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Development and Performance Evaluation of A Liquid Desiccant Air Conditioning System with Hybrid Electrodialysis and Thermal Regeneration

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Abstract

Liquid desiccant air conditioning (LDAC) systems have gained increasing attention due to the improved energy performance and reduced environmental impacts. This paper presents an LDAC system using electrodialysis (ED) as well as low grade heat generated from a hybrid photovoltaic thermal and evacuated tube (PVT-ET) collector for liquid desiccant regeneration. As ED regenerator is a key component in the proposed system, a modified mathematical model is used to simulate the mass transfer of the ED stack. The performance of the model was validated using the experimental data generated based on a lab-scale experimental setup. It is shown that the model predicted concentration of the solution in the regenerated tank matched well with the experimental data. Compared to the LDAC systems using conventional thermal regeneration, the proposed ED system can regenerate the LiCl liquid desiccant solution at a low temperature. The regeneration process can also be operated during night-time. The whole system simulation using TRNSYS showed that the outlet concentration of the spent solution in the thermal regenerator was in the range of 26.87-26.97% (wt/wt). The concentration of the regenerated solution at the ED outlet can be maintained at 29.99% (wt/wt).

Keywords – electrodialysis; regeneration; liquid desiccant; phase change material storage

1. Introduction

The control of indoor air humidity is vital for thermal comfort of human beings and building material sustainability [1, 2]. A better indoor air quality requires a lower relative humidity generally in the range of 30-70% [3]. In buildings, a significant proportion of energy consumed is used for maintaining satisfied indoor thermal comfort [4]. Compared to the mechanical condensation dehumidification, desiccant dehumidification is more energy efficient. Liquid desiccant dehumidification is being considered as one of the promising technologies for building energy efficiency due to its design and performance advantages [3].

As one of the essential processes in liquid desiccant air-conditioning (LDAC) systems, regeneration of weak liquid desiccant has been extensively studied over the last few decades [5-7]. Both thermal regeneration and non-thermal regeneration methods have been investigated [8-11]. Thermal regeneration methods often use heat sources such as solar energy, waste heat and heat pumps to drive liquid desiccant regeneration. In non-thermal regeneration, ultrasonic, reverse osmosis (RO) and electrodialysis (ED) have been considered as alternative strategies for liquid desiccant regeneration. Yao [12], for instance, presented the use of a ultrasonic regenerator for liquid desiccant regeneration. An LDAC system using RO regeneration was developed by Al-Sulaiman *et al*. [13].

Electrodialysis (ED) was first proposed by Li *et al*.[14] as a regeneration method for liquid desiccants. 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 [15, 16]. It was concluded that the double-stage regeneration system can save more energy under the optimized working conditions than that of the single stage regeneration system.

This paper presents an ED enhanced LDAC system integrated with a low temperature thermal regenerator, in which a phase change material (PCM) thermal energy storage is used to reduce the weak solution temperature before entering the ED stack during the time with high solar radiations and heat the weak solution using the stored energy before entering the thermal regenerator during the time with low or no solar radiations. As ED is one of the most important components in this system, a modified mathematical model for the ED stack was used to simulate the mass transfer within the ED and an experimental investigation was also carried out to understand the performance of ED for liquid desiccant regeneration.

2. Development of the ED enhanced LDAC System

The schematic of the proposed ED enhanced LDAC system is shown in Fig. 1. It mainly consists of a hybrid photovoltaic thermal and evacuated tube (PVT-ET) collector, a dehumidifier, a cooling tower, an ED regenerator, a low temperature thermal regenerator, a PCM thermal energy storage, an auxiliary electrical heater and a direct evaporative cooler. There are two main flows of the desiccant solutions in this proposed system. One is the liquid desiccant used for air dehumidification, which was named as regenerated solution. The other is the liquid desiccant that circulates through the PVT-ET collectors, the thermal regenerator, and the PCM thermal energy storage to assist in concentrating the regenerated solution. This solution flow stream has a relatively low concentration and was named as the spent solution. The regenerated solution from the regenerated solution tank is cooled by a closed circuit cooling tower before entering the dehumidifier to ensure a good dehumidification performance.

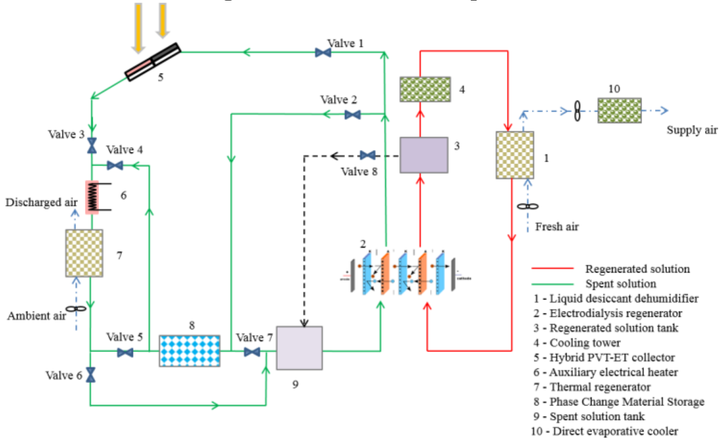


Fig. 1 Schematic of the ED enhanced LDAC system.

This system was designed to allow the liquid desiccant to be regenerated at a relatively low temperature by using both the ED stack and the low temperature thermal regenerator. The inlet concentration of the liquid desiccant in the dehumidifier was designed at around 30.0% (wt/wt). In order to easily remove the water from the spent solution in the low temperature thermal regenerator, a concentration difference between the inlet concentrations of the regenerated and spent solutions to the ED stack was designed as 3.0%. If the spent solution temperature from the PVT-ET collector is high enough, the valves 1, 3, 5 and 7 will be open while the valves 2, 4 and 6 will be closed. The spent solution first flows through the PVT-ET collector, the thermal regenerator and then flows through the PCM storage, where the temperature of the solution will be decreased and the heat will be stored in the PCM thermal storage.

When the solar radiation is low or there is no solar radiation, the valves 1, 3, 5 and 7 will be closed while the valves 2, 4 and 6 will be open. The discharged spent solution from the ED regenerator will first flow through the PCM storage and is then heated by the auxiliary electrical heater to the required regeneration temperature (i.e. 45 °C) and sent to the thermal regenerator.

Due to the water transfer from the spent solution to the regenerated solution during the ED process, the volume of the solution in the spent solution tank will decrease while that in the regenerated solution tank will increase with the operating time. Therefore, the valve 8 will be open when there is a need to adjust the volume in the solution tanks, which allows part of the solution in the regenerated tank to be released into the spent solution tank.

3. Development of the Simulation System

The proposed ED enhanced LDAC system was simulated using TRNSYS [17]. Fig. 2 shows the system components and their interconnections. The major component models used are summarised in Table 1.

Table 1 Summary of major component models used

Component model	Source
PVT collector	TRNSYS Type 50
Evacuated tube collector	TRNSYS Type 538
Auxiliary heater	TRNSYS Type 6
Cooling tower	TRNSYS Type 510
Direct evaporative cooler	TRNSYS Type 506
Dehumidifier/thermal regenerator	Reference [18]
PCM storage	Reference [19]
ED stack	Modified model

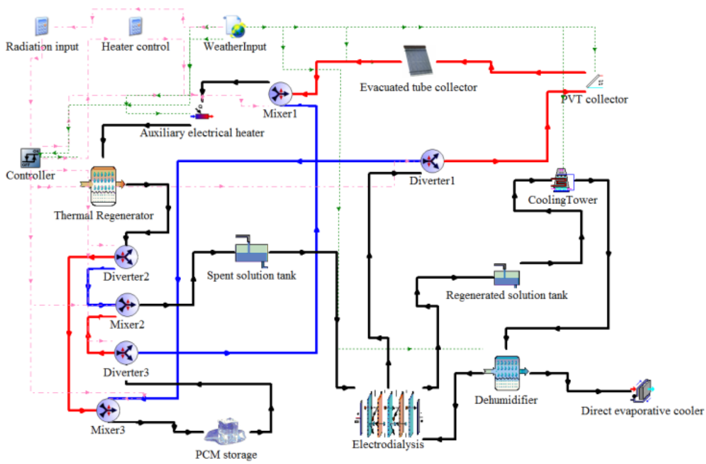


Fig. 2 Illustration of TRNSYS simulation system.

As ED is one of the key components in this proposed system, a modified mathematical model based on the overall mass transport (OMT) equation was used to simulate the mass transfer process within the ED stack.

In this model, the influence of the temperature on the mass transfer in the ED stack was not considered.

The ion flux j_s and solution flux j_V in one membrane pair at the current density i are expressed by the OMT equations as shown in (1) and (2), respectively [20].

$$j_s = \lambda i - \theta(\xi_{reg} - \xi_{spt}) = \lambda i - \theta \Delta\xi \quad (1)$$

$$j_V = \phi i + \tau(\xi_{reg} - \xi_{spt}) = \phi i + \tau \Delta\xi \quad (2)$$

where λ, θ, ϕ and τ are the overall transport number, the overall solute permeability, the overall electro-osmotic permeability, and the overall hydraulic permeability respectively; ξ is the concentration of the solution in the ED stack; $\Delta\xi$ is the concentration difference between the regenerated and spent solutions in the ED stack; the subscript *reg* indicates the regenerated solution; and the subscript *spt* indicates the spent solution. The overall transport number λ and the overall electro-osmotic permeability ϕ in the OMT equation were modified by considering the influence of both concentration and current density on the mass transfer in ED. All membrane pair characteristics were obtained from the designed experiments.

4. Results and Discussions

4.1. ED experimental tests and ED model parameter identification

To identify the parameters of the ED model, a set of experiments were designed and carried out in a lab-scale experimental system with 10 membrane cells (Fig. 3).

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

Fig. 3 Electrodialysis experimental setup.

Fig. 4 shows the variation of the concentration increase of the solution in the regenerated tank with time under different supplied currents in one hour experimental test each. It can be found that the concentration of the regenerated solution linearly increased with the operating time. A higher supply current applied, a larger concentration increase resulted. The enrichment of the concentration increase from 8 to 12 A was higher than that from 4 to 8 A.

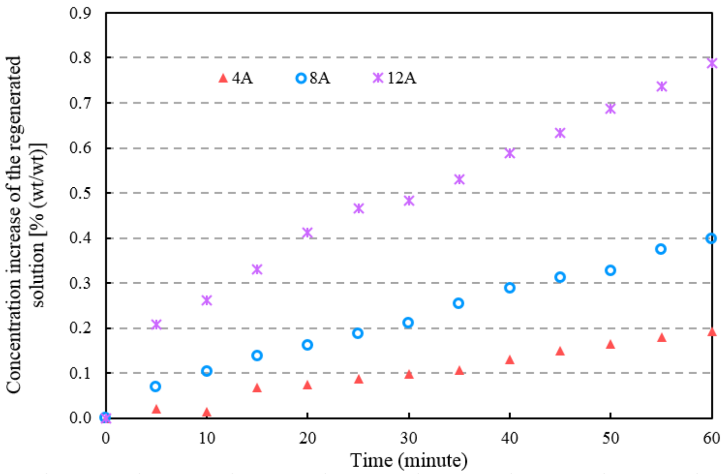


Fig. 4 Concentration increase of the regenerated solution under different supplied currents.

The parameters in the mathematical model were identified using the data collected from the designed experiments. To identify the overall solute permeability θ and the overall hydraulic permeability τ respectively, three experimental tests were carried out under different concentration differences between the spent and regenerated solutions. To identify the overall transport number λ and the overall electro-osmotic ϕ, a set of experiments were carried out under different supply currents and initial solution concentrations. Fig. 5 shows the model validation results using the experimental tests carried out under other test conditions. It can be seen that model simulated concentration of the solution in the regenerated tank agreed well with the experimental data with the relative deviations of ±0.2% for 94% of data sets.

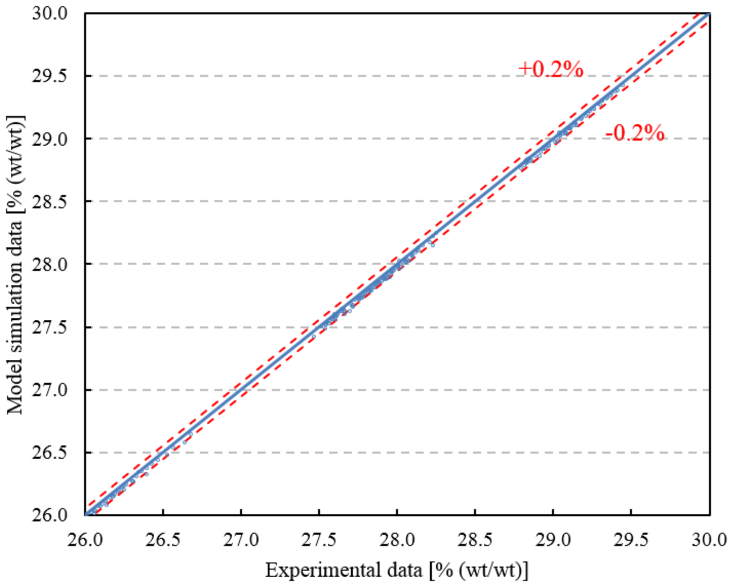


Fig. 5 Model validation for the concentration of the regenerated solution.

4.2. System Simulation Results

The proposed ED enhanced LDAC system was simulated for one day under the summer weather conditions of the tropical city Darwin as shown in Fig. 6.

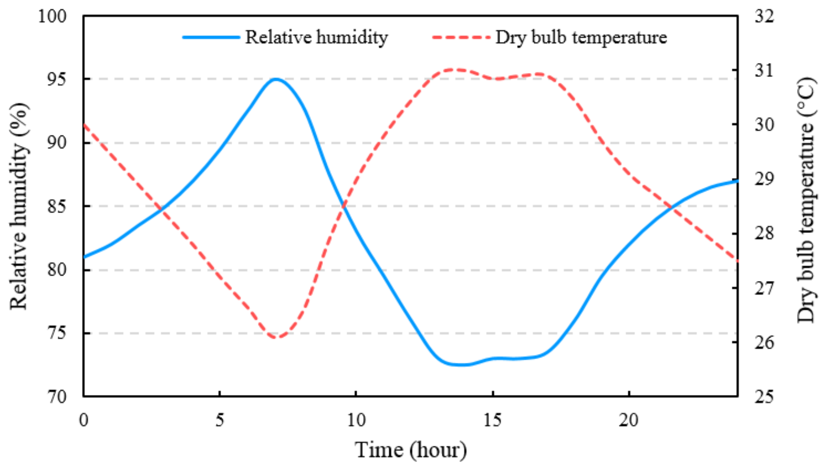
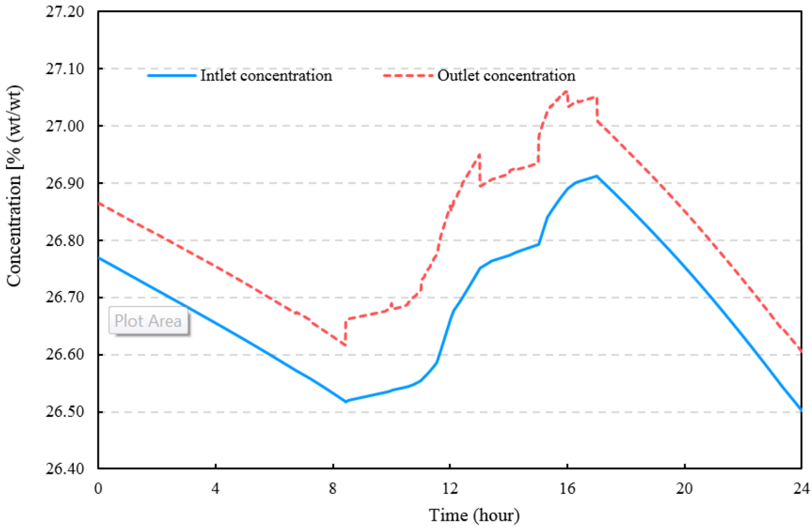
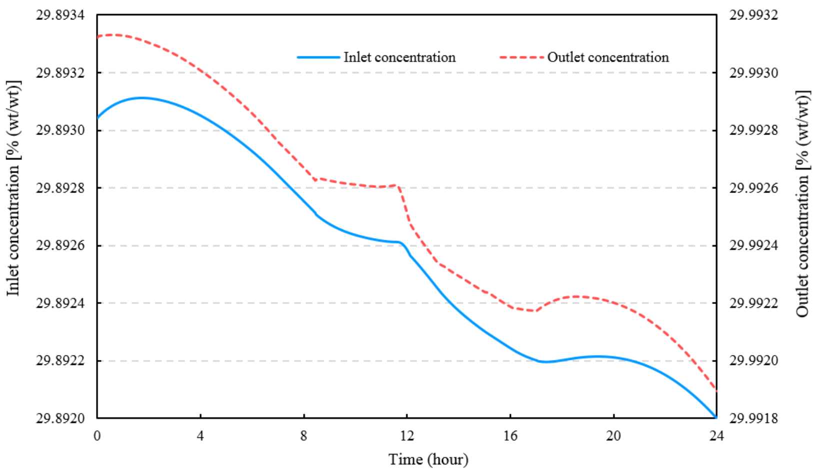


Fig. 6 Ambient air dry bulb temperature and relative humidity.

Fig. 7 shows the profiles of the inlet and outlet concentrations of the spent solution in the thermal regenerator and the inlet and outlet concentrations of the regenerated solution in the ED stack.



(a)



(b)

Fig. 7 Inlet an outlet concentrations of (a) the spent solution in the thermal regenerator and (b) the regenerated solution in ED.

It can be found that the outlet concentration of the spent solution in the thermal regenerator decreased with time with low/no solar radiations while it increased with time with high solar radiations. The inlet and outlet concentrations in the thermal regenerator varied in the range of 26.50% - 26.61% (wt/wt) and 26.91% - 27.06% (wt/wt), respectively. The inlet and outlet concentrations of the regenerated solution in ED kept almost stable during the simulation as the weather has no direct impact on the ED regeneration. It was shown that the inlet and outlet concentration of the regenerated solution in ED was kept at around 29.89% and 29.99% (wt/wt), respectively.

5. Conclusions

This paper proposed a liquid desiccant air conditioning using electrodialysis (ED) and low grade thermal energy for liquid desiccant regeneration. A modified ED model was used to simulate the mass transfer within the ED stack. The model parameters were identified using designed experiments and the performance of the model was also validated using the experimental data generated based on a lab-scale ED experimental setup. The proposed air-conditioning system was simulated using TRNSYS. It was shown that the modified ED model can provide reliable estimates and the concentration of the regenerated solution at the ED outlet can be maintained at around 29.99% (wt/wt) while that of the spent solution at the thermal regenerator outlet varied between 26.91% to 27.06% (wt/wt).

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