The Effect of Mass Flow Rate on the Thermal Performance for Solar Collector with Compound Parabolic Concentrator During the Summer Season

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Abstract

Present study investigated the effect of the summer season on the thermal performance (heat energy and thermal efficiency) of the solar collector with CPC without cover, by designing a proper solar collector with compound parabolic concentrator (CPC). It was implemented a solar collector with a cylindrical receiver diameter 1.5 inches and an acceptance angle of 45° with concentration ratio of 2.613. The surface reflector was made from stainless steel an aperture area of 0.87 m². The orientation of the solar collector at 150° was set as (south-east) direction and 45° inclined angle at Baghdad city. The experimental results showed that the performance of the solar collector was improved significantly as the water circulation mass flow rate increased. The percentage increase in the heat energy and thermal efficiency are (69.95 and 68.68) % respectively in case of the mass flow rate of 300 kg/hr with respect to 60 kg/hr.

Key word: solar collector, compound parabolic concentrator, concentration ratio.

Introduction

It is well known that the solar collector is a special kind of a heat exchanger which is normally converted the solar radiation heat to the heat energy of the various transport fluids like air, water and oil which is usually flowing across the collector. The circulating fluid could be used as directed or circulate way, through a storage tank to be used in need [1]. In fact, the solar collectors with CPC are non-imaging types, which concentrate the solar radiation rays and then reflect them...
on the absorber surface (receiver surface) [2]. Various applications utilize solar collectors during the summer season. Some of them are normally used to supply the hot water in the hotels and hospitals for laundry and bathing applications in addition to the milk dairies (pasteurization, condensation and cleaning), leathers processing industry (drying and tanning), metal finishing industry (phosphating and degreasing) and swimming pool heating. The solar collectors also could be used to pre-feed hot water to the boilers to generate a steam of a steam turbine power plant. Several studies investigated various types of solar, solar collector. Yong Kim, et al. (2007) [3], improved the performance of an evacuated tube solar collector by using CPC tracking with single axis. The performance results heat flux, outlet water temperature and collector efficiency were critically compared with and without using tracking. It was found that the collector efficiency with tracking was much higher by about 14.9% than that without tracking solar collector. Santos Gonzalez, et.al (2011) [4], studied the solar collector with CPC experimentally and numerically. Reasonable comparison was made between the numerical and experimental results. The area of the The collector was equal of 1.33 m². Acceptance angle about 30° and the concentration ratio about 3.5. The result confirmed that the inlet water temperatures were varied from 70°C to 30°C and the water mass flow rates changed from 0.25 kg/s to 0.05 kg/s. The comparison results showed an acceptable agreement. 

Singiresu S. Rao, et.al (2013) [5], optimized a solar collector with CPC and compared with the results of the optimum flat plate. The optimization was carried with three objectives. The first one to maximization of the average solar energy through the annual, the second to maximize the lowest solar energy through the month and the third objective to minimize the cost. The comparison objective to minimize the cost. The comparison between the optimum results of the solar collectors with the flat plate and with the CPC showed a significant reduction of cost per a unit ratio of energy. A full scale of solar collector with a CPC system with an area of (1x0.87) m² was designed by Wisut Chamsa-ard et al (2014) [6] in order to examine the thermal efficiency of the evacuated tube solar collector with CPC. The effect of acceptance angle tube diameter and absorbing on the performance of compound parabolic concentrator solar collector have been experimentally investigated by [8,9]; they concluded that the best thermal of the solar collector with CPC were at acceptance angle of 45° and at largest diameter of absorbing tube.

The objective of the present work is to investigate the performance of the solar collector with CPC for different circulation of mass flow rate during the summer season.

Experimental Work

Figure (1) shows the major components of the solar collector with CPC, which represented by a solar collector system that consists of CPC reflector surface and cooper pipes coated by black thermal dye, plywood, Reflector holder (polyurethane foam), frame, circulating pipes, valves, circulating water pump, thermal storage tank and measuring devices. The dimension of solar collector with CPC was (100x87) cm. All readings were taken from 9 A.M to 1:30 P.M.

(a) Front view  (b) Back view

Figure (1): The test rig system (full- scale solar collector), (100x87) cm

Compound parabolic concentrator

The surface curvature of the compound parabolic concentrator constructs from two curves. First curve from A to B and the second curve from B to C, as shown in Figure (2). There are three independent variables (r, $\theta_{ac}$ and $\theta$), where:

$R = f (r, \theta_{ac}, \theta)$
For a certain surface of the compound parabolic shape the values of radius of the absorber tube \( r \) and the acceptance angle \( \theta_{ac} \) kept constant and the value of the angle \( \theta \), which its values change from zero to the \( \frac{3\pi}{2} - \theta_{ac} \) on the y-axis. It can be seen that the curves of the CPC are symmetric about the y-axis and can obtained from the following equations [7].

a) The equation of the first part of the curve from A to B is:
\[
D = r. \theta \text{ \ for } (|\theta| \leq \theta_{ac} + \frac{\pi}{2}) \tag{1}
\]

b) The equation of the second part of the curve from B to C is:
\[
D = r. \frac{\sqrt{1 + \sin(\theta - \theta_{ac})}}{1 + \sin(\theta - \theta_{ac})} \text{ \ for } (\theta_{ac} - \frac{\pi}{2} \leq |\theta| \leq \frac{3\pi}{2} - \theta_{ac}) \tag{2}
\]

Where: \( R \) is the distance from point D on the absorber tube to point S on the surface of CPC. The concentration ratio of the CPC is a function of the acceptance angle given by following equation [7].
\[
CR = \frac{1}{\sin \left( \frac{\pi}{2} \theta_{ac} \right)} \tag{3}
\]

![Figure 2: The CPC shape [7]](image)

Calculation Procedures

The calculation of the solar collector with CPC performance was made as follows:

a) The volume flow rate of water \( (\dot{V}_w) \)

The volume flow rate of water was measured by flow meter, where the three values of volume flow rate were chosen (60 and 300) (L/hr)

So the mass flow rate can be determined by the equation (4):
\[
\dot{m}_w = \frac{\rho_w \cdot \dot{V}_w}{3600} \tag{4}
\]

b) Heat energy received by the water in the collector \( (Q'_w) \) is:
\[
Q'_w = \dot{m}_w \cdot C_p \cdot \Delta T_w \tag{5}
\]

c) The efficiency of solar collector
\[
\eta_{solar} = \frac{Q'_w}{A_0 \cdot I} \times 100 \tag{6}
\]
d) Heat loss energy $Q_L$

To calculate heat energy loss from the solar collector without cover to the surrounding by using free convection only, the following equations were used [10]: The film temperature as follows:

$$T_f = \left(\frac{T_a + T_s}{2}\right) + 273$$ \hspace{1cm} (7)

And to find the coefficient of thermal volume expansion:

$$\beta = \frac{1}{T_f}$$ \hspace{1cm} (8)

The correction equations of kinematic viscosity, thermal conductivity and Prandtl number, by using the following linear interpolation:

$$\nu = \nu_1 + \frac{T_f - T_1}{T_2 - T_1} \cdot (\nu_2 - \nu_1)$$ \hspace{1cm} (9)

$$k = k_1 + \frac{T_f - T_1}{T_2 - T_1} \cdot (k_2 - k_1)$$ \hspace{1cm} (10)

$$\rho_r = \rho_{r_1} + \frac{T_f - T_1}{T_2 - T_1} \cdot (\rho_{r_2} - \rho_{r_1})$$ \hspace{1cm} (11)

Then to calculate the Grashof number, Nusselt number, heat transfer coefficient and heat lost using the following equations:

$$Gr = \frac{g \cdot \beta \cdot (T_s - T_a) \cdot d^2}{\nu^2}$$ \hspace{1cm} (12)

$$Nu = C \left[ Gr \cdot Pr \right]^{\frac{n}{3}}$$ \hspace{1cm} (13)

Where the values of $C=0.53$ and $n=0.25$ for the value of $Gr\ Pr$ in the range between $(10^4-10^9)$\cite{10}.

$$h = \frac{Nu \cdot k}{d}$$ \hspace{1cm} (14)

$$Q_L = h \cdot A \cdot (T_s - T_a)$$ \hspace{1cm} (15)

Result and Discussion

Figures (3-7) were clearly shown the corresponding performance results for the solar collector with CPC, without cover and during the summer season (summer time) for different mass flow rate along the daytime from 9 a.m. to 1:30 p.m. Figures (3 and 4) display the temperature variation with respect to time for different water circulation mass flow rate (60 and 300) kg/hr. It can clearly noticed that the difference between the inlet and outlet of the water temperature through the collector was increased significantly, when the mass flow rate decreased. Further, the temperature gradient for the water circulation mass flow rate of 300 kg/hr provide a higher value than the water circulation mass flow rate of 60 kg/hr, since the solar radiation intensity were approximately equal for the two cases, and have a higher value at 12 p.m. It was found that the heat lost from the solar collector which was increased with the lower water circulation mass flow rate. The reason for that attributed to the lower values of heat transfer coefficient as well as to the temperature difference between the receiver surface temperature and ambient temperature, as it is shown in Figure (7). It should be noted that the receiver tube had a long time to loss the heat to the surrounding in the case of lower water circulation mass flow rate. Figures (5, 6) show the comparison performance results (heat energy and collector efficiency) of the solar collector with CPC for different water circulation mass flow rate through the collector. It can be seen that the heat energy and thermal solar collector efficiency, increase significantly, as the water circulating mass flow rate increase. The reason for that was attributed to the higher water temperature gradient as well as the higher mass flow rate, since the heat energy is a function of mass flow rate and temperature difference. Accordingly, the heat lost in the case of the higher mass flow rate was lower than the lower mass flow rate as shown in Figure (7). It was clearly observed that the percentage of the heat energy and thermal solar efficiency increase in the water circulation mass flow rate of 300kg/hr with respect to that of 60 kg/hr were (69.95 and 23.79%) respectively at 12 p.m.
Figure (3): Temperature distribution with respect to the time with $\dot{m} = 60 \text{ kg/hr}$ during 11/6/2015.

Figure (4): Temperature distribution with respect to the time with $\dot{m} = 300 \text{ kg/hr}$ during 14/6/2015.

Figure (5): Comparison Heat Energy for two mass flow
6. Conclusion

1. The experimental results are clearly observed that the higher water circulation mass flow rate was given the best performance of the solar collector with CPC.

2. The comparison performance results for heat energy and thermal efficiency of the solar collector with cpc show a better performance in the case of water circulation mass flow rate of 300 Kg/hr than of 60kg/hr. The percentage of the heat energy and thermal efficiency are (69.95 and 68.68) % respectively in case of water circulation mass flow rate of 300kg/hr.

3. The heat lost from the solar collector was decreased significantly with increasing the water circulation mass flow rate.
List Of Symbols:

| SYMBOL | TITLE                        | UNIT      |
|--------|------------------------------|-----------|
| A      | Area of the Collector        | m²        |
| $C_p_w$| Specific heat capacity of water | J/kg.K  |
| d      | Absorber tube diameter       | m         |
| $G_r$  | Grashof number               | ......... |
| g      | Gravitational acceleration   | m/s²      |
| h      | Heat transfer coefficient    | W/m².k    |
| l      | Solar intensity              | W/m²      |
| K      | Thermal conductivity        | W/m.k     |
| m      | Water mass flow rate         | kg/s      |
| Nu     | Nusselt number               | ......... |
| Pr     | Prandtl number               | ......... |
| $Q_L$  | Heat losses                  | W         |
| $r$    | Absorber tube radius         | m         |
| T      | Temperature                  | K         |
| $T_F$  | Film temperature             | K         |
| $\beta$| coefficient of thermal volume expansion | I/K     |
| $\theta$| Incidence angle            | Degree    |
| $\Theta_{ac}$ | Acceptance angle          | Degree    |
| v      | Kinematic viscosity         | m²        |

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