Application of Solar Energy for Regeneration of liquid Desiccant Using Rotating Tilted Wick

Ahamed M. Hamed, El-Shafei B. Zeidan, Ali S. Alosaimy, and Talal K. Kassem

***Abstract*—In the present work, a rotating tilted wick, which is made of a double layer cotton-cloth, has been used as a desiccant regenerator. Calcium chloride solution is applied as the working desiccant. The wick surface, which is impregnated with the desiccant solution, moves between two rotating pulleys at an inclination angle of *20* degrees. The regenerated solution carried by the wick returns to the solution tank at the end of a complete cycle. Desiccant solution concentration in the tank is evaluated and recorded with time. Instantaneous as well as average values of the mass transfer coefficient are evaluated from the experimental measurements. Mathematical model, which can be applied for the prediction of solar radiation intensity and analysis of the proposed system, is developed. Model validation shows a good agreement between measured and predicted values of radiation. Apparent values of system coefficient of performance around *2* could be attained in the dry climate of Taif city. Finally, system operational problems are discussed and highlighted.**

***Index Terms*—**Desiccant, Regeneration, Solar Cooling, Wick

Nomenclature

A	apparent solar radiation at air mass zero, *W/m²*
a	empirical constant (Eqn. (15))
B	atmospheric extinction coefficient
b	empirical constant (Eqn. (15))
C	diffuse radiation factor
C_s	solution concentration, %
c	empirical constant (Eqn. (15))
H	specific enthalpy, *J/kg*
h	hour angle
I	solar radiation intensity, *W/m²*
i	incidence angle
L	latitude angle
m	rate of water evaporation, *kg/s*
n	day number
p	vapor pressure, *mmHg*
Q	heat rate, *W*
R	tilt factor
S	surface tilt angle
T	temperature, *°C*
Z	zenith angle

Greek Symbols

α	solar altitude angle and surface absorptivity
β	mass transfer coefficient, *kg/s.m² mmHg*
δ	declination angle
ρ_g	reflectance of the Earth's surface
τ	transmittance

Subscripts

a	air and absorbed
b	Beam
bn	beam at normal incidence
c	collector
d	diffuse
L	liquid
o	outside
max	maximum
S	solution and surface
t	total and tilted

I. INTRODUCTION

The use of air conditioning and refrigeration is increasing day by day for providing thermal comfort in residential and industrial areas. This technology requires energy consumption and is responsible for the emission of CO_2 and other green house gases such as CFCs, HCFCs, which are considered major ozone-depleting gases. Sorption based systems are promising for providing a safe alternative to CFC-based refrigeration devices. In addition, the application of renewable energy sources, Such as solar energy, is a promising option. Solar cooling is comprised of many attractive features and is one path towards a more sustainable

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energy system. Interest in utilizing solar-driven cooling systems for air-conditioning or refrigeration purposes has grown continuously. This technology, which can efficiently serve large latent loads, will greatly improve indoor air quality by allowing more ventilation as well as controlling humidity more tightly [1]. Solar energy can be used to power a solar cooling system in different ways. The solar cooling system is generally comprised of three sub-systems: the solar energy conversion system, the refrigeration system, and the cooling load. The appropriate cycle in each application depends on cooling demand, power, and the temperature levels of the refrigerated object, as well as the environment [2]. Liquid desiccants are attractive because of their operational flexibility and their capability of absorbing pollutants and bacteria. Compared to solid desiccants, they are generally regenerated at relatively lower temperature and, equally cause lower airside pressure drops. Their disadvantage is their carryover in the process air stream during the dehumidification operation. Technologically, the equipment providing air/solution contact surface (contactor) can be a wetted wall/falling film absorber, a spray chamber or a packed tower. Packed towers are subdivided into regular (structured) or irregular (random) packing ones. The liquid desiccant assisted air conditioning can achieve up to *40%* of energy savings with regard to traditional air conditioning system and those savings become even greater when the energy needed for regeneration is drawn from solar energy or waste heat sources [3-5].

The regenerator is one of the key components in liquid desiccant air-conditioning systems, in which absorbent solution is concentrated and can be reused in the system. The heat required for regenerating the weak desiccant solution is supplied into the regenerator by either hot air or hot desiccant solution. This heat can be provided by any form of low-grade thermal energy which is suitable for solar thermal applications. Solar collector/regenerator (C/R) systems can achieve liquid regeneration at lower temperatures which is suitable for buildings with high outdoor air requirements in high humidity areas [6-10]. Several solar-driven refrigeration systems have been proposed and most of them are economically justified. These systems include sorption systems containing liquid/vapor or solid/vapor absorption/adsorption, vapor compression systems, and hybrid desiccant vapor compression systems [11]. An analytical procedure for calculating the mass of water evaporated from the weak solution in the regenerator in terms of climatic conditions and solution properties at the regenerator inlet has been developed by Kakabayev and Khandurdyev [6]. Different regenerator designs have been examined and a variety of theoretical models have been employed to analyze the regeneration process [12-17].

The heat required for the regeneration process can be supplied by gas, solar or waste heat. In the case of solar energy, solar energy air or water heaters could be used for the regeneration. However, by using direct solar regenerators where the absorbent solution is itself the heat collecting fluid, the regeneration process could be made more effective. The absorber temperature may be less or equal to the collector-plate temperature. The regeneration chamber is also eliminated. Forced parallel flow type solar collector/regenerator is designed and tested by Alizadeh and Saman [18]. The results of their parametric analysis indicated that the air and solution mass flow-rates and the climatic conditions affect the regenerator performance. It was concluded that the proposed solar collector/regenerator performs satisfactorily under the summer conditions of Adelaide, Australia. The regeneration of liquid solution using cross flow of air stream with flowing film of desiccant on the surface of a solar collector/regenerator has been investigated by Kabeel [19]. To evaluate the effect of cross flow of air stream on the performance of the unit, two identical units are constructed and tested in the same conditions of operation. The regeneration in one of the two units is free while the other unit is augmented with air blower. The absorber plate is a black cloth layer. The forced air stream, which flows across the absorber removes the moisture from the liquid solution. The results show enhancement of regeneration efficiency for the forced cross flow compared with the free one. Solar air pretreatment liquid collector/regenerator as a novel solar C/R can achieve liquid regeneration in lower temperature, which is suitable to be employed in the high humidity area is presented in [20]. The heat and mass transfer process was simulated in that liquid regenerator. It has been concluded that the increment of solution outlet concentration increases *70%*, regeneration efficiency augments *45.7%* and storage capacity increases 44% as effective solution proportion falls from *100%* to *62%*. The system of solar air pretreatment C/R shown in figure 1, is composed of air cycle and solution cycle. The air cycle consists of blower, air pretreatment unit and the solar C/R. The air cycle is an open cycle, where air flows into the air pretreatment unit where it contacts with low temperature strong solution and iso-enthalpy dehumidification process takes place. Air then flows into the solar C/R in which the air is heated and humidified through

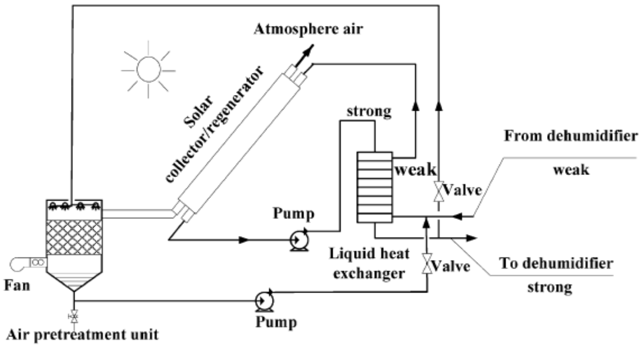


Fig. 1. Schematic diagram of solar air pretreatment collector/regenerator [20].

heat and mass transfer with high temperature diluted solution, finally is ejected to atmosphere.

The solution cycle is consisted of antisepsis solution pump, air pretreatment unit, collector/regenerator and liquid heat exchanger. The diluted solution out of the air pretreatment unit and the dehumidifier enters liquid heat exchanger where it is firstly heated by the strong solution leaving from the collector/regenerator. Then the solution is delivered by antisepsis solution pump into the solar collector/regenerator where the water in the solution is removed by air stream and the solution is regenerated, later comes back to the liquid heat exchanger preheating the cold diluted solution, finally flows into the dehumidifier and air pretreatment unit, respectively, where the solution is diluted by absorbing water vapor in air stream. In this way, a close circulation of dilution, regeneration and once more dilution is constructed. According to whether the flow directions of solution and air stream in the C/R are the same, or not, the novel solution C/R is divided into two working modes of parallel current and countercurrent. The air stream coming from outside is forced by blower. The effects of changing five key variables on the performances of this novel liquid desiccant air-conditioning system have been studied. Increasing the inlet solution temperature in regenerator can improve the system's performance, but it is also restricted by the crystallization limit of desiccant solution. The appropriate mass fluxes of air in the dehumidifier and the regenerator should be accommodated to get this liquid desiccant system performance better [21].

Theoretical and experimental investigation on the application of flat plate solar water heater coupled with air humidifier for regeneration of liquid desiccant has been presented in [22]. The heated water from the storage tank of the solar heating system is circulated in a finned tube air heater. Hot air from the air heater is blown through a packing of a honeycomb type for the purpose of regeneration of calcium chloride ($CaCl_2$) solution. The system comprises a solar water heater with storage tank connected to the air/water heat exchanger. Hot air from the heat exchange is blown to the air humidifier, which functions in this study as a regenerator. Calcium chloride solution is applied as the working desiccant in this study. One of the experimental problems in the application of open solar regenerator is the irregular distribution of the liquid stream on the surface of the regenerator which reduces the effective regeneration area.

A complete impregnation of the regenerator surface could be attained if the wick surface of the regenerator is immersed in a solution tank, which is the main feature of the present design. This work offers a solution for weaknesses of common method with a proposed novel method to regenerate the liquid desiccant in the open solar regenerator system.

II. CLIMATIC CONDITIONS OF TAIF AREA

The area of study is located at the western of Saudi Arabia (see Fig. 2.). In general, the climate of Taif is worm desert for most climatic classification and it is considered as dry climate because rainfall is less than *10* inch. Also, the humidity is less than *40%* for most months. The temperature history of Taif for *7* days is shown in Fig. 3. Also, the dew point for these seven days is demonstrated in Fig. 4.

In the climatic conditions of Taif city, it has been observed that the vapor pressure in air is relatively low. Regeneration of calcium chloride can be carried out such that the solution concentration can reach the crystallization limits at ambient temperature of *25 ºC*. However, the regeneration process can be enhanced by increasing the evaporation area. In the case of hot and dry conditions of ambient air, application of ventilation system will decrease the humidity of closed spaces such as supermarkets and class rooms but the temperature of the conditioned space will increase. Application of absorption air conditioning from such conditions is expected to be most effective compared with vapor compression systems.

Fig. 2. Map of Saudi Arabia showing the location of Taif.

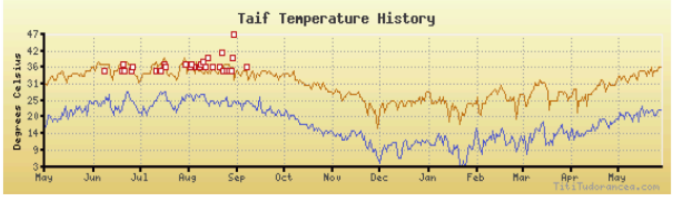


Fig. 3. Temperature history for Taif area.

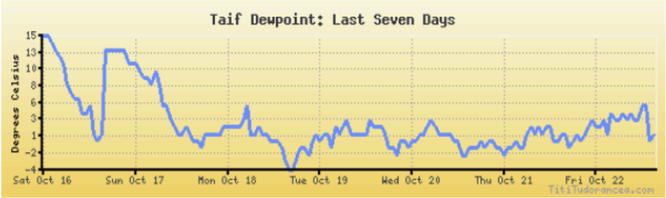


Fig. 4. Dew point temperature for Taif for seven days.

III. THE PROPOSED OPEN SOLAR REGENERATOR

Fig. 5. demonstrates the principles of operation of the open absorption cooling system when a rotating wick is applied as a solar regenerator. Detailed description of the operation of the open absorption cooling cycle can be found in the literature [6, 23]. The weak absorbent solution is heated and subsequently concentrated in the solar regenerator. In the proposed design, the regenerator comprises a rotating blackened-wick surface which rotates between the upper and lower pulleys carrying the solution from tank and returns with regenerated solution as shown in figure. The strong regenerated solution leaves the collector and passes through a liquid column, to allow the strong solution to go from atmospheric pressure to reduced pressure efficiently. The strong solution then passes through a regenerative heat exchanger on its way to the absorber, where the strong solution absorbs water from the evaporator, maintaining the reduced pressure required with the energy supplied by heat from the cold space. The resultant weak solution is pumped from the absorber back to atmospheric pressure through the regenerative heat exchanger and the collector, completing the cycle.

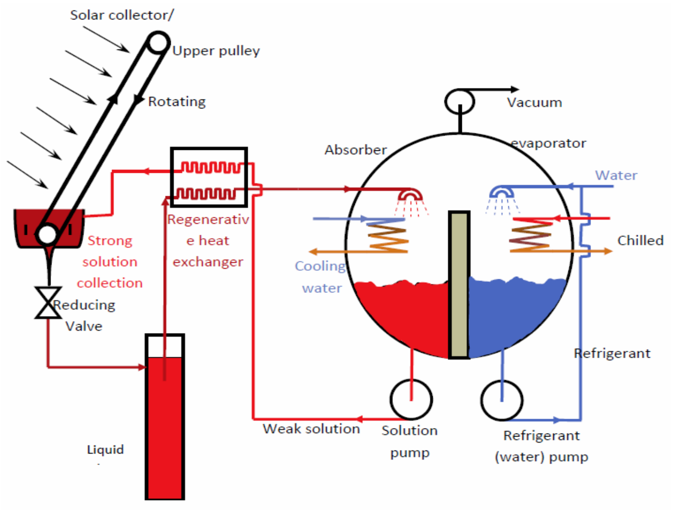


Fig. 5. The Proposed open absorption regeneration system using a rotating wick.

IV. MATHEMATICAL MODEL

A. Solar radiation model

The total radiation incident on a tilted surface could be evaluated in terms of the location, day of the year and time of the day. The total perceived solar radiation can be estimated by the following relationship:

$$I_t = R_B I_B + C I_{Bn}\left(\frac{1+\cos s}{2}\right) + \left(I_B + I_d\right)\rho_g\left(\frac{1-\cos s}{2}\right) \qquad (1)$$

where, I_B is beam radiation on a horizontal surface, R_B is beam radiation tilt factor, I_{Bn} is beam radiation at normal incidence, W/m^2, I_d is the diffuse sky radiation, W/m^2, C is diffuse radiation factor, S is the surface tilt angle, ρ_g is solar reflectance of the Earth's surface. The three terms in the above equation represent the direct, diffuse, and reflected components, respectively.

The terrestrial beam radiation within the atmosphere and on the earth's surface on a typical clear day is calculated using the following relation:

$$I_{Bn} = A\exp\left(\frac{-B}{\sin\alpha}\right)$$

(2)

where, A is an empirically determined constant which represent the apparent solar radiation at air mass zero, W/m^2, B is an apparent atmospheric extinction coefficient and α is the solar altitude angle. The altitude angle α can be evaluated from the following expression:

$$\sin\alpha = \sin L \sin\delta + \cos L \cos\delta \cos h$$

(3)

where L, δ, h are the latitude, declination and hour angles, respectively. The declination angle δ can be calculated as a function of the day number, n as:

$$\delta = 23.45\sin\left[\frac{360}{365}(284+n)\right]$$

(4)

The hour angle is defined by

$$h = \pm\frac{1}{4}(No.\ of\ \min\ from\ local\ solar\ noon)$$

(5)

where the value of h is assumed positive in the after noon period.

In Eqn. (1), the diffuse solar radiation is estimated from:

$$I_d = CF_{ss} I_{Bn}$$

(6)

where, $F_{ss} = 0.5(1 + \cos S)$ is the angle factor between the surface and the sky, and S is the tilt angle of the solar collector. The beam radiation tilt factor R_B is defined by:

$$R_B = \frac{I_{Bt}}{I_B} = \frac{\cos i}{\cos z}$$

(7)

where I_{bt}, I_B are the beam radiation on a tilted surface and on the horizontal surface, respectively. The incidence angle, i, and zenith angle, Z, are calculated from the following expressions,

$$\cos i = \sin(L-s)\sin\delta + \cos(L-s)\cos\delta\cos h \qquad (8)$$

$$\cos z = \sin\alpha$$

(9)

The day length, which is the period from sunrise to sunset, can be evaluated from,

$$daylength = \frac{2}{15}\cos^{-1}(-\tan L \tan \delta)$$

(10)

The solar radiation absorbed by the solution in the wick surface can be obtained from,

$$I_a = I_t \alpha$$

(11)

where α is the regenerator absorptivity and I_a is the absorbed solar radiation.

B. *Wick regenerator model*

A schematic representation of the upward moving wick regenerator is shown in Fig. 6. The regenerator employs an inclined flat blackened wick surface over which is impregnated with absorbent solution to be concentrated. Due to absorption of solar energy by the wick and the mass transfer potential between the desiccant and the ambient air, water evaporates from the liquid surface to the atmospheric air.

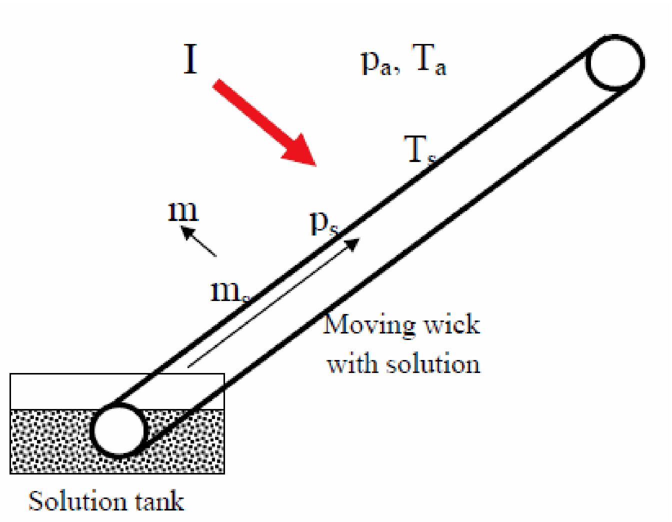


Fig. 6. Physical model of upward moving wick regenerator.

The wick surface is divided into a large number of equal segments of width *dx* with the assumption of constant properties within the segment (air vapor pressure, p_a, and temperature, T_a, and vapor pressure on the solution surface, p_s, temperature, T_s, and concentration, C_s). The main equations include the energy balance and mass balance for each segment of the open-cycle regenerator. These equations are summarized as follows :

Energy balance for the regenerator-segment:

$$I_a dx = m_s dH_s + U_L (T_s - T_0) dx + m h_{fg}$$

(12)

Where m_s is the mass flow rates of solution kg/s, H_s is the specific enthalpies of solution *J/kg*, *m* is the mass of evaporated water, *kg/s*, h_{fg} is latent heat of evaporation of water, *J/kg*, T_o is the outside temperature, and U_L is the overall heat loss coefficient, *W/m*^{2} *°C.*

The rate of mass transport of water vapor:

$$\frac{dm}{dx} = \beta (p_s - p_a)$$

(13)

where β is the mass transfer coefficient, *kg/ s m*^{2} *mmHg*, and the relation between the mass of evaporated water and solution flow rates is given by:

$$C_s = C_{si} /(1 - \frac{m}{m_s})$$

(14)

where C_{si} is the initial concentration of the solution at regenerator inlet.

For calcium chloride solution, the relationship between the solution temperature, concentration and vapor pressure is given by,

$$p_s = a + bT_s + \frac{c}{C_s}$$

15)

where *a*, *b* and *c* are empirical constants [18]. The regenerator performance can be evaluated by the apparent coefficient of performance. The apparent COP is defined as the ratio between the energy consumed to regenerate the water vapor o the total incident solar radiation,

$$COP = m h_{fg} / I_t$$

(16)

It must be emphasized that, when the vapor pressure in air is less than that on the solution surface, the heat required for vapor regeneration can be extracted from the surroundings, therefore values of COP can reach values higher than unity.

V. EXPERIMENTAL STUDY

In the experimental part of this study an experimental solar regenerator using rotating wick has been designed and installed to study the regeneration of calcium chloride using the proposed design. Special emphasis is placed on the analysis of the performance of the open solar regenerator as well as on the transient variation of solution concentration during the regeneration process. Fig. 7. shows a schematic of the experimental test unit. The system comprises of a blackened-wick surface which functions as a belt connecting the two rotating pulleys shown in figure. The driving motor drives the upper pulley, whereas the lower pulley is immersed in the solution tank. The wick surface which is made of double layer black cotton cloth rotates such that the upper surface of the wick is moving upward. Solution concentration in the solution tank as well as in the wick material is evaluated during the experiment. View of the experimental unit is shown in Fig. 8. The solution concentration is evaluated by measurements of solution density and temperature and using the tables of thermo-physical properties [17]. K-type thermocouples connected to a digital thermometer with a resolution of *0.1 ºC* are used for temperature measurements. A digital hygrometer having a resolution of *0.1%* is used for measuring the relative humidity. The solution concentration density is evaluated by measuring the mass and volume. A digital balance of *1 gm* resolution and *7000 gm* measuring range is used for mass measurements. An infrared thermometer is used to measure the temperatures of the moving wick. The solar radiation intensity is measured using Kipp Zonen Pyranometer model (CMP 6) which has a sensitivity of $12.62\ \mu V/W.m^2$ at normal incidence on horizontal pyranometer. Solar radiation on the horizontal surface at Taif city is measured using solar radiation pyranometer.

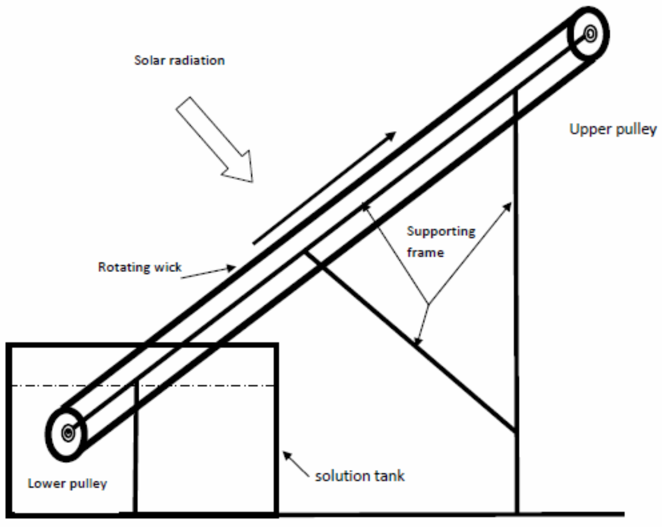


Fig. 7. Schematic diagram of the experimental test unit.

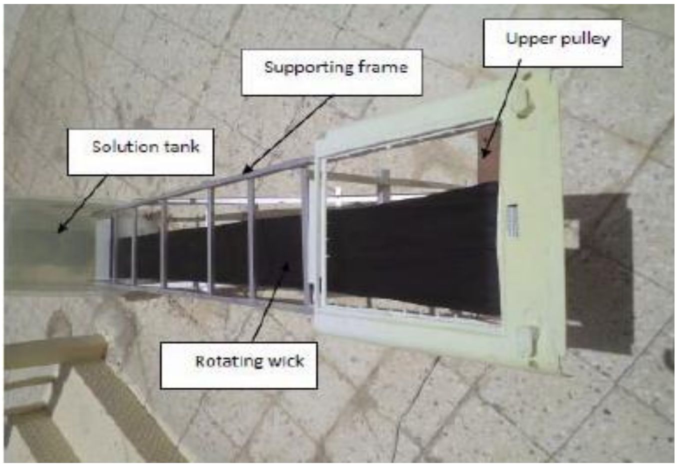


Fig. 8. View of the experimental Rotating desiccant wick.

VI. RESULTS AND DISCUSSION

To validate the solar radiation model, measured and calculated radiation data are plotted on the same graph for two days as shown in Fig. 9. It can be noticed that the measured and calculated results are close to each other and good agreement can be observed. For a regeneration period of *3* hours, solution concentration in the solution tank is evaluated and plotted against time as shown in Fig. 10. As shown in figure, it can be noticed that the solution concentration increases within this regeneration period from *20 %* to *35 %*. In the same graph, the relative mass of evaporated water is plotted. The relative mass of evaporated vapor is defined as the mass of vapor per kilogram of solution in the tank. Transient variation of the mass transfer potential, which is defined by the difference between vapor pressure on the solution surface and that in atmospheric air, can be found from the data presented in Fig. 11. It can be noticed that the vapor pressure on the surface of the solution decreases with time due to the increase in concentration. The variation in solution temperature in wick was small due to continuous impregnation of the wick with solution from the tank. The solution moves from the tank for a period of about *9* minutes (upward and downward), therefore the temperature rise of the solution during one cycle was limited to about *5 ˚C*. Average and instantaneous values of mass transfer coefficient are given in Fig. 12. An average value of mass transfer coefficient of $0.03\ kg/hr.m^2.mm\ Hg$ can be used in calculations of corresponding conditions.

To evaluate the variation of the solution concentration along the wick, a segment of the wick material is impregnated with solution and supported at an inclination angle equals *20* degree, south faced and the solution is regenerated at the open atmosphere at the conditions presented in Table 1. The weight of the wick is measured every *2* minutes. The liner speed of the wick is evaluated by measuring the distance and time for a certain point on the wick surface. By measuring the mass of solution in the wick during regeneration, the instantaneous value of solution concentration is evaluated from Eqn. (14). Experimental data of this test are presented in Table 2. Solution concentration increases with length from *42%* to *55.7%* at a distance of about 4 m. Excessive increase in solution concentration results in crystallization of solution in the wick. Therefore, the solution concentration must be limited during the regeneration process to keep the solution at liquid state.

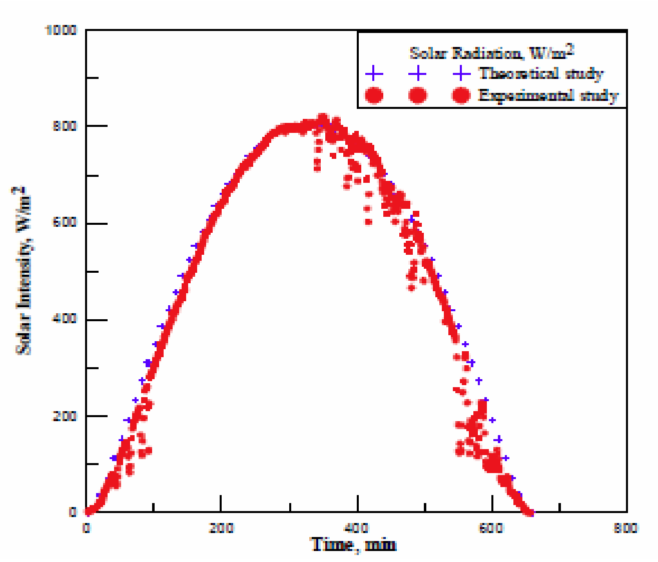
TABLE I

Measuring conditions for the regeneration test of wick segment.

Area, m2	0.2352
Initial mass of solution in the wick, gm	68
Initial concentration, %	42
Mass of wick material, gm	66
Ambient temperature, oC	30
Relative humidity, %	12.5
Average radiation intensity, W/m2	590
Average wind speed, m/s	4
Linear speed of the wick, m/min.	0.4089

TABLE II
Measured variation of solution concentration along the wick

Distance, m	Concentration, %
0	42
0.818	44.92
1.636	48.33
2.453	54.16
3.271	54.16
4.089	55.7



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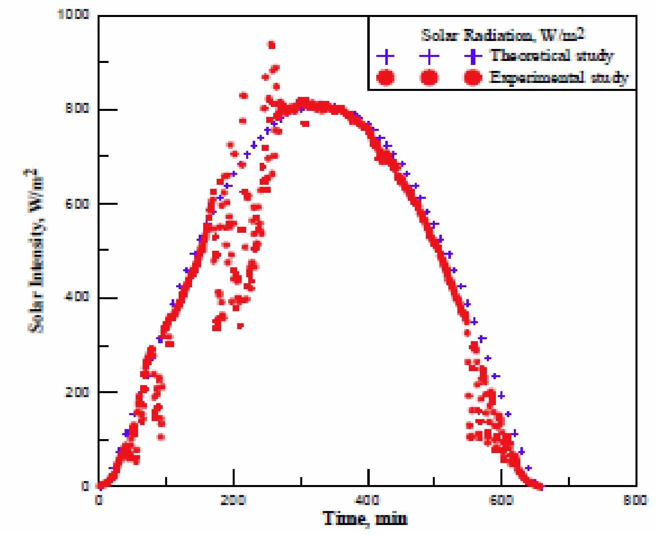

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Fig. 9. Measured and predicted solar radiation intensity for two days.

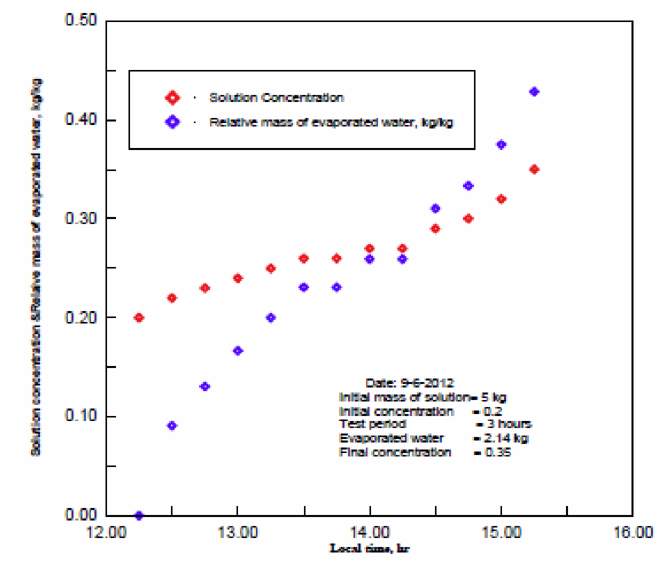

Fig. 10. Variation of solution concentration and mass of evaporated water with time during desiccant regeneration.

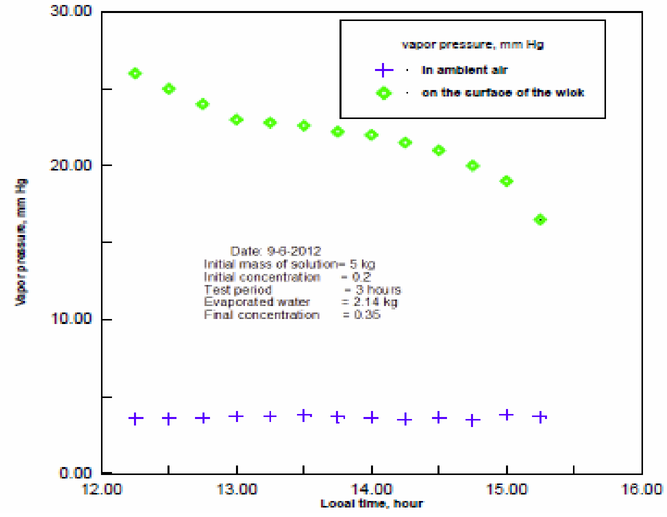

Fig. 11. Transient variation of vapor pressure with time during regeneration process.

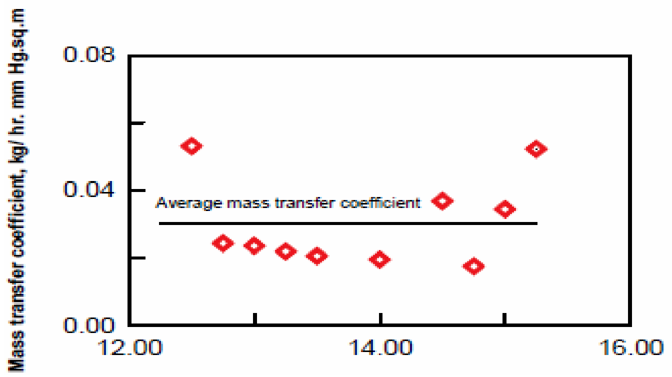

Fig. 12. Average and instantaneous values of mass transfer coefficient.

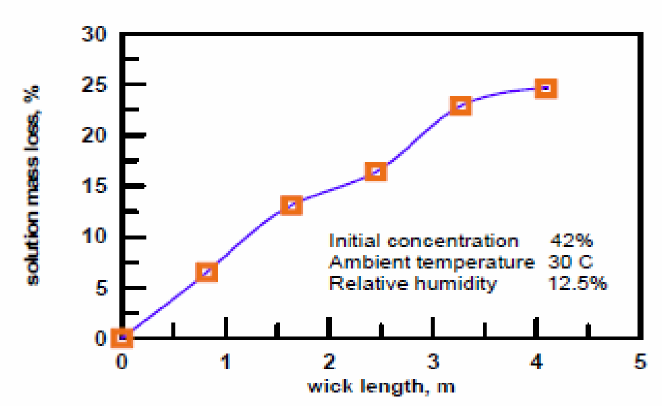

Fig. 13. Mass loss of solution along the wick length.

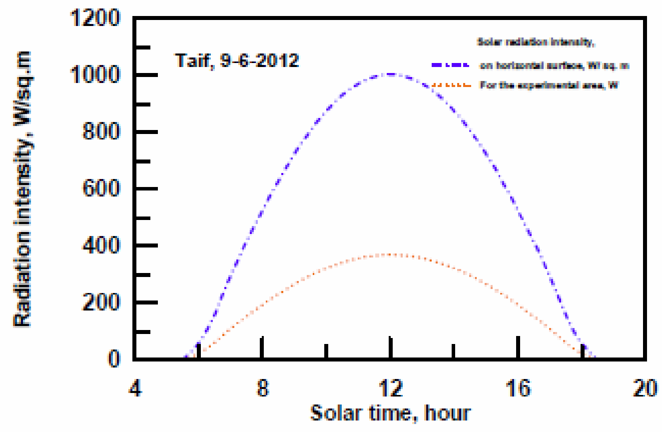

Fig. 14. Solar radiation intensity versus time.

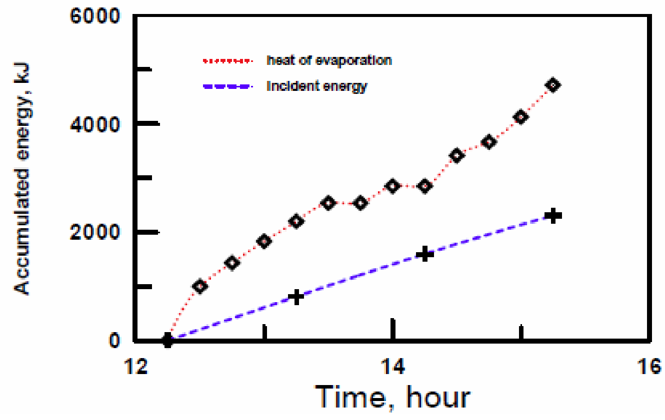

Fig. 15. Accumulated incident energy and heat of evaporation versus time.

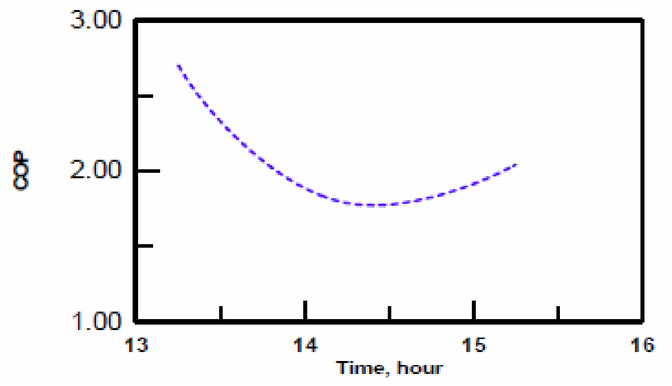

Fig. 16. Apparent value of system COP versus time.

VII. CONCLUSIONS

A novel design for solar-powered desiccant regenerator has been presented and analyzed. In the proposed design, a blackened wick-layer rotating between two pulleys is applied as solar regenerator. Experimental test unit has been designed and installed. The appropriate selection of the desiccant concentration at the end of regeneration has been discussed. Mathematical models for estimation of solar radiation on the wick surface and the system performance are developed. Regenerator coefficient of performance is defined and evaluated. Based on the obtained results, the following conclusions can be drawn:

1- For the corresponding weather conditions of Taif, values of COP higher than *2* could be attained.

2- Experimental results show that $CaCl_2$ solution can be regenerated up to *55.7%* using solar energy when a rotating wick is applied as a regenerator.

3- Measured and predicted values of solar radiation are close to each other which emphasis the validity of the solar radiation model.

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