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Experimental Investigation of Moisture Removal Rate and Dehumidification Effectiveness of an Internally Cooled Liquid Desiccant Air Dehumidifier

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Abstract: Dehumidifier is the most important part in liquid desiccant air conditioning systems. Internally cooled air dehumidifier was found to have better heat and mass transfer performance than the adiabatic one. This paper experimentally studies the performance of an internally cooled dehumidifier using Triethylene Glycol as a desiccant. During the experimental investigation, the dehumidifier inlet parameters, including air flow rate, humidity ratio, temperature, desiccant flow rate, and temperature are varied. The effect of these variables on the moisture condensation rate and dehumidifier effectiveness was studied. It is found that the moisture condensation rate increases with increasing the inlet air flow rate, inlet air humidity ratio, desiccant flow rate, and desiccant solution concentration. While the dehumidifier effectiveness increases with increasing desiccant flow rate and concentration. The dehumidifier effectiveness decreases with increasing inlet air flow rate and humidity ratios.

Keywords: Liquid desiccant; Dehumidifier; Moisture removal rate; Dehumidifier effectiveness.

1. INTRODUCTION

Liquid desiccant air conditioning systems are used as an alternative to the conventional vapour compression systems. The characteristic of these systems is that the electrical energy consumption can be reduced [1,2]. Thus, there is potential for cost savings by using desiccant cooling, especially in applications where the latent cooling load comprises a large portion of the total cooling load. For example, Burns *et al.* [3] found that utilizing desiccant cooling in a supermarket reduced the cost of air conditioning by 60% compared to conventional vapor compression system. Therefore, research leading to reliable, energy efficient, and cost effective desiccant system is highly acknowledged.

Desiccant dehumidifier is a device that employs a desiccant material to produce dehumidification effect. One of the most efficient types of dehumidifiers is the inner cooled dehumidifier using cooling coils to remove the heat generated from dehumidification. Yoon *et al.* [4] used a dehumidifier with one channel flowing air and desiccant solution and another channel flowing cooling water from the cooling tower. Khan and Sulsona [5] selected the apparatus that used by Yoon, except that the cooling water is replaced by refrigerant in their hybrid system to realize the dehumidification of the process air and gave the profiles of humidity and temperature of the process air, the concentration and temperature of the desiccant solution, as well as the quality of refrigerant in the cooling coil. An air dehumidifier where the air is brought in contact with a desiccant (TEG) film falling over a finned tube heat exchanger was analyzed by Peng and Howell [6]. Chebbah [7] presented results from performance modeling of a finned tube coil desiccant air contactor operating at nearly isothermal conditions. In the dehumidifier, for a given desiccant flow rate, a larger number of coil rows decreased the outlet air humidity ratio and temperature. Increasing the desiccant flow rate also decreased the outlet air humidity ratio. However, the outlet temperature increased. Hence, for a specific number of rows, the leaving air enthalpy as a function of liquid flow rate was found to have a minimum value. Increasing the cooling water flow rate and lowering the cooling water temperature resulted in cooler and dryer air leaving the dehumidifier. Both temperature and humidity of the air leaving the dehumidifier increased with increasing inlet desiccant temperature. A larger inlet desiccant concentration resulted in a lower humidity of the air leaving the dehumidifier. Jain *et al.* [8] experimentally tests the performance of the internally cooled dehumidifier, in which the flow direction of air is parallel to desiccant. LiBr aqueous solution is taken as liquid desiccant and cooling water from cooling tower is used as cooling fluid to cool the desiccant in a counter-flow direction. Kessling *et al.* [9], Zhang *et al.* [10], Zhao [11] and Saman *et al.* [12] tested the similar flow-pattern dehumidifiers, in which the flow direction of air is counter-current to desiccant and the flow direction of cooling fluid is cross- flow to desiccant.

Lowenstein *et al.* [13] experimentally tests the performance of a kind of cross-flow dehumidifier, in which the cooling water is in parallel to the desiccant. Khan [14] established the heat and mass transfer model of internally cooled dehumidifier, which air is in cross-flow to the desiccant and the cooling water is also in cross-flow to the desiccant. Several important parameters which strongly influenced the dehumidifier performance are identified based on numerically solved two- dimensional steady state model. One-dimensional difference equations are used by Ren *et al*. [15]. Wu *et al.* [16] described heat and mass transfer performance in the internally cooled dehumidifier with parallel/counter-flow configurations.

This paper aims at investigating experimentally, the performance of an internally cooled dehumidifier using Triethylence Glycol (TEG) as a desiccant. The effects of the dehumidifier inlet parameters such as air flow rate, air humidity ratio, desiccant flow rate, and desiccant concentration on the performance of the dehumidification process are studied. The performance of this process is evaluated in terms of moisture condensation rate and dehumidification effectiveness.

2. INSTRUMENTATION

The inlet, outlet temperature and relative humidity of the dehumidifier were measured by KOBOLD AFK-E Humidity/Temperature meter (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 dehumidifier were measured by a portable digital anemometer CFM Master 8901 Vane Digital Anemometer (Omega Engineering, UK). It measures volume flow rate, air velocity, free area, and Temperature. The inlet and outlet temperature for cooling water were measured by a digital thermometer (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 temperature for strong desiccant were measured by a digital thermometers (P&M, China), operate in the range of (0 to +100 C) with 1 meter RTD metal probes and digital display reading. The flow rate for cooling 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 strong were measured by flow meters (Blue White Industries, Canada), operate in the range of (0 to +280 LPM) liter per minute. The flow rate control of the cooling water and strong desiccant during the experiments are made via valves fixed after each of the four pumps. The air flow rate control in the dehumidifier and cooling tower is made by adjustable speed switch made by FILUX. The TEG concentration was determined by a calibrated hand refractometer (ATAGO, China) it has operative range of (1.445- 1.52).

3. EXPERIMENTAL SETUP

Figure 1 shows the schematic diagram of the system used in this research. The whole system was fabricated in the AlGhaya electromechanical workshop, Khartoum, and assembled on the roof of the Northern Building of the Faculty of Engineering, University of Khartoum. The dehumidifier composed of packed tower, intake–inlet air ducts, cooling tower, strong desiccant storage tank, and circulating pumps. The system uses a 95% Triethylene Glycol (TEG) solution as desiccant. The TEG solution was distributed uniformly over the heat exchanger. The solution passes through the fins of

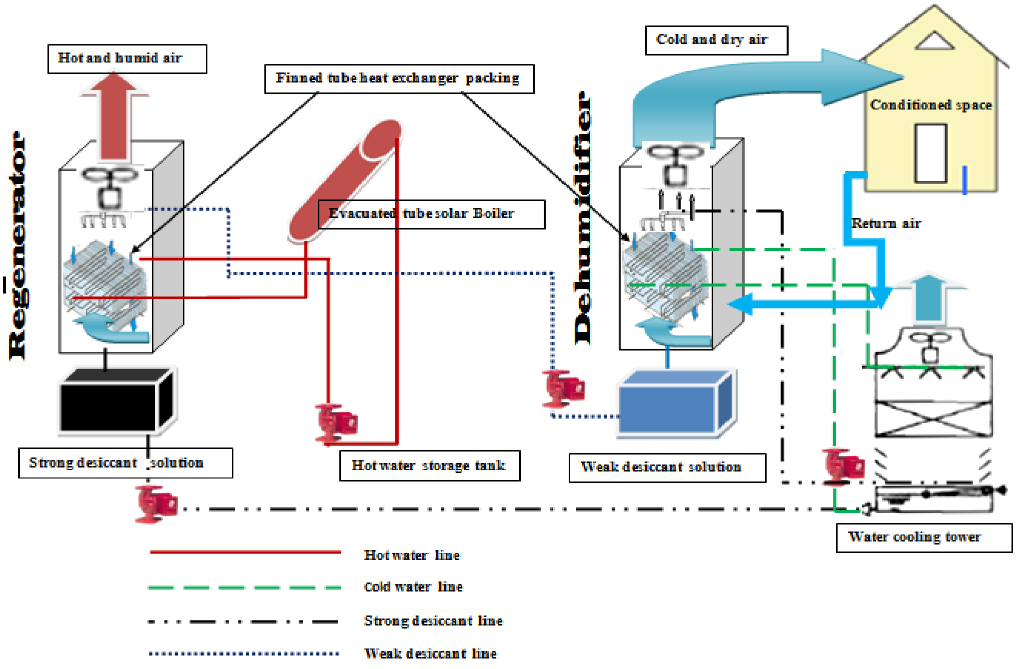

Fig. 1. Schematic diagram of the experimental setup

a plate heat exchanger which holds cold water from the cooling tower by the cold water pump. The solution cools as a result of passing through the fins and is sprinkled down in a laminar flow configuration. The process fresh air, which was drawn by the axial fan enter from the bottom of the vertical section of the dehumidifier in a counter manner to the desiccant flow and flows over the cold surface of the heat exchanger fins. The contact between the humid air under a high vapor pressure and the cold desiccant solution under very low vapor pressure drives the water vapor from the air to the desiccant solution. In addition, cooling of the air occurs due to the contact with the cold solution. The final result of the activity in this section is that the air is dehumidified and cooled down before it is supplied to the conditioned space. The diluted desiccant is circulated to a regenerator which uses hot water from a solar boiler. The hot concentrated desiccant is cooled to a certain temperature by passing it through the cooling water tank before distributing it again over the finned tube heat exchanger. The desiccant temperature and concentration were measured before running each experiment.

4. CALCULATIONS

The performance of the dehumidifier and the regenerator were evaluated by calculating the column effectiveness and moisture condensation rate in the dehumidifier. The column efficiency (dehumidification effectiveness, ε_y) is an air-side characteristic parameter which is related to the mass transfer effectiveness during the dehumidification operation. The effectiveness 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 dehumidifier effectiveness εy can be expressed as:

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

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 dehumidifier with an equilibrium humidity ratio Y_{equ} which 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 it is the function of the inlet desiccant solution temperature and concentration.

$$P_{vap.air.out} = P_{des.in} \qquad (2)$$

The vapor pressure of the commercial liquid desiccant solutions were available as experimental data or predicted equations in the literature. Basically, the liquid desiccant solutions can be classified into aqueous inorganic salt solutions of LiCl, LiBr, and CaCl2, and into aqueous organic solutions of glycols. The experimental vapor pressures of inorganic salt solutions are available in the literature. The vapor pressures of organic salt solutions are available in reports of the Dow Chemical Company [17] (see Fig. 2 and Table 1). 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:

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

where A,B, and C are constants depending on the liquid desiccant temperature and concentration. The vapor pressure (P) is in mmHg, and temperature (T) in C. Vapor pressure of the desiccant solution is an important property since its deference with air determines mass transfer. 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 condensation rate) was calculated from the following relation:

$$\dot{m}_{cond} = (Y_{in} - Y_{out}).A \qquad (5)$$

where A is the column cross-sectional area

5. RESULTS AND DISCUSSION

5.1 The Effect of Air Flow Rate

The variations of moisture condensation rate and dehumidifier effectiveness as a function of the air flow rate are shown in Fig. 3 and 4, respectively. The figures show the effect of air flow rate on moisture condensation rate and dehumidifier effectiveness of air. A higher air flow rate will move the dehumidified air more rapidly away from the interface, this reducing the humidity gradient between the solution and the air stream at the interface. It will enhance the mass transfer coefficient. However, a higher air flow rate means more air needs to be handled in the absorber, which will increase the air humidity ratio through the tower due to the reduced residence time (contact time)for the air in the dehumidifier. The equilibrium humidity of the solution tends to increase due to higher moisture removal. Higher mass transfer coefficient is not enough to remove all the increased moisture rates. This is because the humidity effectiveness decreases with the increase in the air flow rate. These results are consistent with those published in the literature.

5.2 The Effect of Inlet Air Inlet Humidity Ratio

The influence of air inlet humidity ratio on the dehumidifier performance are shown in Fig. 5 and 6. Moisture condensation rate increases with the increasing air inlet humidity ratio. In fact, an increase in air inlet humidity ratio caused an increase in the mass transfer potential within the dehumidifier, and hence an increase in moisture condensation rate is witnessed

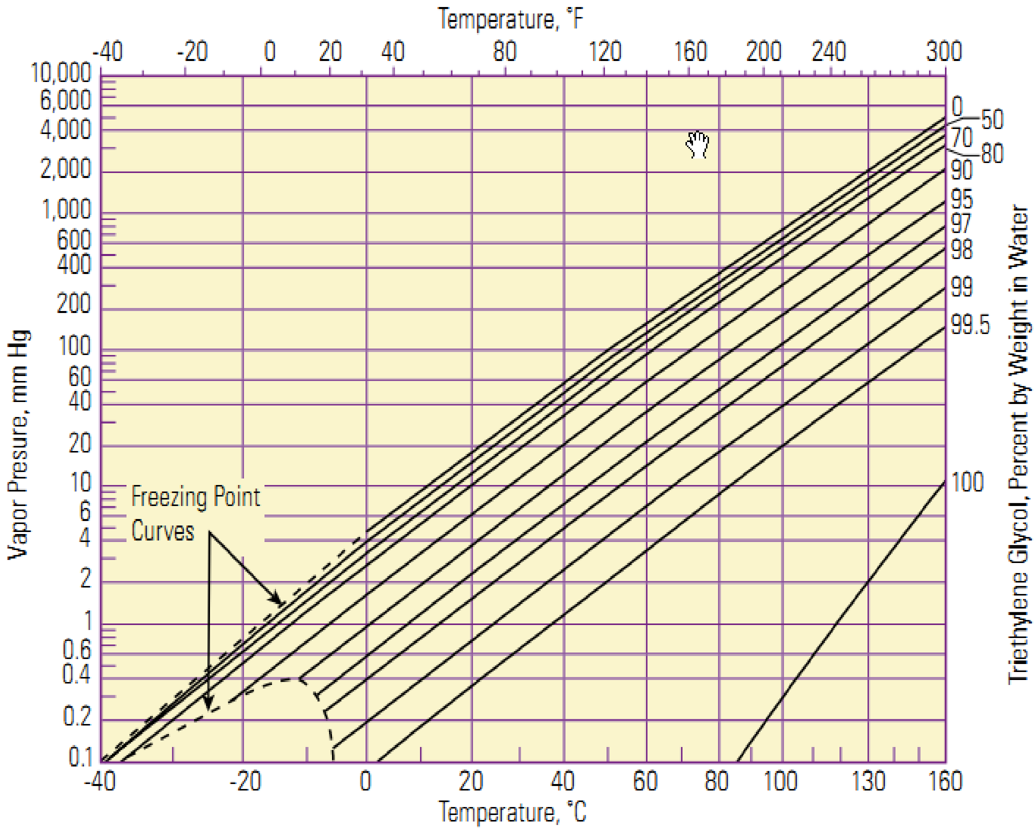

Fig. 2. Vapor Pressures of Aqueous Triethylene Glycol Solution [17]

Table 1. Triethylene Glycol Antoine Constants For Calculating Vapor Pressure

Triethylene Glycol Antoine Constants for Calculating Vapor Pressure 3-Constant Antoine Equation $Log_{10}(P) = A - B/(T + C)$ 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

Source : Ref. [17]

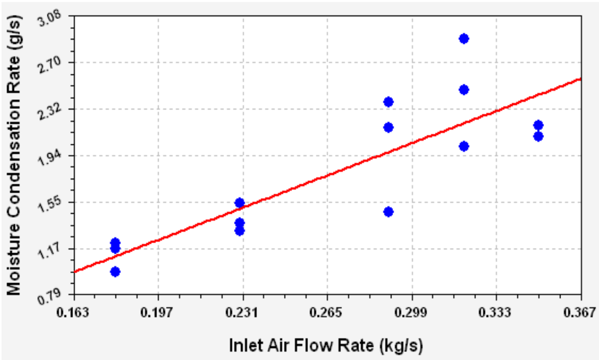

Fig. 3. The effect of air flow rate on the moisture condensation rate

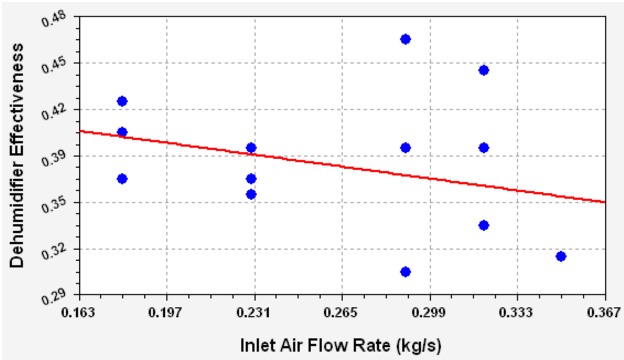

Fig. 4. The effect of air flow rate on the dehumidifier effectiveness ε_y

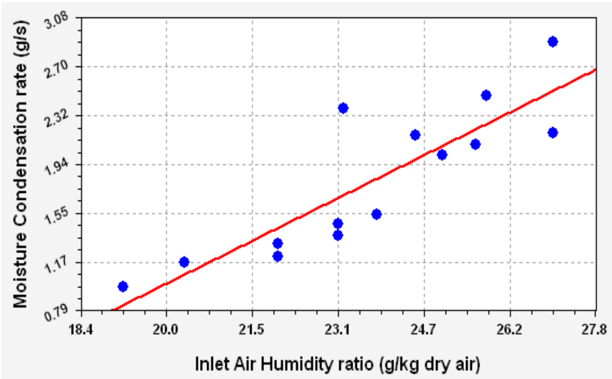

Fig. 5. The effect of inlet air humidity ratio on the moisture condensation rate

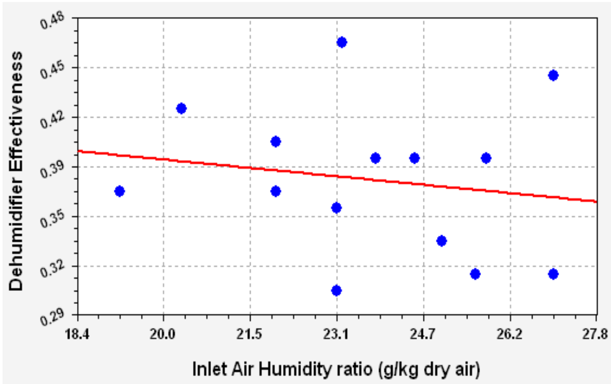

Fig. 6. The effect of inlet air humidity ratio on the dehumidifier effectiveness ε_y

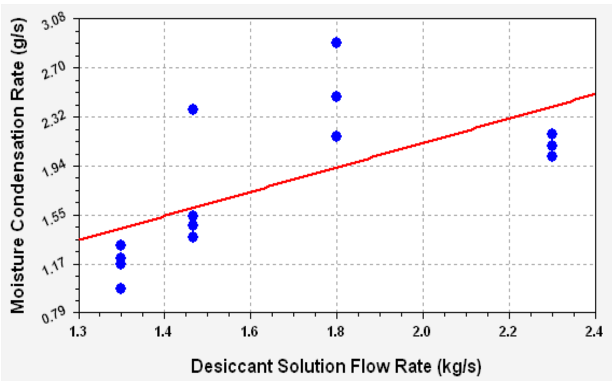

Fig. 7. The effect of desiccant solution flow rate on the moisture condensation rate

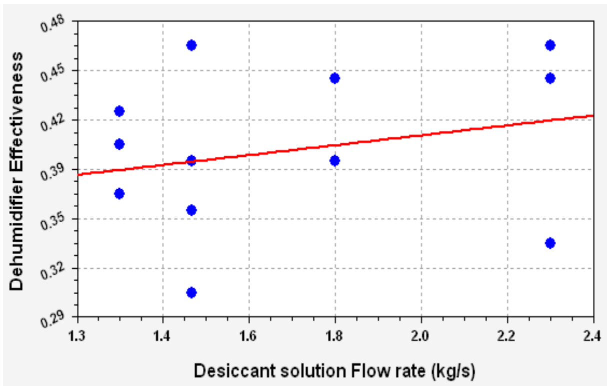

Fig. 8. The effect of desiccant solution flow rate on the dehumidifier effectiveness ε_y

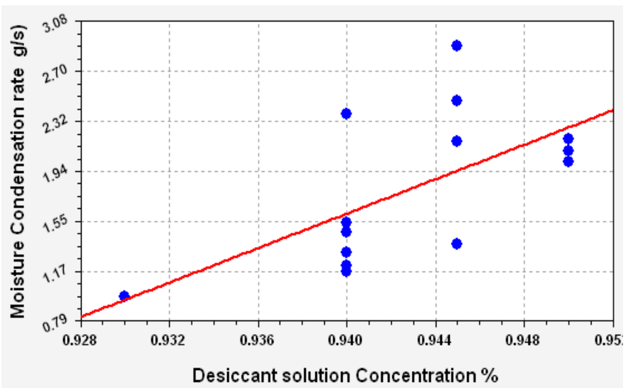

Fig. 9. The effect of desiccant concentration on the moisture condensation rate

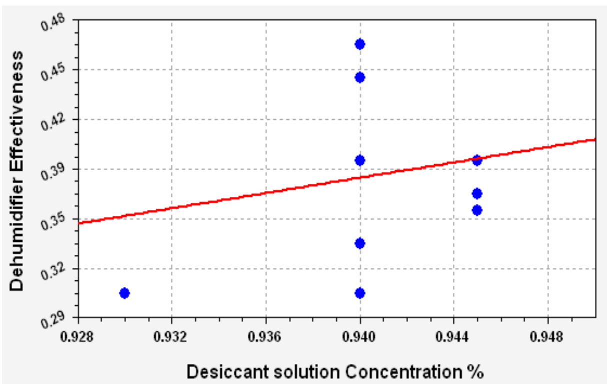

Fig. 10. The effect of desiccant concentration on the dehumidifier effectiveness ε_y

although the air outlet humidity ratio increased. The increase of both air inlet and outlet humidity ratio means increasing $(Y_{in} - Y_{out})$. But $(Y_{in} - Y_{equ})$ increase more, and this led to a decrease in the dehumidifier and enthalpy effectiveness.

5.3 Effect of Desiccant Solution Flow Rate

As shown in Figs 7 and 8 sensible cooling is enhanced when the flow rate of solution is increased. The reason for this is that the driving potential for heat transfer is greater when the temperature difference between solution and moist air remains high as a result of higher solution flow rate. Increasing solution flow rate results in a higher dehumidification rate. It is a fact that absorption heat is released during the dehumidification process. Because the lower solution flow rate yields a lower dehumidification rate, the absorption heat has little impact on the dehumidification rate when compared to the cooling load from the low temperature solution. The driving potential for the mass transfer is greater when the partial pressure difference of water vapor between the solution and the moist air remains high as a result of the higher solution flow rate. Increasing the desiccant flow rate increase the mass transfer coefficient between the desiccant and the air in the dehumidifier. Increasing the desiccant flow rate also increase the wetting area of the packing and, so, increased the mass transfer area. Based on the above aspects, increasing the desiccant flow rate increased the moisture removal rate and the dehumidifier effectiveness.

5.4 The Effect of Desiccant Inlet Concentration

Figs 9 and 10 show the effect of desiccant inlet concentration on the dehumidifier performance. The moisture removal rate and the dehumidifier effectiveness were increased significantly with increasing desiccant inlet concentration. This is because Increasing the desiccant inlet concentration decreased the desiccant surface vapor pressure and, as a result the average water vapor pressure difference between the desiccant and air in the dehumidifier increases, leading to lower air outlet humidity ratio and, hence, higher moisture removal rate. Both Y_{equ} and Y_{out} , in Eq. (1) decreases with increasing desiccant inlet concentration. But $(Y_{in} - Y_{equ})$ decreases more, and this led to an increase in the dehumidifier effectiveness.

6. CONCLUSIONS

The performance of an internally cooled TEG liquid desiccant dehumidifier was investigated experimentally in this study. The results showed that as the inlet air flow increased, the moisture condensation rate increased, coupled with a decrease in the dehumidifier effectiveness.

The same results were observed when the inlet air humidity ratio increased, the moisture condensation rate increased, with a decreasing, the dehumidifier Effectiveness. On the other hand, increasing the inlet desiccant flow rate and concentration increases both the condensation rate and the dehumidifier effectiveness. These results are found to be in consistent with findings of similar studies in the literature.

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Nomenclature

A	cross sectional area of dehumidifier (m^2)
F	Flow rate (kg/s)
M	water condensation rate (g/s)
P	Pressure (mmHg or kPa)
T	Temperature °C
X	Desiccant Concentration (kg TEG/kg solution)
Y	Air humidity ratio (kg water/kg dry air)
ε	Effectiveness (dimensionless)

Abbreviations

TEG	Triethylene Glycol

Subscripts

a	Air
atm	Atmosphere
des	Desiccant
equ	Equilibrium
in	Inlet
out	Out let
sol	Solution
vap	Vapor
y	Air humidity ratio