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Extraction of Water from Atmospheric Air Using Double Slope Condensation Surface.

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Extraction of water from atmospheric air using double slope condensation surface

استخلاص المياه من الهواء الجوي باستخدام سطح تكثيف ذي ميل مزدوج

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KEYWORDS:
water extraction; air; double slope; condensation; solar; desiccant

الملخص العربي:- **هذا البحث تم دراسة استخراج المياة من الهواء باستخدام سطح تكثيف ذى ميل مزدوج حيث يتم استخدام الطاقة الشمسية كمصدر للحرارة و ملح كلوريد الكاسيوم كممتص للرطوبة . الجهاز العملى المستخدم فى تلك الدراسة عبارة عن جزئين . الجزء الاول عبارة عن جسم على شكل منشور ثلاثي مثبت عليه تسع قنوات تحتوى على خليط من الرمل ومحلول كلوريد الكالسيوم بينما الجزء الأخر عبارة عن جسم على شكل منشور ثلاثي شفاف يعمل كسطح شفاف لاشعة الشمس و تكثف المياة. يُعرَض السطح الممتص للهواء الجوى اثناء الليل حيث يمتص محلول كلوريد الكالسيوم الرطوبة من الهواء الجوي .فى وقت الشروق يتم تغطية السطح الممتص بالسطح الشفاف باحكام حيث يسمح بمرور اشعة الشمس للسطح الممتص. الماء المتكثف يتم تجميعه فى المجارى المائلة المثبتة فى الجزء السفلى للسطح الشفاف. تم قياس درجات الحرارة للسطح الشفاف وبخار الماء والسطح الممتص وتم ايضا قياس شدة الاشعاع الشمسى و كمية المياة المتجمعة لكل ساعة اثناء التجربة خلال عدة ايام. تشير القياسات العملية أن كمية المياه المكثفة تعتمد على الظروف المحيطة حيث اقصى كمية مياة تم تجميعها يوم التاسع عشر من اغسطس لعام 2015 مقدارها (735) جم/م^2. يوم مناظرة لشدة اشعاع تراكمى لليوم الواحد مقداره (7806) وات . ساعة /م^2 . تم اعداد نموذج رياضى لحساب شدة الاشعاع الشمسى وكمية المياة المتجمعه وبمقارنته بالنتائج العملية تم الوصول لنتائج متقاربة.**

***Abstract*— In this study, extraction of water from atmospheric air using double slope condensation surface is investigated. Solar energy as a heat source and Calcium Chloride (CaCl2) as the desiccant are used. The experimental apparatus involves two parts. The first part, which functions as absorber has nine channels containing mixture of Calcium Chloride (CaCl2) and sand while the second part, which functions as transparent and condensation surface has a prism shape. At night, the absorber is exposed to atmospheric air where Calcium Chloride (CaCl2) absorbs moisture from atmospheric air. At sunrise, the absorber is covered tightly with the transparent and condensation surface that allows the transmission of sun rays to the absorber. Condensate is collected in sloping channels that fixed at the bottom inner surface of transparent cover. The temperature of transparent surface, air-vapor mixture and absorber surface, solar radiations intensity and amount of collected water are recorded during the experiments at various operating days. Experimental measurements indicate that the condensed water productivity changes with ambient conditions. It is found that the maximum yield for Aug.19th,2015 was 735 gm /m2.day for accumulative solar radiation of about 7806 W.hr/m2.day. A mathematical model is developed to estimate the solar radiation intensity and amount of collected water. Its results are compared with the experimental data and a reasonable agreement between theoretical results and experimental measurements is attained.**

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I. INTRODUCTION

According to the World Health Organization, about 20% of the world's people live in the regions, which don't have enough water for their needs. In the present days, water needs for drinking, food production and agriculture are considered one of the most critical challenges facing the world. This is because of the lack and scarcity of fresh water resources, and the increasing ground water salinity. A third of the people living on the earth will likely face water shortages by 2025 with the global population increasing by 80 million every year. This threatening water crisis is linked to food production because agriculture accounts for 70% of all fresh water used, and obtaining irrigation water in dry regions using classical methods has severe environmental effects [1]. Many countries have a high solar energy potential. This high solar energy potential can be best used for water production for irrigation needs in arid regions.

In the case of Egypt, many people live in small crowded areas around the Nile Valley, which is about 5% of the total area of Egypt, where the fresh water is available. Due to lack of fresh water availability in Egypt, few people live in vast areas in the Western and Eastern Desert and Sinai Peninsula [2] where limited under-ground water resources are available. The problem of providing fresh water to these arid regions can be solved using one of the following methods [3]:

1- Transportation of water from other locations;

2- Desalination of saline water (ground and underground);

3- Extraction of water from atmospheric air.

Water transportation through these regions is usually very expensive and has a high initial cost. Also, desalination depends on the presence of saline water resources, which are usually rare in these regions. Atmospheric air is a huge and renewable reservoir of water. This endless source of water is available everywhere on the earth's surface. The extraction of water from atmospheric air has several advantages compared with the other methods. The amount of water in atmospheric air is evaluated as 14000 km^3, and the amount of fresh water in the earth is only about 1200 km^3 [4]. The suitable solution for providing fresh water in remote regions is dependent on geographical and climatic nature, extent of the ability to create the infrastructure and the required quantities of fresh water. The extraction of water from atmospheric air is one of the most suitable solutions for fresh water providing for societies that couldn't stand with the high initial cost, especially, this method can be easily co-operated with renewable energy sources such as solar energy.

There are three common methods to extract water from atmospheric air. First, cooling moist air to a temperature lower than the air dew point. Second, wet collection from fog. Third, absorbing water vapor from moist air using a solid or a liquid desiccant, with subsequent recovery of the extracted water by heating the desiccant and condensing the evaporated water. The first and third methods can use solar energy in their techniques.

The early work on extracting water from atmospheric air was published in 1947 in one of the form of a patent to get water from the atmosphere [5]. An apparatus consisting of a system of vertical and inclined channels in the earth to collect water from atmospheric air by cooling moist air to a temperature lower than its dew point has been proposed. After that, successive research has been done by different investigators to extract water from atmospheric air by cooling moist air to a temperature lower than the air dew point. For example, A. Khalil [6] investigated the process of air cooling as a possible technique for extracting fresh water from air for United Arab Emirates (UAE) climatic conditions. In addition, he indicated that the quantity of condensate yield was dependent upon different parameters, namely the proper-ties of humid air, air velocity, cooling coil sur-face area and heat exchange arrangement. Bortolini et al. [7] used gas compression refrigerator to produce drinking water through atmospheric air dehumidification. The researchers optimized the volumetric flow of the external humid air to maximize the condensed water quantity, in relation to the weather conditions (air pressure, temperature and humidity), and evaluate the energy consumption per liter of drinking produced water. At the end, they presented the implementation of the proposed approach to a case study of a residential user in Dubai, United Arab Emirates, evaluating and comparing three various control strategies: constant, hourly variable and monthly variable volumetric air flow. They suggested that the monthly variable volumetric air control strategy as the one to adopt.

There are many studies related to water extraction from atmospheric air by absorbing water vapor from moist air using a solid or a liquid desiccant, with subsequent recovery of the extracted water by heating the desiccant and condensing the evaporated water. For instance, Hall [8] proposed a system to produce water from atmospheric air by absorption using ethylene glycol as a liquid desiccant with subsequent recovery in a solar still. The researcher studied the influences of humidity and temperature on the recovered water and presented the results in the form of a composition-psychometric chart. Hamed [9] tested two methods for water extract from atmospheric air using solar energy. The first method was based on cooling moist air to a temperature lower than the air dew point using solar absorption cooling system. The second method was based on the moisture absorption from atmospheric air during the night using Calcium Chloride ($CaCl_2$) solution as a liquid desiccant, with subsequent recovery of absorbed water during the day. He recommended that the second method is most suitable application of solar energy for water recovery from air. Abualhamayel and Gandhidasan [10] used a suitable liquid desiccant for fresh water ex-traction from the humid atmosphere. The daytime moisture desorption and the nighttime moisture absorption took place in the same unit. By solving the energy balance equations, the researchers computed analytically the unit performance for typical summer climatic data for August month in Dhahran, Saudi Arabia. For the given operating conditions, the produced water was about 1.92 kg per m^2 of the unit. Gad et al. [11] applied the solar desiccant/collector system to produce 1.5 liter of fresh water/day.m^2 from atmospheric air. Their system had three parts: an air-cooled condenser consisting of two parallel flat plates, a corrugated bed and a flat plate collector with a movable glass cover. Kabeel [12] explored the glass pyramid shape capability with a multi-shelf solar system for water extraction from humid air. The researcher used two pyramids with various types of beds on the shelves. He investigated experimentally the system at various climatic conditions to study the pyramid shape effect on the absorption and regeneration processes. He found that the cloths bed absorbed more solution (9 kg) as compared to the saw wood bed (8 kg). The produced water amount was 2.5 liter/day.m^2. The pyramid shape with four glass surfaces and multi-shelves enhanced the produced water by 90-95% compared with solar desiccant/collector system with horizontal and corrugated beds. Hamed et al. [13] used the solar energy to heat a sandy bed impregnated with Calcium Chloride ($CaCl_2$) for water recovery from atmospheric air. The researchers evaluated the influences of various parameters on the system productivity during regeneration. For this purpose, the researchers designed and installed an experimental unit in climatic conditions of Taif area, Saudi Arabia. The experimental unit that had a surface area of 0.5 m^2, comprised a solar/desiccant collector unit containing sandy bed impregnated with Calcium Chloride ($CaCl_2$). Measurements show that about 1.0-liter pure water/m^2 could be regenerated from the desiccant bed at the climatic conditions of Taif. Liquid desiccant with initial concentration of 30% could be regenerated to a final concentration of about 44%.

The aim of the present experimental and theoretical study is to investigate the effect of different operating parameters (solar radiation intensity, ambient temperature and bed configurations) on the performance of the water ex-traction system. For this purpose, the sand bed impregnated with a calcium chloride solution is used as absorber and solar radiation as a heat resource. A triangular prism surface is used as transparent and condensation surface which cover a bed at day-time.

II. Experimental work

In the present study, a double sloped condensation surface covering a layer of the ground surface will be applied for regeneration and condensation of water. The ground layer, which is impregnated with Calcium Chloride ($CaCl_2$) solution, will function as an absorber. For this purpose, an apparatus consists of two parts is designed and fabricated. The first part, which functions, as abed of absorber, has a triangular prism (200 cm x 37 cm x 36 cm), the bottom is covered with fiber plate (50 cm x 200 cm). Channel (11 cm x 200 cm) is fixed at the top of a triangular prism and eight channels (5 cm x 200 cm) are fixed at the main sides of the prism as shown in Fig.1. The other part which functions as transparent and condensation sur-face, has a triangular prism shape (210 cm x 65 cm x 51 cm), the sides are made of transparent acrylic as shown in Fig.2. A sloping channels which function as collector of condensate water, are fixed at the bottom of every side of condensation surface. A 0.005 m^3 of sand is distributed equally through channels and impregnated with a Calcium Chloride solution having a concentration of about 37%. The experiments are carried out at outdoor conditions on the roof of the Solar Energy Laboratory, Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University. At night, absorber is exposed to atmospheric air where desiccant absorbs water vapor from atmospheric air and becomes diluted. At the start of sunrises, the absorbing bed is covered with the condensation surface. It absorbs the incident solar radiation and, thereby, the temperature of the bed increases gradually. Evaporation of vapor from the bed occurs due to the vapor pressure difference between the solution at the bed and the condensation surface. Vapor condensate at the condensation surface which has a lower temperature.

Evaporation and condensation stop when the vapor pressure of the bed solution is equal to that of the condensation surface. Fig.3, shows the experimental apparatus through day-time where water vapor condenses on condensation surface. The experiment has been repeated every day in the periods (01-02/08/2015) and (17-21/08/2015).In these periods, it was recorded only the amount of collecting water productivity through day-time to ensure that apparatus work properly. The experiment has been repeated again in the periods (18-22/09/2015) and (13-17/10/2015). In these periods, water productivity, solar radiation intensity and temperature of bed surface, condensation surface and air gap between bed surface and condensation surface are recorded through the day-time. The previous parameters are recorded for right and left side of the apparatus. The right side faces the incident solar radiation from sunrise to afternoon and then, the left side faces it to sunset.

III. Mathematical model

A. Productivity model

The theoretical model for regeneration investigated the heat balance of the proposed system at daytime. The following assumptions are made to develop the model:

1- One-dimension heat transfer under quasi steady state condition.

2- Thermal properties of the system components are assumed constants.

3- The system is completely closed during day time operation.

4- Simultaneous condensation and evaporation processes are assumed.

The system consists of bed and cover, both in the form of a prism. The system is divided into right side, which is facing the sun at sunrise and left side, which is facing the sun in the afternoon. The daytime is divided into the time from sunrise to afternoon and the time from afternoon to sunset. The heat balance of the bed and cover are studied at each side through the day time. During the period from sunrise to afternoon, the incident solar radiation with an intensity (H) passes through the apparatus as shown by dashed lines in Fig.4. The heat balance equations of right acrylic cover in the period from sunrise to afternoon can be expressed by following relation corresponding to Fig.4.

$$C_C \frac{\partial T_{C-R}}{\partial t} = (\alpha_C * H * A_{C-R} + Q_R) - Q_{CR-a} \quad (1)$$

Where C_C is the thermal capacity of the cover and it is evaluated by the following equation:

$$C_C = m_{acry} * c_{acry} \quad (2)$$

Q_R, is the summation of heat transfer from the right bed to the right cover by conduction, radiation and evaporation;

$$Q_R = Q_{r-R} + Q_{c-R} + Q_{ev-R} \quad (3)$$

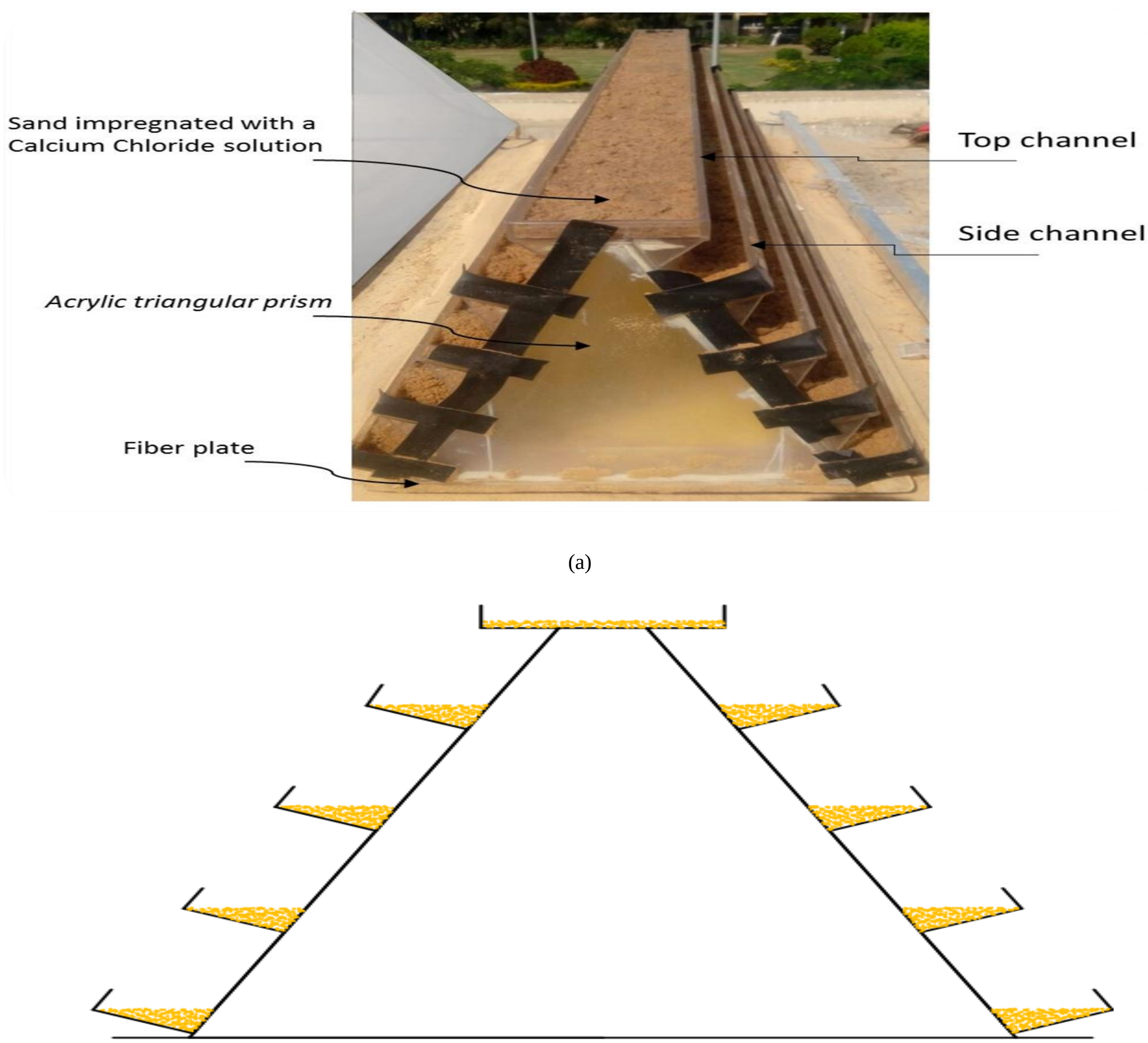
The heat transfer from the right bed to the right cover by conduction (Q_{c-R}) can be calculated by the following relation;

$$Q_{c-R} = K_a * n * A_s * \frac{T_{s-R} - T_{C-R}}{\Delta X} \quad (4)$$

Where K_a, A_b, ΔX, and T_{s-R}, are thermal conductivity of air, surface area of bed, thickness of air gab between cover and bed, and bed surface temperature at right side, respectively. The bed surface temperature at right side can be expressed in terms of average right bed temperature as follows:

$$T_{S-R} = T_{b-R} + \alpha_b * \tau_C * H \left(\frac{\delta_b}{2K_b}\right) \quad (5)$$

Where $\delta_{b,}$ and K_b, are bed thickness and bed thermal conductivity; respectively.



(a)

(b)

Fig.1. (a) Photograph of the absorbing bed; and (b) schematic diagram of the bed.

Fig .3. Photograph of experimental apparatus during the day-time.

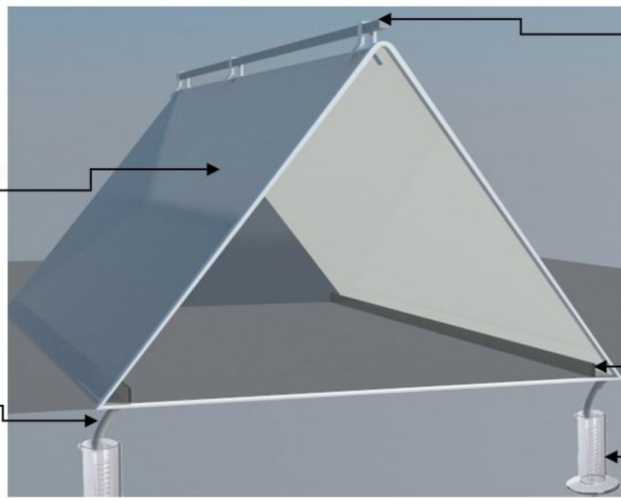


Fig.2. schematic of transparent and condensation surface

Gad et al [11] reported that dunkel's model is suitable to evaluate the heat transfer from right bed to right cover by radiation;

$$Q_{r-R} = F_{b-C} * \sigma * n * A_s * [(T_{s-R} + 273)^4 - (T_{b-R} + 273)^4] \quad (6)$$

Where F_{b-c} is the shape factor between bed and cover, and it is assumed to equal unity in this analysis;

$$Q_{ev-R} = 0.0061 \left[(T_{b-R} - T_{C-R}) + \frac{(P_{b-R} - P_{C-R})(T_{b-R} + 273)}{(0.265 - P_{b-R})} \right]^{\frac{1}{3}} * (P_{b-R} - P_{C-R}) * L * n * A_s \quad (7)$$

Where, P_{b-R}, P_{C-R} are partial pressure of water vapor at the right bed surface and cover, respectively. The partial pressure of water vapor at the cover can be assumed to be saturation pressure of water vapor corresponding to a right cover temperature which can be calculated by the following equation;

$$\log p = [-3.21254 + 3.13619 * 10^{-2} * T - 1.22512 * 10^{-4} * T^2 + 3.63841 * 10^{-7} * T^3 - 5.67607 * 10^{-10} * T^4] \quad (8)$$

The partial pressure of water vapor at the right bed (p_{b-R}) can be calculated as a function of solution concentration and average bed temperature in the unit of (mmHg) within a temperature range from 10°C to 65°C and concentration from 20% to 50% according to the following relations [3];

$$\ln p_{b-R} = A(X) - \frac{B(X)}{T_b + 111.96} \quad (9)$$

Where, A (X) and B (X) are regression parameters, which can be expressed in terms of solution concentration;

$$A(X) = 10.0624 + 4.4674X \quad (10)$$

$$B(X) = 739.828 + 1450.96X \quad (11)$$

For a temperature range from 60 °C to 100 °C, the partial pressure of water vapor at the bed can be calculated by the following equation;

$$ln\ p = A - \frac{B}{T + 273} \quad (12)$$

A and B, are defined in terms of concentration as given by [11]. The concentration of solution can be expressed as the ratio of mass of dry salt ($m_{d.s}$) to the total mass of solution (m_{sol}), which equals the summation of the mass of water and mass of dry salt;

$$X = \frac{m_{d.s}}{m_{sol}} \quad (13)$$

$$m_{sol} = m_{d.s} + m_w \quad (14)$$

The mass of dry salt can be expressed as a product of the concentration and mass of a solid salt.

$$m_{d.s} = X_{s.s} * m_{s.s} \quad (15)$$

The instantaneous value of a mass of solution can be calculated from the following equation;

$$m_{sol(i)} = m_{sol(i-1)} - m_{evap(i)} \quad (16)$$

Where m_{evap} is the mass of vaporized vapor from solution and the subscripts (i) and (i-1) refer to the instantaneous and previous values, respectively.

$$m_{evap} = \frac{Q_{ev-R}}{L} \quad (17)$$

The initial value of solution at start of experiment can be calculated as a function of initial concentration of solution:

$$m_{sol(0)} = \frac{m_{d.s}}{X_0} \quad (18)$$

Where X_o, is an initial concentration of solution which can be calculated as expressed in [2] by;

$$X_0 = \frac{[lnp_v - (a_o - \frac{b_o}{T_b + 119.6})}{(a_1 - \frac{b_1}{T_b + 119.6})} \quad (19)$$

where: a_o=10.0624 b_o= 739.828 a_1=4.4674 b_1=1450.96

p_v, is a water vapor pressure which can be assumed to equal a saturation pressure of water vapor corresponding to ambient air temperature (Ta) at start of experiment as given in Eq.(8).

$$Q_{CR-a} = h_{c-a} * A_c(t_{C-R} - t_a) + F_{c-sky}\sigma A_c[(t_{C-R} + 273)^4 - (t_a + 273)^4] \quad (20)$$

Where, $F_{c\text{-}sky}$ is the shape factor between the cover and surroundings and it is considered equal unity. A_C, is the surface area of right cover. $h_{c\text{-}a}$ is the heat transfer coefficient between cover and ambient air and it can be expressed as a function of wind speed as evaluated by Mac Adam's relation as follows [3]:

$$h_{c-a} = a + bv^n \quad (21)$$

Where, a, b and n are constants equal 5.61, 1.09 and1, respectively, and "v" is a wind speed in (m/s). Referring to Fig.4, the right bed heat balance can be expressed in the period from sunrise to afternoon as follows:

$$C_{b-R}\frac{\partial T_{b-R}}{\partial t} = (\alpha_b * \tau_C * H * n * A_s) - (Q_R + Q_r + Q_c) \quad (22)$$

Where, $C_{b\text{-}R}$ is the thermal capacity of the system in the right bed, which consists of sand, $CaCL_2$ salt, acrylic bed and water .It can be calculated by the sum of mass and specific heat product of system elements as given in the following relation;

$$C_{b-R} = m_{C-R} * c_{acry} + m_{W-R} * c_W + m_{sand-R} * c_{sand} + m_{CaCL_2-R} * c_{CaCL_2} \quad (23)$$

Heat transfer by conduction (Q_c) and by radiation (Q_r) from the right bed to the left bed can be expressed by;

$$Q_c = K_a * n * A_{s.b} * \frac{T_{b-R} - T_{b-L}}{d} \quad (24)$$

$$Q_r = \sigma * n * A_{s.b} * [(T_{b-R} + 273)^4 - (T_{b-L} + 273)^4] \quad (25)$$

Referring to Fig.4, the left cover heat balance can be expressed in the period from sunrise to afternoon as follows:

$$C_C\frac{\partial T_{C-L}}{\partial t} = (\alpha_C * \tau_C{}^3 * H * A_C + Q_L) - Q_{CL-a} \quad (26)$$

Where, Q_L, is the summation of heat transfer from the left bed to the left cover by conduction, radiation and evaporation.

$$Q_L = Q_{r-L} + Q_{c-L} + Q_{ev-L} \quad (27)$$

$Q_{c\text{-}L}$, $Q_{r\text{-}L}$, $Q_{ev\text{-}L}$, and $Q_{Cl\text{-}a}$, can be calculated by modifying the parameters of a previous equations from (4) to (20) from right side to left side. Referring to Fig.4, the left bed heat balance can be expressed in the period from the sunrise to the afternoon as follows:

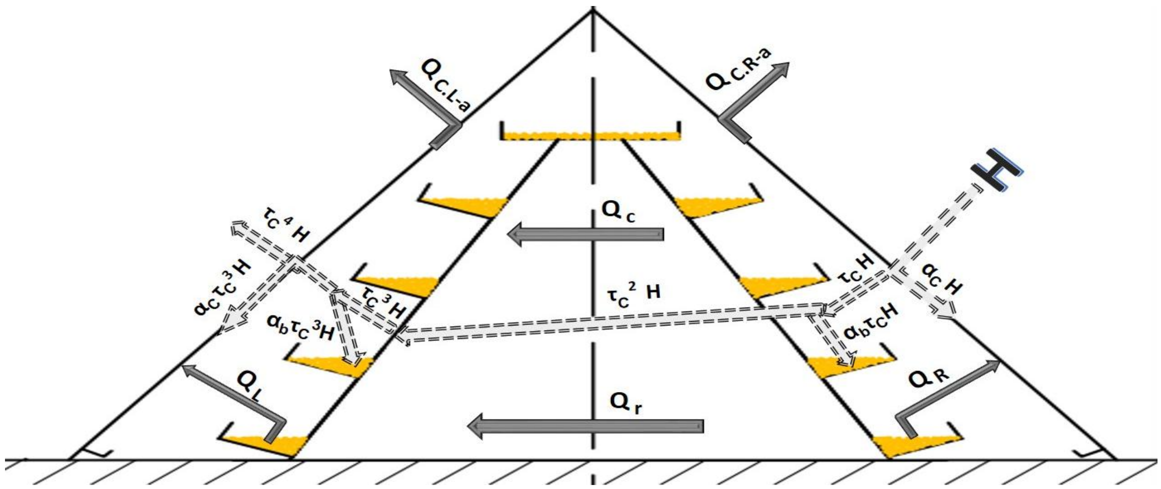


Fig .4. Energy flow diagram from sunrise to afternoon for proposed system.

$$C_{b-L}\frac{\partial T_{b-L}}{\partial t} = (\alpha_b * \tau_C{}^3 * H * \mathrm{n} * A_s + Q_r + Q_c) - (\mathrm{Q}_L) \quad (28)$$

$$C_{b-L} = m_{C-L} * c_C + \mathrm{m}_{\mathrm{W-L}} * \mathrm{c_W} + \mathrm{m}_{\mathrm{sand}} * \mathrm{c_{sand}} + \mathrm{m}_{\mathrm{CaCL_2}} * \mathrm{c_{CaCL_2}} \quad (29)$$

During the period from afternoon to sunset, the incident solar radiation with an intensity (H) path change to direct from left to right side and the heat balance equation of the cover and bed on the left and right side during this period can be expressed by the following relations;

$$C_C\frac{\partial T_{C-R}}{\partial t} = (\alpha_C * \tau_C{}^3 * H * A_C + Q_R) - Q_{cR-a} \quad (30)$$

$$C_C\frac{\partial t_{C-L}}{\partial t} = (\alpha_C * H * A_C + Q_L) - Q_{cL-a} \quad (31)$$

$$C_{b.R}\frac{\partial t_{b-R}}{\partial t} = (\alpha_b * \tau_C{}^3 * H * \mathrm{n} * A_s) - (Q_R + Q_r + Q_c) \quad (32)$$

$$C_{b.L}\frac{\partial T_{b-L}}{\partial t} = (\alpha_b * \tau_C * H * \mathrm{n} * A_s + Q_r + Q_c) - (Q_L) \quad (33)$$

Amount of water evaporated from every bed can be calculated by equations;

$$\dot{m}_{evap-R(i)} = \frac{Q_{ev-R(i)}}{L} \quad (34)$$

$$\dot{m}_{evap-L(i)} = \frac{Q_{ev-L(i)}}{L} \quad (35)$$

If $t_{b\text{-}R} > t_{b\text{-}L}$

$$V_T = \sum_{i=1}^{z} \frac{Q_{ev-\mathrm{R}(i)}}{L} * \left(\frac{A_C}{\mathrm{A_{cond}}}\right) \quad (36)$$

If $\mathbf{t}_{\mathbf{b\text{-}R}} < \mathbf{t}_{\mathbf{b\text{-}L}}$

$$V_T = \sum_{i=1}^{z} \frac{Q_{ev-\mathrm{L}(i)}}{L} * \left(\frac{A_C}{\mathrm{A_{cond}}}\right) \quad (37)$$

Where, $\frac{A_C}{\mathrm{A_{cond}}}$ is the ratio of the cover surface area to the total condensation surface area including the area of the cold side of the bed. This ratio is used as a correction factor of productivity because it is found that some of the evaporated water condenses on the bed surface with lower temperature. The system efficiency can be defined as the ratio of heat required to evaporate water (Q_{evap}) to the accumulated incident radiation (H) as follows:

$$\zeta = \frac{\sum \mathrm{Q_{evap}}}{\mathrm{H}_T} \quad (38)$$

The previous equations are solved numerically. Euler method is applied for solving the equations by taking one minute as a step through a day-time. Weather meteorological data (wind speed and ambient temperature) per minute through a day time are taken from the internet weather meteorological site [14] and used as known data. The computer program evaluates the system transient parameters; temperature of cover and bed, partial pressure of water at bed and cover, heat transfer by conduction, evaporation and radiation from bed to cover and concentration of solution at the right and left sides per every minute. Then, performance parameters; productivity, water evaporation and system efficiency are evaluated.

B. Solar radiation model

The total solar radiation incident on horizontal surface can be evaluated by the following relation;

$$H = H_B + H_d \quad (39)$$

Where H_B is a beam radiation on a horizontal surface, which can be evaluated as a function of solar altitude angle (α) and beam radiation at normal incidence (H_{Bn}) as follows:

$$H_B = H_{Bn} \sin(\alpha) \quad (40)$$

$$H_{Bn} = A \exp\left(\frac{-B}{\sin(\alpha)}\right) \quad (41)$$

Where A, and B, are apparent solar radiation at air mass zero (W/m^2) and atmospheric extinction coefficient (dimensionless), respectively. Solar altitude angle (α) can be expressed in terms of latitude (L_A), declination (δ) and hour (h) angles as follows:

$$\sin\alpha = \sin L_A * \sin\delta + \cos L_A * \cos\delta * \cos h \quad (42)$$

$$\delta = 23.45 * [\sin(\frac{360}{365} * (284 + N))] \quad (43)$$

$$h = \pm\frac{1}{4}(\text{No. min from local solar noon}) \quad (44)$$

Where the value of (h) is assumed positive from solar noon to sunset and negative from sunrise to noontime. Latitude angle is taken for our location (Mansoura, Egypt) about (31^o N). The diffuse sky radiation (H_d) in equation (38) can be calculated by;

$$H_d = C_d * H_{Bn} * f_{ss} \quad (45)$$

Where C_d and f_{ss}, are a diffuse radiation factor and angle factor between the surface and the sky, respectively.

IV. RESULTS AND DISCUSSION

Experiments have been carried out in different months (August, September and October), 2015 at different ambient conditions, which results in clear changes in the accumulative productivity. Fig.5 shows the total water productivity per day for all test days. It is clear that the month of August has the highest water productivity while the month of October has the lowest water productivity, corresponding to accumulative solar radiation intensity as shown in Fig.6.

Fig.7 shows the temperatures of condensation surface (T_C), air-vapor (T_V) and absorber bed (T_b) on the left and right sides, as well as the solar radiation for the period (15-17/10/2015). It can be noticed that the solar radiation increases gradually from sunrise to its maximum value at afternoon, then de-creased gradually as well as all temperatures increased gradually from sunrise to afternoon then decreased gradually to sunset. From sunrise to afternoon, the temperature at the right side is higher than the left side temperature where the right side faces the sun. Then, the left side faces the sunbeams and its temperature becomes higher than the right side.

Fig.8 shows a comparison between numerical and experimental results for system temperatures. It is observed that the theoretical bed temperature close to experimental bed temperature throughout the daytime except the period around noontime. Theoretical and experimental cover temperatures are close at every side except in the period from afternoon to the time before sunset when the left cover faces sun. In the period from sunrise to the time before afternoon, when the right cover faces sun, its cover temperature has some divergence in the values between experimental and numerical. The theoretical and experimental values of solar radiation intensity are shown in Fig.9.

Fig.10 shows the cumulative productivity with time. It can be noticed that numerical values of evaporated water are higher than the experimental ones. This is due to the losses of the evaporated water, which condenses on the lower temperature surfaces in the system.

It is observed from Fig.11, that evaporation heat transfer at east side is higher than west side in the period from sunrise to afternoon when the productivity at west side is more than east side. And vice versa in the period from afternoon to sunset. Also, the temperature of east bed and cover are higher than west side at the same period of high quantity of evaporation heat transfer as shown in Fig.12.

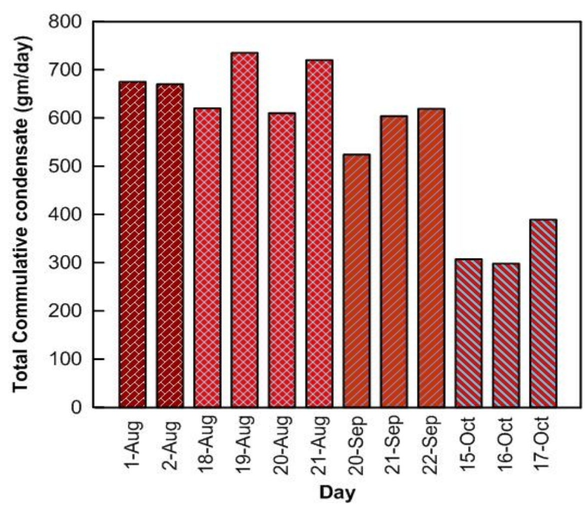


Fig.5. The accumulative water productivity per day for all test days

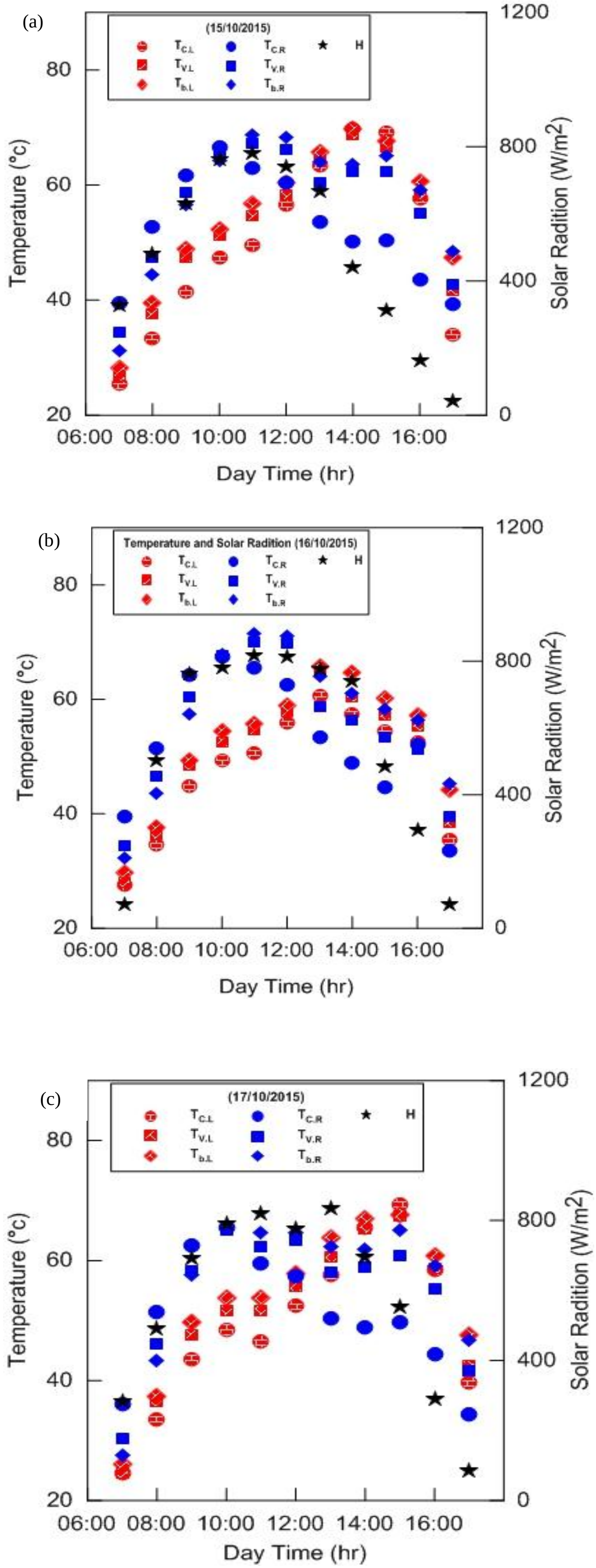


Fig.7. Experimental hourly temperature and solar radiation for the period (15-17/10/2015).

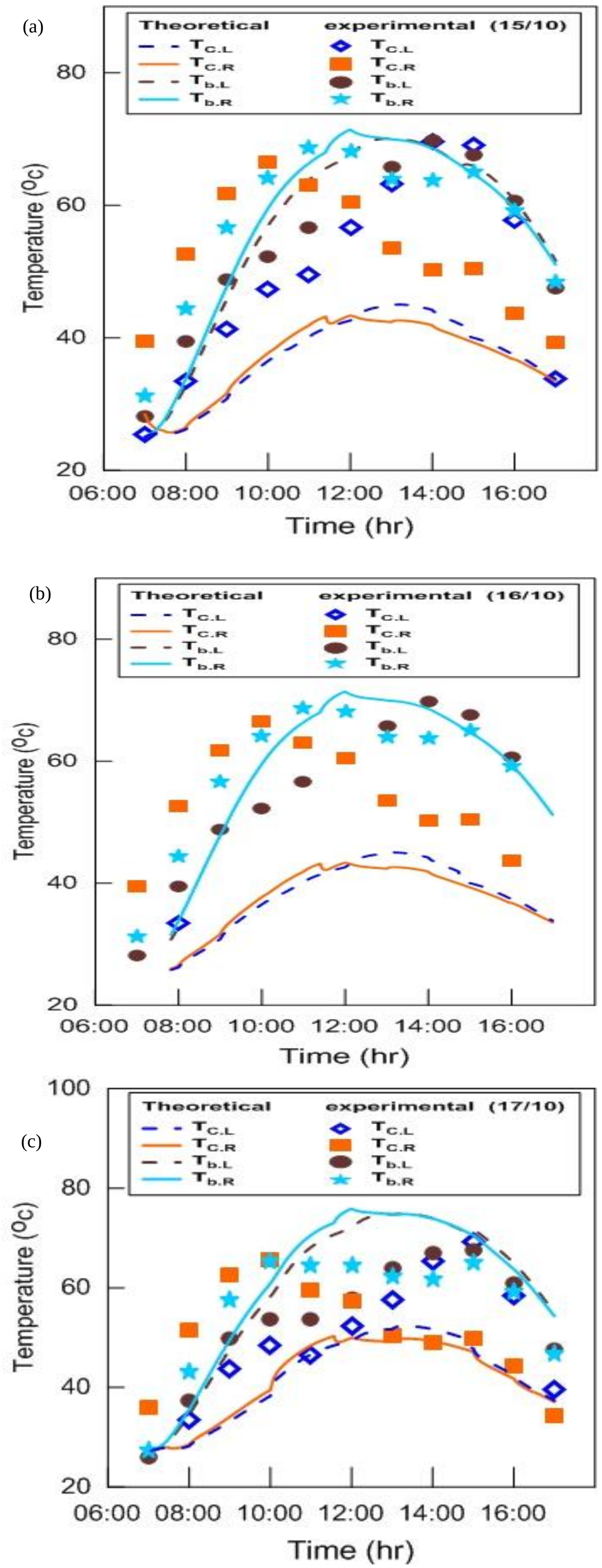


Fig .8. Comparison between theoretical and experimental temperature.

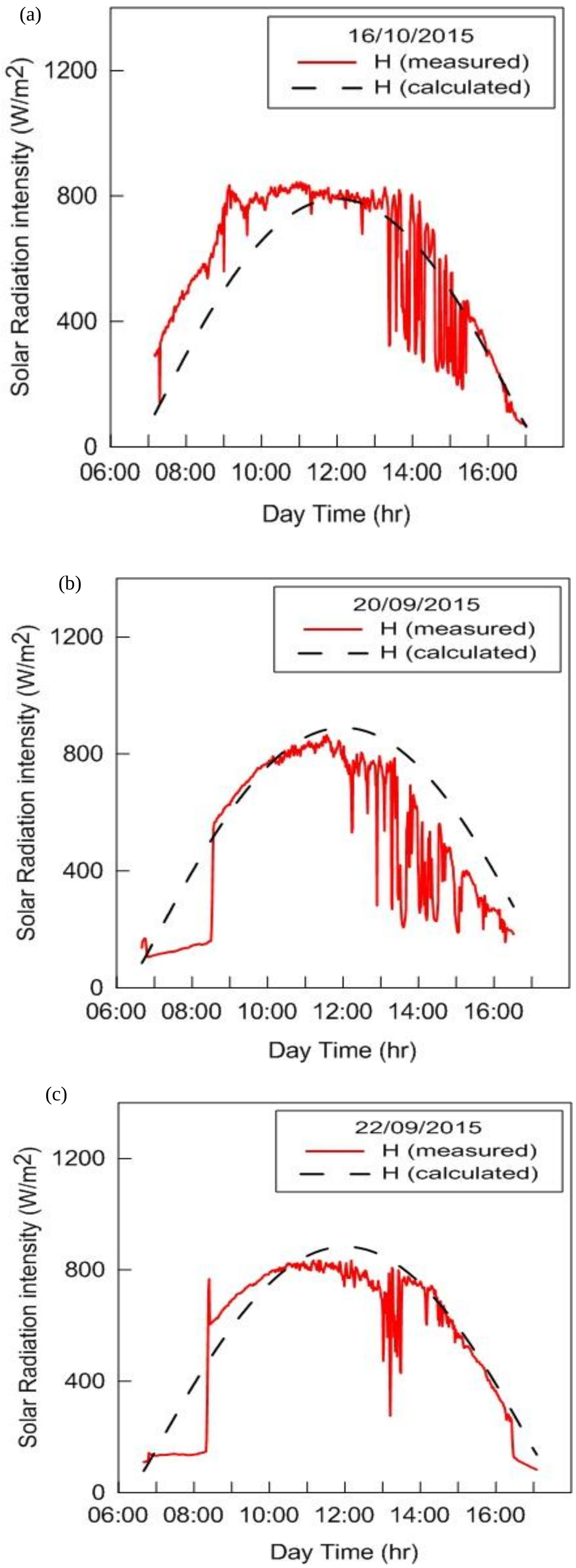


Fig.9. Comparison between theoretical and measurement solar radiation intensity.

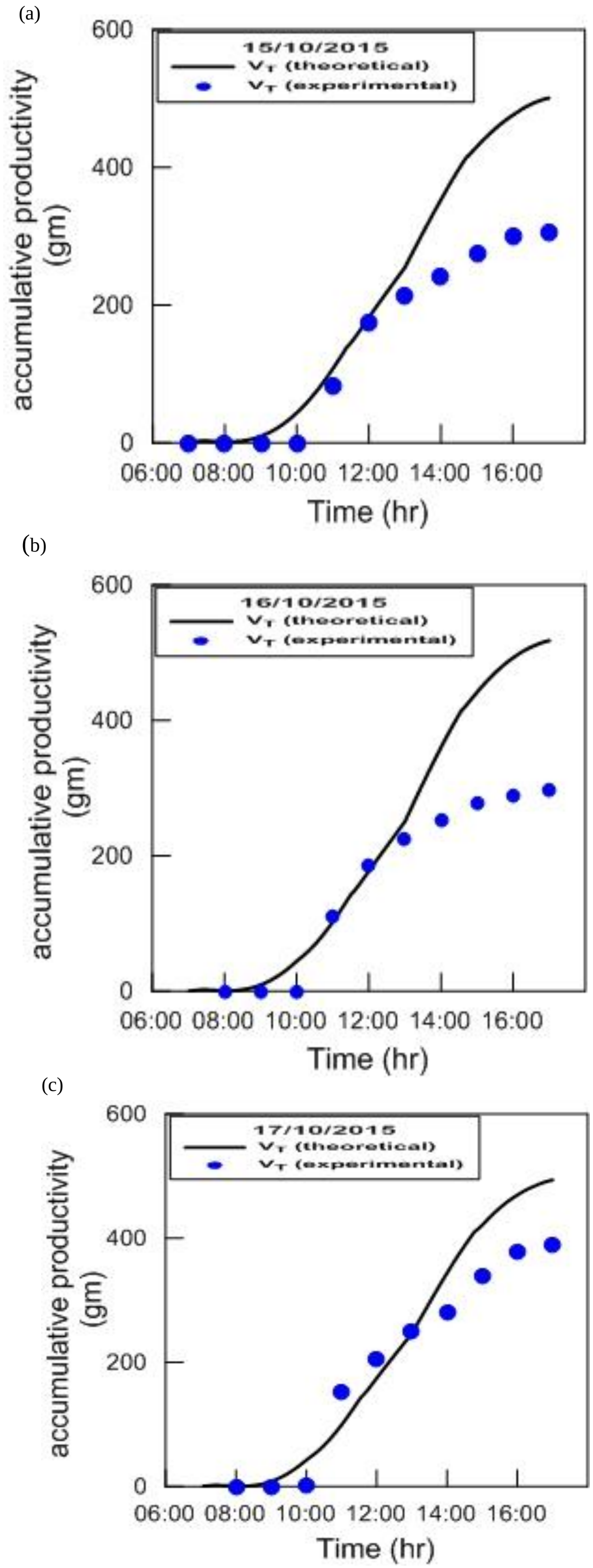


Fig .10. Comparison between theoretical and experimental productivity.

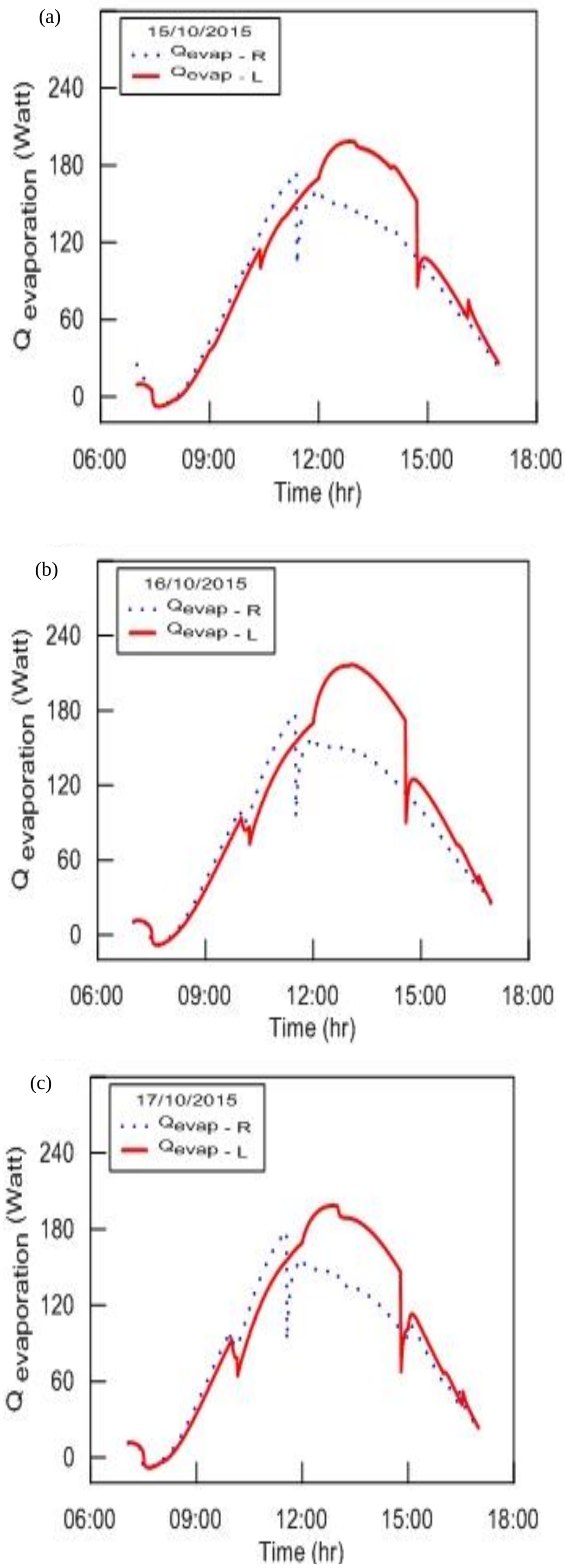


Fig.11. Comparison between heat transfer by evaporation at right and left side.

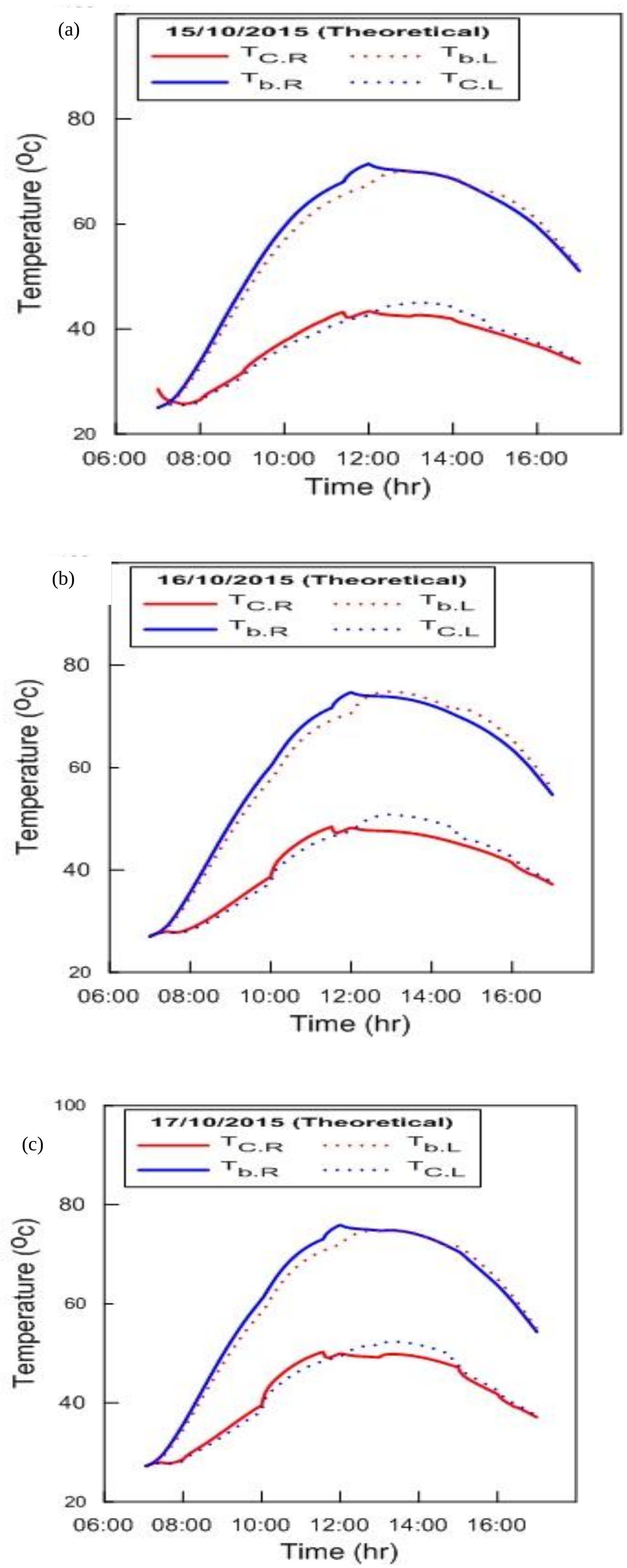


Fig.12. Theoretical temperature bed and cover at right and left side.

V. DAILY EFFICIENCY

The daily efficiency of the system is calculated by the following equation. It is observed from Fig. 13, that the daily efficiency of the system is low because of the lowering value of productivity comparisons with accumulative solar radiation intensity.

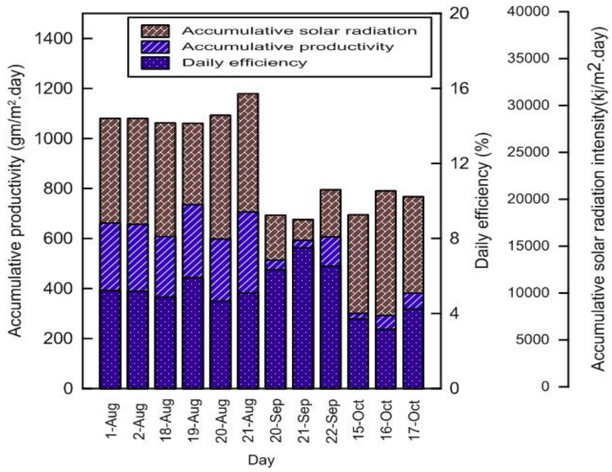


Fig.13. Daily efficiency corresponding to accumulative solar radiation and productivity

$$\zeta = \frac{\sum V_T * L}{H_T} \quad (45)$$

Where $\sum V_T$ is the accumulated mass of the collected water during the daytime. L is the latent heat of vaporization of water which is taken as an average value of 2275 kJ/kg.

VI. UNCERTAINTY ANALYSIS

In this study, the measuring experimental parameters are condensation surface, vapor and bed temperature on right and left sides, solar radiation intensity and cumulative water productivity. TPM-30 Digital temperature thermometers with measuring accuracy of ±1oC are used for measuring temperatures. TES-1333R solar power meter with an accuracy of ±10 W/m2 is used for measuring solar radiation intensity. Graduated flask with measuring accuracy of ±2.5 gm is used for measuring the amount of collected water. The maximum uncertainties of the evaluated parameters are estimated by using the following expression [16];

$$\omega_x = \sqrt{\left(\frac{\partial X}{\partial X_1}\right)^2 \omega_{X_1}{}^2 + \cdots + \left(\frac{\partial X}{\partial X_n}\right)^2 \omega_{X_n}{}^2} \quad (46)$$

Where ω_x is the uncertainty of the variable x, ω_{xn} is the uncertainty of parameter and x_n is the parameter of interest. Analysis of experimental error shows that the maximum uncertainties in the different evaluated parameters are as presented in Table.1.

TABLE. 1
. UNCERTAINTY IN EVALUATED PARAMETERS

Parameter	Uncertainty
Accumulated productivity, gm/m2.day.	± 7.9
Accumulated solar radiation, W.hr/m2.day	± 31.6
Daily efficiency,%	± 0.57

VII. CONCLUSION

Extracting water from air by desiccant using oblique condensation surface and solar energy as a heating source is presented. From the experimental study and numerical investigation, the following conclusions could be drawn:

1. The water productivity is dependent on ambient conditions and a maximum value of about 735 gm/m^2.day is recorded.
2. The difference between the temperature of condensation surface and air-vapor has a great effect on water productivity.
3. The system has low daily efficiency where its maximum value is about 7 percent.
4. Orientation of bed surface must be selected such that the bed temperature has the same values for most of the operation period.

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