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Experimental study on the performance of membrane based multi-effect dehumidifier regenerator powered by solar energy

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Abstract

This study aims to provide an experimental performance analysis of a membrane based multi-effect regenerator for dehumidification application powered by solar thermal energy. The regenerator system is used as a desiccant solution concentrator to re-concentrate the salt solution by removing some water content in the used solution from the dehumidification system. The concentrated solution can also be used as a solar energy storage system by storing the high concentrated desiccant solution to be used in the de-humidifier. In the membrane based multi-effect regenerator, the merits of multi-effect evaporation and membrane’s mass transfer process are applied. It uses an energy recovering process by using the multi-effect evaporation concept and the membrane’s mass transfer process driven by low grade temperature and pressure gradient. In this study, different operating parameters such as feed flow rates, feed concentration and heating temperature were examined to determine the optimum performance of this membrane based multi-effect regenerator.

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Keywords: membrane, multi-effect evaporator, regenerator

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1. Introduction

Air-conditioning is one of the biggest energy consumers in the building sector particularly in commercial and residential buildings. It accounts for up to 60% of the electricity consumptions of the building. The majority of these air-conditioning systems are electrically driven and they are used to cool the air and remove the moisture from the air to reduce the RH value by using conventional Direct-Expansion (DX) cooling coil and vapour compression method. Combining these two functions in one single system is not efficient as the air has to be cooled to below its dew point to reduce the moisture. Very often the air has to be re-heated to bring the cooling to an acceptable comfort level. Electrical energy is hence not only utilized for cooling but also for removing the latent heat. The re-heating also consumes additional energy causing the overall system to be inefficient and adding more stress to the electrical grid. An efficient dehumidifying process to replace or to complement the existing conventional cooling coil and vapour compression system is urgently needed and is one of the many key areas of research interest especially in tropical countries where the humidity, RH value, is in the 80s. Membrane based liquid desiccant dehumidifier has recently gain much attention in liquid desiccant air-conditioning (LDAC) system due to its merit of zero contamination or carryover and resistance to corrosion. In this paper, to concentrate the liquid desiccant for dehumidification, a 4-stage V-MEMD (vacuum multi-effect-membrane-distillation) system, a patented and product of memsys® for de-salination and water treatment, is used as a concentrator (regenerator)[Wolfgang Heinzl, et al.]. The objective is to test and evaluate the effectiveness and performance of such multi-effect distillation system with desiccant salt solution. The advantages of multi-effect evaporation and the merit of the membrane’s mass transfer process are combined in this de-salination system. The multi-effect design allows energy recovery to be achieved to reduce the overall thermal energy consumption [5]. Improved mass transfer driven by low grade temperature and pressure gradient is applied in this system using the membrane separation process and vacuum [2][3][4]. This study aims to determine the performance of the V-MEMD system used in LDAC using LiCl as the desiccant salt. Different operating parameters such as the liquid desiccant feed flow rate, feed concentration and heating temperature are studied and presented.

<table>
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<td>PR</td>
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<td>m&lt;sub&gt;dist&lt;/sub&gt;</td>
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<tr>
<td>H&lt;sub&gt;in&lt;/sub&gt;</td>
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<td>h&lt;sub&gt;fg&lt;/sub&gt;</td>
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2. System descriptions

Fig 1. shows a partially one stage of membrane module and the concept of a single stage V-MEMD system. A typical system for the LDAC application will consist of a number of such stages depending on the capacity of the LDAC system. Each stage is made up of six Poly Propylene plastic foil frames (PP foil frame) and five membrane frames. The modules are welded alternately with spacer between the PP foil frame and the membrane frame. This spacer provides space to create a channel between the PP foil and membrane frames allowing the solution to flow uniformly. Steam generated by the solar thermal heat through a heat exchanger flows from the steam riser condenses in the first stage PP foil frame due to the cooler diluted feed solution (Forward feed flow). The temperature of the feed solution is in turn increased by the heat arising from the steam condensation recovering some of the thermal energy to generate more steam from the feed solution to be passed to the next stage. The recovered heat together with the lower pressure creates temperature gradient, consequently water vapour partial pressure gradient across the membrane. As a result, the vapor (steam) from feed solution passes through the membrane and the steam produced is channeled to the next stage to be condensed again. The transfer of heat and
mass from stage to stage by condensation and evaporation helps to recover the thermal heat allowing the recovery of water and at the same time concentrating the liquid desiccant feed solution in a multi-stage or multi-effect system under vacuum condition. Details are described in Wolfgang Heinzl, et al. [1] paper.
2.1. Experimental set-up

Fig 2. shows a schematic diagram of the V-MEMD system regenerator powered by solar energy. The main multi-effect regenerator has six key components namely, steam riser, 4-stage distillation modules, condenser, heat exchangers and a vacuum pump. The steam riser module is made of PTFE membrane and the condenser module is constructed using PP foils. Hot water from the solar collector system or auxiliary heater flows through a heat exchanger, a pump in the secondary loop of the heat exchanger circulates the hot water in the steam riser. Due to the temperature and pressure gradient across the membrane, the frame operate under a vacuum environment, water vapor is produced and the generated steam crosses the PTFE membrane where it is channeled to the foil modules of the 1st stage of the regenerator. The steam condenses by the cooler feed solution flowing on the other side of the foil. In this regenerator, the condensate from the first stage is circulated back to the heat exchanger to top up the water loss due to the condensation. The temperature of the feed solution rises by capturing the latent heat of condensation at the foil. The temperature and pressure gradient due to the temperature and pressure difference across the membrane causes the steam to flow across the membrane where the steam is then channeled to the next stage or effect. The vaporization causes the diluted feed solution to increase in concentration where it is channeled to the next stage for further concentration. In the next stage, the steam generated from the membrane frame of first stage flows into the foil frame of second stage, condensing into steam and at same time, the latent heat of condensation is recovered once again by heating up the partially concentrated feed solution flowing from the first stage.

This process is repeated in the four stages. Finally, the steam generated from the fourth and last stage of this 4-effect regenerator unit goes into the foil frames of the condenser. In this last stage, all the remaining steam generated
is condensed by the cooler heat sink of the condenser unit where the temperature is maintained by the circulation of cold water.

2.2. Materials

The four stages and the steam riser and the condenser modules are made from synthetic material to avoid the high corrosiveness of the liquid desiccant salt solution. For the membrane modules, hydrophobic PTFE membrane laminate (functional layer: PTFE, back material: Polypropylene) with a reference pore size of 0.2 μm, and 0.12 ~ 0.2 mm thickness are used for the separation process. The desiccant salt used for the feed solution in this experimental test and evaluation was LiCl with a mass concentration (Mass fraction) of 8% to 22%.

3. Results and discussion

A total of 12 experiments with different experimental parameters were carried out using LiCl desiccant solution as the feed with concentrations varying from 8% to 22% of mass fraction and feed flow rates between 40 L/Hr and 60 L/Hr. The heating source temperature used ranges from 50 °C to 80 °C. This is obtained from the solar thermal collectors as shown in Fig. 3. Fig. 4 shows the temperature and pressure charts of the regenerator operating with an 8% feed concentration and 40L/Hr feed flow rate with 65 °C heating temperature.

![Fig. 4. Temperature and pressure profiles against time (feed at 8% concentration, 40L/Hr. flow rate and 65 °C of heat source).](image)

The heat energy input, \( H_{\text{in}} \) (kW), to the system is calculated from the hot water flow rate and temperature difference of the hot water flowing and out of the steam riser (See in Fig.4). The performance of the regenerator is expressed as the performance ratio, \( PR \) (kW\text{dist}/kW\text{input}), and is calculated based on the following equation;

\[
PR = \frac{m_{\text{dist}} \times h_{\text{fg}}}{H_{\text{in}}}
\]

(1)

The variation of thermal performance ratio \( PR \) and distillate flux with feed flow rate and heating temperature is illustrated in Fig. 5 for 8% concentration feed inlet and in Fig. 6 for 22% concentration feed inlet. The results show that the thermal performance ratio varies from 2 to 2.15 depending on the heating temperature and feed flow rate. These \( PR \) values are comparable with that of the conventional multi-effect evaporator [6]. However, for the higher concentration of 22%, the \( PR \) value drops sharply from around 2 to 0.6 as shown in Figs. 5 and 6. The reason for the
drop in PR for higher concentration feed may be due to the lower thermal conductivity [7] (that can cause decreasing over all heat transfer coefficient) and higher boiling point or lower vapour pressure of the salt solution at higher concentration.

![Performance Ratio and Flux Vs. Heating Temp at Input 8% Concentration](image1)

Fig. 5. Thermal Performance Ratio and Distillate Flux against with vary heating Temperature and feed Flow Rate at 8% Concentration of feed inlet.

![Performance Ratio, Flux Vs. Heating Temp at Input 22% Concentration](image2)

Fig. 6. Thermal Performance Ratio and Distillate Flux against with vary heating Temperature and feed Flow Rate at 22% Concentration of feed inlet.

The results show that both the distillate flux and thermal performance ratio increases with increase in heating temperature for both the low and high concentration feed solution as shown in Figs. 5 and 6. The increase in flux and PR may be attributed to the fact that the higher heating temperature increases the pressure difference and hence the vapour pressure of the desiccant salt solution in each of the stages between the first and last stage. This increase in
pressure difference and vapour pressure of the salt solution in a partial vacuum condition increases the water vapour separation rate from the salt and hence enhance the thermal performance ratio and flux yield.

Fig. 7 shows that the variation of the concentrations of the outlet solution with the feed flow rate at different heating temperatures and feed concentration. For lower concentration and lower feed flow rate, the concentration difference between inlet and outlet solution is large – the regeneration is more effective. However, at higher concentration and flow rate, the concentration difference becomes smaller. From the result, it can be seen that the feed flow rate has a bigger impact on the performance in terms of concentration difference between inlet and outlet as compared with that of heating temperature. The reduction in performance could be possibly due to the fact that the higher flow rate reduces the resident time of the desiccant salt solution in the module for vaporization to take place. This has a direct impact on the energy consumption and the performance ratio as can be seen in Fig 6.

4. Conclusions

Thermal performance ratio \( \frac{kW_{\text{dist}}}{kW_{\text{input}}} \) and distillate flux \( \frac{L/Hr}{m^2} \) have been measured under different operating parameters; feed concentrations (mass fraction) from 8% to 22% with various flow rates from 40 L/Hr to 60 L/Hr, and heating temperature ranging from 50 °C to 80 °C. The distillate flux and thermal performance ratio depend on the inlet feed concentration, feed flow rate and heat source temperature. The results show that a higher flow rate and heat source temperature can enhance the PR and distillate flux, but the concentration difference between inlet and outlet drops with high feed flow rate. The study shows that this 4-stage V-MEMD system, a patented and product of memsys® designed for desalination, performs very well under ultra-low heat source (Heating temperature 50 °C) for 8% feed concentration. However, at higher concentration, the overall performance drops drastically.

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