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Experimental study of heat and mass transfer of Solar Powered liquid desiccant regeneration system

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Abstract: Liquid desiccant regeneration has an important effect on the performance of a liquid desiccant air conditioning system. Instead of a conventional packed regenerator an internally heated regenerator is proposed to achieve better regeneration performance. This paper presents an experimental investigation on the performance of the internally heated counter flow desiccant regeneration system. Triethylene Glycol (TEG) solution is used as the working desiccant material in this system. The structured packing used in this system was a finned tube heat exchanger. The effects of inlet parameters such as air flow rate, relative humidity, desiccant solution flow rate and desiccant solution concentration on the performance of the system are studied. The performance of the system is evaluated using the water evaporation rate, regenerator effectiveness, and enthalpy effectiveness.

Keywords:

1. INTRODUCTION

Liquid desiccant cooling system driven by solar energy or other heat sources has emerged as a potential alternative or as a supplement to conventional vapor compression systems for cooling and air conditioning. Dehumidification and regeneration are the key processes. Many studies have been dedicated to the investigation of performance of liquid desiccant dehumidifiers and regenerators.
Regenerators are units used to reconcentrate the weak desiccant during the process by removing the water content. The water content will be transferred from the desiccant to the air because the desiccant has a higher vapor pressure than water. Regeneration of desiccants using solar energy can be brought about by different methods. Based on the methods of regenerating the weak desiccants, regenerators can be divided into different categories. By using direct type solar regenerators where the desiccant is itself the heat collecting fluid, the regeneration process can be made more effective. The desiccant temperature is more or less equal to the collector plate temperature. The heat and mass transfer occurring in these regenerators have been studied well by Peng and Howell, [1]. Although the direct type solar regenerators are effective in operation, the corrosion problems associated with the liquid desiccant solution on the energy absorbing surface and the problems of dust and dirt cannot be ignored. On the other hand, a solar air heater or water heater can either supply the heat required for the regeneration process. For example, Lof [2] and Leboeuf and Lof [3] proposed a space cooling system in which the weak triethylene glycol is regenerated by solar heated air. Lodwig et al. [4] tested a liquid desiccant cooling system using hot water from solar flat-plate collectors to power a Niagara ''Hygrol'' system.
The possibility of providing cooling and air conditioning by means of energy from the sun has attracted attention since the early development of solar technology. The necessity of air conditioning for thermal comfort in hot areas of the world and the abundance of sunshine in these areas has always intrigued the mind of researchers on how to combine the two to get the most benefit [5] . Among the various thermal applications of solar energy, cooling is one of the more complex, in both concept and construction. This is one of the reasons why its utilization at present is not as widespread as space or water heating. Here it is not sufficient to collect the heat, store and distribute it. The energy must be converted to cold by means of a suitable device, capable for absorbing heat at a low temperature from the conditioned space, and rejecting it into the higher temperature of the outside air.
For regenerating the weak liquid desiccants, different regenerator designs have been studied by researchers. For example, Jain et al. [6] conducted experimental and theoretical studies of regeneration of aqueous lithium bromide solution in a falling film plate regenerator suitable for a desiccant augmented cooling system. In that study, the heating of the desiccant solution is done by circulating oil heated in a tank by immersion heaters. Scalabrin and

Scaltriti [7] analyzed a spray tower in which a stream of scavenging air comes into direct contact with the weak lithium chloride solution sprinkled over a tube bank heated internally by warm water.

Martin and Goswami [8] used triethylene glycol (TEG) as the liquid desiccant and packed bed as the regenerator to conduct an experimental study, and the work presented effects of inlet parameters of the air and desiccant on humidity effectiveness of the regeneration and water evaporation rate. Chung et al. [9] analyzed the mass transfer performance of an air stripping tower experimentally applying TEG as the liquid desiccant. Fumo and Goswami [10] chose aqueous lithium chloride (LiCleH2O) as the liquid desiccant and packed tower with counter flow as the regenerator to carry out an experimental study on the desiccant regeneration and a finite difference model was developed and showed very good agreement with the experimental findings.

In packed regenerator, heat and mass transfer happen only between the air and desiccant. There is no extra heat transferred into the regenerator, which is an adiabatic regenerator, so desiccant temperature would become lower and lower with the progress of regeneration in the regenerator. It is very possible that the liquid desiccant regeneration would decay quickly. Internally heated regeneration could be an alternative to solve this problem [11].Ren et al. [12] developed an analytical model for internally cooled or heated liquid desiccant air contact unit and found the model conforming with the numerical model. To the best of our knowledge, very little work was conducted on the detail of performance of the internally heated regenerator. Yin YG et al. [13] conducted an experimental study on the analysis of the heat and mass transfer behavior of an internally cooled/heated dehumidifier/regenerator and based on the experimental results, a heat and mass transfer model was developed and validated [14].

In the present study, an experimental chamber was constructed for investigating counter-flow regenerator using Triethylene Glycol (TEG) as the desiccant. The packing used in this experiment was a finned tube internally heated radiator. The effects of air and desiccant inlet parameters on the regenerator performance are experimentally investigated.

2. Experimental setup and Procedure

The experimental rig was developed to investigate the factors affecting the performance of this regenerator. As shown in figure Figure1 the main components of the regenerator are composed of packed tower, solar boiler, weak desiccant storage tank, and circulating pumps.

After the system was assembled, all the reading instruments were put in their specified positions, and all the electrical connections were ready, the system was turned on gradually in the following steps: The regeneration water temperature was checked at the solar boiler to range from 80C to 90 C. The weak liquid desiccant level in the storage tank was checked to be enough for the desiccant closed cycle operations. The regeneration water pump P4 was turned on to heat the finned tube radiator before the weak desiccant was sprayed for regeneration process. The weak desiccant pump P3 was turned on at the same time with the regenerator fan at medium speed to avoid the carryover problem of TEG which is one of the disadvantages of the Triethylene Glycol.

After the above 4 steps were completed successively, data records were taken at 10 to 15 minutes time interval. The readings during the experiment included the following: Air inlet temperature, relative humidity, and flow rate for the regenerator. Regeneration water inlet temperature, outlet temperature and flow rate. Weak desiccant inlet temperature, outlet temperature and flow rate. Air outlet temperature, the relative humidity, and flow rate from the regenerator packing fins.

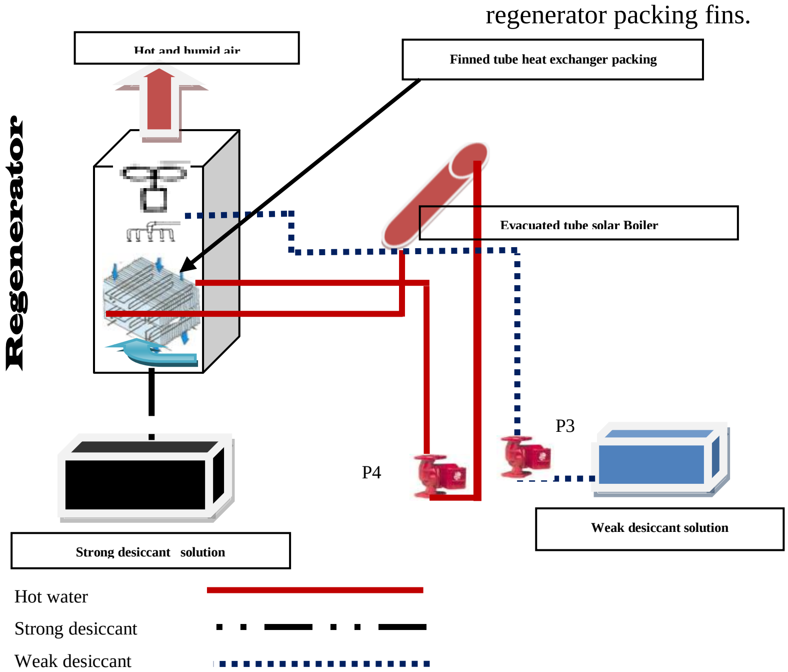


Fig (1). Schematics of experimental setup

3. Instrumentation

The following measuring instruments were used to read the data. The basic independent variables to measure the regenerator are inlet & outlet temperatures of air, water, and liquid desiccant, Flow rate of air, water, and liquid desiccant, inlet and outlet relative humidity of air, and the concentration of the liquid desiccant. The inlet, outlet temperature and relative humidity of the regenerator were measured by KOBOLD AFK-E Humidity/Temperature meter (made by KOBOLD Instruments Inc – Germany). This meter operates in the range of (0-100% for relative humidity and (-40 to +180 C) for temperature. with RTD metal probes 3 meters long, and digital readout display at the end. The inlet and outlet air flow rate of the regenerator were measured by a portable digital anemometer CFM Master 8901 Vane Digital Anemometer (obtained from Omega Engineering). It measures volume flow rate, air velocity, free area, and Temperature. The inlet and outlet temperature for the regeneration hot water were measured by a digital thermometer (made by P&M China). This thermometer operates in the range of (0 to +100 C) with RTD metal probes 2 meter long at the end and digital display reading. The inlet and outlet temperatures for weak desiccant were measured by a digital thermometer (made by P & M China), operate in the range of (0 to +100 C) with 1 meter RTD metal probes at the end and digital display reading. The flow rate for regeneration water was measured by flow meters (made by AMI). It operates in the range of (0 to +130) liter per minute. The flow rate for weak desiccant was measured by flow meters (made by Blue White Industries CADADA), operate in the range of (0 to +280 LPM) liter per minute. The flow rate control of the, regeneration water, and the weak desiccant during the experiments are done via valves fixed after each of the four pumps P3, and P4. The air flow rate control in the regenerator was done by adjustable speed switch made by FILUX. The TEG concentration was determined by a calibrated refractive index meter.

4. Theoretical Analysis

In the regeneration process, the vapor pressure in the liquid should be higher than the vapor pressure in the air so that the water can evaporate from the desiccant to the air. Therefore, as the liquid vapor pressure increases with desiccant temperature, the potential for heat and mass transfer increases. The hot water from the solar boiler was used to heat the liquid desiccant as it flows down and passes through the fins of the internally heated packing.

The concentration of the outlet desiccant solution is an essential criterion for assessing the performance of the regenerator, whether this concentration approaches that of the initial solution flowing into the dehumidifier is the core of this issue. As a result, a parameter is needed to measure the extent to which the weak desiccant solution is regenerated. The performance of the regenerator was evaluated by calculating the column effectiveness, enthalpy effectiveness and the moisture removal rate in the regenerator.

The regeneration effectiveness ε_y is defined as the ratio of the actual change in moisture content of the air stream to the maximum possible change in its moisture content under a given set of operating conditions. Thus the regeneration effectiveness ε_y can be expressed as:

$$\varepsilon_y = \frac{Y_{out} - Y_{in}}{Y_{equ} - Y_{in}} \qquad (1)$$

Where Y_{in} and Y_{out} are the absolute humidities of the air at the inlet and outlet conditions, respectively, and Y_{equ} is the absolute humidity of the air at equilibrium with the desiccant solution (TEG) at the desiccant inlet concentration and temperature. For counterflow configuration in a packed bed, the maximum achievable difference in the air humidity is obtained when the outlet air is in equilibrium with the inlet desiccant solution (the top of the packed bed). In this case, the air leave the regenerator with the equilibrium humidity ratio Y_{equ} that would be obtained when the partial pressure of water in the air is equal to the vapor pressure of the inlet desiccant solution, i.e., when the driving force for mass transfer is zero. Hence, the equilibrium humidity ratio is a function of the inlet desiccant solution vapor pressure, and thus is a function of the inlet desiccant solution temperature and concentration.

$$P_{vap.air.out} = P_{des.in} \quad = f\left(T_{des}, X\right) \qquad (2)$$

The Antoine equation is one of the most popular equations for predicting the vapor pressure of the TEG desiccant solution and is usually correlated as:

$$Log_{10}\left(P_{sol}\right) = A - \frac{B}{T + C} \qquad (3)$$

Where A,B,&C are constants depending on the liquid desiccant temperature and concentration. The equilibrium humidity ratio Y_{equ} of air in contact with TEG solution is given by the perfect gas relation as follows :

$$Y_{equ} = 0.62185 \frac{P_{sol}}{P_{atm} - P_{sol}} \qquad (4)$$

The rate of moisture removal from the air (water evaporation rate) was calculated from the following relation:

$$\dot{m}_{evap} = (Y_{out} - Y_{in}).A$$

Where A is the column cross-sectional area.

Table (1). Triethylene Glycol Antoine Constants for calculating Vapor Pressure

Triethylene Glycol Antoine Constants for Calculating Vapor Pressure
3-Constant Antoine Equation $\text{Log}_{10}(P) = A - B/(T + C)$
P = mm Hg, T = °C

TriEG, Wt%	A	B	C
0	7.959199	1663.545	227.575
50	7.922294	1671.501	228.031
70	7.878546	1681.363	228.237
80	7.837076	1697.006	228.769
90	7.726126	1728.047	229.823
95	7.620215	1806.257	236.227
97	7.495349	1841.522	238.048
98	7.404435	1881.474	240.666
99	7.211145	1926.114	242.799
99.5	7.042989	1970.802	242.865
100	7.472115	2022.898	152.573

5. Results and Discussion:

The results obtained in this study are presented in figs. 2-4

5.1 The effect of inlet Air flow rate:

The variations of moisture removal rate, regenerator effectiveness, and enthalpy effectiveness as a function of the air flow rate are shown in **Fig2 (a), Fig3.(a), and Fig4 (a)** respectively. The figures indicated that moisture removal rate increased with increasing air flow rate, while regenerator effectiveness, and enthalpy effectiveness are decreased. The increase of moisture removal rate is due to the better contact between the air and the liquid desiccant which increases the mass transfer coefficient between the air and desiccant. The decrease of regenerator effectiveness and the enthalpy effectiveness was due to decrease of air outlet humidity ratio, Y_{out} (equation (1) which is due to the decrease of air stayed time within the regenerator while increasing air flow rate.

5.2 Effect of inlet Air humidity ratio

The influence of air inlet humidity ratio on the regenerator performance is shown in **Fig2 (b), Fig3.-(b), and Fig4 (b)** respectively. Moisture removal rate decreases with increasing the inlet humidity ratio, while regenerator effectiveness, and the enthalpy effectiveness are increasing with increasing air inlet humidity ratio. In fact, an increase in air inlet humidity ratio caused a decrease in the mass transfer potential within the regenerator, and hence a decrease in moisture removal rate although air outlet humidity ratio increased. The increase of both air inlet and outlet humidity ratio led to increase of regenerator effectiveness and enthalpy effectiveness.

5.3 Effect of desiccant flow rate:

Moisture removal rate ,regenerator effectiveness and enthalpy effectiveness are increased with increasing desiccant flow rate, as shown in **Fig2.(c), Fig3.(c), and Fig4.(c)** respectively. When the desiccant flow rate was increased, there would be a good wetting area, and hence a good contact area between air and desiccant which will enhance the heat and mass transfer. When the contact was enhanced, more water vapor would be released and thus increasing Y_{out}. This would also lead to an improvement in the regenerator effectiveness and enthalpy effectiveness.

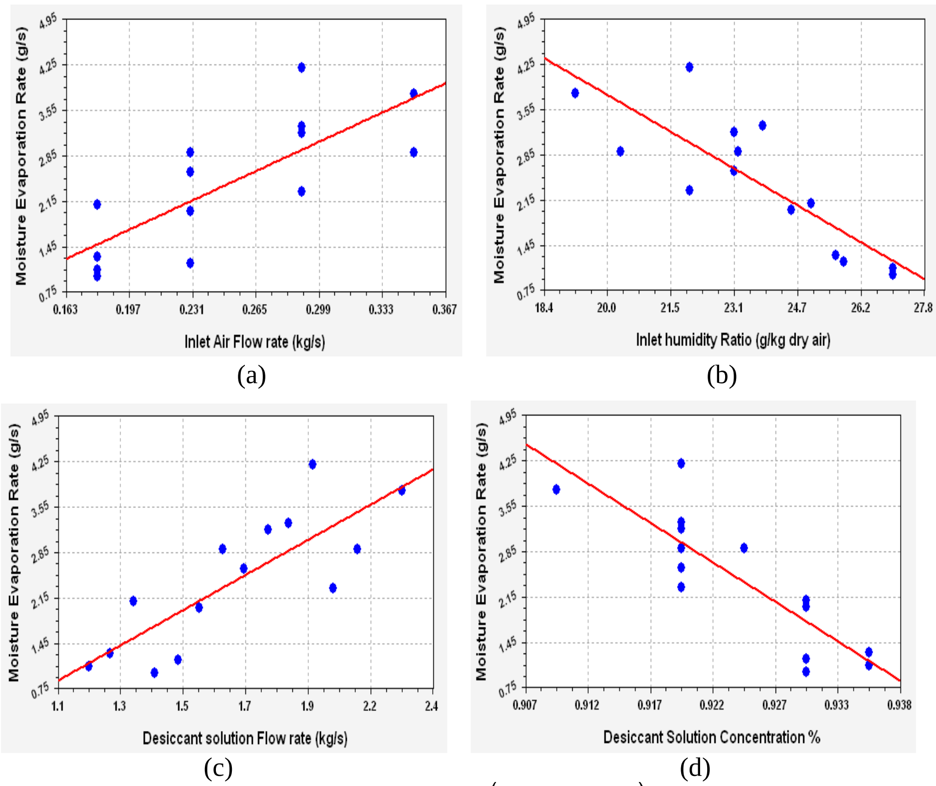
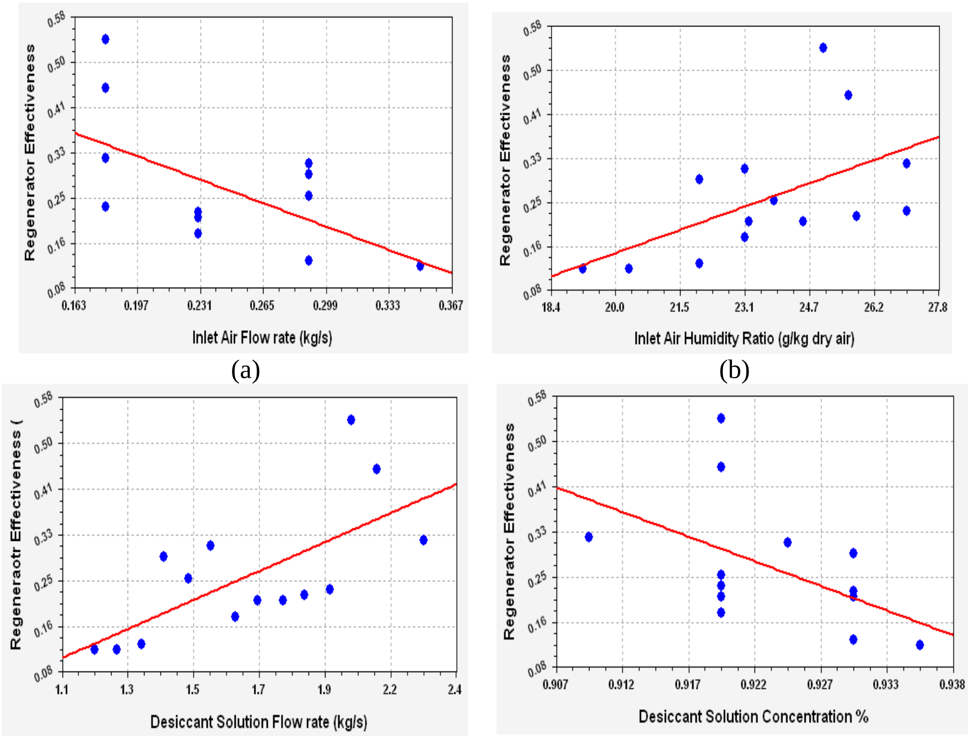


Fig (2). The moisture evaporation rate $\left(m_{evap}(g/s)\right)$ versus inlet variables:

(a) Inlet air flow rate (kg/s) (b) Inlet air humidity ratio (g/kg dry air)
(c) Desiccant solution flow rate (kg/s) (d) Desiccant solution concentration (%)

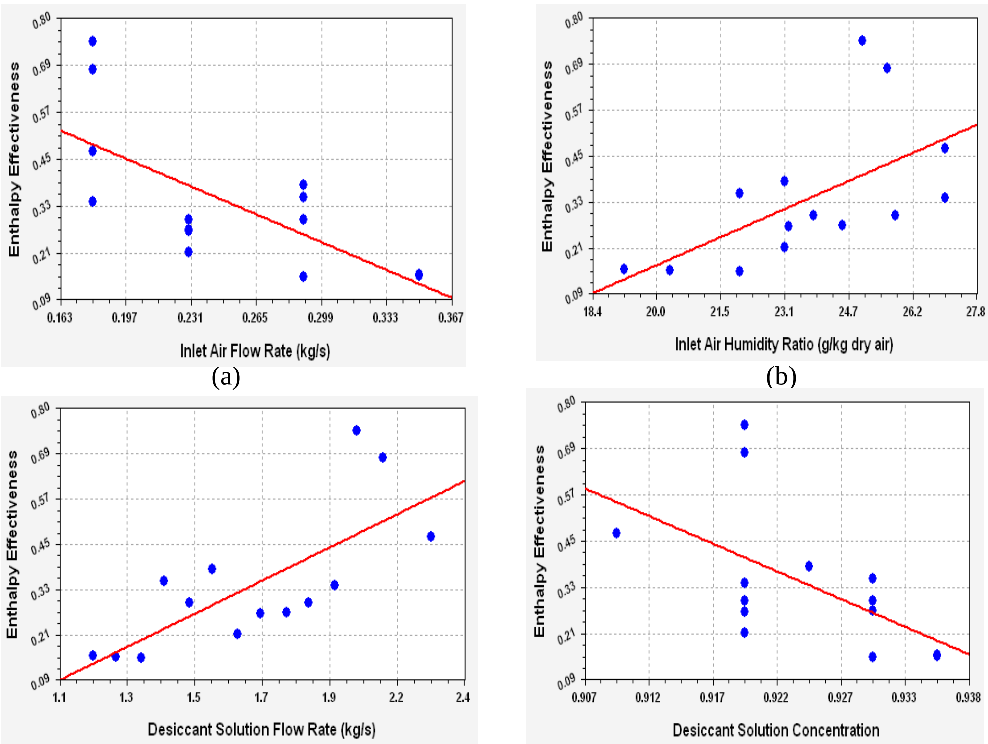


(a) (b)

(c) (d)

Fig (3). The Regenerator Effectiveness (ε_y) versus inlet variables:

(a) Inlet air flow rate (kg/s) (b) Inlet air humidity ratio (g/kg dry air)
(c) Desiccant solution flow rate (kg/s) (d) Desiccant solution concentration (%)



(a) (b)

(c) (d)

Fig. (4) The Dehumidifier Effectiveness (ε_h) versus inlet variables:

(a) Inlet air flow rate (kg/s) (b) Inlet air humidity ratio (g/kg dry air)
(c) Desiccant solution flow rate (kg/s) (d) Desiccant solution concentration (%)

5.4 The effect of desiccant inlet concentration

The effect of desiccant inlet concentration on the regenerator performance is shown in **Fig2.(d), Fig3.(d), and Fig4.(d)** respectively. The figures showed that the moisture removal rate, the regenerator effectiveness, and the enthalpy effectiveness are decreased with increasing desiccant inlet concentration. This may be explained as follows. Increasing desiccant inlet concentration decreases desiccant surface vapor pressure and so decreases the mass transfer potential within the regenerator, which leads to lower air outlet humidity ratio and hence lower moisture removal rate. Air outlet humidity ratio and desiccant inlet equivalent humidity ratio both decreases with increasing desiccant inlet concentration, and hence the regenerator and enthalpy effectiveness decreases.

6. Conclusions:

The performance of an internally cooled TEG liquid desiccant regenerator was investigated experimentally in this study. The results showed that the moisture evaporation rate increase as inlet air and desiccant flow rate increased. But it decrease as inlet air humidity ratio and desiccant concentration increase. The results also showed that the regenerator and enthalpy Effectiveness increase as inlet humidity ratio and inlet desiccant flow rate increased. But the regenerator and enthalpy effectiveness decrease as the inlet air flow rate and desiccant solution concentration increased. These results are in good agreement with those published by others.

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