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Analysis of the Experimental and Theoretical Performance of the Two-dimension Concentrating Solar Collector

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Abstract

Objective: Due to the problems of environmental pollution and near future depletion of crude oil, which the main source of energy solar energy becomes an important alternative energy source. Therefore, this work focuses on the potential use of solar energy in driving cooling and refrigeration systems. **Methods/Statistical Analysis:** For this purpose, a two-dimensional glazed compound parabolic concentrator solar system is designed and fabricated to operate in Iraq, (Hilla city 32.4o latitude and 44.4o longitude), weather conditions. The absorber consists of a flat plate with serpentine copper tube with 28.575 mm diameter. The CPC has the following dimensions (250 cm length, 92 cm aperture width, 20 cm absorber width and 90 cm height). The solar radiation intensity is measured by Watchdog 2000 Series weather Station. Water is used as the circulating fluid where two mass flow low rates are tested. **Findings**: The results show that the minimum and maximum measured solar intensity during 2016 in Iraq is 399 W/m2 and 1039 W/m2 respectively while the maximum summer temperature is 50oC. The maximum glazed and unglazed absorber temperatures are recorded in August, which are 148oC and 120oC respectively while the reflector and aperture glazing temperatures are 69oC and 43oC respectively. The maximum measure hot water temperature is 9oC at a flow rate of 0.0277 kg/s and 94oC and a flow rate of 0.0377 kg/s. It is also found that the a maximum thermal efficiency of 67% is obtained at a flow rate of 0.0277 kg/s while it increases to 69% at a flow rate of 0.0377 kg/s. The maximum theoretical thermal efficiency obtained is 73% at a flow rate of 0.0277 kg/s and 75% at a flow rate of 0.0377 kg/s. **Application/Improvements:** The results of this study show that there is a good potential for using solar energy as an alternative energy source in different applications such to generate electrical energy, to produce hot water and steam and in absorption adsorption cooling systems.

Keywords: Performance of Solar Collector, Solarwater Heater, 2D CPC

1. Introduction

Solar power is durable; nothing is polluted and low-cost source of energy. Many applications require high levels of energy at temperatures over 100°C, which can be obtained using concentrators. The concentrating collector increases the amount of incident energy on the receiver surface as compared to that fall on the concentrator aperture. This increase is achieved using reflective or refractive surfaces that focus the radiation on an appropriate absorber/receiver. Concentrating collectors can increase the solar radiation intensity to about 10000 folds[1]. The focusing collector is a collector of Winston as shown in Figure 1. The 2D-concentrating collector consists of left and right mirrors in the shape of a parabola which reflects the incident solar radiation onto the absorber. The right

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and left points have a common point of contact. The absorber location is the distance between focuses of the two parabolas[1–3]. Most applications that demand temperatures below the 90°C use flat plate collectors and large research efforts are already made. In applications where the range of temperature is (90-300°C), the suitable collector is the concentrating type[1,2]. In analyzed four kinds of concentrating collectors which vary in the form of the absorber[4,5]. Numerous researchers discuss the effect of height, acceptance angle and width of the collector. Norton et al. investigate the possible use of compound parabolic concentrator in rural areas[6]. The heat losses by convection can be minimized by inverted absorber configuration which can achieve higher temperatures. LIXI Zhang et al. designed a heat generation system with a load capacity of 10 kW[7]. The concentrating collector array is used as the primary heat source with an equal concentration ratio of 5 and auxiliary heat source as a gas boiler. The shape of the collector is analyzed for thermal efficiency and the collector array is ranged suitably. Luisa I. and Feliciano-Cruz evaluated the Solar Thermal Power Plant in Puerto Rico and proposed the use of the (CPC) as the solar collector of choice. In this work, the solar collector is designed, fabricated and tested under Iraq weather conditions[8].

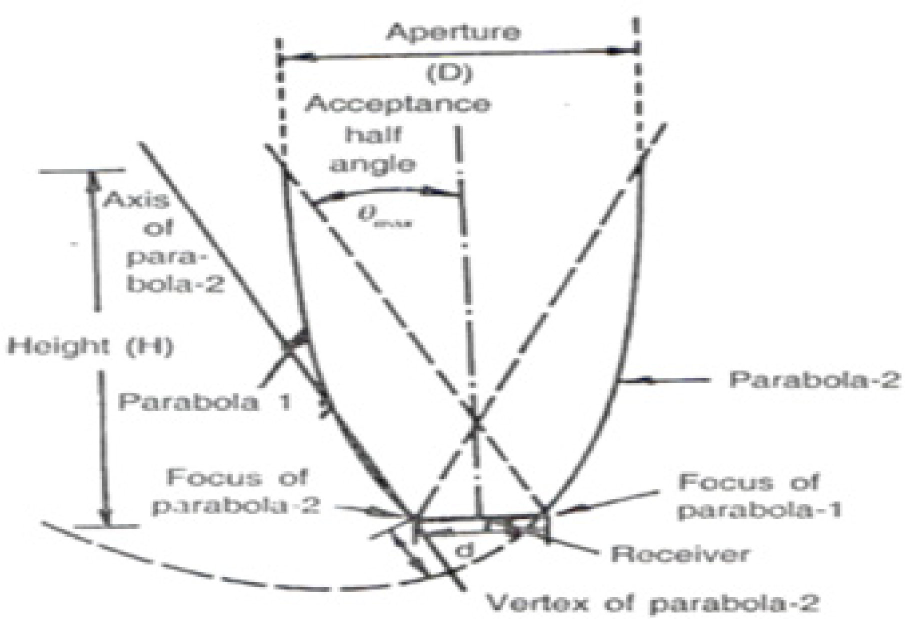

Figure 1. Compound parabolic concentrator[15].

2. Solar Radiation Calculation

Total solar radiation on an exposed surface includes the determination of beam and diffuse radiation, calculated after estimating solar time and location. As the sun passes through the atmosphere, it deteriorates in proportion to the length of its path according to the extinction factor B, to produce natural radiation on the Earth's surface[9–12]. The latitude angle equals to 32.4° N for Babylon province. The standard meridian of the local time zone for Iraq (it is 45°). The longitude location concerned equal to 44.4°E for Babylon area. The β slope of the collector. B = 21° in summer and β = 43° in winter.

$$I_{DN} = A_1 * \exp\left(-\frac{P_L}{P_o} * \frac{B}{cos(\theta_z)}\right) \quad (1)$$

Where,

$\frac{P_L}{P_o}$ is Pressure ratio at the relevant site relative to the standard atmospheric pressure given as:

$$\frac{P_L}{P_o} = \exp(-0.0001184 * H_{alt}) \quad (2)$$

Where, H_{alt} is the altitude in meters above sea level.

The values of the sun's extraterrestrial density A_1, the atmospheric extinction factor B, and the clouded C1 factor In[10] on any day of the month using the following equations:

$$A_1 = 1158 * \left[1 + 0.066 * \cos\left(360 * \frac{ND}{370}\right)\right] \quad (3)$$

$$B = 0.175 * [1 - 0.2 * \cos(0.93 * ND)] - 0.0045 * [1 - \cos(1.86 * ND)] \quad (4)$$

$$C_1 = 0.0965 * \left[1 - 0.42 * \cos\left(\left(\frac{360}{370}\right) * ND\right)\right] - 0.0075 * [1 - \cos(1.95 * ND] \quad (5)$$

Where, ND is the number of day.

The sun altitude angle α and declination angle δ are given by[9] as:

$$\cos\theta_z = \sin\alpha = (\cos\square * \cos\delta * \cos\omega + \sin\delta * \sin\square) \quad (6)$$

$$\delta = 23.45 * \sin\left[360 * \frac{(ND - 80)}{370}\right] \quad (7)$$

Where,

$\square$ is the latitude angle. (Equal to 32.4°).

ω is the angle of time or angle of solar period known as the position of the angle away from the solar afternoon caused by the rotation of the earth. This angle is expressed in degree as

$$\omega = 15 * [Ast - 12] \quad (8)$$

$$Solartime = Standardtime + \left(\frac{E}{60}\right) - \frac{(L_{st} - L_{loc})}{15} \quad (9)$$

Where:

L_{st} is the standard meridian of local time zone for Iraq is (45°)

L_{loc} is the longitude location concerned equal to (44.4° E).

Table 1. Ak and Bk coefficients for equation[10]

K	A_K	B_K
0	$2.0870 * 10^{-4}$	0
1	$9.2869 * 10^{-3}$	$1.2229 * 10^{-1}$
2	$-5.2258 * 10^{-2}$	$-1.2698 * 10^{-1}$
3	$-2.1867 * 10^{-3}$	$-2.9823 * 10^{-3}$
4	$-2.1867 * 10^{-3}$	$-2.9823 * 10^{-3}$
5	$-1.51 * 10$	$-2.3463 * 10^{-4}$

E is time equation, which is calculated as[11]:

$$E = \sum_{k=0}^{k=5}\left[A_k cos\left(\frac{(2*\pi*K*N_n)}{365.25}\right) + B_k sin\left(\frac{(2*\pi*K*N_n)}{365.25}\right)\right] \quad (10)$$

Where, N_n is the number of the day in a 4-year cycle, with N_n = 1 being January 1st of the leap year and N_n = 1461 corresponding to December 31 of the 4th year of cycle. A_k, B_k are constant given in Table 1.

The beam irradiance can be computed as:

$$I_b = I_{DN} * cos\theta_1 \quad (11)$$

The general definition of incident angle can be expressed for any surface orientation as[12]:

$$cos\theta 1 = (sin\delta * sin\phi * cos\beta) - (sin\delta * cos\phi * cos\gamma) + (cos\delta * cos\beta * cos\phi * cos\omega) + (cos\delta * cos\phi * sin\beta * cos\gamma * cos\omega) + (cos\delta * sin\beta * sin\gamma * sin\omega) \quad (12)$$

Where,

γ is surface azimuth angle.

β tilt angle. B = 21° in summer

β = 43°in winter

The diffuse radiation on the tilted collector can be calculated by[9]:

$$I_d = I_{ND} * \left[C_1 * \left(\frac{(1+cos\beta)}{2}\right) + s*(C_1 + sin\alpha) * \left(\frac{(1-cos\beta)}{2}\right)\right] \quad (13)$$

Where, *s* is the reflectivity of ordinary ground taken as 0.2.

The total solar radiation incident is.

$$I_T = I_{beam} + I_{diffuse} \quad (14)$$

2.1 Thermal Efficiency Calculation

The useful energy Qu can be calculated as was done earlier if we know the absorbed energy Ia and UL. The isolation, ICPC within the acceptance angle of CPC with concentration ratio, C, is found in[1,6].

$$I_{CPC} = I_T - \left(1 - \frac{1}{C}\right) * I_d \quad (15)$$

Where I_T and I_d are the total and diffuse radiation respectively on the aperture plane. Now the absorbed radiation Ia in terms of I_{CPC} is[1]:

$$I_a = I_{CPC} * \tau_{cover} * \tau_{CPC} * \alpha_r \quad (16)$$

$$I_a = I_T * \tau_{cover} * \tau_{CPC} * \alpha_r * \gamma \quad (17)$$

$$\gamma = 1 - \left(1 - \frac{1}{C}\right) * \frac{I_d}{I_T} \quad (18)$$

Where τ_{cover} = transmissivity of cover.

τ_{CPC} = effective transmissivity of CPC.

α_r = absorbtivity of receiver.

γ = correction factor for diffuse radiation.

The empirical expression of U_L for a CPC with tubular absorber coated with selective coating and the entire collector covered with a transparent cover is given as[6]:

$$U_L = (0.18 + 16.95 * \varepsilon_r)[0.212 + 0.00255 * T_a + (0.00186 + 0.000012 * T_a) * (T_r - T_a)] \quad (19)$$

Where

T_a= ambient temperature, ºC

T_r= absorber temperature, ºC

ε_r = emissivity of absorber surface

U_L= collector heat loss coefficient, W/m^2 *K of absorber area.

A concentrating collector (CPC) collector is generally covered with a transparent cover and is tilted towards the south with long axis in the East- West direction. CPC is tilted to receive both beam radiation within the acceptance angle. The absorber or receiver can be of any shape but generally tubes or tubes fixed on a flat plate coated with a black selective paint as shown in Figure.

The rate of useful energy collection is given as[1]:

$$Q_{u,th} = A_a * F_R * \left[I_a - \left(\frac{U_L}{C}\right)\left(T_{fi} - T_a\right)\right] \quad (20)$$

Where , $A_a = D * L$

the heat removal efficiency factor is given as[1]:

$$F_R = \left(\frac{(\dot{m} * C_f)}{(A_{abs} * U_L)}\right) * \left[1 - exp\left(-\frac{(A_{abs} * U_L * \acute{F})}{(\dot{m} * C_f)}\right)\right] \quad (21)$$

The collector efficiency factor is given as[1]:

$$\acute{F} = \frac{\left(\left(\frac{1}{U_L}\right)\right)}{\left(\left(\frac{1}{U_L}\right) + \left(\frac{(d * U_L)}{(N * \pi * D_{abs,i} h_{ci})}\right)\right)} \quad (22)$$

Where

Hci = The inside heat transfer coefficient inthe tube can be calculated from Nu[1].

$$N_u = 0.023 * Re^{0.8} * Pr^{0.4} \quad (23)$$

$$N_u = \frac{h_{ci} * D_{abs,i}}{K} \quad (24)$$

The outlet fluid temperature is calculated from equation as:

$$\square_{\square,\square} = \square_{\square,\square} + \frac{\square_\square}{\dot{\square} * \square_\square} \quad (25)$$

$$\square_{\square,\square} = \frac{\square_{\square,\square} + \square_{\square,\square}}{2} \quad (26)$$

$$\square_\square = \square_{\square,\square} + \frac{\dot{\square} * \square_\square * (\square_{\square,\square} - \square_{\square,\square})}{h_{\square\square} * \square * \square_{\square,\square\square\square} * \square} \quad (27)$$

The efficiency of collector can be calculated from the equation as:

$$\square_{\square h} = \frac{\square_{\square,\square h}}{\square_\square * \square_{\square\square\square\square}} \quad (28)$$

The experimental useful energy obtained from compound parabolic concentrator solar collector (CPC) is given as:

$$\square_{\square,\square\square\square} = \dot{\square} * \square_\square(\square_{\square,\square} - \square_{\square,\square}) \quad (29)$$

$$\square_{\square\square\square} = \frac{\square_{\square,\square\square\square}}{\square_\square * \square_{\square\square\square\square}} \quad (30)$$

3. The Design Calculation

The two-concentrating collector consists of three main components:

1. Reflector: Two mirrors in the form of parabolas are made of stainless steel mirror image paper. 2. Absorber: It is the concentrating collector where the entire amount of heat after reflection is absorbed. It is made of the serpentine copper tube fixed on a flat plat MS (16 gauge). The copper tube and the flat plate are black coated. 3. Aperture cover: The opening and the side openings of the collector are closed with the toughened glass of 4 mm thickness. The solar radiation that enters the concentrator at the maximum acceptance angle is reflected significantly on the absorption surface. The governing equations required to design CPC are found in[13–17].

The concentration Ratio is (C = D/d). The reflector is constructed for a half acceptance angle of ($\theta max = 11.54°$). The distance between MN and CD is the full height of the CPC, as in Figure 2. The absorber CM is flat plate type. Part of the solar radiation falls on the absorber directly while the other reaches the absorber via the reflector.

The second law of thermodynamics applies that to the maximum concentration ratio should be given regarding half acceptance angle as Concentration Ratio (C) = $1/\sin_{\theta max}$[8]. It can be set (D)/d = (1/ ($\sin_{\theta max}$)) and that this concentration is as far as possible for the angle of acceptance $2\theta max$[13]. Figure 2 illustrates the cross-section of the compound parabolic concentrator with flat plate absorber.

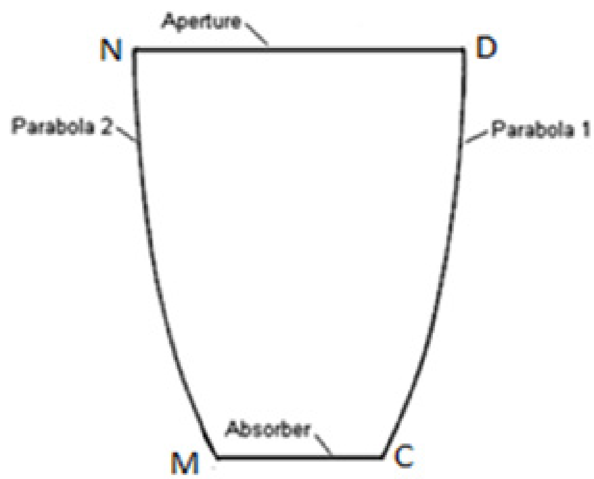

Figure 2. Compound parabolic concentrator[15].

The full dimensions of two compound parabolic concentrators are shown in the Figure 3. The two-dimension compound parabolic concentrator funnels the radiation from aperture cover to the absorber. The focuses of parabolas 1 and 2 are at M and C respectively. In[13] derived some general relations for full compound parabolic concentrator with the flat absorber. Cartesian coordinate system is shown in Figure 1 and the parabola equation is determined by the parabolic profile. The Full CPC is given by $H = D/2\ (1+1/(\sin\theta_{max}))\cos\theta_{max}$. The coordinates of point D: $x = b\cos\theta_{max}$, $y = b\ (1-\sin\theta_{max})/2)$. These coordinates of point D are used to draw a curve which represents the right-hand parabola. The mirror image gives the left parabola, which is produced in the two-dimensional concentrating collector. The upper part of the CPC can be removed (truncated) with little loss in performance[13]. The CPC is usually truncated by about (2/3) of its height to prevent interception of solar radiation by the upper part of the reflector. Cost of the truncated CPC is reduced without affecting its performance, with only a small loss in (concentration ratio). Also, truncation reduces the shadowing effect.

The cut is done by drawing a horizontal line through the reflector at the specified height (2/3 of the calculated height). The truncation does not affect the acceptance angle. The advantage of this type of CPC is that it does not require continuous tracking when it is oriented eastward and westward. The concentration of (3 to 11) and small

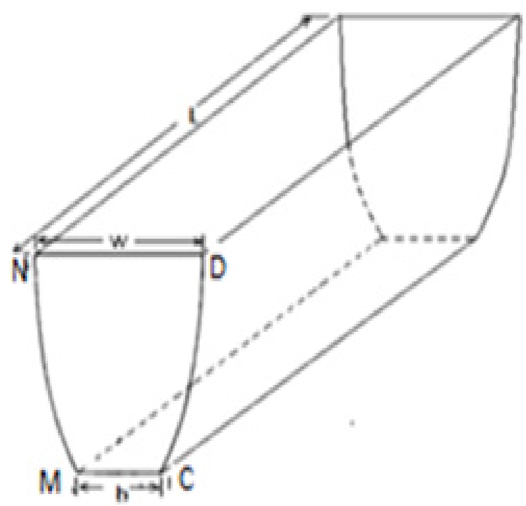

Figure 3. 2-D compound parabolic concentrator.

Height of CPC	Absorber width	Aperture width	Axial length	Concentration Ratio
98 cm	20 cm	92 cm	250 cm	4.5

tilt times are needed throughout the year. The calculated dimensions of the CPC after truncation are shown.

4. Rig Construction

The reflector shape is drawn on a large sheet of paper for the full scale. Stainless steel sheets are used as dimensions required for two reflecting surfaces. Welding technique is used to fix absorber plate with the reflector. The full-scale drawing is used to set the reflector profile (parabola). To keep the aperture area constant the top distance between the two mirrors is held constant by riveting these reflectors to the frame. A thermocouple measures the temperature of the mirror surface. The aperture opening is closed by a 4 mm glass sheet. A serpentine copper tube of 28.575 mm diameter is fixed on the mild steel plate. The collector is constructed so that it can be tilted by in any direction.

5. Experimental Setup

Collector is tested for different days in different months under outdoor conditions. Temperatures of absorber sur-

(a)

(b)

Figure 4. a. The experimental rig. b. Watchdog 2000 Series weather stations.

face, aperture cover surface and reflectors are recorded. Also, solar radiation is measured during the day. The experimental setup is shown in Figure 4a.

Instruments used in this study:

1. Thermocouples: Double-type Constantine iron is used to measure the temperature of absorption, reflector surfaces and surrounding areas. 2. The digital indicator is used to display the temperature (in °C) of the surface to which the thermocouple is attached. 3. Watchdog weather station is used to measure solar radiation intensity throughout the day (Watchdog 2000 Series weather Stations is shown in Figure 4b.

6. Results and Discussions

The theoretical analysis was performed using MATLAB 2017 program to determine the efficiency of collector, useful heat, mean temperature and hot water circulation

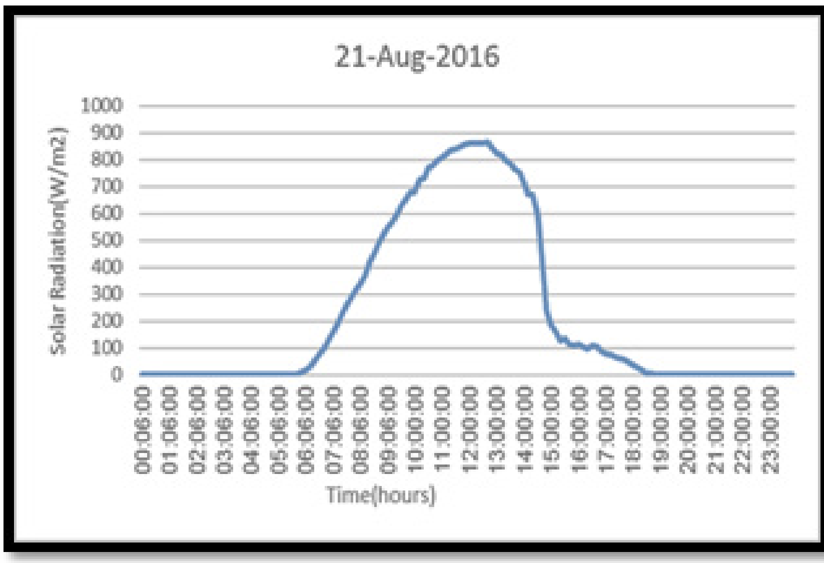

Figure 5. Measured hourly solar radiation for the day 21/8/2016.

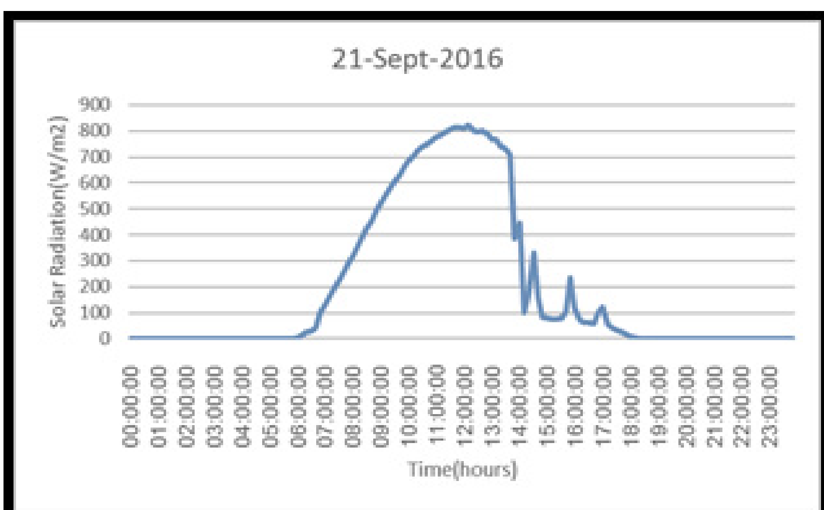

Figure 6. Measured hourly solar radiation for the day 21/9/2016.

temperature. Dimensions and collector specifications were introduced into the program to determine theoretical thermal efficiency. The solar radiation is determined theoretically and experimentally. The ambient temperature and inlet flow temperature is measured experimentally in the winter and summer seasons in Babylon province. The radiation intensity is low during morning hours and reaches its maximum value at noon time. The aperture glass cover has high transitivity (0.92). Therefore most of the radiation is transferred to the inverter and plate absorption surface. Each surface of the mirror reflects the radiation on the absorption surface that contains absorbent (0.95) as specified by the manufacturer. This means that most absorption transfer absorbs radiation. Figures 5-7 illustrate the variation of the solar radiation with daytime hours on the 21st day of Aug., Sept. and Oct. These figures explain that the maximum radiation occurs at noon to an afternoon at 13:00 PM. Figures also show that August has higher solar radiation than other two months because of the sun declination angle decrease from 21

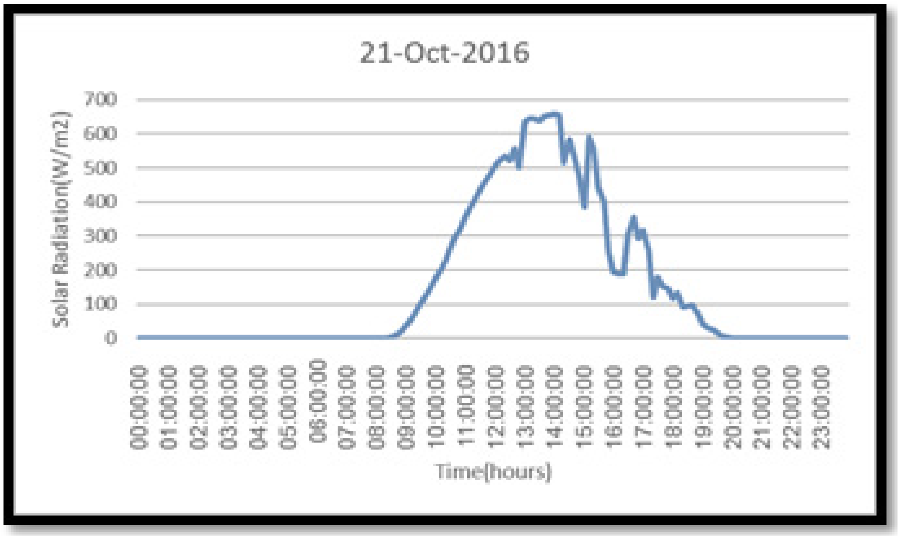

Figure 7. Measured hourly solar radiation for the day21/10/2016.

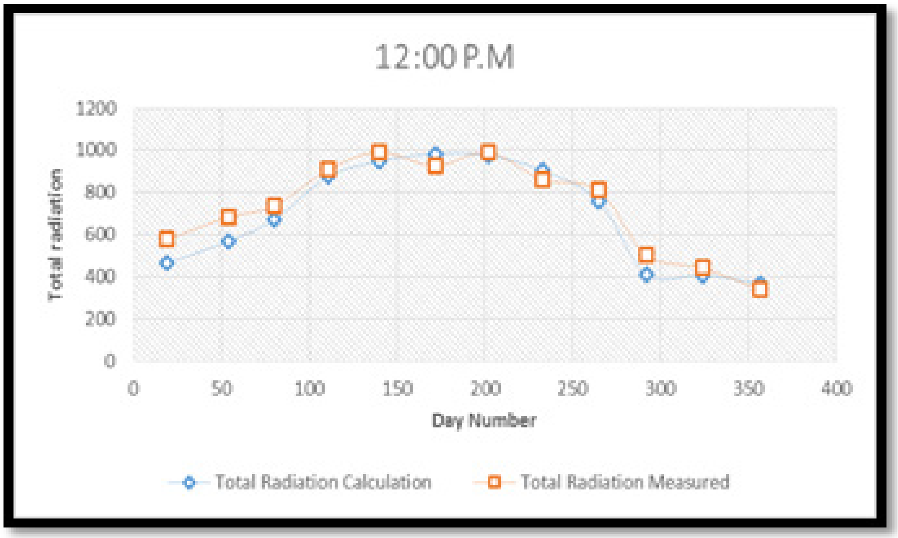

Figure 8. The variation of solar radiation in year at 21st for each month at 12:00 P.M.

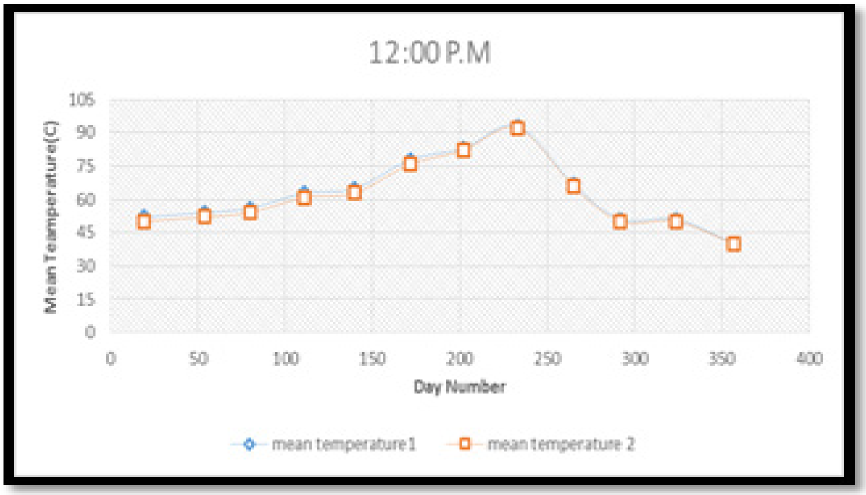

Figure 9. The variation of efficiency at different mass flow rate in year at 21st for each month at 12:00 P.M.

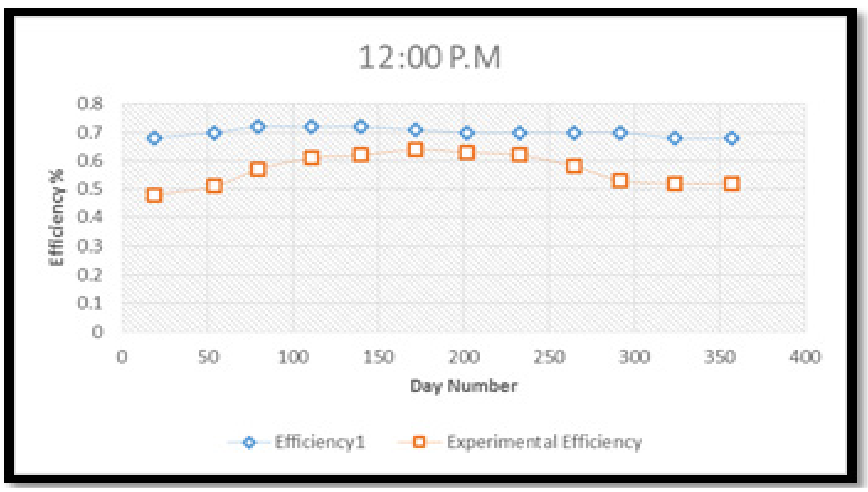

Figure 10. The variation of total solar radiation (theoretical and experimental) in year at 21st for each month at 12:00 P.M.

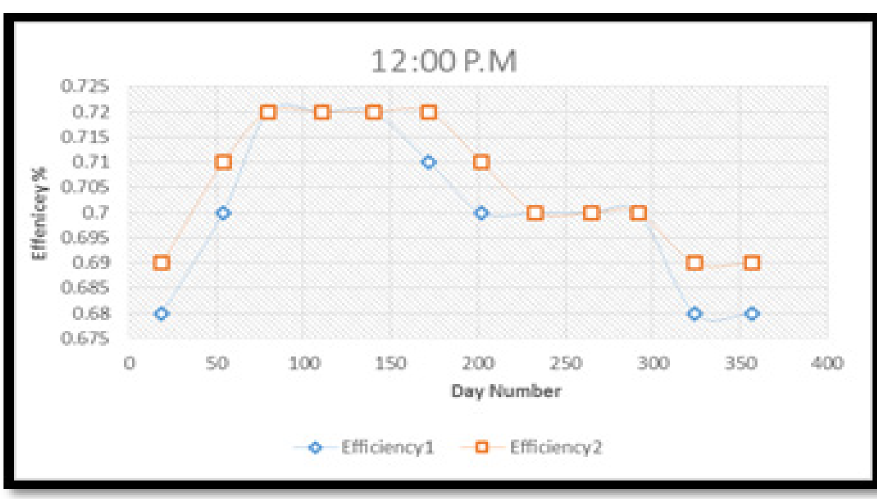

Figure 11. The variation of mean fluid temperature in year at 21st for each month at 12:00 P.M.

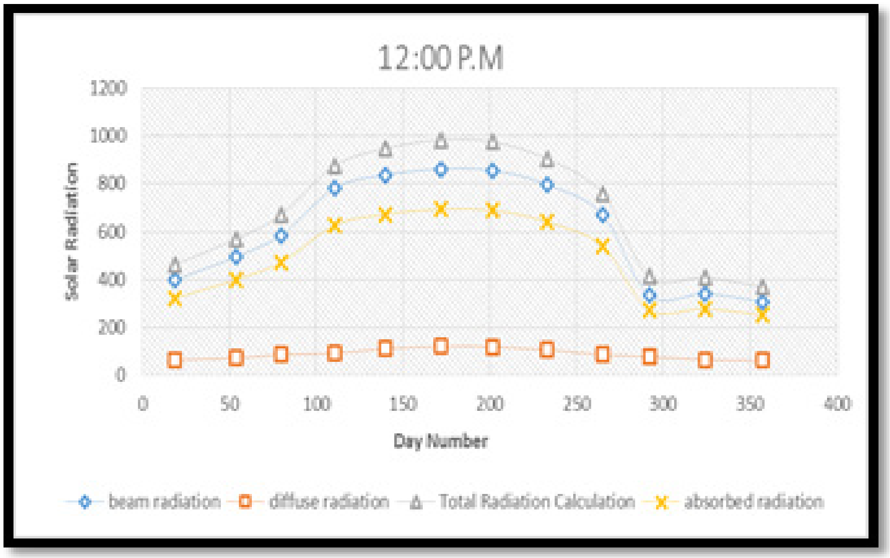

Figure 12. . The variation of efficiency (theoretical and experimental) in year at 21st for each month at 12:00 P.M.

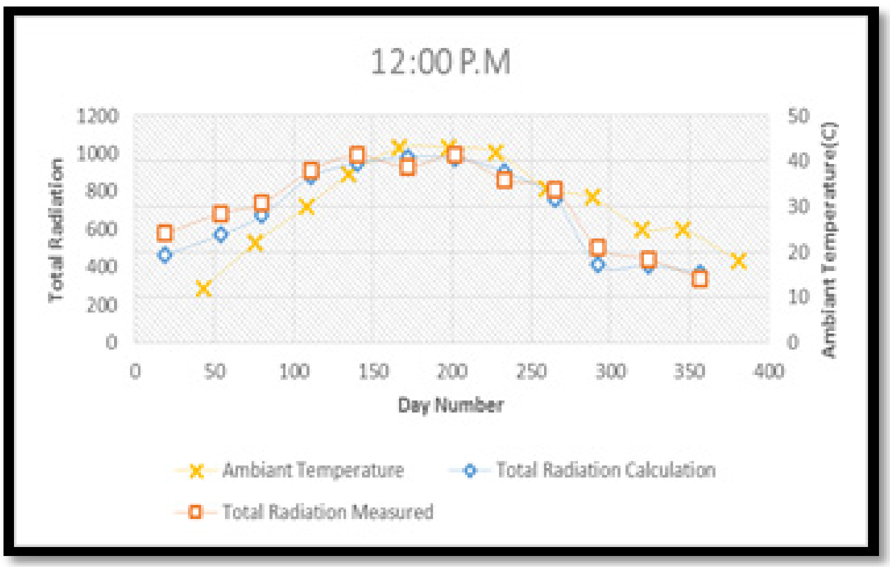

Figure 13. The variation of total solar radiation (measured and calculation) and ambient temperature in year at 21st for each month at 12:00 P.M.

Aug. to 21 Oct. i.e. (11.754°, -0.2018° and -11.754°) respectively because of higher solar radiation than other two months. These figures show that the absorber temperature reaches its maximum value at about 13:00 PM. The absorber temperature peaks after the maximum radiation. It is apparent from this recorded temperature that there is a real feasibility of using solar energy in refrigeration absorption systems. Figure 8 showed the variation the (total solar radiation, beam solar radiation, diffuse radiation and absorb radiation) with day number for the year at 21^{st} for each month at noon. Figure 9 illustrated the variation of the thermal efficiency with day number of year at 21^{st} for each month in the summer and winter seasons with different mass flow rate, The figure shows the high overall flow rate and this gives high efficiency ranging from (67)% to (75)% for the flow rate values in

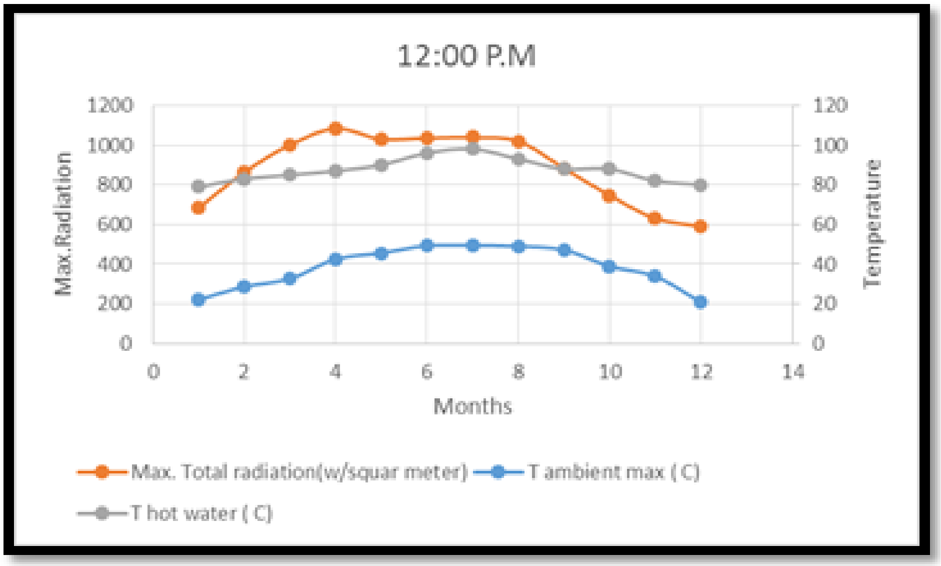

Figure 14. The variation of max. total solar radiation with hot water temperature and ambient temperature in year at 21st for each month at 12:00 P.M.

the range (0.0277-0.0377) kg/s. The temperature difference (ΔT) is in the range (40°C-60°C) for flow rate range (0.0277-0.0377) kg/s. Figure 10 illustrated the variation of total solar radiation (theoretical and experimental) in the year at 21st for each month at 12:00 P.M. Figure 11 illustrated the variation of mean fluid temperature in the year at 21st for each month at 12:00 P.M. with different mass flow rate (0.0277-0.0377) kg/s, when increasing the mass flow rate refers to decrease the outlet temperature and mean fluid temperature. Figure 12 shows a comparison between the thermal efficiency of CPC with the theoretical and experimental. Figure 13 demonstrates the relation between (total radiation, beam radiation, diffuse radiation and absorb radiation) in year at 21st for each month at 12:00 P.M. The figures indicate that the increase in solar radiation leads to an increase in useful energy and an increase in the overall flow rate leading to a decrease in useful energy. Also, the figures show that the useful energy range is (200-700) W/m^2 and the total solar radiation range is (370-990) W/m^2 and the diffused solar radiation range is (60-120) W/m2. Figure 14 show the variation of maximum solar radiation with hot water temperature and ambient temperature.

7. Conclusions

1. The thermal efficiency range is (67)% to (75)% at flow rate range (0.0277-0.0377) kg/s. 2. An increase in solar radiation leads to an increase in useful energy, increasing the overall flow rate leads to a decrease in beneficial energy. 3. Higher solar radiation is recorded at noon to afternoon (about 13:00 PM). 4. Maximum absorber temperature is recorded in (June, July and August) month because of higher solar radiation. 5. The absorber surface temperature peaks after the maximum solar radiation. 6. The applications of the non-imaging concentrator (CPC) is suitable for absorption refrigeration system.

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