ANALYTICAL AND EXPERIMENTAL MASS TRANSFER ANALYSES ON REGENERATION OF LIQUID DESICCANTS USING A SOLAR THERMAL COLLECTOR

Summary

This paper analyses diurnal evaporation of water during solar regeneration of LiCl and $CaCl_2$ solutions using an analytical equation, convective mass transfer principle and conservation of energy and desiccant mass desiccant and found out that there is good agreement to each other. The optical, and heat transfer constants of the regenerator and mass transfer coefficient and vapor pressure constant required for the analytical and conservation relation were also determined for LiCl and $CaCl_2$ solutions. The optical efficiency of unglazed, single glazed and double glazed solar regenerator were found to be 94.9%, 77% and 62.5%, respectively. The average overall collector heat loss, coefficient was found to be 13.7 $W/m^{2o}C$ for hot and 12.2 $W/m^{2o}C$ for moderate weather conditions, respectively. The convective heat loss coefficient and mass transfer coefficient during regeneration of lithium chloride solution film were found to be of 7.5 $W/m2^oC$ and 0.007 m/s (and 0.006 m/s for $CaCl_2$ solution), respectively for solution temperature in the range of 49-63^{o}C.

Keyword: Solar Liquid desiccant regenerator, Calcium & Lithium chlorides, Optical efficiency of solar thermal collectors; heat and mass transfer coefficients of solar collectors; Sorption air-conditioning technology.

Field of application for the findings: Solar air conditioning and refrigeration

Addressed audience: Journal

Results and discussion: Kim & Ferreira (2008), recommended that future research and development on solar refrigeration should focus on low temperature sorption systems since solar electric and thermo-mechanical systems are more expensive. One such sorption system is an open type soption air cooling system that uses flat or corrugated solar collector for regenerating liquid desiccants. The solar regenerator was fabricated from black painted 18 gauge corrugated GI sheets of 2.2 m x 1.84 m absorber area, a 3.2 mm window glass cover and a 12 mm thick bottom thermocol insulation in a wooden frame. The test was conducted outdoor in the city of Delhi.

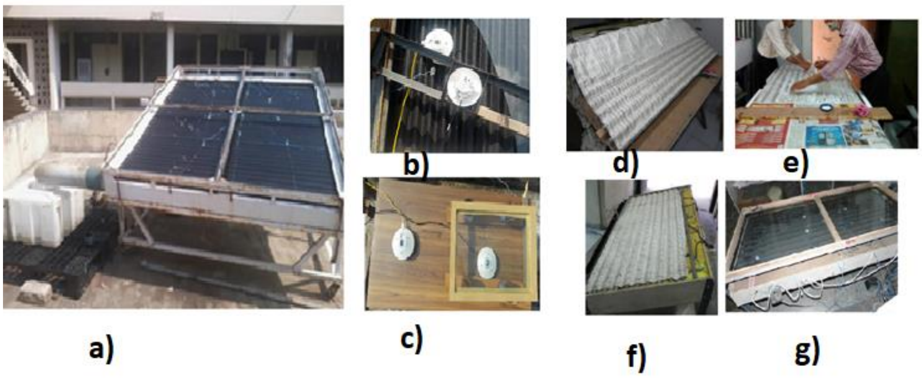

Fig. 1: Solar experimental regenerator and optical and heat transfer coefficients test rig used in this study

The heat and mass transfer performance of this system was experimentally and theoretically analyzed. Experimentation is preferable over analytical evaluation. However, experimentation is tedious, labor intensive and time consuming in order to determine the transient and seasonal performance. Further weather conditions also differ from location to location across the globe. As a result, analytical solution is equally important as experimentation to decide the size of the solar regenerator as per the standard cooling load and evaporation requirement of different localities based on ASHRAE standard. However, the optical and heat & mass transfer coefficients were commonly assumed in both analytical and experimental studies (Mullick & Gupta, Hiam et al., 1992; Hawlader et al., 1993). To bring the research effort towards integrating this open type solar liquid desiccant regenerator with an air conditioning or dehumidification system, standardizing the performance estimating methods and determination unknown parameters through experimentation are important. The analytical relation developed by Collier (1979) for simulating the rate of evaporation of water per unit width (w) of the solar regenerator absorber was

$$m'_v = \frac{G_o\left[\frac{A_3}{A_2}k_2+\beta(P_{sol,o}-P_{air,o})\right]}{k_1-k_2}\exp\left(k_1.\frac{x}{G_o}\right) - \frac{G_o\left[\frac{A_3}{A_2}k_1+\beta(P_{sol,o}-P_{air,o})\right]}{k_1-k_2}\exp\left(k_2.\frac{x}{G_o}\right) + \frac{A_3}{A_2}G_o \quad (1)$$

Eq. 1 was obtained by combining energy balance (Eq. 2) and species transfer principle (Eq.3) for a solution flowing over the entire solar absorber surface and solving the relations analytically after applying the appropriate boundary conditions.

$$\eta_{opt}I - U'_L.(T-T_\infty)x - G_o\frac{dT}{dx} - h_{fg}\frac{dm'_v}{dx} = 0 \quad (2)$$

$$m'_v = \beta.\left(P_{v,sol} - P_{v,air}\right) \quad (3)$$

The total mass of water evaporated from the solar collector surface during a given interval of time (Δt) based on Collier's equation will be

$$m_{v,\Delta t,Collier} = m'_v.w.\Delta t \quad (4)$$

Three distinct categories of data are required for estimating the mass of water evaporated from liquid desiccant solutions using Eq. (1-4). These are environmental or meteorological data, solar C/R system data such 1) optical efficiency (η_{opt}) and collector heat loss factor (U'_L) which are reported in the abstract; 2) the mass transfer coefficient in the species transfer equation, and thermo-physical property data of liquid desiccant such as specific heat, energy of evaporation and vapor pressure constants which are dependent on the concentration and temperature. According to Hawlader et al. (1993) attempts to analyze the solar C/R met with rather limited success due to simplified assumptions of the heat and mass transfer parameters that deny the complexity of real problems. The experimental values of the optical and the heat & mass transfer constants of the solar C/R that would help to evaluate its actual solar energy conversion capacity and efficiency were not reported (usually assumed). In this paper, to determine the optical efficiencies, the incident solar flux , transmitted solar flux through a glass or double glass (Fig.2) and reflected solar flux from the absorber surface were measured by using three Pyranometers : Pyranometer A was directly exposed to the sun, Pyranometer B measures incident flux after transmission through a single glass or double glass or a single glass covered with 3/8 mm thick solution and Pyranometer C faces the absorber and measures the reflect solar flux (Fig.1 b & c), respectively. The calculated values of the optical efficiency, heat loss factor and convective mass transfer coefficients are reported in the abstract.

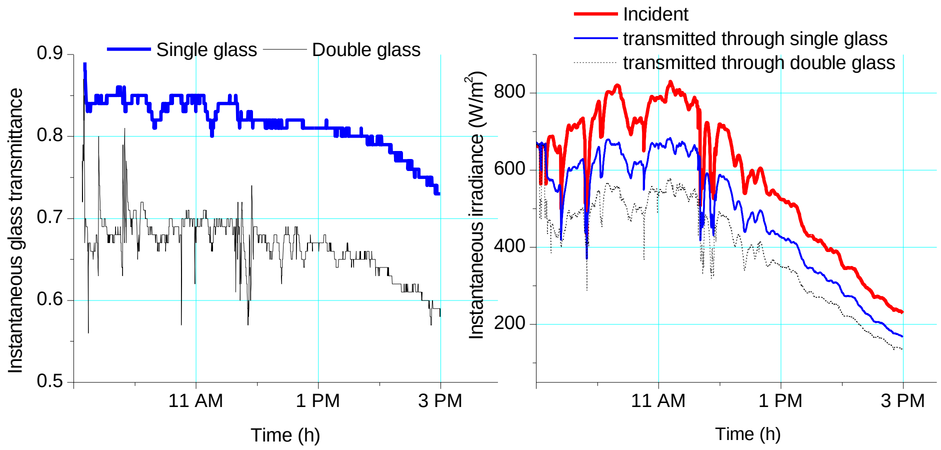

Fig.2. Variation of solar irradiance and solar transmittance coefficient of single & double glass

In the simulation study of evaporation rate of the regenerator, the simplest relation for the vapor pressure of water in the solution is approximated to be directly proportional to the solution temperature and inversely proportional to the desiccant concentration after the model introduced by Collier (1979) which is given by

$$P_{v,sol} = a\,T + \frac{b}{\xi} + c \quad (5)$$

Only Kakabaev & Khandurdyev (1969), Collier (1979), Gandhidasan (1983a/b and 1994) and Kaushik et al. (1992) have reported vapor pressure constants (a,b and c) for calcium chloride and lithium chloride solution which are not consistence in the values of the pressure constants and some of the data are missed. In addition, these constants are functional only for narrow ranges of concentration and temperature. Since, the accuracy of simulation regeneration studies depends heavily on the vapor pressure constants of water in a liquid desiccant, the vapor pressure constant of liquid desiccant should be estimated properly to evaluate the simulated regeneration performance of a solar C/R accurately. In this work, the values of vapour pressure constants for calcium chloride and lithium chloride in concentration range of 0.3 to 0.5 and 0.3 to 0.46 , respectively are generated using the correlation of vapor pressure equations of Conde (2004) and Eq, (5) and solving the resulting matrix using Matlab curve fitting tools. Table 1 shows sample values for LiCl solution.

Tab. 1: Values of vapor pressure coefficients in Eq. (6.12) for lithium chloride solution in concentration range of 0.4-0.46

Temperature (oC)	a (kPa/K)	b (kPa)	c (kPa)
[30-35]	0.0468	1.269	-16.52
(35-40]	0.0619	1.694	-22.16
(40-45]	0.08099	2.237	-29.41
(45-50]	0.1049	2.926	-38.63
(50-55]	0.1345	3.792	-50.23
(55-60]	0.171	4.869	-64.71
(60-65]	0.2144	6.172	-82.22

The evaporation flux of water from solar regenerator can also be independently estimated by using species transfer relation (Eq.6) and the total mass of water vapour evaporated from the solar regenerator in a time interval can be estimated by multiplying the mass flux with time interval and absorber area(Eq.7).:

$$m_v'' = h_m\left(\rho_{v,sol} - \rho_{v,air}\right) \quad (6)$$

$$m_{v,\Delta t} = m_v'' * A_{ab} * \Delta t \quad (7)$$

The saturated pressure at the solution surface ($P_{v,sol}$) and partial pressure of water in ambient air ($P_{v,air}$) were estimated using the correlations given by Conde (2004) and ASHRAE, (2009). Based on the analogy of heat and mass transfer relation (Incropera et al., 2011). and measured plat, glass and ventilation air temperatures of the solar regenerator, the ratio of, the convective mass transfer coefficient at the interface of the solution and the air was found to be $h_m = \frac{h_c}{1127.2}\ (\frac{m}{s})$ Other relations are also used for determining the evaporation performance of the solar regenerator based on energy conservation Eq. 8 (Tafesse et al., 2023) and conservation of desiccant mass in the solution tank Eq. 9 (Tafesse et al., 2014) :

$$m_{v,\Delta t} = \frac{\eta_{opt} I A_{ab} \Delta t - U'_L\, A_{ab}\, (T_P - T_\infty)\, \Delta t + M_{sol,t}\left(C_{P_{sol},t+\Delta t} T_{sol,t+\Delta t} - C_{P_{sol},t} T_{sol,t}\right)}{h_{fg,av} - C_{P_{sol},t+\Delta t}\, T_{sol,t+\Delta t}} \quad (8)$$

$$m_{v,\Delta t} = m_d \left[\frac{1}{\xi_{t_o+(n-1)*\Delta t}} - \frac{1}{\xi_{t_o+n*\Delta t}}\right], \text{where } n = 1,2,\ldots \quad (9)$$

The estimated evaporation rate of water by Collier equation (Eq. 1) using the optical, heat and mass transfer and vapor pressure coefficients obtained in this work is found to be in good agreement with mass of water evaporated from LiCl solution evaluated by using desiccant mass conservation (Eq.9), energy balance (Eq.8) and species transfer principle (Eq.7) as shown in Fig. 3.

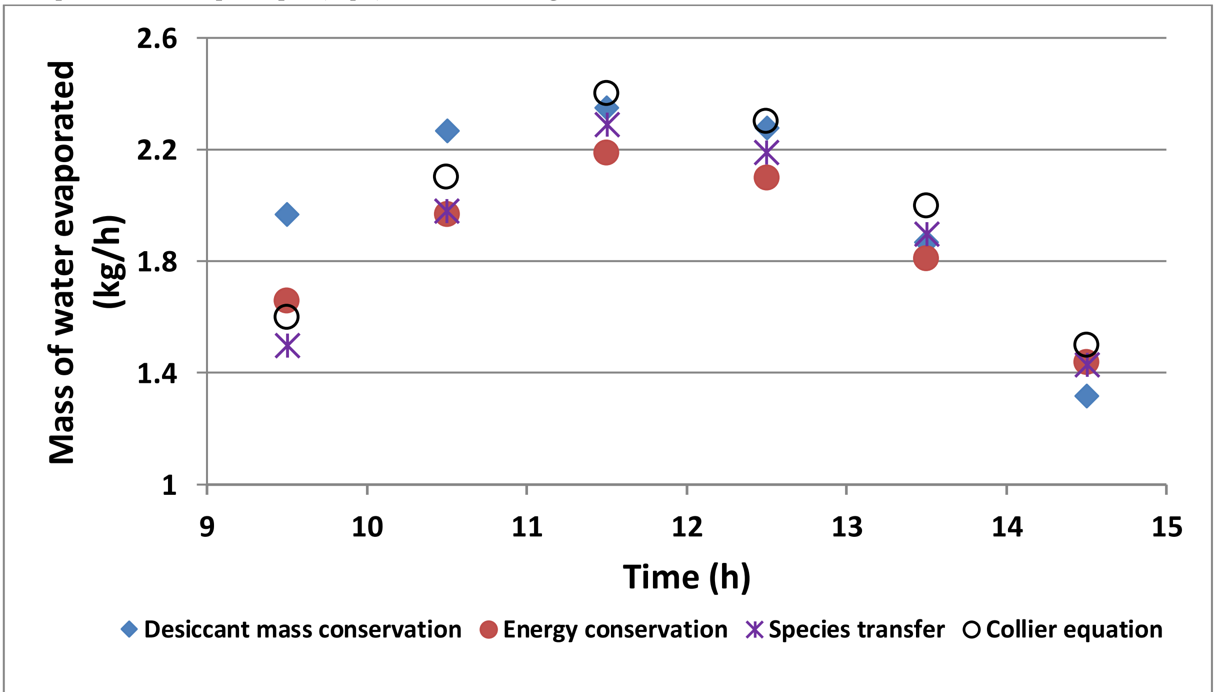

Fig. 3: Analytical and experimental mass transfer performance of a liquid desiccant solar regenerator