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Habtamu Tafesse Gezahegn

Indian Institute of Technology, Delhi, India, gezisha@yahoo.com

Subhash Chandra Mullick

Indian Institute of Technology, Delhi, India, mullick_students@yahoo.com

Sanjeev Jain

Indian Institute of Technology, Delhi, India, sanjeevj@iitd.ac.in

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Transient Performance of a Liquid Desiccant Solar Regenerator

GE ZHAHE G N abta Tra f e s S e u b h a s a n M u l l i c k a n d S a n j e e v J A I N

¹Indian Institute of Technology, Department of Mechanical Engineering
New Delhi, Delhi, India
gezisha@yahoo.com

²Indian Institute of Technology, Delhi, Center for Energy
New Delhi, Delhi, India
mullick_students@yahoo.com

³Indian Institute of Technology, Delhi, Department of Mechanical Engineering
New Delhi, Delhi, India
sanjeevj@iitd.ac.in

* Corresponding Author

ABSTRACT

A solar liquid desiccant cooling system uses renewable energy and natural refrigerant, which is attractive. Its main components are air dehumidifier, solar liquid desiccant cooling system, and solar regenerator. In this cooling system, desiccant absorbs water from air in the dehumidifier and is regenerated in the solar regenerator. This makes regeneration of a liquid desiccant more efficient and that requires thermal energy. The regeneration can be obtained from sun with the type solar collector cum regenerator. A solar regenerator cum regenerator is used during sunny hours. Detailed analysis of the performance of the system is carried out with a liquid desiccant air conditioning system. Theoretical and experimental performance of liquid desiccant cooling system is compared with actual weather conditions. A solar collector cum regenerator is used as a solar regenerator. The solar regenerator is made of corrugated sheet metal, thermocol insulation, and supporting frame. The solar collector cum regenerator was mounted on a metal support structure. The corrugated absorber was coated with iron oxide to minimize corrosion.

This paper presents the results of the performance of the solar liquid desiccant cooling system. The concentration, mass of water evaporated, and mean daily evaporation rate of desiccant concentration increase, total mass of water evaporated and mean daily evaporation rate of desiccant concentration of LiCl and CaCl₂ solutions were found to be 0.46 & 0.073313 & 17 kg and 36 & 43%, respectively. Typical results were obtained during the experimental period in the month of May. The mass of water evaporated was as expected. The experimental procedure and analysis are useful in designing solar components of open cycle liquid desiccant cooling systems.

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

1. INTRODUCTION

Solar liquid desiccant cooling system mainly consists of air dehumidifier, solar liquid desiccant cooling system, and solar regenerator. In this cooling system, a concentrated desiccant solution is used to dehumidify the airstream in an air dehumidifier and is sent to the solar regenerator. In the regenerator, the diluted desiccant solution is regenerated by evaporating the moisture ab-

dehumidifier using solar energy the possible solar liquid desiccant regeneration system which was introduced by M. D. Collins (1974) and produced a strong desiccant solution by evaporating water from dilute desiccant solution using a solar energy converter and simultaneous mass & heat transfer device. An open type solar liquid desiccant system that determines the cooling performance is that for every kilogram of water absorbed in the dehumidifier, the same amount must be dehumidified in the regenerator. The common desiccant in the solar liquid desiccant system is $\text{CaCl}_2 \cdot \text{H}_2\text{O}$ solution because of its excellent desiccant properties. Since the nature of solar energy is intermittent, evaluating the transient performance of the system is crucial.

Several theoretical and experimental studies have been carried out on solar regeneration of liquid desiccant in open/closed solar C/R. The general parameters that are used to identify the performance of solar liquid desiccant systems are: evaporation rate (kg/m²/h), condensation rate (kg/m²/h), energy rate (kJ/m²/h), and efficiency (Peng & Kaushik et al., 1985; Kumar & Dhandapani, 1988; efficiency of water evaporated (Matta, 1982; temperature, evaporation rate, and condensation rate (Gandhidasan & Fagbenle, 1983; concentration and figure of merit (Fagbenle & Karayiannis, 1993; mass transfer coefficient, evaporation rate, condensation rate, and separation rate (Alizadeh & Saman, 2002; Elsar, 2008); evaporation rate and figure of merit (Alizadeh & Saman, 2002; mass transfer rate, and figure of merit (Yutong & Yang, 2010). One of the most common performance indicators is the mass of water evaporated per unit mass of desiccant at inlet and at outlet from the solar regenerator as a function of the mass of water evaporated. Edwards & Garg (1979) used mass balance of the ventilated inlet and outlet of the regenerator to estimate rate of evaporation of water for a case. However, even distribution of scavenging air is necessary (Yutong & Yang, 2010).

In theoretical studies, the rate of evaporation is estimated by using conservation of solution mass with conservation of energy or species stream energy balance and convective mass transfer equations were combined to develop analytical models for evaporation rate (Kaur & Kaudinya, 1989; Kumar, 1989; Gandhidasan, 1994; Alizadeh & Saman, 2002; Kaur & Kumar, 2008), simplified models (Gandhidasan, 1983; Fagbenle & Karayiannis, 1993), numerical relations (Peng & Kaushik & Kaudinya, 1989). A combination of mass and conservation of energy equations were also used (Johansen & Grossmann et al., 1992 and Yutong & Yang, 2010). Various assumptions and give only approximate results for solar C/R. The most complicated component is the condensation rate. Some studies have performed numerical parameters and methods for the design and analysis of solar C/R with an air conditioning system.

Estimating evaporation rate of water in solar liquid desiccant regeneration over the solar C/R is particularly small solar C/R is particularly difficult because it is difficult to measure the rate of flowing liquid desiccant and humidity ratio simultaneously using pycnometer and digital density since water evaporation is slow and it is difficult to apply this method to flow and density measuring in situ. However, the evaporation rate of the liquid desiccant with temperature and throughout the regeneration process is directly related to the mass of solution stored in the circulating the liquid desiccant over the solar C/R. The evaporation rate throughout sun still in the evaporation of water occurs in the solar C/R through the pressure difference between ventilation air and vapor on the surface of the desiccant.

solution becomes a necessity the solution can gain time as it is the experimental procedure used to estimate the transient performance of a solar collector

In the present work, an attempt is made to indicate the transient performance of a solar C/R cycle liquid desiccant air cooling system the role of a liquid desiccant is the in the dehumidifier and rejection of the same moisture of the desiccant and a cyclically stored during the moisture. Moreover, moisture removal rate from the solution is directly dependent on the inlet concentration of the desiccant solution to be the area of the desiccant from the evaporator of the solar C/R is clearly seen in the work of (Kabeel and Kabeel (2005) on regeneration of a solar C/R cycle liquid desiccant air cooling system. The solar C/R reported in collector efficiency, figure of merit, effectiveness, and reality, the function of the device is to collect solar energy by the absorber plate and the solution, and utilize some fraction of it to make the solar C/R energy converter. Hence, the proper term to be applied is the combined efficiency of solar collection and evaporation: solar C/R efficiency. It is 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

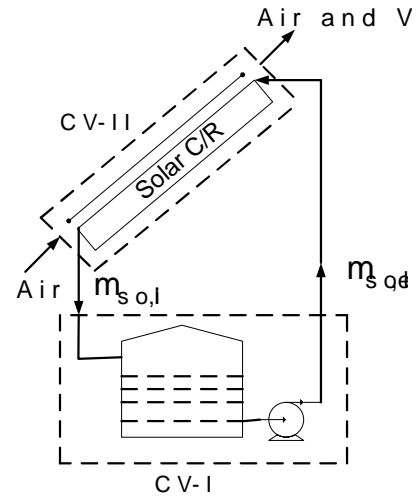
2. EXPERIMENTAL SETUP AND INSTRUMENTATION

The experimental system consists of a solar C/R and a centrifugal pump (FABRIKALFA) fabricated using galvanized GI sheet of 2200 mm (length) x 1200 mm (width) x 1.2 mm (thickness) mounted on a 2600 mm x 2000 mm wooden covering height of 85 mm from the absorber plate, solution is distributed and PVC discharge pipe of length 2800 mm at the end of the sheet. The absorber plate is painted with a corrosion resistant paint. The desiccant solution is absorbed continuously through the absorber plate. The solar C/R is used to absorb the desiccant solution. Even though the solar C/R surface temperature is a very important data essential to completely assess the performance of the solar C/R, data of initial mass desiccant in the solution, solution density and air density are the solar C/R are sufficient to determine its performance. The data were collected using RTD and with the help of a data logger every ten seconds regeneration. In addition, a digital densitometer was used to measure the density of the solution every 30 minutes. The RTD was calibrated at ice and then immersed in water and calibrated in water according to the standard. The initial height of solution tank and absorber area of the plate were measured using a tape rule and a densitometer, respectively. The uncertainty in estimating solution volume was 0.625 l and 1 mm error in height of the solution tank using the principle of the parameters of the solar C/R were estimated using uncertainty analysis (Dunn, 2005)

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

3. DATA REDUCTION

The initial solution concentration is measured and added to the solution of desiccant in the solution. The concentration of the solution is circulated over the absorber plate for some time until thermal equilibrium is reached between the absorber plate and the solution. The absorber plate temperature at the beginning of experimentation, due to early morning radiation.



a. Experimental system

b. Schematic diagram

Figure Experimental system and its schematic diagram

3.1 Mass of Water Evaporated

During experimentation, solar regeneration of aqueous solution of lithium chloride is carried out by continuously circulating the liquid desiccant over the absorber surface. Evaporation of water from the solution occurs in the solar regenerator as the solution flows over the absorber in contact with the atmospheric air trapped between the solution and the glazing gap by natural convection. The outlet liquid desiccant from the solar regenerator is allowed to mix with the solution in the tank at the start of experimentation and the mass of solution in the tank after 30 minute time interval; about 10% of the solution is collected in the solution pipelines. Applying conservation of mass principle to the two control volumes gives the mass of water evaporated as

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

Measuring the final mass of solution contained in the pipelines, absorber plate and the solution tank, it is found from mass of desiccant in the solution that the mass remains constant throughout the solar regeneration processes, i.e., the final and the initial mass of solution after regeneration are equal.

$$m_{d,i} \dot{\delta} = m_{d,f} \dot{\delta} \quad (3)$$

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

$$m_{s,o,f} \dot{\delta} = m_{s,o,i} \dot{\delta} \frac{\chi_i}{\chi_f} \quad (4)$$

Substituting equation (4) into equation (2) and rearranging gives the mass of water evaporated as

$$m_v \dot{\delta} = m_{s,o,i} \dot{\delta} \left(\frac{\chi_i}{\chi_f} - 1 \right) \quad (5)$$

From the solar regeneration experiment conducted, appreciable change in concentration of the solution is 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 was found to be insignificant over the period of time and present time as the initial and the final thermodynamic states of the liquid from the solution between this time intervals, "t, would be

$$m_{v, \delta t} \delta = m_{s, o, t_0} \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta - \frac{1}{\delta} \frac{\partial \rho}{\partial x_{o, t_0}} \delta \quad (6)$$

Between the time step, the mass of water evaporated will be

$$m_{v, \delta t} \delta = m_{s, o, t_0} \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta - \frac{1}{\delta} \frac{\partial \rho}{\partial x_{o, t_0}} \delta \quad (7)$$

The expression to the left of the equals sign in (7) represents the mass of desiccant in the tank at the corresponding times, and is always constant throughout the solar radiation period. The expressions by the right side of the equals sign in (7) are used to determine the transient mass of water evaporated from the solution. (7) Through simplification of (7) to

$$m_{v, \delta t} \delta = m_d \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta - \frac{1}{\delta} \frac{\partial \rho}{\partial x_{o, t_0}} \delta \quad \text{where } \delta = 1, 2, \dots \quad (8)$$

Equation (8) gives the mass of water evaporated from the tank at the beginning of the solar radiation period and after some time interval, the mass of water evaporated per unit area of the absorber plate

$$m' \delta = \frac{m_{v, \delta t} \delta}{A_{a, b}} \quad (9)$$

3.2 Desiccant Concentration

Conde (2004) has reported empirical concentration as a function of concentration of temperature and density of water, for lithium chloride and calcium chloride. The expressions are rearranged to give the following concentration of lithium chloride and calcium chloride in the solution measured solution density and temperature:

$$0.100 \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta - 0.303 \frac{\partial x_{o, \delta}^2}{\partial x_{o, t_0}^2} \delta + 0.540 \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta \frac{\partial r_{s, o, l}}{\partial r_{H_2, O}} \delta = 0 \quad (10)$$

$$0.105 \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta - 0.43 \frac{\partial x_{o, \delta}^2}{\partial x_{o, t_0}^2} \delta + 0.836 \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta \frac{\partial r_{s, o, l}}{\partial r_{H_2, O}} \delta = 0 \quad (11)$$

$$\frac{\partial r_{H_2, O}}{\partial r_{s, o, l}} \delta = 0.392 \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta + 1.9937 \frac{\partial x_{o, \delta}^2}{\partial x_{o, t_0}^2} \delta + 1.0985 \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta \frac{\partial r_{s, o, l}}{\partial r_{H_2, O}} \delta - 0.5094 \frac{\partial x_{o, \delta}}{\partial x_{o, t_0}} \delta \frac{\partial r_{s, o, l}}{\partial r_{H_2, O}} \delta \quad (12)$$

3.3 Solar Efficiency

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

$$\eta_{C/R} \delta = \frac{Q_{e, v, a}}{I \cdot A_p \delta} \quad (13)$$

When the pressure of water in the solution approaches the air interface at the solution surface, water migrates to the air. This migration of water molecules to evaporate it. The rate of water evaporation is given by equation (14)

$$Q_{ev} = m_{v0} h_{fg} + m_{v0} \frac{\partial h}{\partial x} \quad (14)$$

The average latent heat is an value of the latent heat of fusion and current state. The latent heat of vaporization of liquid component is that corresponding to the vapor of pure component, by an assumed differential enthalpy of fusion (Cengel & Ghajar, 2004). The differential enthalpy of dilution of LiCl is predicted by

$$\frac{\partial h}{\partial x} = 6.905 + 4.57 \frac{\partial x}{\partial x} - 0.8 \frac{\partial^2 x}{\partial x^2} - 0.196 \frac{\partial^3 x}{\partial x^3} - 0.226 \frac{\partial^4 x}{\partial x^4} \quad (15)$$

$$\frac{\partial h}{\partial x} = -9.55 + 30.19 \frac{\partial x}{\partial x} - 0.8 \frac{\partial^2 x}{\partial x^2} - 0.196 \frac{\partial^3 x}{\partial x^3} - 0.226 \frac{\partial^4 x}{\partial x^4} \quad (16)$$

4. RESULTS AND DISCUSSION

4.1 Transient Performance of C/R Regeneration Solution
 Initial mass of solution and desiccant in the tank can be obtained from, initial density, and initial temperature. Assumption is that initial temperature is 30°C. For this case instantaneous irradiance is constant at 700 W/m² and varies by 70% variation over a period of 10 seconds. The minimum and maximum solution temperature remains constant or increases by 0.1°C and starts decreasing by the same amount. The irradiance and solution temperature are graphically depicted in Figure 2 with three hour mean data superimposed on the mass transfer rate. The energy of evaporation is determined by thermodynamic properties, the arithmetic mean over a period of 1 hour on solution temperature and a constant solar C/R together with the measured solution density rate. The instantaneous irradiance data is within two times the standard deviation of the mean irradiance. The times intervals represent the standard deviation of the solar irradiance at 9 AM was 593 W/m² and 746 W/m². The mean irradiance and standard deviation are 675.9 and 49.4 respectively.

Figure 2. Transient variation of irradiance & solution temperature

4.1.1 Desiccant concentration of the measured solutions during the experiment. As shown in Figure 2, the density of solution was continuously increased from 1.193 up to 1.283 g/cm³ and a total of 7.5% increase is a key indicator of evaporation of water from the solution. The concentration of LiCl also obtained is equal to 10% at every hour; for instance the concentration at 9 am was 0.233 and 0.446/kg respectively by total increase in concentration is 6%. The uncertainty by centrifugal time was calculated to be ±0.01 kg/kg. The concentration of LiCl for the remaining time interval was also indicated in Figure 2. The transient trend of concentration increase is the same as the increase in density increasing with time. This trend is different from the trend reported by Kaur et al. (2015) which were indeed similar to rate of evaporation of water with time. Hourly concentration of LiCl is also shown in Figure 3; when the peak density was 2.03% and changes of 0.386 to 0.409 in 1 hr and the trend of concentration change of the desiccant with time was same as the rate of evaporation. (1.023) 2.0% and J. Yang et al. (2011) reported that for dehumidification of air from the air at 12.5°C and 0.4 g/kg, respectively. However, Katejanekarn & Kumar (2009) has used LiCl concentration which will result in lesser dehumidification of air.

4.1.2 Mass of water and amount of LiCl solution (m_{s,0}) and the initial mass of desiccant solution (m_d) were 45.8 and 5.12 kg, respectively. The LiCl concentration (m_{s,0}/m_d) was 0.53. Hence (m_{s,0}) and (m_d) between these two quantities were found to be 4.20 kg and 20 g/m² respectively. Likewise, the evaporation rate of water in regeneration intervals were calculated and the results are shown in Figure 4. The mass of LiCl in the solution and mass of water evaporated were (1.45 kg) and (0.25 kg) respectively. The density of desiccant concentration was 0.25 kg/kg and 0.3 kg/kg, respectively; the maximum concentration of water was 4%, and it did not change. The mass of water evaporated over a 24 hr day was 13.06 kg from the atmospheric mass of water evaporated per unit area, 2.16 kg/m² and 0.25 kg/m² respectively. Kaur et al. (2015) reported peak evaporation rate of LiCl solution evaporated under weather condition of Delhi.

4.1.3 Solar C/R The efficiency of evaporation of water from aqueous solution and air were 27 and 32723.7 kJ/kg, respectively. The average latent heat of evaporation was 2712.5 kJ/kg. Thus, the energy of evaporation simultaneously with the evaporation equation was 4678.3 kJ with a ±0.06% error. The total energy intercepted by the solar area (2.6 m x 1.2 m) in this time period was 12651.04 kJ. The coefficient of C/R efficiency in this time period was 0.37 and the average C/R efficiency was about 3.9% time interval. Similarly, the solar C/R efficiency was calculated as 0.25 and 0.37, shown graphically in Figure 5. The energy falling on the aperture area of the solar collector was utilized for evaporating water and the average efficiency of regeneration,

4.2 Transient Solar C/R Regeneration Performance and Justification. Similar solar regeneration performance and justification was also shown in Figure 3. The initial concentration was 38.4 mg/L, 2.8% respectively. From 9 am up to 4 pm, the concentration of LiCl increased to 0.7 kg/kg due to evaporation of 17 kg water. The peak water evaporation area was 0.765 kg/m² and an irradiance of 6.0 kW/m² and a peak value of 0.25 g/kg was reported by Kabeel et al. (2015) for regeneration solution of concentration of 0.135 g/kg. The C/R efficiency was 0.365 and 0.386, and 4 pm with peak value of 0.25 for this typical time. The daily efficiency of the solar C/R was 4 amount of energy intercepted by the solar C/R for evaporating water were respectively. The regeneration performance of LiCl solution was better than LiCl solution because water in solution is higher than LiCl solution for the same concentration and

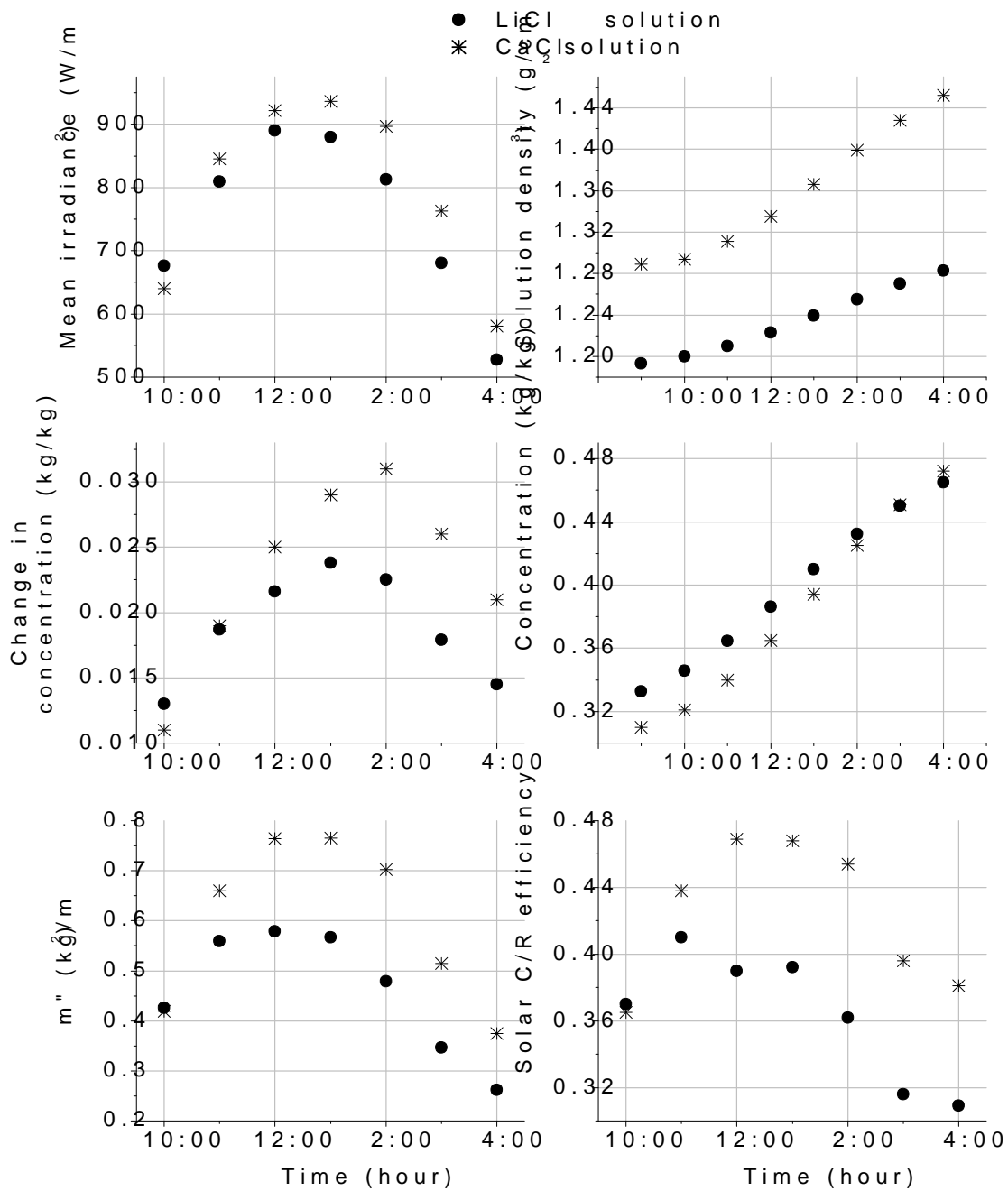


Figure 10. Transient performance of a solar C/R on regeneration of LiCl and CaCl2 solutions

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 CaCl2 solutions over hot & humid, hot & dry, and moderate temperature conditions in Delhi. And it was found that the mass of water evaporated from the liquid solution is proportional to the mean solar irradiance and inversely proportional to the concentration of the solution. The trend of the mass of water evaporated was the same as the irradiance. The solar C/R efficiency is inversely proportional to the concentration of the solution and its trend is related to the evaporation of water as the concentration is increasing and it is same as the trend of solution density. Therefore, the same

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