concentration and volume variations of the solution in the spent solution tank were determined in the similar way as those of the regenerated solution. Fig. 9 shows the decrease of the concentration and volume of the liquid desiccant in the spent solution tank in experiment 1. It can be seen that both the volume and concentration of the solution in the spent solution tank decreased with time. At the end of the experiment, the concentration of the solution in the spent solution tank decreased by 1.17% (wt/wt) while the volume of the solution reduced by 0.26 L. The decrease in the volume of the spent solution tank also revealed that water transferred from the spent solution to the regenerated solution due to the osmosis and electro-osmosis.

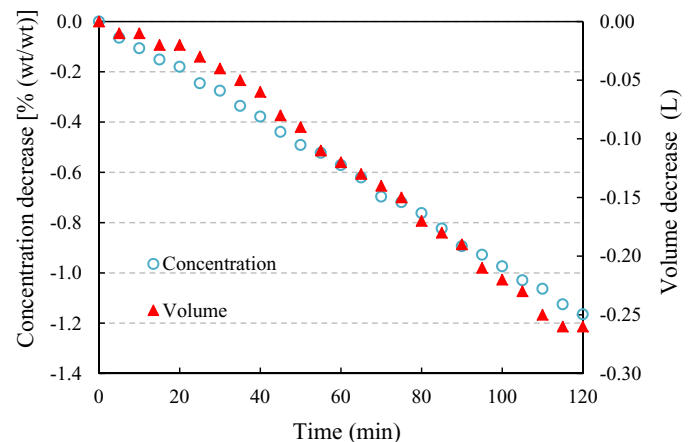


Fig. 9. Concentration and volume decrease of the solution in the spent solution tank – initial concentration of the solutions in the regenerated and spent tanks of 27.71% (wt/wt), supplied current density of 38.1 mA/cm² and circulation flow rate of 60 L/h.

5. Conclusions

This study demonstrated that the capability of ED for regenerating LiCl liquid desiccant solution decreased with the increase of the circulation flow rate due to the decreased residence time. ED can achieve a higher concentration increase and a higher volume increase of the solution in the regenerated tank with a lower initial concentration of the solutions in the regenerated and spent tanks. As expected, increasing supplied current density increased the concentration increase and the volume increase of the solution in the regenerated tank. As the concentration difference between the regenerated and spent solutions has a significant impact on the ED regeneration performance due to the back diffusion and osmosis, it should be controlled within a reasonable range in order to achieve a better regeneration performance and ensure that the ED stack can continuously regenerate the solution in the regenerated tank to the required value. At the current density of 57.1 mA/cm², the circulation flow rate of 100 L/h, and the initial concentrations of the spent and regenerated solutions of 23.96% and 28.77% (wt/wt) respectively, ED could enrich the concentration of the liquid desiccant solution when the concentration difference between the regenerated and spent solutions was below 5.86% (wt/wt). The maximum and minimum current efficiencies among all experiments were 73.54% and 55.17%, respectively.

The results from this study showed that ED can be used for LiCl liquid desiccant regeneration if it is appropriately designed and integrated into the liquid desiccant air conditioning (LDAC) systems and the operating conditions of the ED are properly selected. However, there are many questions such as how to integrate ED into LDAC systems and how to optimise the ED regeneration performance still remaining to be answered in the future research.

Acknowledgements

The authors would like to thank Mr. Craig McLauchlan and Mr. John Barron for their technical support. This research was supported by SMALL GRANT from University of Wollongong.

Appendix. Calculation of solution concentration

During the experimental tests, the mass concentration of the LiCl solution was not directly measured and it was derived on the basis of the density and temperature measurements. In order to determine the relationship of the mass concentration with the density and temperature of the LiCl solution, a total of 14 samples of lithium chloride solutions with different concentrations varied from around 10% (wt/wt) to around 36% (wt/wt) with around 2% (wt/wt) increments were prepared. For each sample, the density and temperature of the solution were measured by the density metre in a temperature range of 15.0–40.0 °C with a 1.0 °C increment. The maximum temperature of 40.0 °C was selected due to the fact that the maximum allowable temperature measurement of the density metre was 40.0 °C and it is also expected that ED will work with a relatively low temperature when it is used for liquid desiccant regeneration. The mass concentrations of the prepared samples were determined using the gravimetric method.

Based on the data measured for 14 samples prepared, a regression equation, as expressed in the equation below, was then developed through trial and error tests.

$$\xi = a_0 + a_1 \cdot t + a_2 \cdot \ln(t) + a_3 \cdot \ln(t) \cdot e^{\rho} + a_4 \cdot t \cdot \rho + a_5 \cdot \rho \cdot \ln(t)$$

where ξ , t and ρ are the mass concentration, temperature and density of the lithium chloride solution respectively, and a_0 – a_5 are the coefficients and the values used were 0.2402, 0.03201, –0.9326, –0.2866, –0.02735 and 1.599, respectively.

References

- [1] T. Zhang, X. Liu, Y. Jiang, Performance optimization of heat pump driven liquid desiccant dehumidification systems, *Energy Build.* 52 (2012) 132–144.
- [2] W. Lin, Z. Ma, M.I. Sohel, P. Cooper, Development and evaluation of a ceiling ventilation system enhanced by solar photovoltaic thermal collectors and phase change materials, *Energy Convers. Manag.* 88 (2014) 218–230.
- [3] H. Kreiner, A. Passer, H. Wallbaum, A new systematic approach to improve the sustainability performance of office buildings in the early design stage, *Energy Build.* 109 (2015) 385–396.
- [4] L. Zhang, N. Zhang, A heat pump driven and hollow fiber membrane-based liquid desiccant air dehumidification system: modeling and experimental validation, *Energy* 65 (2014) 441–451.
- [5] A.T. Mohammad, B.S. Mat, M.Y. Sulaiman, K. Sopian, A.A. Al-Abidi, Survey of hybrid liquid desiccant air conditioning systems, *Renew. Sustain. Energy Rev.* 20 (2013) 186–200.
- [6] A.T. Mohammad, S.B. Mat, M.Y. Sulaiman, K. Sopian, A.A. Al-Abidi, Survey of liquid desiccant dehumidification system based on integrated vapor compression technology for building applications, *Energy Build.* 62 (2013) 1–14.
- [7] W. Zhu, Z. Li, S. Liu, S. Liu, Y. Jiang, In situ performance of independent humidity control air-conditioning system driven by heat pumps, *Energy Build.* 42 (2010) 1747–1752.
- [8] A.K. Mohaisen, Z. Ma, Development and modelling of a solar assisted liquid desiccant dehumidification air-conditioning system, *Build. Simul.* 8 (2015) 123–135.
- [9] P. Farese, Technology: How to build a low-energy future, *Nature* 488 (2012) 275–277.
- [10] S. Misha, S. Mat, M.H. Ruslan, K. Sopian, Review of solid/liquid desiccant in the drying applications and its regeneration methods, *Renew. Sustain. Energy Rev.* 16 (2012) 4686–4707.
- [11] A.A. Al-Farayehi, P. Gandhidasan, S. Younus Ahmed, Regeneration of liquid desiccants using membrane technology, *Energy Convers. Manag.* 40 (1999) 1405–1411.
- [12] E. Elsarag, Evaporation rate of a novel tilted solar liquid desiccant regeneration system, *Solar Energy* 82 (2008) 663–668.
- [13] X. Niu, F. Xiao, Z. Ma, Investigation on capacity matching in liquid desiccant and heat pump hybrid air-conditioning systems, *Int. J. Refrig.* 35 (2012) 160–170.
- [14] S. Yamaguchi, J. Jeong, K. Saito, H. Miyauchi, M. Harada, Hybrid liquid desiccant air-conditioning system: experiments and simulations, *Appl. Therm. Eng.* 31 (2011) 3741–3747.
- [15] Y. Yao, Using power ultrasound for the regeneration of dehumidifiers in desiccant air-conditioning systems: a review of prospective studies and unexplored issues, *Renew. Sustain. Energy Rev.* 14 (2010) 1860–1873.
- [16] F.A. Al-Sulaiman, P. Gandhidasan, S.M. Zubair, Liquid desiccant based two-stage evaporative cooling system using reverse osmosis (RO) process for regeneration, *Appl. Therm. Eng.* 27 (2007) 2449–2454.
- [17] X. Li, X. Zhang, Photovoltaic-electrodialysis regeneration method for liquid desiccant cooling system, *Solar Energy* 83 (2009) 2195–2204.
- [18] Q. Cheng, X. Zhang, A solar desiccant pre-treatment electro dialysis regeneration system for liquid desiccant air-conditioning system, *Energy Build.* 67 (2013) 434–444.
- [19] X. Li, X. Zhang, S. Quan, Single-stage and double-stage photovoltaic driven regeneration for liquid desiccant cooling system, *Appl. Energy* 88 (2011) 4908–4917.
- [20] Q. Cheng, X. Zhang, X. Li, Double-stage photovoltaic/thermal ED regeneration for liquid desiccant cooling system, *Energy Build.* 51 (2012) 64–72.
- [21] Q. Cheng, Y. Xu, X. Zhang, Experimental investigation of an electro dialysis regenerator for liquid desiccant, *Energy Build.* 67 (2013) 419–425.
- [22] Q. Cheng, X. Zhang, X. Li, Performance analysis of a new desiccant pre-treatment electro dialysis regeneration system for liquid desiccant, *Energy Build.* 66 (2013) 1–15.
- [23] X. Li, X. Zhang, Membrane air-conditioning system driven by renewable energy, *Energy Convers. Manag.* 53 (2012) 189–195.
- [24] A.H. Galama, M. Saakes, H. Bruning, H.H.M. Rijnaarts, J.W. Post, Seawater pre-desalination with electro dialysis, *Desalination* 342 (2014) 61–69.
- [25] D. Valero, V. García-García, E. Expósito, A. Aldaz, V. Montiel, Application of electro dialysis for the treatment of almond industry wastewater, *J. Membr. Sci.* 476 (2015) 580–589.
- [26] X. Zhang, C. Li, X. Wang, Y. Wang, T. Xu, Recovery of hydrochloric acid from simulated chemo synthesis aluminum foils wastewater: an integration of diffusion dialysis and conventional electro dialysis, *J. Membr. Sci.* 409–410 (2012) 257–263.
- [27] A. Doyen, L. Saucier, L. Beaulieu, Y. Pouliot, L. Bazinet, Electro separation of an antibacterial peptide fraction from snow crab by-products hydrolysate by electro dialysis with ultrafiltration membranes, *Food Chem.* 132 (2012) 1177–1184.
- [28] X. Li, X. Zhang, Q. Cheng, Photovoltaic driven liquid dehumidification air-conditioning system, *Adv. Mater. Res.* 805–806 (2013) 125–130.
- [29] X. Li, X. Zhang, Q. Chen, Research on mass transfer and actual performance of the membrane regeneration air-conditioning system, *Energy Convers. Manag.* 106 (2015) 84–92.
- [30] N. Boniardi, R. Rota, G. Nano, B. Mazza, Lactic acid production by electro dialysis. Part I: Experimental tests, *J. Appl. Electrochem.* 27 (1997) 125–133.

- [31] M. Sadrzadeh, A. Razmi, T. Mohammadi, Separation of monovalent, divalent and trivalent ions from wastewater at various operating conditions using electro dialysis, *Desalination* 205 (2007) 53–61.
- [32] M. Fidaleo, M. Moresi, Optimal strategy to model the electro dialytic recovery of a strong electrolyte, *J. Membr. Sci.* 260 (2005) 90–111.
- [33] A.H. Abdel-Salam, G. Ge, C.J. Simonson, Performance analysis of a membrane liquid desiccant air-conditioning system, *Energy Build.* 62 (2013) 559–569.
- [34] W.S. Winston Ho, K.K. Sirkar, *Membrane Handbook*, Springer, New York, 1992.
- [35] Y. Tanaka, *Ion Exchange Membrane Electro dialysis: Fundamentals, Desalination, Separation*, Nova Science Publishers, Inc., New York, 2010.
- [36] H. Strathmann, *Membrane Science and Technology*, Elsevier B.V., The Netherlands, 2004.
- [37] W. Yang, L. Sun, Y. Chen, Experimental investigations of the performance of a solar-ground source heat pump system operated in heating modes, *Energy Build.* 89 (2015) 97–111.
- [38] S. Jaisankar, J. Ananth, S. Thulasi, S.T. Jayasuthakar, K.N. Sheeba, A comprehensive review on solar water heaters, *Renew. Sustain. Energy Rev.* 15 (2011) 3045–3050.
- [39] G.S. Luo, S. Pan, J.G. Liu, Use of the electro dialysis process to concentrate a formic acid solution, *Desalination* 150 (2002) 227–234.
- [40] H. Meng, B. Li, B. Gong, C. Li, The removal of aniline from wastewater by electro dialysis in the presence of hydrochloric acid, *Desalin. Water Treat.* 51 (2013) 5155–5163.
- [41] M. Aider, S. Brunet, L. Bazinet, Effect of solution flow velocity and electric field strength on chitosan oligomer electromigration kinetics and their separation in an electro dialysis with ultrafiltration membrane (EDUF) system, *Sep. Purif. Technol.* 69 (2009) 63–70.
- [42] X. Zuo, S. Yu, W. Shi, Effect of some parameters on the performance of electro dialysis using new type of PVDF–SiO₂ ion-exchange membranes with single salt solution, *Desalination* 290 (2012) 83–88.
- [43] M.B.S. Ali, A. Mnif, B. Hamrouni, M. Dhahbi, Electro dialytic desalination of brackish water: effect of process parameters and water characteristics, *Ionics* 16 (2010) 621–629.
- [44] M. Sadrzadeh, A. Razmi, T. Mohammadi, Separation of different ions from wastewater at various operating conditions using electro dialysis, *Sep. Purif. Technol.* 54 (2007) 147–156.
- [45] H.R. Balmann, R. Cerro, V. Sanchez, Purification of bioproducts by free-flow zone electrophoresis: choice of processing parameters, *Electrophoresis* 19 (1998) 1117–1126.
- [46] Q. Wang, T. Ying, T. Jiang, D. Yang, M.M. Jahangir, Demineralization of soybean oligosaccharides extract from sweet slurry by conventional electro dialysis, *J. Food Eng.* 95 (2009) 410–415.
- [47] R. Nikbakht, M. Sadrzadeh, T. Mohammadi, Effect of operating parameters on concentration of citric acid using electro dialysis, *J. Food Eng.* 83 (2007) 596–604.
- [48] M.B.S. Ali, B. Hamrouni, M. Dhahbi, Electro dialytic defluoridation of brackish water: effect of process parameters and water characteristics, *CLEAN – Soil Air Water* 38 (2010) 623–629.
- [49] S. Koneshan, R.M. Lynden-Bell, J.C. Rasaiah, Friction coefficients of ions in aqueous solution at 25 °C, *J. Am. Chem. Soc.* 120 (1998) 12041–12050.
- [50] R. Valerdi-Pérez, J.A. Ibáñez-Mengual, Current-voltage curves for an electro dialysis reversal pilot plant: determination of limiting currents, *Desalination* 141 (2001) 23–37.
- [51] E. Vera, J. Sandeaux, F. Persin, G. Pourcelly, M. Dornier, J. Ruales, Decidification of clarified tropical fruit juices by electro dialysis. Part I. Influence of operating conditions on the process performances, *J. Food Eng.* 78 (2007) 1427–1438.