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ABSTRACT

A solar liquid desiccant air cooling system cools air in two stages: dehumidification followed by sensible cooling. It uses concentrated liquid desiccant to dehumidify the process air and reject the absorbed moisture to the ambient air through solar thermal heating in a solar collector cum regenerator (C/R). For the dehumidifier the liquid desiccant must be cold and strong in desiccant to reduce tendency of evaporation of water in the solution so that it can absorb water vapor from the process air. But, in the solar regenerator the solution must be hot to enhance evaporation of water from the solution to the regeneration air which requires thermal energy. The solar collector cum regenerator performance decides the overall cooling performance because for every kilogram of water dehumidified, at least the same amount must be rejected in the solar regenerator. Direct coupling of the solar regenerator with the dehumidifier may not be possible since the moisture removed in the dehumidifier may not get evaporated in the solar regenerator simultaneously. The solar thermal energy collection and the operating conditions decide the regeneration capacity of the solar collector cum regenerator.

This paper presents experimental solar regeneration performance of $CaCl_2$-H_2O and $LiCl$-H_2O solutions using two different sized solar C/R of absorber area 1.47 and 4 m^2 inclined at 14° from the horizontal. The diurnal mass of water evaporated from LiCl and $CaCl_2$ solutions at different concentrations is reported. The water evaporation per unit absorber area was found to be independent of C/R size for experiments carried out on the two regenerators for both LiCl and $CaCl_2$ solutions for similar levels of irradiance and initial desiccant concentration. In addition, the paper discusses some basic solar C/R design issues and explores the coupling possibility of a solar C/R with a liquid desiccant cooling system. The results presented are useful in deciding the size of a solar C/R for coupling with a liquid desiccant cooling system of desired capacity.

Keywords: Regeneration, solar collector cum regenerator, liquid desiccant, desiccant cooling system, dehumidification

1. INTRODUCTION

There have been several experimental and theoretical studies on the regeneration performance of liquid desiccants using solar C/R. Exploring the possibility of directly coupling a solar C/R is of interest in addition to theoretical & experimental regeneration studies. The possibility of directly integrating a solar C/R with an open cycle absorption cooling system was proposed and analyzed by several researchers like Collier (1979), Haim et al. (1992), Hawlader et al. (1993), Kuashik et al. (1985) and Yang & Wang (2001). In solar assisted open cycle absorption cooling system, chilled water is produced through flashing of water in the evaporator at vacuum pressure and the flashed vapor flows to absorber for absorption by concentrated desiccant (absorbent). Then the weak desiccant solution is regenerated in the solar C/R. The potential of integrating a solar C/R with open type liquid desiccant cooling system

was evaluated theoretically by Gandhidasan (1994) and Katejanekarn & Kumar (2008) and experimentally by Katejanekarn et al. (2009). The system consisted of dehumidifier, heat exchangers, evaporative cooler, and solar C/R. Entire system of solar assisted open type liquid desiccant cooling system operates at atmospheric pressure which is an advantage compared to open cycle absorption cooling. Solar C/R is the critical component because for every kilogram of water dehumidified or absorbed, the same amount should be desorbed in the solar C/R (Collier, 1979) and the C/R performance directly translates to the cooling system performance (Hawlader et al., 1993). However, it is difficult to control the liquid desiccant concentration using solar C/R exactly to the same inlet concentration required in the dehumidifier or the absorber if the liquid desiccant at outlet of dehumidifier or absorber is directly fed to solar C/R. This is because solar energy is intermittent and varies during sunshine hours, as a result desorption rate may not exactly match with the absorption rate in a once through system. Alternatively, a solar C/R can be integrated with an open type liquid desiccant air cooling system by collecting the outlet solution from dehumidifier in a buffer storage tank, keeping a dedicated concentrated solution tank for inlet to the dehumidifier and regenerating weak desiccant solution from another storage tank coupled with the solar C/R as indicated in Figure 1. Concentrated liquid desiccant should be stored in the cold & strong solution tank at desired desiccant concentration to operate the air dehumidifier. The outlet liquid desiccant from the air dehumidifier is then stored in the buffer tank which is regenerated in the solar C/R. This arrangement will provide the desired concentration of desiccant to the dehumidifier at all times (independent of the solar C/R) and help store concentrated liquid desiccant which gets cooled for future use. Further, cooling can be achieved using cooling water, if required. However, larger quantities of liquid desiccant would be required.
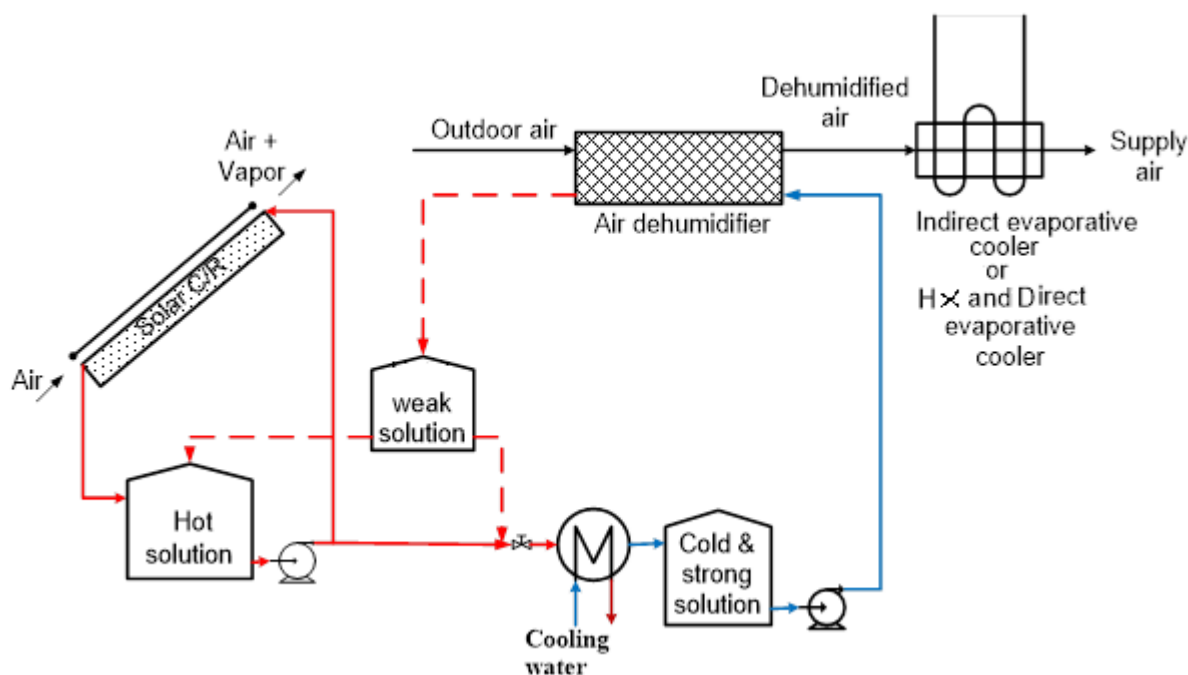

Figure 1: Schematic diagram of a liquid desiccant cooling system with solar C/R

Experimental regeneration performance of unglazed (Hawlader et al, 1997), single glazed (Mullick & Gupta, 1994; Hawlader et al., 1997, Alizadeh & Saman, 2002) and double glazed (Yang & Wang 1998) solar C/R were studied for forced or free convection regeneration. Performance of unglazed regenerator was reported to be better than single glazed solar C/R (Hawlader et al., 1997) which needs further exploration. Double glazing the solar C/R reduces the optical efficiency of the solar C/R. Designing the solar C/R with single glass may be preferable to unglazed C/R since glazing is essential to reduce contamination by dust which reduces desiccation capacity of liquid desiccant.

Forced air regeneration was reported to be better than free convection (Alizadeh & Saman, 2002). Identical glazed solar C/Rs (one for free convection and the other one for forced convection) operating in parallel absorb the same amount of heat from the sun and their regeneration capacity remain the same. At low ambient temperatures forced convection increases the heat loss from the solution surface and thereby decreases the solution temperature that may affect regeneration. Free convection regeneration is preferable over forced convection, since it does not require any fan/blower that adds demand for electric power.

Estimating the evaporation rate of water from liquid desiccant flowing over the absorber surface of a solar C/R is crucial but challenging since the evaporation rate of water from the absorber surface in a single run (from inlet to exit of solar C/R) depending on several factors including design of the collector, solar radiation, ambient temperature, humidity ratio etc.. It was also investigated for different time intervals by different researchers e.g. for about eight to nine minute in a continuous flow, batch mode operation between 10:30 am to 12:30 pm (Hawlader et al., 1997), every hour from 9 am up to 4pm (Yang & Wang 1994; Kabeel, 2005) and for about an hour every 10 minutes (Elsarrag, 2008).

The aim of this paper is to evaluate experimental solar regeneration performance of calcium chloride and lithium chloride solutions using two different sized single glazed solar C/R for free convection experimentation every hour from 9 am up to 4 pm.

2. EXPERMENTAL SETUPS AND DATA REDUCTION

The experimental system consists of a solar C/R, a polyethylene solution tank and a centrifugal pump (Figure 2). The solar C/R was fabricated using 18 gauge corrugated GI, single glass covering at a height of 85 mm from the absorber sheet, a concentric pipe solution distributor, and a 15 cm diameter PVC discharge pipe of length 2300 mm at the end of the sheet. The absorber area of solar C/R-A was 2.2 m x 1.84 m and that of solar C/R-B was 0.8 m x 1.84 m. The absorber plate of each solar C/R was painted with iron oxide before blackboard paint to avoid corrosion of the plate. A centrifugal pump was used to circulate the desiccant solution over the absorber plate continuously through the solution distributor. Only one solution tank was used to supply and collect liquid desiccant.
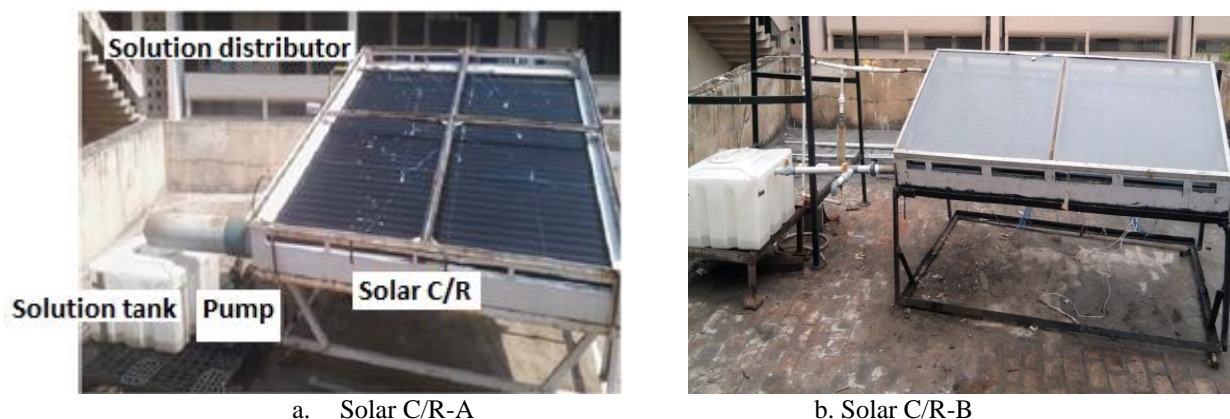

a. Solar C/R-A   b. Solar C/R-B

Figure 2: Experimental regeneration setups

The solution temperature and the irradiance were collected using RTD and Pyranometer with the help of a data logger every ten seconds during the entire solar regeneration time. A hand held digital densitometer was used to measure the solution density in the tank at every 30 minute time interval. The RTD was calibrated at ice and boiling point of water and the densitometer was calibrated against pure water density according to the manufacturer's guideline. The initial height of solution in the tank and absorber area of the plate were measured using a scale and a tape rule, respectively. The uncertainties of densitometer, pyranometer, RTD and tape rule/scale were 0.001 g/cm^3, 3% of pyranometer reading (Kipp & Zonen), 0.5°C and 1mm, respectively. The uncertainty in estimating solution volume was 0.625 litre which corresponds to 2 mm error in height measurement of solution in the tank using a

scale.Uncertainty of the performance indicating parameters of the solar C/R were estimated using general uncertainty analysis (Dunn, 2005):

$$\sum_{i}^{n} \frac{\partial R}{\partial x, i} U_{x,i} \tag{1}$$

The maximum uncertainty in evaluating the mass of water evaporated, increase in concentration and solar C/R efficiency calculated over a period of an hour were found to be 0.05 kg, 0.0014 kg/kg, and 0.02, respectively. Sample analyse is discussed by Gezahegn et al. (2014).The initial solution density, temperature and height in the tank were measured and recorded to estimate the initial mass of desiccant in the solution at the start of regeneration experimentation. Then, the solution was circulated over the absorber plate for some time until thermal equilibrium was attained between the solution in the tank and the solution on the absorber plate. The mass of water evaporated, increase in concentration and solar C/R efficiency over a period of time (between the nth and the $(n-1)^{th}$ time step) can be found from (Gezahegn et al., 2014):

$$m_{v,\Delta t} = m_d * \left(\frac{1}{\xi_{t_o +(n-1).\Delta t}} - \frac{1}{\xi_{t_o +n.\Delta t}} \right) \quad where \quad n = 1, 2, \dots \tag{2}$$

The mass of water evaporated per unit area of the absorber plate is given by

$$m'' = \frac{m_{v,\Delta t}}{A_{ab}} \tag{3}$$

For lithium chloride and calcium chloride solutions in the concentration range of $0 \le \xi \le 0.56$ and $0 \le \xi \le 0.6$, respectively. The following equations were used to calculate the concentration of lithium chloride and calcium chloride in the solution, respectively at any time from measured solution density and temperature:

$$0.100791 \left(\frac{\xi}{1-\xi} \right)^3 - 0.303792 \left(\frac{\xi}{1-\xi} \right)^2 + 0.540966 \left(\frac{\xi}{1-\xi} \right) + 1 - \frac{\rho_{sol}\,(\xi, T_{sol})}{\rho_{H_2O}\,(T_{sol})} = 0 \tag{4}$$

$$0.100791 \left(\frac{\xi}{1-\xi} \right)^3 - 0.303792 \left(\frac{\xi}{1-\xi} \right)^2 + 0.540966 \left(\frac{\xi}{1-\xi} \right) + 1 - \frac{\rho_{sol}\,(\xi, T_{sol})}{\rho_{H_2O}\,(T_{sol})} = 0 \tag{5}$$

$$\rho_{H_2O}\,(T_{sol}) = 0.322 \left(\begin{array}{l} 1 + 1.9937718430\,\tau^{1/3} + 1.0985211604\,\tau^{2/3} - 0.5094492996\,\tau^{5/3} \\ -1.761912427\,\tau^{16/3} - 44.9005480267\,\tau^{43/3} - 723692.2618632\,\tau^{110/3} \end{array} \right) \tag{6}$$

$$\tau = 1 - \theta = 1 - \frac{T_{sol} + 273.15}{647} \tag{7}$$

The solar C/R efficiency based on absorber area is given by

$$\eta_{CR} = \frac{Q_{eva}}{Q_{ab}} = \frac{m_{v,\Delta t}\,(2551 + \Delta h_d)}{I.A_{ab}.\Delta t} \tag{8}$$

The differential enthalpy of evaporation for LiCl and CaCl$_2$ solutions, respectively are given by (Conde, 2004)

$$\Delta h_d = (169.105 + 457.85\theta) \left[1 + \left(\frac{\xi}{0.845(0.6-\xi)} \right)^{-1.965} \right]^{-2.265} \tag{9}$$

$$\Delta h_d = \left(-955.69 + 3011.974\theta\right)\left[1 + \left(\frac{\xi}{0.855(0.8 - \xi)}\right)^{-1.965}\right]^{-2.265} \tag{10}$$

The C/R performance directly translates to desiccant cooling system performance and the amount of water evaporated from the liquid desiccant on the C/R is a measure of the cooling system capacity (Hawlader *et al.*, 1993). The cooling capacity is thus given by

$$Q_o = \frac{Q_{eva}}{\Delta t} = \frac{m_{v,\Delta t}\left(2551 + \Delta h_d\right)}{\Delta t} = A_{ab}\, m''\left(2551 + \Delta h_d\right) \tag{11}$$

4. RESULTS AND DISCUSSION

Performance of two solar collectors cum regenerators were analyzed on the basis of experimental data collected from 9 am up to 4 pm in the summer month of May in Delhi for regeneration of $CaCl_2$ and LiCl solutions in terms of mass of water evaporated, increase in concentration of desiccant in the solution, and solar collector cum regenerator efficiency. The ratio of the absorber area of solar C/R-A to the absorber area of solar C/R-B was 2.75.

4.1 Experimental Performance of Solar C/R-B
Three days performance (also experimentally collected data) of solar C/R-B for regeneration of low, medium and high concentration LiCl solution in the month of May are shown in Figure 3. The initial solution volume and concentration at the start of experimentation (9 am) for low, medium and high concentration lithium chloride solution were 31.2 litre & 0.29 kg/kg, 25.1 litre & 0.36 kg/kg, and 20.3 litre & 0.41 kg/kg, respectively. The regeneration of the solution was carried out up to 4 pm. The final concentrations attained for regeneration of low, medium and high concentration lithium chloride solutions was 0.36, 0.41 and 0.48 kg/kg, respectively as a result of evaporation of 6.9 kg/day , 4.2 kg/day and 3.4 kg/day of water from the solutions. The day average incident irradiance and solar C/R efficiency for the low, medium and high concentration LiCl solutions were 732.3W/m^2 & 66.8%, 615.6 W/m^2 & 57.3%, and 705.6 W/m^2 & 36.1%, respectively. The evaporation flux of water in a day for the low, medium and high concentration solution was 0.67, 0.41 and 0.33 kg/h.m^2, respectively.

Similar three day data and performance of glazed solar C/R-B, from 9 am up to 4 pm, for regeneration of low concentration (0.30 -0.35), medium concentration (0.36- 0.41) and high concentration (0.41- 0.48) calcium chloride solution in the month of May are shown in Figure 4. The initial volume of calcium chloride solution (9 am) used for the regeneration experiment and the total mass of water evaporated over the day for low, medium and high concentration were 35.8 litre & 6.5 kg/day, 31.2 litre & 4.6 kg/day, and 23.7 litre & 3.9 kg/day, respectively. The day average evaporation flux, incident irradiance and solar C/R efficiency were, respectively 0.63 kg/h.m^2, 785.9 W/m^2 & 59.8% for low concentration, 0.45 kg/h.m^2, 590.4 W/m^2 & 57.5% for medium concentration and 0.37 kg/h.m^2 , 646.6 W/m^2 & 45.1% for higher concentration. These results signify that regeneration performance of liquid desiccants using solar C/R is strongly dependent on the concentration of desiccant and also the irradiance.
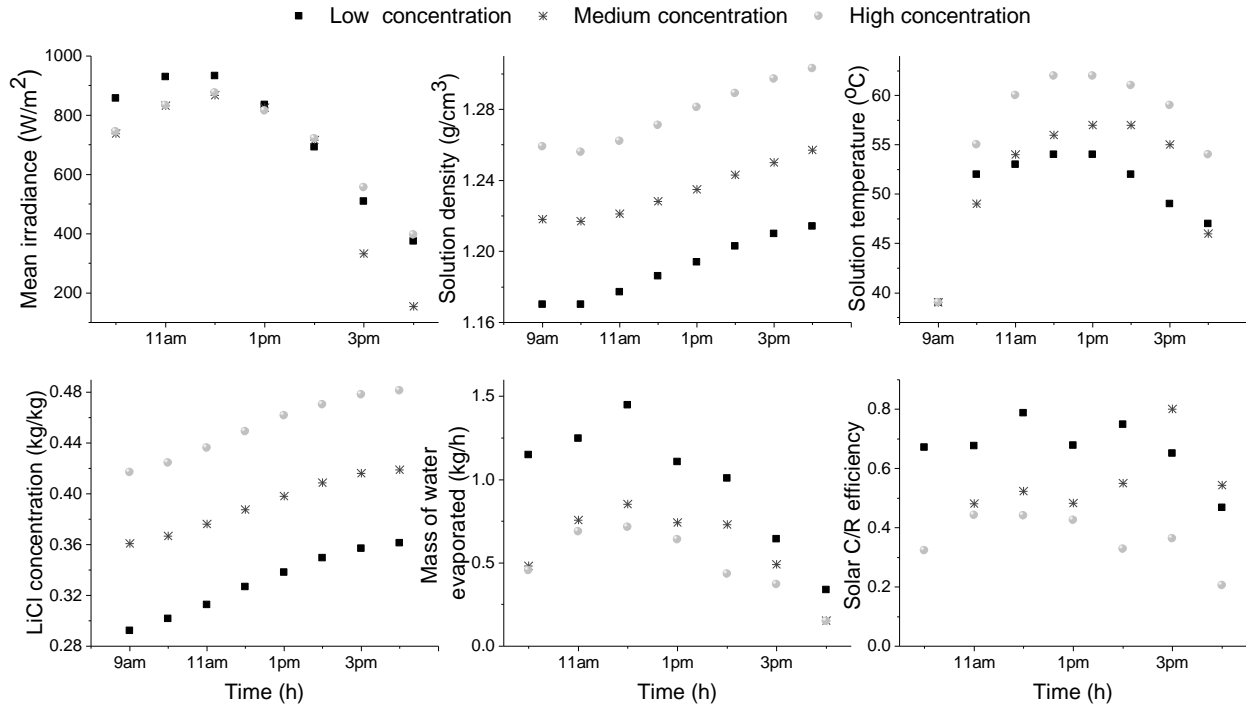
Figure 3: Experimental performance of glazed solar C/R-B for regeneration of LiCl solution
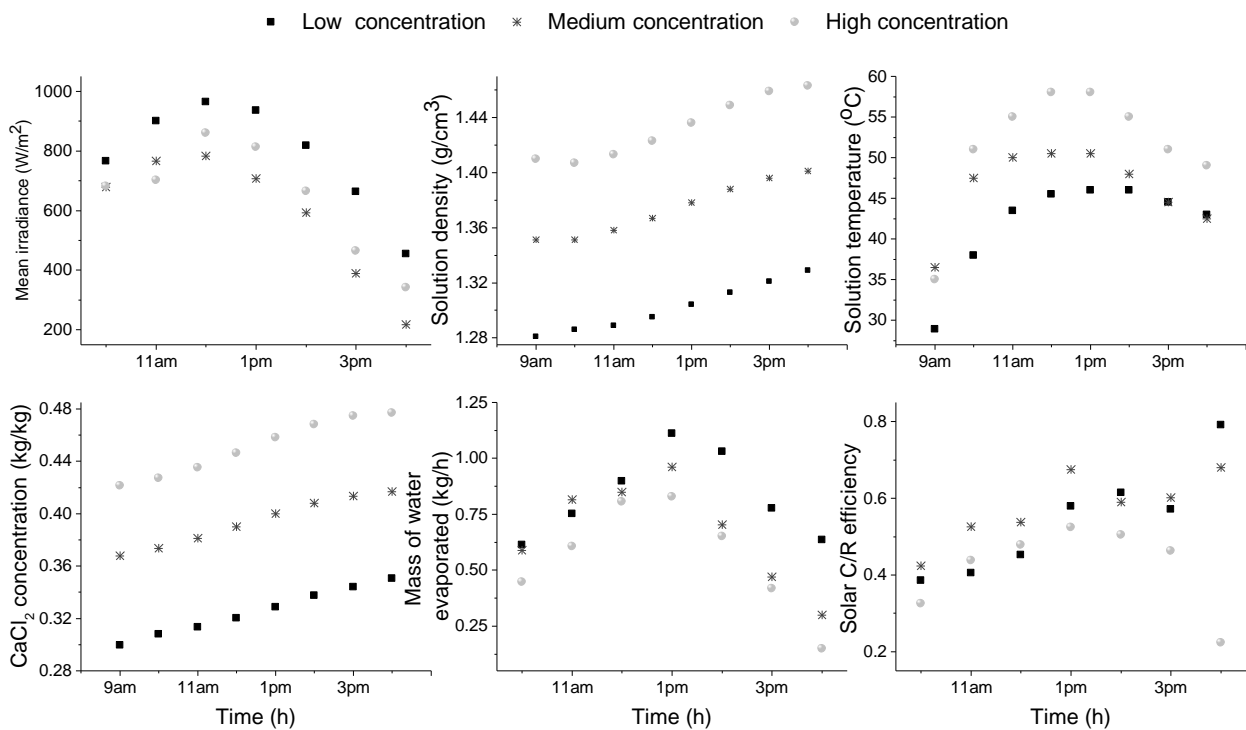

Figure 4: Experimental performance of glazed solar C/R-B for regeneration of CaCl$_2$ solution with time
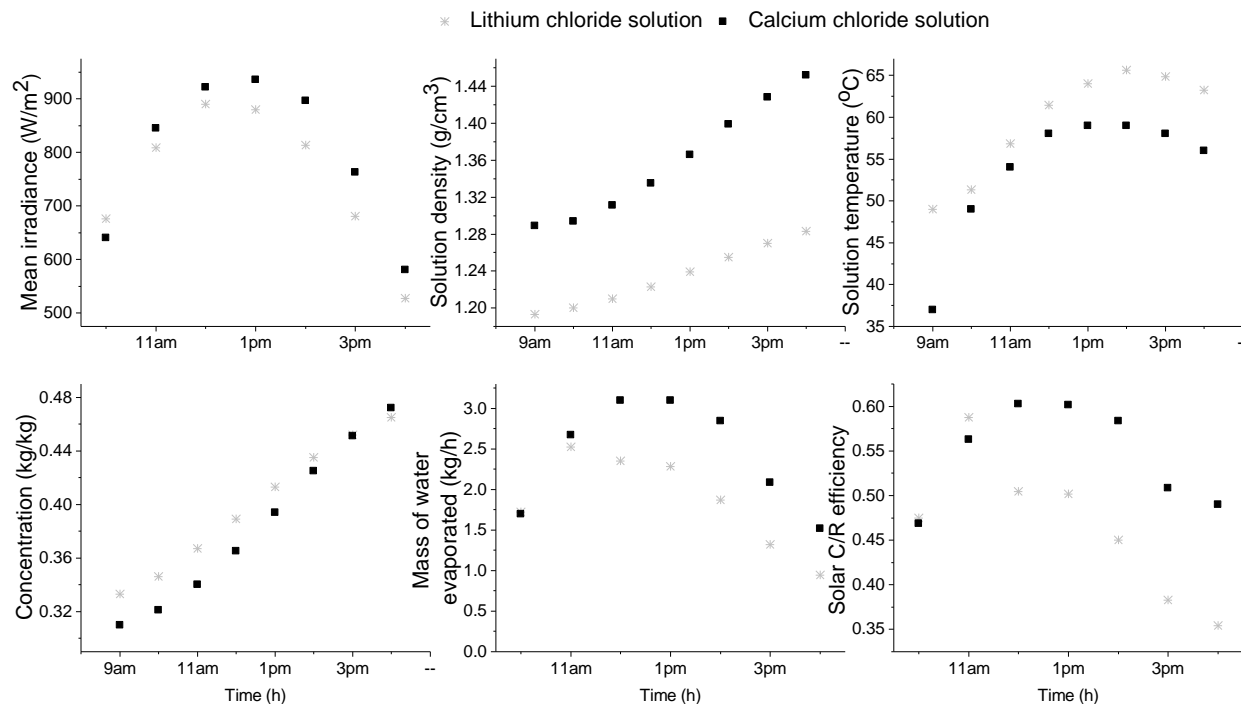
Figure 5: Performance of glazed solar C/R-A for regeneration of LiCl and CaCl$_2$ solutions with time

4.2 Experimental Performance of Solar C/R- A

Typical performance of glazed solar C/R- A for regeneration of lithium chloride and calcium chloride solutions (both 38.4 litre) for separate days in May are shown in Figure 5. The total mass of water evaporated from LiCl solution was 13.0 kg/day as a result the lithium chloride concentration increased from 33.2% at 9 am to 46.4% at 4 pm. The day average evaporation flux of water from lithium chloride solution was 0.45 kg/h.m^2. For calcium chloride a total of 17.0 kg/day of water was evaporated and the concentration of calcium chloride in the solution increased from 31.0% at 9 am to 47.2% at 4 pm and the day average evaporation flux of water was 0.60 kg/h.m^2. The day average irradiance and solar C/R efficiency were 753.7 W/m^2 & 46.5% for lithium chloride solution and 797.6 W/m^2 & 54.5% for calcium chloride solutions. A single day regeneration of solar C/R-A is equivalent to two to three day regeneration of solar C/R-B, which is mainly due to the difference in their absorber areas.

4.3 Comparison of Experimental Performance of Solar C/Rs

Figure 6 and Figure 7 show experimental performance of C/R-A and C/R-B for regeneration of LiCl and CaCl$_2$ solutions, respectively for similar irradiance and initial desiccant concentration. As seen in Figure 6, total mass of water evaporated from LiCl solution using solar C/R-A (2.2 m x 1.84 m) and C/R-B (1.84 m x 0.8 m) were 10.3 kg/day and 4.0 kg/day, respectively. But for both C/R, hourly evaporation flux of water were almost equal and the day average evaporation flux of water from C/R-A and C/R-B were 0.42 and 0.45 kg/m^2.h, respectively. As shown in Figure 7, the total mass of water evaporated between 9 am and 3 pm from CaCl$_2$ solution using C/R-A and C/R-B were 15.4 kg and 5.4 kg, respectively. The day average evaporation flux of water for regeneration of calcium chloride solution using C/R-A and C/R-B were 0.63 and 0.61 kg/m^2.h, respectively. The ratio of total mass of water evaporated from C/R-A to total mass of water evaporated from C/R-B was 2.57 for lithium chloride solution and 2.85 for calcium chloride solution, which are close to the ratio of absorber area of C/R-A to absorber area of C/R-B. These results indicate that total mass of water evaporated is almost a linear function of collector size or absorber area and the evaporation flux of water is independent of the absorber area for similar irradiance and desiccant concentration. Having a large regenerator does not affect the performance in any significant way even in free convection.
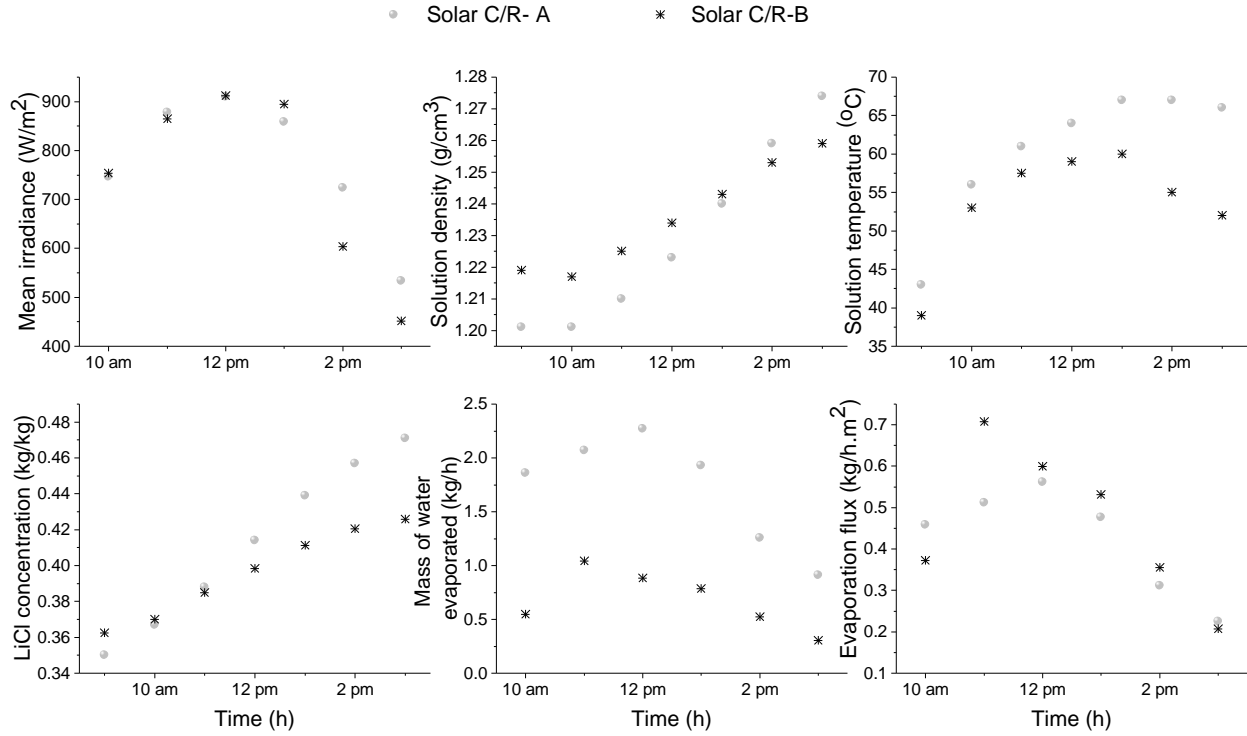
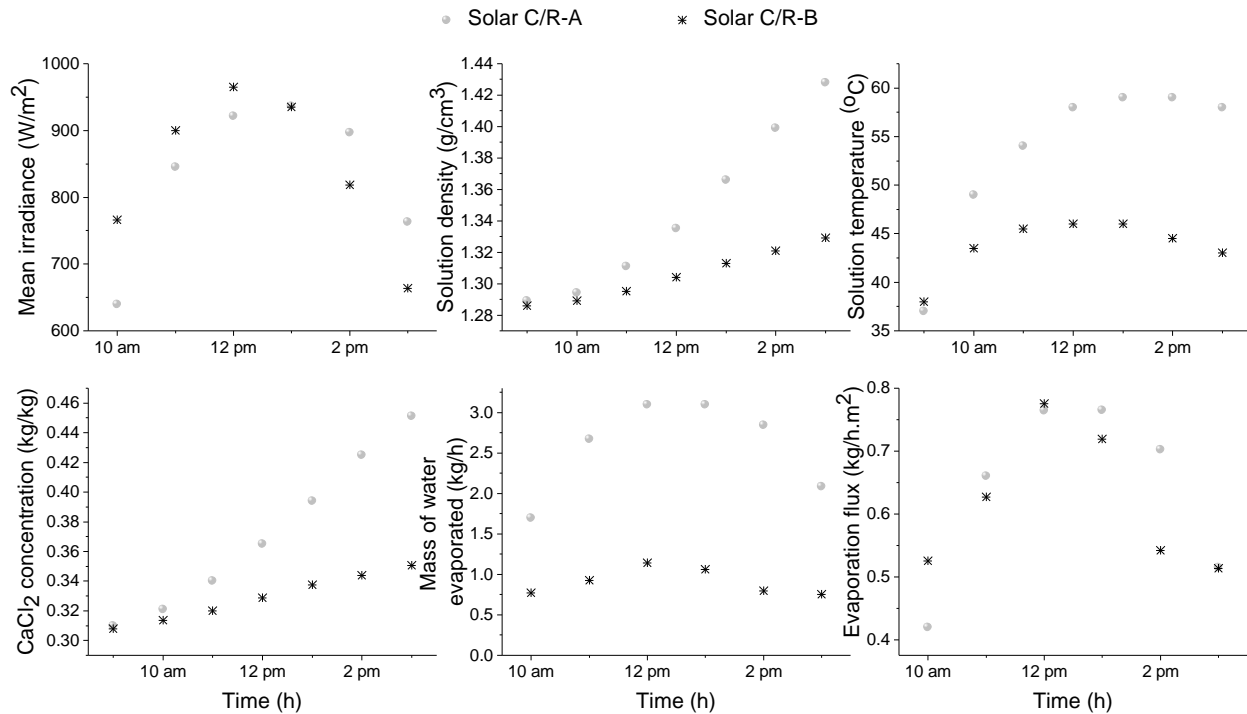**Figure 6:** Experimental performance of solar C/R-A and C/R-B for regeneration of LiCl solution

Figure 7: Experimental performance of solar C/R-A and C/R-B for regeneration of $CaCl_2$ solution

Hawlader *et al*., (1993) recommended that for dehumidification of air using LiCl solution the concentration of desiccant at inlet to the air dehumidifier to be 0.4 kg/kg. For operating unit cooling load (3.52 kW), the absorber area of the solar collector cum regenerator can be approximately estimated using day average performance data of the solar collector cum regenerator with the help of Eq. (8). The absorber area of the solar C/R, for unit cooling load was found to be 10.2 m^2 using regeneration performance data of LiCl solution shown in Figure 5 (day average LiCl concentration, irradiance and solar C/R efficiency were of 0.4 kg/kg, 0.754 kW/m^2 and 0.46, respectively). Alternatively, the absorber area for unit cooling load for this day can be calculated using the day average evaporation flux (0.45 kg/h.m^2) and the latent heat of vaporization of water from LiCl solution (2808.5 kJ/kg) using Eq. (11) and it was found to be 10.0 m^2.

5. CONCLUSIONS

In this paper, two different sized solar collector cum regenerator of absorber area of 4.0 m^2 (C/R-A) and 1.47 m^2 (C/R-B) were used to study experimental regeneration performances of LiCl and $CaCl_2$ solutions. The following main conclusions emerged from the study:

- For regenerating low concentration (0.29-0.36), medium concentration (0.36-0.41) and high concentration (0.41 - 0.48) lithium chloride solution using C/R-B, the day average vapor flux were found to be 0.67, 0.41 and 0.33 kg/h.m^2, respectively. For regeneration of low concentration (0.30-0.35), medium concentration (0.36 - 0.41) and high concentration (0.41-0.48) calcium chloride solution for C/R-B, the day average evaporation flux of water was found to be 0.63, 0.45 and 0.37 kg/h.m^2, respectively.
- The day average evaporation flux of water using solar C/R-A for regeneration of lithium chloride (for concentration range 0.33-0.46) and calcium chloride solutions (for concentration range 0.31-0.47) was 0.45 and 0.60 kg/h.m^2, respectively.
- The water evaporation per unit absorber area was found to be independent of C/R size for experiments carried out using solar C/R-A and solar C/R-B for both LiCl and $CaCl_2$ solutions for similar level of irradiance and initial desiccant concentration.
- An estimated absorber area of a solar collector cum regenerator required for operating unit cooling load of a desiccant cooling system (at lithium chloride concentration of 0.4 in May) was found to be 10.2 m^2 .

NOMENCLATURE

A_{ab}	absorber area	(m^2)
Δh_d	differential enthalpy of dilution	(kJ/kg)
I	mean irradiance	(W/m^2)
m	mass of water evaporated	(kg/h)
m''	evaporation flux	(kg/m^2.h)
Q_{eva}	total energy over a period of time	(kJ)
Q_o	cooling load	(kW)
R	arbitrary result parameter	(varies)
T	mean temperature	(^{o}C)
U	uncertainty of an instrument or a calculated result	(varies)
ξ	desiccant concentration	(kg/kg)
ρ	mass density	(kg/m^3)
θ	reduced temperature of water at solution temperature	(-)
τ	reduced temperature of water at solution temperature	(-)
η_{CR}	solar collector cum regenerator efficiency	(-)

Subscript

ab	absorber
C / R; *CR*	collector cum regenerator
d	desiccant
eva	evaporation
sol	solution
v	evaporated water

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