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ABSTRACT

A solar liquid desiccant cooling system uses renewable energy and natural refr attractive. Its main components are air dehumidifier, solar liquid desiccant cooler. In this cooling system, a strong liquid desiccant absorbs water from air in the dehumidi in the solar regenerator. This makes regeneration of a liquid desiccant cooling system one that requires thermal energy. The required energy for regeneration can be obtained from sun with the type solar collector cum regenerator. It also enables storage of energy in the form of rege during non-sunshine hours. Detailed analysis of the performance is important for integrating it with a liquid desiccant air cooling system development. This and experimental performa liquid desiccant solar regenerator under actual weather conditions. A solar collector cum regenerator of effective solar area of 4 m² was fabricated using corrugated sheet, layers of thermocol insulat insulation board, glass, supporting frames. The solar collector cum regenerator was mour metal supporting structure inclined at 14°. The corrugated absorber was coated with iron oxide minimize corrosion.

This paper presents the transient performance of solar collector cum regenerator in terms of increase in concentration, mass of water evaporated and collector efficiency. Desiccant concentration increase, total mass of water evaporated and mean daily solar collector cum regenerator efficiency of LiCl and $CaCl_2$ solutions were found to be 0.46 & 0.41, 31.3 & 17 kg and 36 & 43%, respect typical results were obtained from experiments carried out on separate days 9 and 14 in the month of May. The mass of water evaporated was estimated using an equation derived by applying conser mass in the solution. The experimental procedure and the results are useful in designing solar components of open cycle liquid desiccant cooling systems.

Keywords: Solar energy, liquid desiccant, solar collector cum regenerator, sor

1. INTRODUCTION

Solar liquid desiccant cooling system mainly consists of air dehumidifier, solar liquid des evaporative cooler. In this cooling system, a concentrated liquid desiccant absorbs moisture from the airstream in an air dehumidifier and the diluted desiccant flows to the solar regenerator. In the r diluted desiccant solution is regenerated (concentrated) by evaporating the moisture ab

dehumidifier using solar energy. One among the possible solar liquid desiccant regene… corrugated solar C/R which was introduced by Mullick & Gupta (1974). This C/R produ… strong desiccant solution by evaporating water from dilute desiccant soluti… regenerator, an energy converter and simultaneous mass & heat transfer device. A… open type solar liquid desiccant air conditioning system that determines the cooling performance… kilogram of water absorbed in the dehumidifier, the same amount must be d… 1979). The common desiccant in the C/R is LiCl-H_2O solution because of its excellent desiccation p… $CaCl_2$-H_2O solution is also used for low cost dehumidifier (Xiong et al., 2010). Since the nature of solar energy is intermittent, evaluating the transient performance of the… experiment is crucial.

Several theoretical and experimental studies have been carried out on solar regeneration of liquid… open/closed solar C/R. The present paper is focused on estimating the performance of… collector generator and identifying parameters that are used to indicate its performance… used to indicate the performance of the solar C/R collector efficiency (Mullick & Gupta, 1974), mass of water evaporated and energy rate (Collier, 1979), mass of water evaporated (Peng & Ho… Kaushik et al., 1985; Kumar & Devotta, 1990; Gandhidasan, 1983), efficiency and mass of water evaporated (Mattar, 1982), temperature, evaporation rate, regeneration efficiency (Yang & Wang, 1995), energy efficiency (Gandhidasan & Al-Farayedhi, 1994), temperature, concentration and figure of merit (Hawlader et al., 1992), temperature, concentration and evaporation rate (Kaushik et al., 1993; Katejanekarn & Kumar, 2008), mass of water evaporated, figure of merit (Fagbenle & Karayiannis, 1999), mass transfer coefficient, evaporation rate, energy of generator and efficiency (Kabeel, 2005), evaporation rate (Alizadeh & Saman, 2002a; Elsarrag, 2008), temperature, evaporation rate and efficiency (Alizadeh & Saman, 2002b), mass transfer rate, and heat & mass transfer coefficients (Hawlader et al., 1993; Yutong & Yang, 2010). One of the most common performance index of the C/R is the mass of water evaporated. In the experimental study (Hawlader et al., 1993; Yang & Wang, 1995, 1998 and Kabeel, 2005) used equations developed based on conservation of desiccant mass at inlet and at outlet from the solar regenerator as a function of… the mass of water evaporated. Elsarrag (2008) and Yutong & Yang (2010) used mass balance of the ventilat… inlet and outlet of the regenerator to estimate rate of evaporation of water for a case… However, uneven distribution of the scavenging air may contribute to errors (Yutong & Yang, 2010)

In theoretical studies, the evaporation rate of water was estimated by combining conservation of solution m… with conservation of energy or species transfer by principle of heat and convective mas… equations were combined to develop analytical equations (Collier, 1979; Kaushik & Kaudinya, 1989; Kumar & Devotta, 1989; Gandhidasan, 1994; Alizadeh & Saman, 2002a; Katejanekarn & Kumar, 2008), simplified by (Gandhidasan, 1983; Fagbenle & Karayiann… numerical relations (Peng & Howell, 1982; Hsu et al., 1985; Kaushik & Kaudinya, 1989). A comb… conservation of mass and conservation of energy equations were also used (Johannsen & Grossman, 1983; Hawlader et al., 1992 and Yutong & Yang, 2010). The methods involve various assumptions and give only approximate. Hawlader et al. (1992) mentioned that solar C/R is the most complicated component of open absorption cooling system and a study of the performance procedure, parameters and methods of the solar C/R is research effort towards in… solar C/R with an air dehumidification system

Estimating evaporation rate of water from liquid desiccant flowing over the solar C/R ab… particularly small size solar C/R, is impractical because it is difficult to measure th… of flowing liquid desiccant continuously and simultaneously using pycnomet… digital density since quantity of evaporating is minute. To apply this, continuous flow and density measuring instruments were needed to measure the variation of the density of the liquid desiccant… with temperature and throughout the regeneration time. In this study, the mass of solution stored in tank by circulating the liquid desiccant over the solar absorber plate o… throughout sunshine. The evaporation of water occurs in the solar C/R through th… pressure difference between vapor ventilation air and vapor on the surface of the solution…

solution can be measured manually at the solution tank at certain time interval easily. This was the experimental procedure used to estimate the transient performance of the study solar collector

In the present work, mass of water evaporated, concentration increase of desiccant in the solu efficiency are selected to indicate the transient performance of the solar C/R. In the open cycle liquid desiccant air cooling system the role of a liquid desiccant is the in the dehumidifier and rejection of the same amount of water in the solar cyclically for its use during non-sunshine hours. Moreover, moisture removal rate from the s directly dependent on the inlet concentration of the desiccant, which is the outlet concentration of the desiccant from the solar C/R. The evaporation of water from the solar C/R is clearly research but transient concentration increase is not available except in the work of Kaushik (1985) and Kabeel (2005) on regeneration of solutions of $CaCl_2$ and LiCl. The energy performance of the solar C/R reported in terms of collector efficiency, figure of merit, effectiveness, and reality, the function of the device is to collect the solar energy through absorption and to convert it energy by the absorber plate and the solution, and utilize some fraction of make the solar C/R energy convertor. Hence, the proper term to express the performance is the combined efficiency of solar collection and evaporation: solar C/R ef helpful in estimating the net amount of solar energy (area of the solar C/R should be considered as one among the critical performance indicators of the

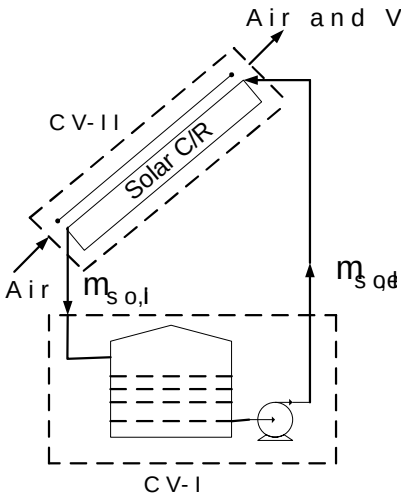
2. EXPERMENTAL SETUP AND INSTRUMENTATION

The experimental system consists of a solar C/R, solution tank, and a centrifugal pump (F solar C/R was fabricated using 18 gauge corrugated GI sheet of 2200 mm (length) x 18 12 cm thermocol insulator at its bottom in a 2600 mm x 2000 mm box, with a single glass covering height of 85 mm from the absorber sheet. A perforated PVC pipe, solution distributor, and PVC discha pipe of length 2300 mm at the end of the sheet. The absorber plate was black painted paint to avoid corrosion of it. A centrifugal pump was used to circulate the desiccant solution over the absorber plate continuously through the solution distributor. The tank was used to store liquid desic volume. Even though solar C/R surface temperature, properties of solution, meteorological data essential to completely understand the performance of solar C/R, only data of initial mass desiccant in the solution, variation of solution density, temperature and radiation incident on the solar C/R are sufficient enough to determine its experimental performance. The solution temperature and irradiance were collected using RTD and Pyranometer with the help of a data logger every ten second regeneration time. In addition, a digital hydrometer/densitometer was used to measure the solution density in the tank at every 30 minute time. The RTD was calibrated at ice and boiling point of water, and densitometer was calibrated at pure water density according to the manual. The initial height of solution tank and absorber area of the plate were measured using steel scale and a ta densitometer, pyranometer (Kipp & Zonen), RTD and tape rule is $0.001\ g/cm^3$, 2% of pyranometer reading, 0.5°C and 1mm, respectively. The uncertainty in estimating solution volume was 0.625 l mm error in height measurement of solution in the tank using scale. Uncertainty of the performance parameters of the solar C/R were estimated using general uncertainty analysis (Dunn, 2005):

$$U_R^2 = \sum_{i}^{N} \left(\frac{\partial R}{\partial x_i} U_{x,i} \right)^2 \qquad (1$$

3. DATA REDUCTION

The initial solution temperature, height and the weight were measured and recorded to estimate the initial mass of desiccant in the solution at the start of experimentation. Then, the solution was circulated absorber plate for some time until thermal equilibrium was attained between the solution in the tank and the sol on the absorber plate. The absorber plate temperature is usually more than the solution temperature by 25°C at the beginning of experimentation, due to early morning radiation.



a. Experimental system b. Schem

Figure 1 Experimental system and its schematic diagram

3.1 Mass of Water Evaporated

During experimentation, solar regeneration of aqueous solution of lithium chlo
out by continuously circulating the liquid desiccant over the absorber surf
pump. Evaporation of water from occurs in the solar regenerator as the soluti
the absorber in contact with the atmospheric air trapped between the soluti
into the glazing gap by natural convection stream of flow and leaves through ope
The outlet liquid desiccant from the solar regenerator is allowed to mix cont
stored in the solution tank as shown in Figure 1b. The difference between the initi
solution in the tank at the start of experimentation and the mass of solu
corrugated plate after 30 minute time interval; about 1.8 liters of the solution ac
solution pipelines. Applying conservation of mass principle to the two cont
gives the mass of water evaporated as

$$m_v(\theta) = m_{s,o,i} - m_{s,o,f} \quad (2)$$

Measuring the final mass of solution contained in the pipelines, absorber pl
found from mass of desiccant in the solution tank. Moisture absorbed by the desiccant remains c
throughout the solar regeneration processes, i.e., the final and the initial m
after regeneration are equal.

$$m_{d,i}(\theta) = m_{d,f}(\theta) \Rightarrow m_{s,o,i} * \partial x_i(\theta) = m_{s,o,f} * \partial x_f(\theta) = m_d \quad (3)$$

Thus, the final mass of solution in the pipelines, absorber plate and tank can be expressed
terms of the initial & final concentration and the initial mass of solution in the tank as

$$m_{s,o,f}(\theta) = m_{s,o,i} * \frac{\partial x_i}{\partial x_f} \quad (4$$

Substituting equation (4) into equation (2) and rearranging gives the mass
desiccant as

$$m_v(\theta) = m_{s,o,i} * \partial x_i * \left(\frac{1}{\partial x_f} - \frac{1}{\partial x_i}\right) \quad (5$$

From the solar regeneration experiment conducted, appreciable change in
observed only after heating of the solution. The change in concentration of the

between inlet and outlet of the solar C/R is negligible. This is due to small … solar collection area of the experimental setup used. Considering the previous and present time as the initial and the final thermodynamic states of the liq… from the solution between this time intervals, Δt, would be

$$m_{v(t)} = m_{s,o,t_o} * X_{t_o} \left(\frac{1}{X_{t_o}} - \frac{1}{X_{t_o+\Delta t}} \right) \quad (6)$$

Between n^{th} and $(n-1)^{th}$ time step, the mass of water evaporated will be

$$m_{v(t)} = \left(m_{s,o,t_o} - \sum_{1}^{n} m_{v,t_o+(n-1)\Delta t} \right) * X_{t_o+(n-1)\Delta t} * \left(\frac{1}{X_{t_o+(n-1)\Delta t}} - \frac{1}{X_{t_o+n\Delta t}} \right) \quad (7)$$

The expression to the left of the asterisk in equation (7) represents the mass of desiccant in t… at the corresponding times, and is always constant throughout the solar re… expressions by the mass of the desiccant in the solution, computational time required to determine the transient mass of water evaporated from the solution (equation 7) can be simplified to

$$m_{v(t)} = m_d * \left(\frac{1}{X_{t_o+(n-1)\Delta t}} - \frac{1}{X_{t_o+n\Delta t}} \right) \quad \text{where } n = 1, 2, \ldots \quad (8)$$

Equation (8) gives the mass of water evaporated from the solution accurately for known initial mass of d… the solution in tank at beginning of experiment and concentrations of the solution before and after some time interval. The mass of water evaporated per unit area of the absorber plat…

$$m'' = \frac{m_{v(t)}}{A_{ab}} \quad (9)$$

3.2 Desiccant Concentration

Conde (2004) has reported empirical correlations for solution density as function of concentration of … temperature and density of water, for lithium chloride and calcium chloride … $0 \le X \le 0.5$ and $0 \le X \le 0.6$, respectively. These expressions are rearranged to give the following equations f… calculating the concentration of lithium chloride and calcium chloride in the solu… measured solution density and temperature:

$$0.100791\left(\frac{X}{1-X}\right)^3 - 0.303792\left(\frac{X}{1-X}\right)^2 + 0.540966\left(\frac{X}{1-X}\right) + 1 - \frac{\rho_{sol}(X, T_{sol})}{\rho_{H_2O}(T_{sol})} = 0 \quad (10)$$

$$0.105684\left(\frac{X}{1-X}\right)^3 - 0.4363\left(\frac{X}{1-X}\right)^2 + 0.836014\left(\frac{X}{1-X}\right) + 1 - \frac{\rho_{sol}(X, T_{sol})}{\rho_{H_2O}(T_{sol})} = 0 \quad (11)$$

$$\rho_{H_2O}(T_{sol}) = 322\left(1 + 1.9937718434\,\tau^{1/3} + 1.0985211604\,\tau^{2/3} - 0.5094492996\,\tau^{5/3} - 1.761919742\,\tau^{16/3} - 44.9005480267\,\tau^{43/3} - 723692.2618632\,\tau^{110/3} \right) \quad (12)$$

3.3 Solar C/R Efficiency

The solar C/R efficiency can be defined as the ratio of the desired effect to the input energy. For a… desired effect is the collection of solar energy to evaporate the water from the … is the total insolation falling on the aperture area of the C/R. It is given by:

$$\eta_{CR} = \frac{Q_{eva}}{I.A_{ap}\Delta t} \quad (13)$$

When the vapor pressure of water in the solution exceeds the partial vapor pressure of water in the air interf… solution surface, water migrates to the air. This migration of water takes wi… utilized to evaporate it. The energy for evaporation of water is approximated by equation (14).

$$Q_{eva} = m_{v} h_{fg,av} = m_{v}\left(2501 + \Delta h_d\right) \quad (14)$$

The average latent heat is the mean value of the latent heat at the previous and current time. The latent heat of vaporization of water from the liquid desiccant is greater than that corresponding to the vaporization of pure water (2501 kJ/kg), by an amount called the differential enthalpy of dilution, Δh_d (Conde, 2004). The differential enthalpy of dilution for LiCl and $CaCl_2$ solutions respectively are given by

$$\Delta h_d = \left(1619.05 + 4575.85\,\theta\right)\left[1 + \left(\frac{x}{0.845\,(0.6 - x)}\right)^{-1.965}\right]^{-2.26} \quad (15)$$

$$\Delta h_d = \left(-955.690 + 3011.974\,\theta\right)\left[1 + \left(\frac{x}{0.855\,(0.8 - x)}\right)^{-1.965}\right]^{-2.26} \quad (16)$$

4. RESULTS AND DISCUSSION

4.1 Transient Performance of Solar C/R Regeneration for LiCl Solution

Initial mass of solution and desiccant in the tank can be obtained from initial solution volume, measured initial density, and initial temperature. For LiCl solution on this day, it is 28.4 liters, 1249 kg/m³ and 29 °C. For this day, instantaneous irradiance either remains constant or changes by ±4 W/m² (a maximum variation of 0.67%) around 9 am and every 10 seconds from 9 am to 4 pm. The instantaneous solution temperature either remains constant or increases by 0.1 °C every 10 seconds up to 1:30 pm and starts decreasing by the same amount afterwards. The irradiance and solution temperature for LiCl are graphically depicted in Figure 2 with the one hour mean data superimposed on it. Since the mass of water evaporated and energy of evaporation are functions of thermodynamic properties, the arithmetic mean over a period of 1 hour on solution temperature and irradiance were used to evaluate the solar C/R performance together with the measured solution density at each hour. The instantaneous irradiance data between ±2σ within two times the standard deviation of the mean irradiance curve over the times intervals represent the irradiance reported by the solar C/R. For this day, the instantaneous irradiance at 9 am was 593 W/m² and at 1:30 pm was 748 W/m². The mean irradiance and standard deviation were 675.9 and 49.4 W/m², respectively.

Figure 2: Transient variation of irradiance & solution temperature w

4.1.1 Desiccant concentration: The variation of the measured solution density is shown in Fig 3. As indicated the density of solution was increasing continuously with time from 1.193 up to 1.289 g/cm^3 between 9 am and 4 pm (a total of 7.5% increase), which is a key indicator of evaporation of water from the solutio… increases due to sensible heat from 49.2 $^\circ$C at 9 am up to 62.8 $^\circ$C at 4 pm (Figure 2). The concentration of LiCl solution was obtained using equation (10) at every hour; for instance the conc… at 9 am and 4 pm were 0.33 and 0.46 kg/kg, respectively. The total increase in concentration was 39.6%. The uncertainty of concentration for all time intervals was calculated to be U_{con} ±0.001 kg/kg. The concentration of LiCl for the remaining time intervals was calculated and graphically indicated in Fig 3. The transient trend of concentration increase is the same as the increase i… increasing with time. This trend is different from the trend reported by Ka… (2005), which were increasing and decreasing similar to rate of evaporation of water with time. Hour… concentration of LiCl is also shown in Figure 3; the peak value was 2.3% when the concentration changes from 0.386 to 0.409 between 12 and 1 pm. The trend of concentration change of the desicca… with time was same as the rate of evaporation. Hawlader et al. (1993), Wang & Yang et al. (2011) reported that for dehumidification of air the concentration of LiCl solution to be 0.4… 0.6, respectively. However, Katejanekarn & Kumar (2009) has used LiCl con… the dehumidifier, which will result in lesser dehumidification of air.

4.1.2 Mass of water evaporated: At 9 am the initial LiCl solution mass (m_{sol}) and the initial mass of desiccan… solution (m_d) were 45.8 and 15.12 kg, respectively. The LiCl concentration (X_{ini}) was 0.33. Hence (m_w) and (m'') between these time intervals calculated using equations (8) and (9) were found to be 1.7 kg and 0.42 kg/m^2, respectively. Likewise, the evaporated mass of water for the rest of solar regeneration intervals were calculated and the results are shown in Figure 3. The uncertainty of LiCl in the solution and mass of water evaporated were calculated using equation (1) considering the uncertainty of volume, solution density, and desiccant concentration and were found to be ±0.25 kg/kg and ±0.03 kg/kg, respectively; the maximum calculated uncertainty in mass of water evaporated was 4% at noon time. The total mass of water evaporated over the day (from 9 am to 4 pm) was 13.0 kg. The mass of water evaporated per unit area between 11 am-12 pm, 12-1 pm and 1-4 pm were 0.42, 0.57 kg/m^2 and 0.26 kg/m^2, respectively. Kaushik et al. (1985) reported peak evaporation of 0.16 kg/m^2 from LiCl solution regenerated under weather condition of Delhi.

4.1.3 Solar C/R efficiency: The latent heat of evaporation of water from aqueous solution at 9 am and 10 am were 2701.3 and 2723.7 kJ/kg, respectively. The average latent heat (h_{fga}) was 2712.5 kJ/kg. Thus, the energy (Q_{ev}) utilized for evaporation of water from the solution simultaneously with the evap… using equation (4), was 4678.3 kJ with an uncertainty of ±86 kJ. The total energy intercepted by the sol… area (2.6 m x 2 m) in this time period was 12651.9 ± 43.4 kJ. Hence, the solar C/R efficiency in this time period was 0.37 and the error in its calculation was ±0.01; the uncertainty was about 3.9 %… time interval. Similarly, the solar C/R efficiency was calculated for the remaining time intervals and shown graphically in Fig 9. Out of 98 MJ of energy falling on the aperture area of the sol… was utilized for evaporating water and, over the day, the average hourly efficiency of regeneration, 36%…

4.2 Transient Performance of Solar C/R Regeneration of $CaCl_2$ Solution

Similar solar regeneration performance analysis was carried out for $CaCl_2$ … shown in Figure 3. The initial $CaCl_2$ solution mass and $CaCl_2$ were 38.4 and 17.28 kg, respectively. From 9 a… up to 4 pm, the concentration of calcium chloride increased from 0.31 to 0.4 kg/kg due to evaporation of 17 kg w… The peak mass of water evaporated per unit area was 0.765 kg/m^2 when the mean irradiance was 936.0 W/m^2 between 12 and 1 pm. A peak value of 0.8 kg/m^2 evaporation was reported by Kabeel (2005) for regeneration of calcium chloride solution of concentration 0.35. The solar C/R efficiency was varying from 36% to 41% between 9 am and 4 pm with peak value 46% for this typical day. The mean daily efficiency of the solar C/R was 4… amount of energy intercepted by the solar C/R and energy utilized for evaporating water wer… respectively. The regeneration performance of $CaCl_2$ solution was better than LiCl solution because … water in $CaCl_2$ solution is higher than LiCl solution for the same concentration an…

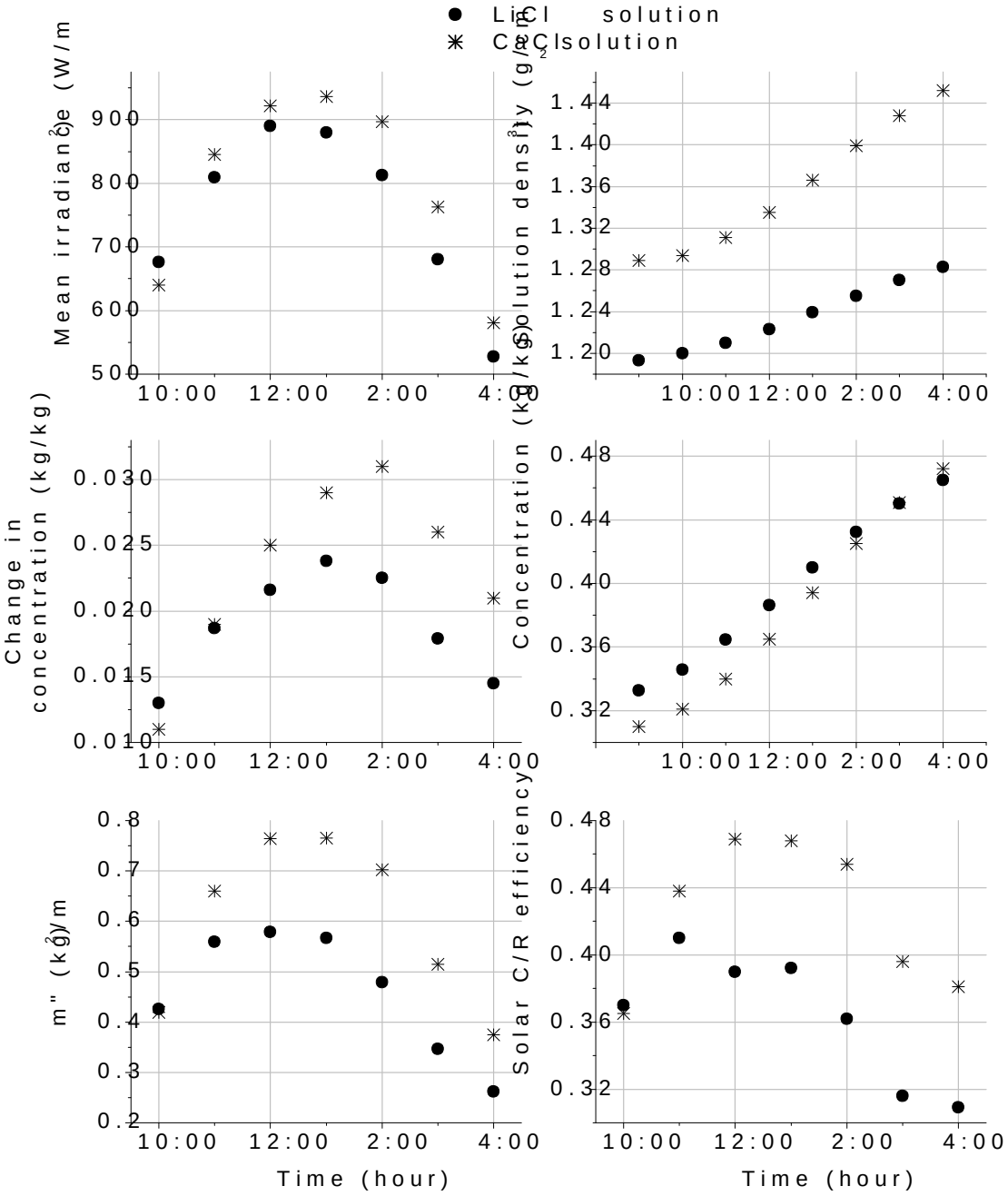


Figure 3 Transient performance of a solar C/R on regeneration of LiCl and $CaCl_2$ solutions

4.3 Overall Transient Performance of Solar C/R

The transient performance of glazed and unglazed solar C/R were evaluated for regeneration of LiCl and $CaCl_2$ solutions over hot & humid, hot & dry, and moderate temperature in Delhi. And it was found that the mass of water evaporated from the liquid desiccant in the solution. The trend of irradiance and inversely proportional to the concentration of desiccant in the solution. The trend of evaporated was the same as the irradiance. The solar C/R efficiency is inversely proportional to the concentration and its trend is related to the evaporated mass of water. But the trend of solar C/R efficiency is increasing and it is same as the trend of solution density. Hence, the same

performance of the solar C/R in May (hot & dry) was better than October (humid). Evaporation rate of water and mean daily solar C/R efficiency ranges from ... respectively for LiCl solution of initial concentration about 0.32 and mean ... For $CaCl_2$ solution these experimental values were 13 to 16.6 and 36.2 to 48.4%, respectively ... 0.31 and mean daily irradiance of about 700 W/m². The performance of glazed and unglazed solar ... to each other. Contamination of liquid desiccant by dust, foreign bodies and clogging of di... for the unglazed regenerator than the glazed one.

5. CONCLUSIONS

This paper presents experimental results for regeneration of liquid desiccant using a glazed type solar C/R. The mass of water evaporated was estimated based on the conservation of desiccant mass. The performance of the solar C/R was evaluated for solar regeneration of solutions of LiCl and $CaCl_2$ for climatic conditions of Delhi in terms of increase in concentration, mass of water evaporated and solar C/R efficiency. Typical values for water evaporated during solar C/R of 4 m² area from 9 am to 4 pm was about 4 kg for LiCl solution with initial concentration of 0.28-0.34 kg/kg. The average evaporation flux was 0.138 g/(m².s) at mean daily solar C/R efficiency of about 39.9%.

NOMENCLATURE

A	area	(m²)
Δh_d	differential heat of dilution	(kJ/kg)
I	mean irradiance	(W/m²)
m	mass	(kg)
m'	mass of water evaporated per unit absorber area	(kg/m²)
Q	total energy over a time period	(kJ)
R	arbitrary measured parameter	(varies)
T	mean temperature	(°C)
U	uncertainty of a measured or calculated result	(varies)
ξ	desiccant concentration	(kg/kg)
ρ	mass density	(g/cm³)
θ	reduced temperature of solution to water temperature	(-)
$\theta^* = 1-\theta$	reduced temperature of solution to water temperature	(-)
η_{CR}	solar collector cum regenerator efficiency	(-)

Subscript

ab	absorber
ap	aperture
C/R; CR	collector cum regenerator
d	desiccant
ev	evaporation
so	solution
v	evaporated water

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