Effect of Temperature and Specific Humidity of the Air on Performance of Celdek Packed Liquid Desiccant Regenerator

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Abstract
Current paper presents experimental study of the effect of inlet process parameters of humid air on different output parameters of counter flow liquid desiccant regeneration system. Temperature and specific humidity are selected as inlet process parameters. Regenerator is the heart of liquid desiccant air cooling system. Celdek structured pads with packing density 390 m^2/m^3 as packing material and calcium chloride as liquid desiccant are used in the present research. Air and desiccant solution flow in counter flow direction with respect to each other. One parameter is varied at a time and others are kept constant. Different outlet parameters studied are outlet specific humidity, evaporation flow rate, outlet temperature of air, outlet temperature of solution and effectiveness of the regenerator. Variation of evaporation rate at average found is 51.86 % which is maximum increase among all output parameters. Decrease in solution output temperature obtained is 4.75 % with varying specific humidity of air.

Keywords: Desiccant; air; regenerator; celdek pads; specific humidity; effectiveness; evaporation flow rate; temperature.

1. INTRODUCTION

Desiccant regeneration is an important operation in liquid desiccant dehumidification systems. Several techniques are available for this operation, but liquid desiccant technology is mostly used because this technology is flexible in operation and it can treat inorganic and organic impurities present in the air (Oberg and Goswami, 1998). It can use a lower regeneration temperature from solar energy. Desiccant cooling technology is beneficial when Moisture level is high and confined control over moisture level is mandatory. When humidity is challenging to interior spaces in food stores (freezer case moisture), ice arenas (fogging) and hospitals (bacteria), desiccant systems are most useful. These systems have numerous profits comprising lower use of CFCs, improved indoor air quality, lower energy consumption, using renewable energy or waste heat. The performance of liquid desiccant dehumidification systems is studied by various researchers [Abdulghani et al., 2002; Abdul-Wahab et al., 2004; Jain et al., 2000; Liu et al., 2006; Moon et al., 2009; Patnaik et al., 1990; Zurigat et al., 2004; Salarian et al., 2011]. The performance of stand-alone liquid desiccant systems is studied by Ritunesh et al. (2009). Alosaimy (2013) has investigated novel configuration of solar powered desiccant dehumidification system.

Researchers (Elsarrag, 2006; Gandhidasan, 2005; Sultan et al., 2002) have worked to investigate the performance of regenerator. The effect of different operating parameters on the performance of regenerator of a structured packed regenerator using TEG is studied experimentally by

Elsarrag, (2006). Cellulose rigid pads are used as packing material and different layers are used in a zig-zag manner to diminish carryoverof TEG. Study of main components, dehumidifier and regenerator, is carried out by different researchers [Factor and Grossmann, 1980; Steven et al., 1989; Martin and Goswami, 2000; Fumo and Goswami, 2002; Bassuoni, 2011; Bakhtiar et al., 2012; Narayan et al., 2013; Zhao et al., 2014). A theoretical model is developed for a column with LiBr as desiccant solution by Factor and Grossman (1980). Bounzenada (2014) has presented an experimental study of dehumidification/regeneration processes using LiBr as liquid desiccant in direct contact with the air at different operating conditions. Rakesh and Asati (2016,17) also studied the effect of inlet parameters on the performance of celdek packed liquid desiccant absorber andregenerator.

Objective of the present paper is to investigate the effect of temperature and inlet specific humidity of air on different output parameters of structured packed regenerator using calcium chloride as a desiccant in counter flow with respect to the flow of air.

2. DESICCANT AND PACKING MATERIALS

Desiccant materials have great affinity toward moisture due to differences in vapor pressure. We are mostly aware with desiccants such as silica gel packages that are included with new electronics or textile products. These desiccants may be in the form of a solid or a liquid. Different types of packing materials and desiccants have been used by the researchers. Desiccants are selected based on their capability to grasp large quantities of water and ability to be reactivated. Solid and liquid desiccant are two main types of desiccants used in desiccant cooling systems. Liquid desiccants are more useful in comparison to solid desiccants. Liquid desiccants have several advantages over solid desiccants. The pressure drop through the liquid desiccant is lower than that through a solid desiccant system. Due to the, and thus, A number of small units can be coupled to meet demands of large buildings because liquid desiccant can be pumped from one nit to another. Liquid desiccants include TEG, calcium chloride, lithium chloride, lithium bromide, and their mixtures. Liquid desiccants can add or absorb moisture from air, depending on the vapor pressure difference between the desiccant solution and surrounding air. Structured pads with a specific surface area of 390 m^2/m^3, corrugated angle of 60° and calcium chloride solution as desiccant are used in air dehumidification system in a cross flow manner by Bassuoni (2011). Bouzenada (2014) has studied the mass transfer during the dehumidification and regeneration operation using hygroscopic material calcium chloride and calcium chloride dehydrates.

The Celdek pad comprises of particularly impregnated and corrugated cellulose paper sheets with 45^{o} flute angles are bonded together. These pads are self-supporting with great absorbance. Celdek pads have more advantages over other packings. These pads give high evaporation efficiency. Pressure drop through these pads in wet condition is very low as compared with other packings. Operating cost of these pads is also less. Drift carry over through these pads is negligible. These pads are strong and self-supporting and have long life time. It is very easy to install these pads. Celdek pads are also environment friendly.

Many researchers have worked with TEG as desiccant but only a limited research is available in which $CaCl_2$ has been used as desiccant. Bassuoni (2011) has explored the performance of structured packing desiccant dehumidifier in cross flow manner with calcium chloride as desiccant. Alosaimy (2013) has investigated novel configuration of solar powered desiccant dehumidification system. Combination of celdek pads as packing material and calcium chloride as liquid desiccant in counter flow direction has not ever been used by any researcher. So, $CaCl_2$ is chosen as a liquid desiccant because of its good characteristics as compared to other salt solution. Celdek packing is selected as desiccant-air-contact device for present investigations.

3. EXPERIMANTAL SET UP

The detail of experimental set-up used in this study for desiccant regeneration is shown in figure 1. The experimental set-up is fabricated in IET Bhaddal, Ropar, Punjab to study the hot and humid environment on north India. Present experimental set up has two separate desiccant solution tanks, a week solution tank connected to the top of the tower and another strong solution tank is used to collect desiccant at the bottom.

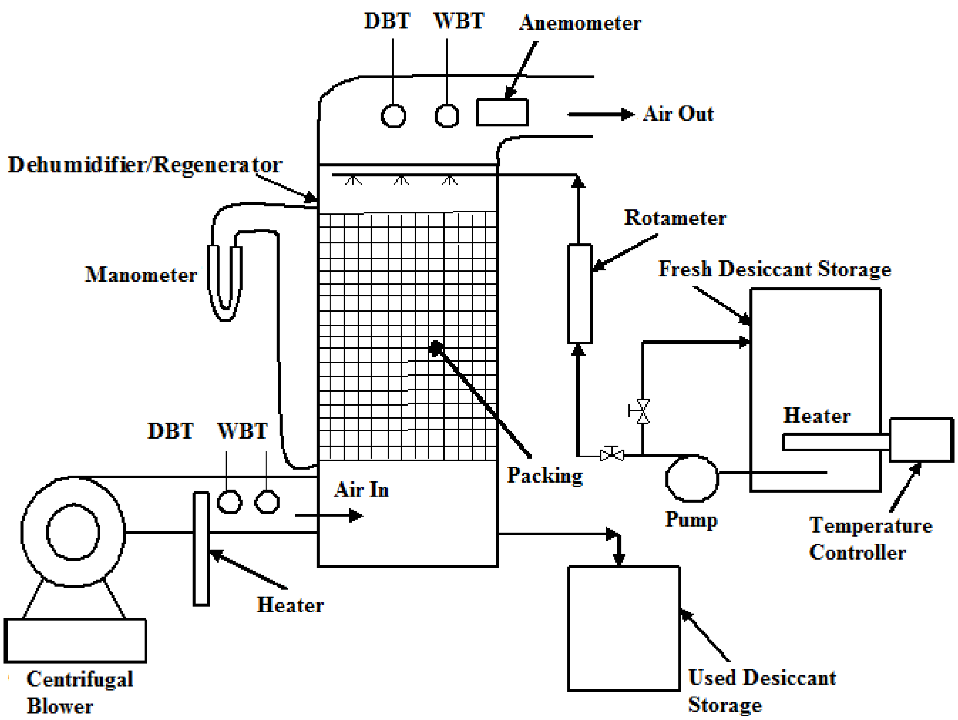


Fig-1: Schematic diagram of the experimantal set up

Regenerator with dimensions of $0.6 \times 0.3 \times 0.9$ m^3 is used in this experimentation. Hot air is introduced at the bottom of regenerator through the duct with the help of a centrifugal blower. Blower is attached with a variance to vary the flow rate of air in the regeneration system. A duct heater has been used to vary the temperature of inlet air. Digital temperature controller with RTD is attached in the solution tank to control the temperature and concentration of solution. Desiccant at the required temperature is pumped into the top of the packing through rotameter. Solution is distributed over the celdek packing with the help of a tray. Desiccant solution and hot air flow in counter clockwise direction with respect to each other. Vapour pressure of desiccant solution is more than of hot air in regeneration. So when desiccant solution comes into contact with hot air, evaporation of water takes place at the interface and concentration of solution increases and this is called regeneration process. The strong desiccant solution flows by gravity to the storage tank. A bypass system with the help of valve has been used to control the flow rate of solution in the regenerator. Excess solution is bypassed to the solution tank with this bypassed system.

Dry bulb and wet bulb air temperatures are measured with help of RTDs at the inlet and exit of the regenerator. Two more RTDs are used to measure the inlet and exit temperatures of desiccant solution. Range of RTDs is 0^oC to 100^oC and resolution is 0.1^oC. The flow rate of desiccant solution is measured with a calibrated rotameter with range 40 LPH to 500 LPH. The air flow rate is controlled with the help of centrifugal blower and measured with the help of a vane type portable digital anemometer. Concentration of desiccant solution is measured with hydrometer. Hydrometer with range 1.300 to 1.500 and accuracy of 0.001 is used to measure specific gravity of solution and it is converted to concentration by using tables of properties of solution from DOW's handbook of calcium chloride by Dow (2003). Specific humidity at inlet and outlet of regenerator is found out from psychrometric charts. Specifications of different measuring devices are given in table 1.

The experiments are run in different weather conditions in hot and humid outdoor conditions. The input process parameters for the study are mass flow rate of air, solution flow rate and concentration of desiccant. Different outlet parameters are outlet specific humidity, evaporation flow rate, outlet temperature of air, outlet temperature of desiccant solution and effectiveness of the regenerator.

Table-1: Measuring device specifications and accuracy

Device	Type	Accuracy	Operating Range
Thermometers	RTD	0.1^oC	$0\text{-}100^oC$
Flow meter	Rotameter	2 %	40-500 LPH
Anemometer	Vane	2 %	0.4-30 m/s
Hydrometer	Hand	0.001	1.300-1.500

4. PERFORMANCE PARAMETERS

The performance of the regenerator is assessed by the water evaporation rate and the regenerator effectiveness. Water evaporation rate is calculated from equation (1)

$$\dot{m}_{evap} = (\omega_o - \omega_{in}).\dot{m}_a \quad \text{………………………………………..1}$$

The regenerator effectiveness, ε, is defined as the ratio of the actual change in specific humidity of the air leaving the regenerator to the maximum possible change in specific humidity. It is expressed mathematically as:

$$\varepsilon = \frac{\omega_o - \omega_{in}}{\omega_{eql} - \omega_{in}} \quad \text{……………………………….. 2}$$

Where, ω_{eql} is equilibrium moisture contents of desiccant defined in terms of water vapour pressure (p_v) of desiccant solution at the given concentration and temperature as

$$\omega_{eql} = 0.62\frac{p_v}{p_{atm} - p_v} \quad \text{…………………………………………….3}$$

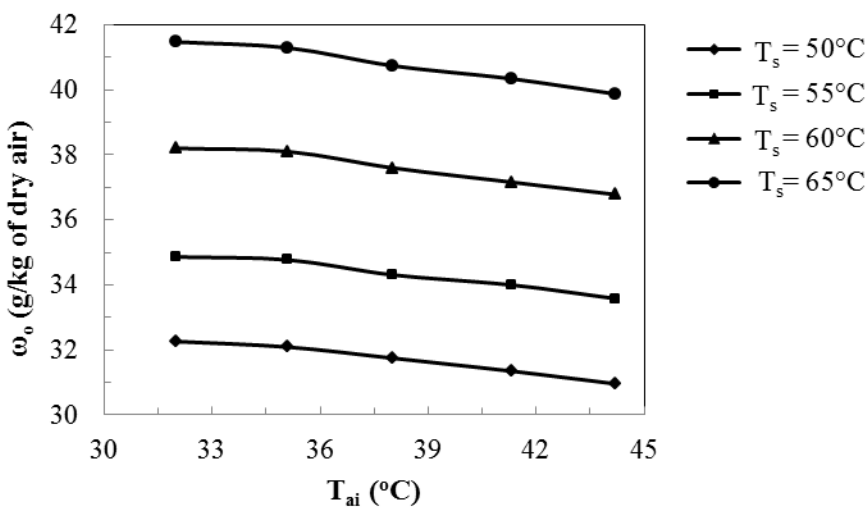
5. RESULTS AND DISCISSION

Regeneration temperature is varied from 50°C to 65°C with the increments of 5°C in reservoir during whole experimentation. Different outlet parameters are specific humidity at outlet, evaporation flow rate, air outlet temperature, solution's outlet temperature and effectiveness of the regenerator.

5.1. Effect of Inlet Temperature of Air

Figure 2 shows the graphs of the experimental variations of output parameters with respect to inlet temperature of air at different regeneration temperatures. As inlet temperature of the air is increased from 40.3°C to 42.3°C at constant regeneration temperature of 55°C to 65°C with an increment of 5°C, specific humidity at outlet of regenerator increases as shown by figure 2(a). With increase in air temperature, system temperature increases due to sensible heat transfer from air to desiccant and consequently temperature of desiccant solution increases. Vapour pressure of desiccant solution increases due to increase n temperature of desiccant. Vapour pressure difference between desiccant solution and air is driving potential for increase in mass transfer of the system and an increase in vapour pressure increases the evaporation rate as shown by figure 2(b). Outlet temperature of air decreases with increase in inlet temperature of air (fig. 2c) because evaporation produces cooling effects. Temperature of desiccant solution increases due to increase in heat transfer from air to desiccant solution as temperature of air is increased. Effectiveness of regenerator increases with an increase in inlet temperature of the air as shown in figure 2(e) because specific humidity of air at outlet of regenerator increases with increase in vapour pressure.

Similar trends are also observed, when air inlet temperature is increased from 55°C to 65°C with an increment of 5°C because as temperature of solution increases, vapour pressure further increases.



Fig,(a)

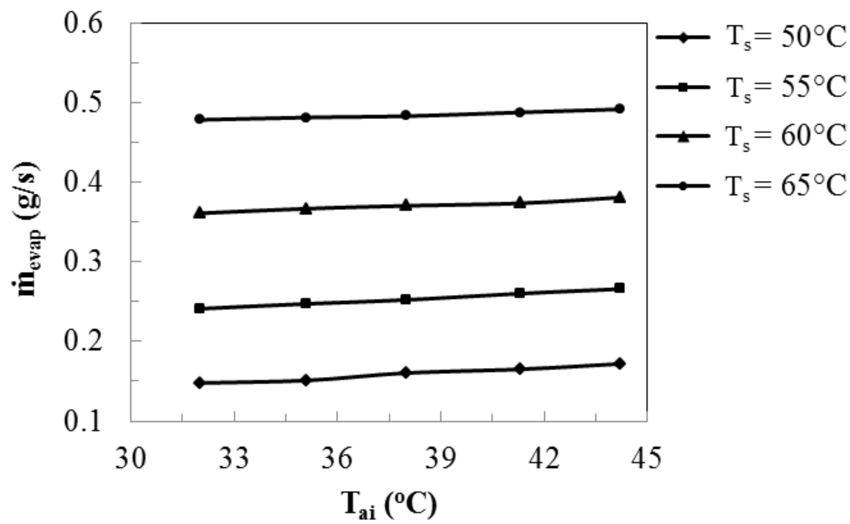
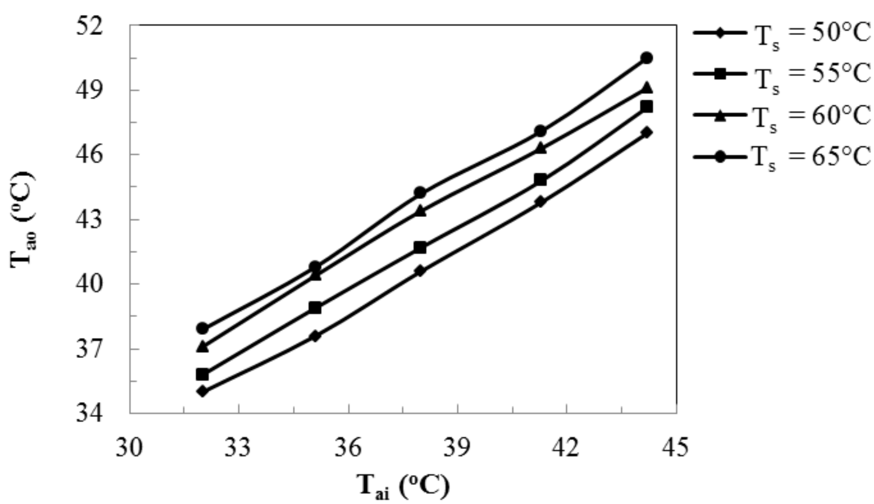

0.6
0.5
0.4
0.3
0.2
0.1
30
33
36
39
42
45
$\dot{m}_{evap}$ (g/s)
T_{ai} (°C)
T_s= 50°C
T_s= 55°C
T_s= 60°C
T_s= 65°C

Fig.(b)


52
49
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43
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33
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42
45
T_{ao} (°C)
T_{ai} (°C)
T_s = 50°C
T_s = 55°C
T_s = 60°C
T_s = 65°C

Fig.(c)

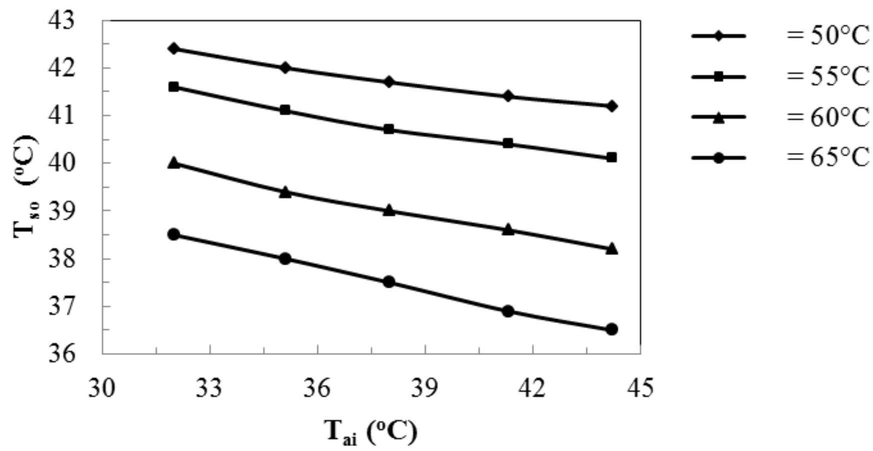


Fig.(d)

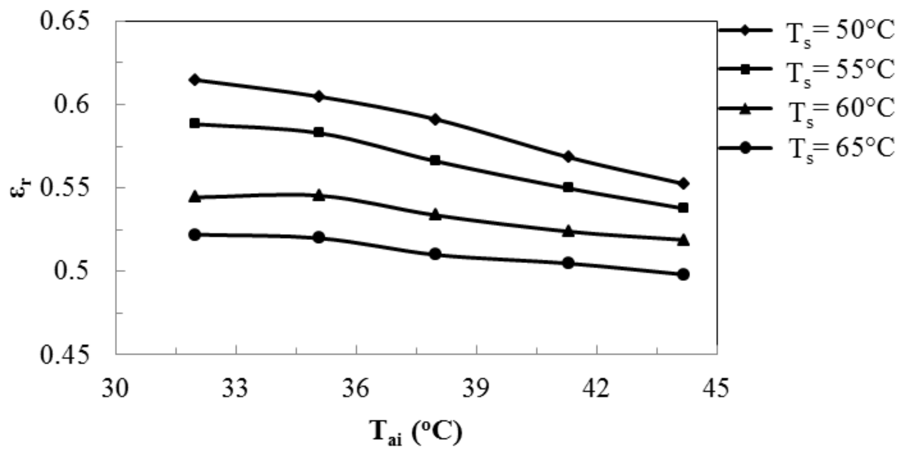


Figure 2. Effect of inlet temperature of air on effectiveness of regenerator

5.2. Effect of Inlet Specific Humidity of Air

Figure 3 shows the experimental variations of output parameters with respect to inlet specific humidity at different regeneration temperatures. As inlet specific humidity of the air is increased from 25.63 g/kg of dry air to 27.22 g/kg of dry air at constant regeneration temperature of 55^{o}C to 65^{o}C with an increment of 5^{o}C, there is increase in specific humidity at outlet of regenerator as shown in figure 3(a). With increase in inlet specific humidity, system temperature increases due to heat transfer between air and desiccant and consequently specific humidity of the system at outlet increases. For the given inlet concentration, higher the solution temperature, higher the vapour pressure on the solution surface. Vapour pressure difference between desiccant solution and hot air is the driving potential for the mass transfer of the system. Therefore, increase in vapour pressure increases the evaporation rate at slow rate as shown by figure 3(b).

Air outlet temperature and solution outlet temperature are inversely proportional to the inlet specific humidity as shown in figures 3(c-d). Air temperature slightly increases with the increase in inlet specific humidity and but this increase in air temperature is very less as compared with temperature of desiccant solution and in overall air outlet temperature decreases. Moderate decrease in output temperature of solution is due to the slight evaporation of water in the interface of air and desiccant solution.

Figure 3(e) shows the effect of inlet specific humidity of the air on the effectiveness of regenerator at constant regeneration temperature. Effectiveness increases with an increase in inlet specific humidity of the air. It is due to the reason that as inlet specific humidity of the air is increased, there is increase in outlet specific humidity of the air and it is responsible for increase in effectiveness of regenerator.

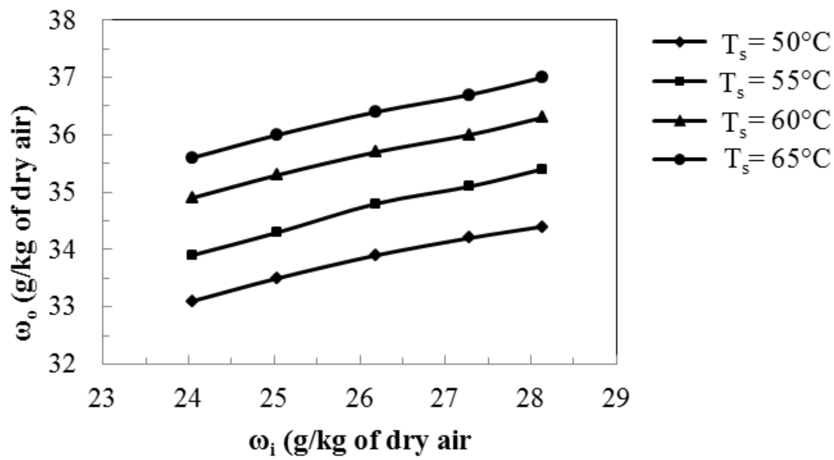


Fig.(a)

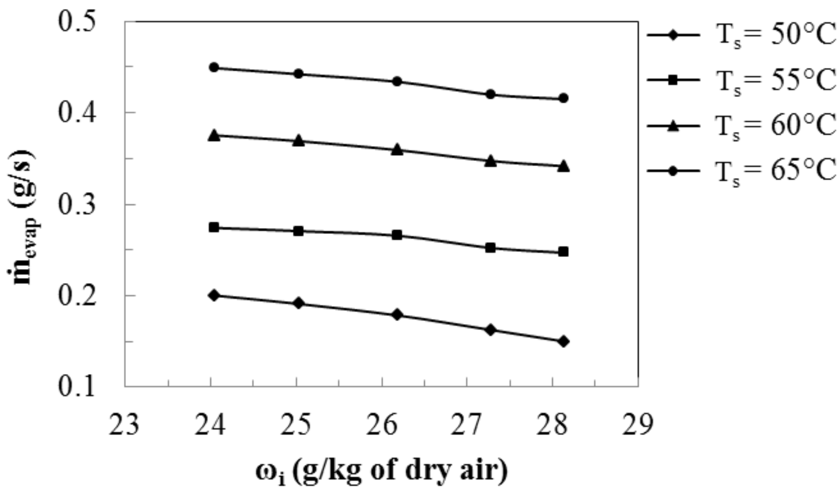


Fig.(b)

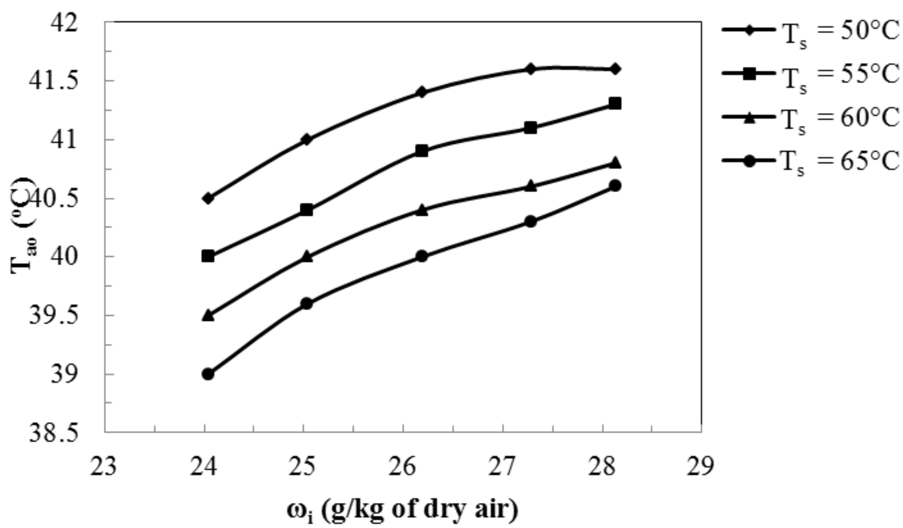
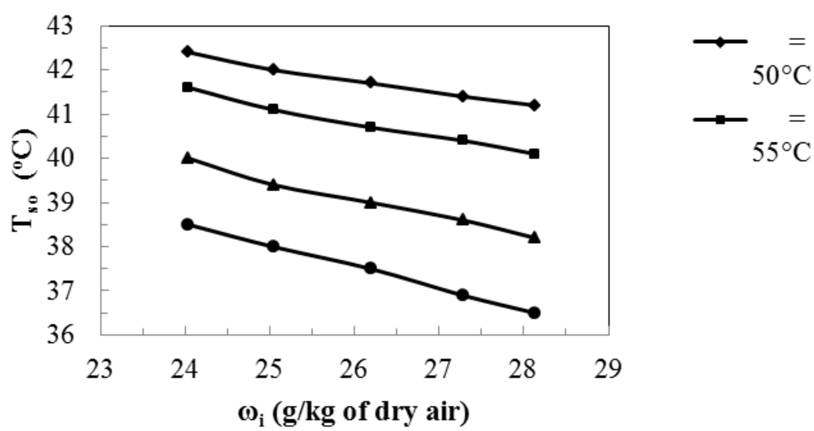

42
41.5
41
40.5
40
39.5
39
38.5
23
24
25
26
27
28
29
T_{ao} (°C)
ω_i (g/kg of dry air)
T_s = 50°C
T_s = 55°C
T_s = 60°C
T_s = 65°C

Fig.(c)


43
42
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T_{so} (°C)
ω_i (g/kg of dry air)
=
50°C
=
55°C

Fig.(d)

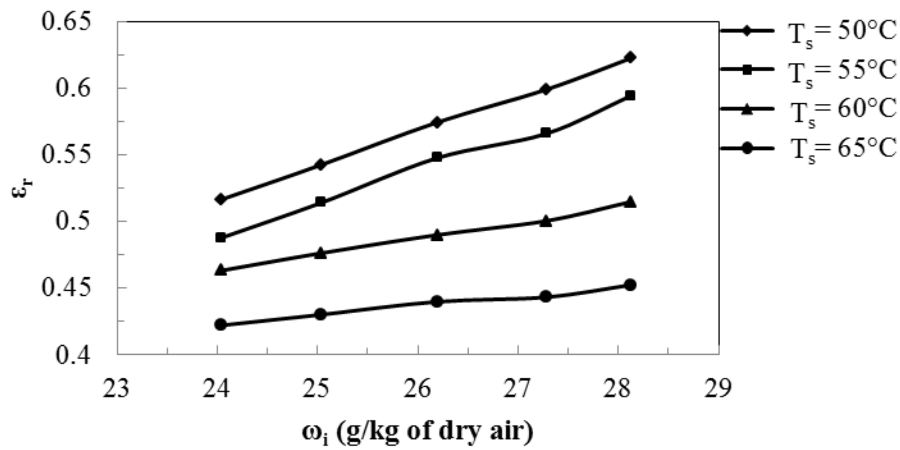

Fig.(e)

Figure 3. Effect of inlet specific humidity of air on effectiveness of regenerator

6. CONCLUSIONS

The effect of different operating parameters on various output parameters of a structured packed regenerator using calcium chloride as desiccant are investigated experimentally. Flow of the desiccant solution and hot air is kept in counter flow direction with respect to each other. Performance of the regenerator is studied in the form of specific humidity, water evaporation flow rate, outlet air temperature, outlet solution temperature and effectiveness of regenerator. Specific humidity of air, evaporation flow rate, solution temperature and effectiveness of regenerator increases by 11.69 %, 51.86 %, 4.75 % and 23.73 % respectively when temperature of air in increases while temperature of air at outlet decreases by 3.14 %. When inlet specific humidity of the air is increased, outlet specific humidity, evaporation flow rate and effectiveness inceases while tempearture of air and solution decreases. Decrease in outlet temperature of air and solution achieved are 3.12 % and 4.75 % respectively when specific humidity is increased by 5 %.

Nomenclature

A	Cross sectional area of regenerator [m^2]
C	Concentration of solution [kg of desiccant/kg of solution]
Cp	Specific heat of solution [kJ/kg.K]
h	Specific enthalpy [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
T	Temperature [^{o}C]

Subscripts

a	air
ai	inlet of air

ao	outlet of air
atm	atmospheric
eql	equilibrium
evap	evaporation rate
i,	inlet
o	outlet
s	solution
si	inlet of solution
so	outlet of solution
v	vapour

Greek letters

ω	Specific humidity [kg/kg of dry air]
ε	effectiveness

Abbreviations

$CaCl_2$	Calcium chloride
CFC	Chloro floro carbon
LiBr	Lithiam Bromide
LPH	Litre per hour
RTD	Resistance temperature detector
TEG	Tri ethylene glycol

REFERENCES

1. Abdulghani, A.A., Gandhidasan, P. and Al-Mutairi, M.A. (2002) 'Evaluation of heat and mass transfer coefficients in a gauze-type structured packing air dehumidifier operating with liquid desiccant', International Journal of Refrigeration, Vol. 25, pp. 330-339.
2. Abdul-Wahab, S.A., Zurigat, Y.H. and Arabi, A. (2004) 'Predictions of moisture removal rate and dehumidification effectiveness for structured liquid desiccant air dehumidifier', Energy, Vol. 29, pp. 19-34.
3. Alosaimy, A.S. (2013) 'Application of evaporative air coolers coupled with solar water heater for dehumidification of indoor air', International Journal of Mechanical & Mechatronics Engineering, Vol. 13, pp. 60-68.
4. Bakhtiar, A., Rokhman, F.C. and Kwang, H. (2012) 'A novel method to evaluate the performance of liquid desiccant air dehumidifier system', Energy and Buildings, Vol. 44, pp. 39-44.
5. Bassuoni, M.M. (2011) 'An experimental study of structured packing dehumidifier/regenerator operating with liquid desiccant', Energy, Vol. 36, pp. 2628-2638. DOI: 10.1016/J.Energy.2011.02.004.
6. Bouzenada, S., Salmon, T., Fraikin, L., Kaabi, A. and Leonard, A. (2014) 'Experimental study on mass transfer comparison of two liquid desiccants aqueous solutions'', Renewable Energy and Power Quality Journal, ISSN 2172-038X, No. 12.
7. Dow(2003), Calcium chloride handbook, Dow Chemical Company, Michigan, USA.

8. Elsarrag, E. (2006) ‘Performance Study on a Structured Packed Liquid Desiccant Regenerator’, Solar Energy, Vol. 80, pp. 1624-1631.
9. Factor, H.M. and Grossman, G. (1980) ‘A Packed Bed Dehumidifier/Regenerator for Solar Air Conditioning with Liquid Desiccants’, Solar Energy, Vol. 24, pp. 541-550.
10. Fumo, N. and Goswami, D.Y. (2002) ‘Study of an aqueous lithium chloride desiccant system: air dehumidification and desiccant regeneration’, Solar Energy, Vol. 72, pp. 351-361.
11. Gandhidsan, P. (2005) ‘Quick performance predictions of liquid desiccant regeneration in a packed bed’, Solar Energy, Vol. 79, pp. 47–55.
12. Ghadamian, H., Assadi, K.M. and Ataei, A. (2011) ‘An Experimental and modeling study of a dehumidification tower’, International Journal of the Physical Sciences, Vol. 6, pp. 2852-2860.
13. Jain, S., Dhar, P.L. and Kaushik, S.C.(2000) ‘Experimental studies on dehumidifier and regenerator of a liquid desiccant cooling system’, Applied Thermal Engineering, Vol. 20, pp. 253-67.
14. Kline, S.J. and McClintock, F.A. (1953) ‘Describing uncertainties in single sample experiments’, Mechanical Engineering. Vol. 75, pp. 3-8.
15. Liu, X.H., Zhang, Y., Qu, K.Y. and Jiang, V. (2006) ‘Experimental study on mass transfer performances of cross flow dehumidifier using liquid desiccant’, Energy Conversion and Management, Vol. 47, pp. 2682-2692.
16. Martin, V. and Goswami, D.Y. (2000) ‘Effectiveness of heat and mass transfer processes in a packed bed liquid desiccant dehumidifier/regenerator’, HVAC&R Research, Vol. 6, pp. 21-39.
17. Moon, C.G., Bansal, P.K. and Jain, S. (2009) ‘New mass transfer performance data of a cross-flow liquid desiccant dehumidification system’, International Journal of Refrigeration, Vol. 32, pp. 524-533.
18. Narayan, P.G., Chehayeb, K.M., Mcgovern, R.K., Thiel, G., Zubairyed, M., Lienhard V. and John, H. (2013) ‘Thermodynamic balancing of the humidification dehumidification desalination system by mass extraction and injection’, International Journal of Heat and Mass Transfer, Vol. 57, pp. 756-770.
19. Oberg, V. and Goswami, D.Y. (1998) ‘Experimental study of heat and mass transfer in a packed bed liquid desiccant air dehumidifier’, Journal of Solar Energy Engineering, Vol. 120, pp. 289-297.
20. Patnaik, S., Lenz, T.G. and Lof, G.O.G. (2000) ‘Performance studies for an experimental solar open-cycle liquid desiccant air dehumidification system’, Solar Energy, Vol. 44, pp. 123-135.
21. Ritunesh, K., Dhar, P.L., Sanjeev, J. and Asati, A.K. ‘Multi absorber stand-alone liquid desiccant air-conditioning systems for higher performance’, Solar Energy, Vol. 83, pp. 761-772.Salarian, H.,
22. Sultan, G.I., Hamed, A.M. and Sultan, A.A. (2002) ‘The effect of inlet parameters on the performance of packed tower-regenerator’, Renewable Energy, Vol. 26, pp. 271-283.

23. Stevens, D.I., Braun, J.E. and Klein, S.A. (2000) 'An effectiveness model of liquid-desiccant system heat/mass exchangers', Solar Energy, Vol. 42, pp. 449-455.
24. Zhao, K., Liu, X.H., Zhang, T. and Jiang, Y. (2014) 'Performance of temperature and humidity independent control air-conditioning system in an office building', Energy and Buildings, Vol. 43, pp. 1895-1903.
25. Zurigat, Y.H., Abu-Arabi, M.K. and Abdul-Wahab, S.A. (2004) 'Air dehumidification by triethylene glycol desiccant in a packed column', Energy Conversion and Management, Vol. 45, pp. 141–155. doi:10.1016/S0196-8904(03)00109-2.
26. Kumar R. and Asati A K. (2016) "Experimental Study on Performance of Celdek Packed Liquid Desiccant Dehumidifier," Heat and Mass Transfer, ISSN 0947-7411, Vol. 52, No. 9, pp 1821-1832, DOI:10.1007/s00231-015-1704-2.
27. Kumar R., Asati, A.K.(2017), "Study on the Performance of Celdek Packed Counter Flow Liquid Desiccant Regenerator," Journal of Mechanical Science and Technology, ISSN 1738 494X, 31(9) 4489-4498, doi 10.1007/s12206-017-0849-y.