Design and Performance Analysis of a V-Trough Photovoltaic Concentrator

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Abstract

The idea of concentrating solar energy to increase the output power of photovoltaic (PV) collectors is an area that has received significant attention in recent years. In this study, a design model for a V-trough concentrating PV solar collector by using one and two plane reflectors is theoretically analyzed and validated with experimental measurements data. The angle between the PV collector and reflector and the tilt of PV collector are fixed at 120^{o} and 60^{o}, respectively. Variation of the total solar radiation received by the PV collector without reflector for horizontal surface, for normal incidence, with tilt angle 60^{o}, with one reflector and with two reflectors for a selected day in 15-January during the time period from 7:30 AM to 4:30 PM in Baghdad city for different view factor between the PV collector and reflector (F_{r-c}) is studied. The results indicated that the total solar radiation at solar noon for F_{r-c}=0.21 is 1265 W/m^2 when using two reflectors, in other words 61% enhancement. On the other hand, there is 120% enhancement of two reflectors system in comparison with horizontal surface without reflector. The Isc at solar noon increase from 0.16 A for PV collector without reflector to 0.22 A with one reflector which represent 37.5% enhancement and to 0.3 A with two reflectors which represent 87.5% enhancement, while the open circuit voltage (V_{OC}) increase from 8.35 volt for PV collector without reflector to 8.43 volt with one reflector and to 8.4 volt with two reflectors.

Keywords: Solar PV Concentrators, V-Trough Photovoltaic Concentrator

تصميم وتحليل أداء لمركز فوتوفولتائي V- الحوضي

علاء حسين شنيشل

قسم الفيزياء – كلية التربية – الجامعة المستنصرية

الخلاصة

فكرة تركيز الطاقة الشمسية لزيادة انتاج القدرة الخارجة من المجمعات الفوتوفولتائية (PV) هي من المجالات التي لاقت اهتمام كبيرفي السنوات الاخيرة. في هذه الدراسة، تم تحليل نموذج تصميم مركز فوتوفولتائيV-الحوضي نظرياً باستخدام عاكس مستوي واحد وعاكسين والتحقق منها من خلال بيانات القياسات العملية . تم تثبيت الزاوية بين المجمع الفوتوفولتائي والعاكس وزاوية ميل المجمع الفوتوفولتائي على 120^o و60^o، على التوالي .تم دراسة تغير قيمة الإشعاع الشمسي الكلي المستلمة من قبل المجمع الفوتوفولتائي بدون عاكس لسطح أفقي، لسقوط عمودي، بزاوية ميل 60^o، مع عاكس واحد وعاكسين ليوم محدد في 15 يناير خلال الفترة من 07:30 AM إلى 4:30 PM لمدينة بغداد لقيم مختلفة من عامل الاستقبال بين المجمع الفوتوفولتائي والعاكس (F_{r-c}) .أشارت النتائج إلى أن الإشعاع الشمسي الكلي عند الظهيرة عندما (F_{r-c} =0.21) هو ($1265\ W/m^2$) عند استخدام عاكسين ، وبعبارة أخرى 61٪ تحسين في الاداء .من ناحية أخرى، هناك 120٪ تحسين في الاداء باستخدام عاكسين مقارنة مع سطح أفقي بدون عاكس .تيار دائرة القصر عند الظهيرة يزداد من 0.16 A للمجمع الفوتوفولتائي (PV) بدون عاكس إلى 0.22 A مع عاكس واحد والتي تمثل تحسين بنسبة 37.5٪ وإلى 0.3 A مع عاكسين والتي تمثل تحسين 87.5٪ ، في حين أن فولتية الدائرة المفتوحة (VOC) تزداد من 8.35 فولت للمجمع الفوتوفولتائي بدون عاكس الى 8.43 فولت مع عاكس واحد وإلى 8.4 فولت مع عاكسين.

الكلمات المفتاحية : المركزات الفوتوفولتائية الشمسية ، مركز فوتوفولتائي V- الحوضي

Introduction

The Photovoltaic (PV) solar cell material contributes about 60% of the total cost of PV system. PV electrical power generation cost can be reduced by reducing utilization of solar cell material to widespread and commercializes the PV technology in near future [1]. It is well known that the output power from the PV systems is proportional to the amount of the incidental solar radiation. It is evident that increasing the incident solar radiation on a PV module leads to an increase in the PV module’s power output [2]. Concentrator techniques are found helpful in reduced PV material consumption/watt of generated output power, in other words, the costly PV solar cell would replace by cheaper reflector material such as glass mirror, aluminum sheets or foils, acrylic mirror sheets etc [3]. Percentage area of solar cell incorporated in PV module is reduced by the value of concentration ratio as compared to one-sun concentration [4]. Several researchers investigated the effects of concentrating reflectors on solar PV and thermal systems' performance. Alaa indicated that The water temperature in the fabricated evacuated tube solar thermal collector with reflective surfaces reach to about 60 °C after thirty minutes, while without reflective surfaces reach to about 45 °C which means that 25% gain by using reflective surfaces [5]. Palaskar et al shows experimental recordings of the performance of simple PV module and modified PV module for Mumbai latitude. The modified PV module by adding Aluminum reflectors was able to produce more PV power and efficiency of 22 % and 21 % respectively as compared to simple PV module [3]. Sangani et al concluded that the output power was increased 40% by using of V-trough concentrator system in comparison with flat PV systems. In this case the cost/ unit watt of electricity generated from PV module is reduced by 24% from 7.72 to 5.88 $/W for the V-trough concentrator system in comparison with flat PV system [6]. Ronnelid et al investigated the performance of PV modules with planar reflectors with variable length and tilts for Swedish conditions. They showed that a flat stationary reflector can increase the annual output of the PV module in the order of 20-25 percent [7]. Ahmad et al studied PV modules with and without a tilted plane reflector. They indicated that the planar reflectors can improve the annual energy output of PV modules by about 22% [8]. Perers showed that using booster reflectors for solar collector leads to an increase of 30 percent in annual performance with only a 10 percent increase in the installation cost for the solar collector system [9]. The aim of this paper is to study the effect of one and two sides of flat reflectors (V-trough concentrator) on photovoltaic solar cell power output theoretically and experimentally.

V-Trough Concentrator

Solar concentrators are classified by their optical characteristics such as focal shape, the concentration factor, distribution of illumination, and optical standard. Concentration factor X (the number of suns) is the ratio of the mean radiant flux density on a receiver area Gx compared to the average normal global irradiance G [10]:

$$X = \frac{G_x}{G}$$

(1)

The classification according to the concentration factor includes the following conditions [11]:

(i) Low concentration photovoltaic (LCPV): (1–40X),

(ii) Medium concentration photovoltaic (MCPV): (40–300X),

(iii) High concentration photovoltaic (HCPV): (300–2000X).

Also the efficiencies of different PV cells can be obtained from the following equation [12]:

$$\eta = \frac{P_{max}}{A_r\, E_e}$$

(2)

Where η is the efficiency, $P_{\max}$ is the ratio of the optimal electric power delivered by the PV cell, Ar is the area of the PV cell exposed to solar radiation, Ee is the solar irradiance received by the PV. One of the disadvantages of the high and medium concentrating systems is the necessity of a tracking system to track the sun movement. Tracking systems are costly, consume electric energy and require continuous maintenance. They are not well suited to use this technique for small remote loads and, more recently, building integrated applications. The advantages of using low concentration CPV systems are the exclusion of the tracking system, the solar cells used by low concentrations are usually silicon cells with a typical efficiency of 15% In comparison with triple-junction solar cells required for the high concentration CPV systems of an efficiency 40% [13], the irradiance distribution on the collector will be more uniform as compared with curved reflectors. This makes low concentration PV systems more appealing for use, especially for small building applications [14]. V-trough concentrator (figure 1) is one type of low concentration CPV systems that cause to reduce the price of the PV electrical power by using conventional solar PV cells. V-trough are static concentrators, wherein the light intensity is boosted by placing reflectors to the sides of the PV module. Since, these are the non-imaging type of concentrators hence, diurnal tracking of the sun is not required and the added cost of the V-troughs is low as they are simple to manufacture [6].

Figure (1): V-trough PV concentrator

Design of the V-Trough Concentrator

The performance of the concentrator is simulated using the analytical solution presented by Fraidenraich (1992 and 1998) for a V-trough concentrator. For the proposed design Fraidenraich's equations simplify substantially, as only one reflection off each sidewall needs to be considered, this ensures uniform illumination of the absorber and allows standard polycrystalline cells to be used. It is possible to increase the solar radiation incident on a PV module by use of planar reflectors. When the ground-reflected radiation was taken into account, with the ground assumed to be a horizontal diffuse reflector infinite in extent. When the ground reflectance normally of the order of 0.2 and low collector slopes, the contributions of ground-reflected radiation are small. However, with ground reflectance of 0.6 to 0.7 typical of snow and with high slopes, the contribution of reflected radiation of surfaces may be substantial [15].

In this paper, consider one and two intersecting planes, the receiving surface *c* (i.e., a solar PV collector) and two diffuse plane reflectors. The angle between the solar PV collector and one reflector plane is ψ. The angle $\psi = 180^{\circ} - \beta$ if the reflector is horizontal, but the analysis is not restricted to a horizontal reflector. The length of the assembly is *m*. The other dimensions of the PV collector and reflector are *n* and *p*, as shown in figure (2).

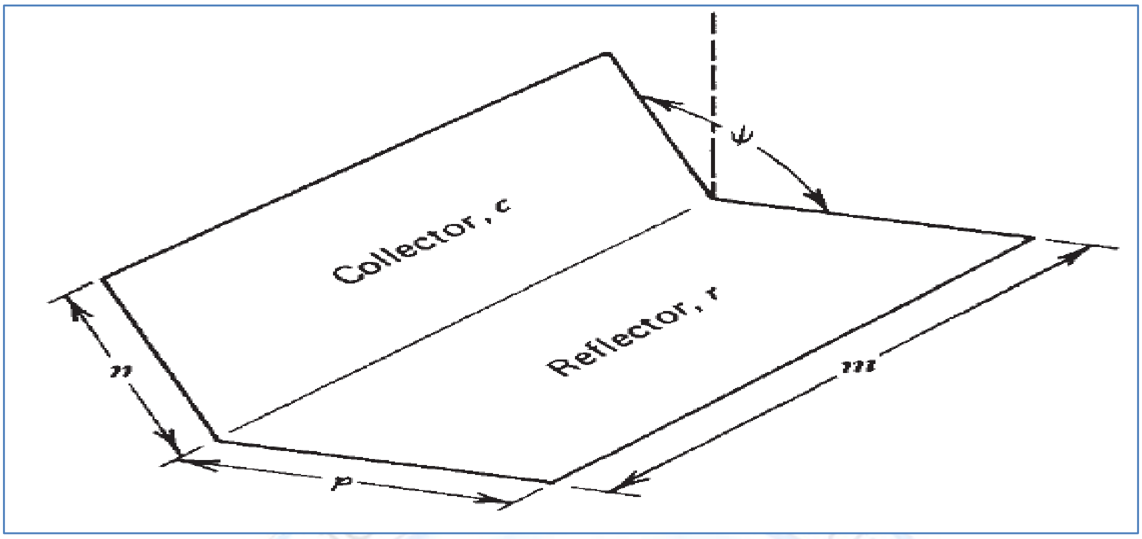


Figure (2): Geometric relationship of an energy receiving surface (collector, c) and reflecting surface (r) [15]

The total solar radiation incident on the surface of PV solar collector is given by [14]:

$$I_T = I_b R_b + I_d F_{c-s} + I_r \rho_r F_{c-r} + I \rho_g F_{c-g} \quad (3)$$

Where I_b, I_d are the beam and diffuse solar radiation, respectively, R_b is the ratio of beam radiation on tilted surface to that on horizontal surface which is given by the following equation [16]:

$$R_b = \frac{\cos(\emptyset-\beta)\cos\delta\cos\omega+\sin(\emptyset-\beta)\sin\delta}{\cos\emptyset\cos\delta\cos\omega+\sin\emptyset\sin\delta} \quad (4)$$

$Fc{-}s$ *is* the view factor between collector and sky that is given by [17]:

$$Fc{-}s = (1 + \cos\beta)/2 \quad (5)$$

$Fc{-}r$ is *is* the view factor between collector and reflector which can be obtained from the reciprocity relationship [17]:

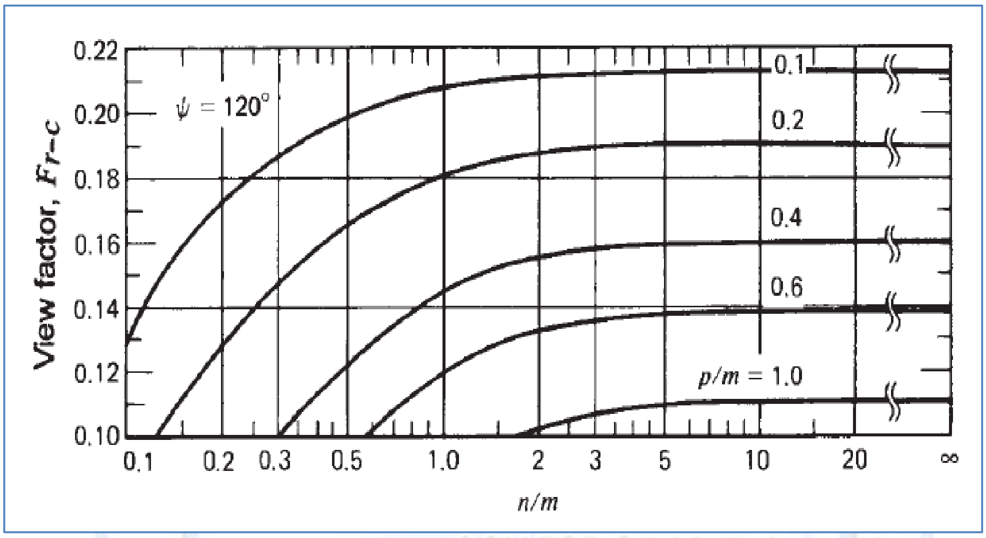
$$AcFc{-}r = ArFr{-}c \quad (6)$$

and $Fc{-}g$ *is* the view factor between collector and ground which can be obtained from the following summation rule [17]:

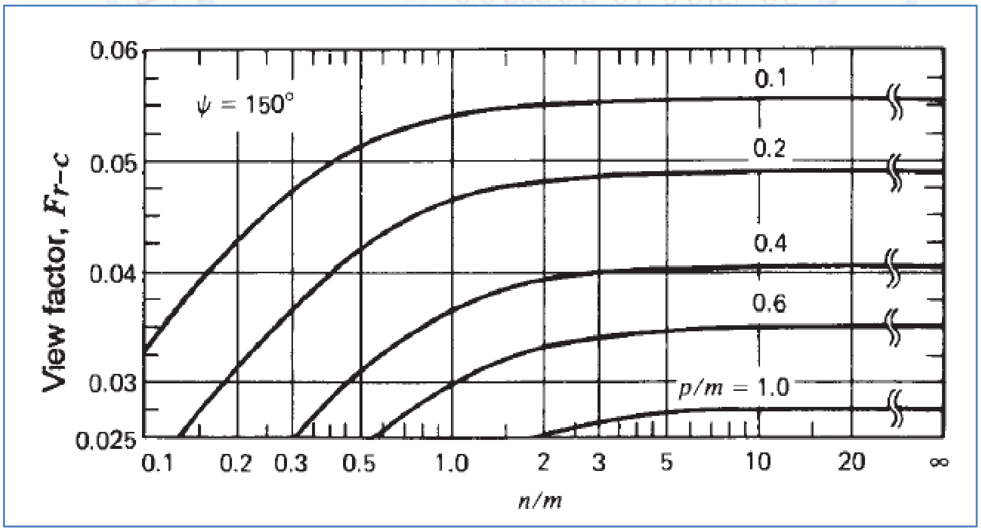
$$\sum F_{c-i} = F_{c-r} + F_{c-s} + F_{c-g} = 1$$

(7)

The view factor *Fr−c* is shown in Figure (3) as a function of the ratios *n/m* and *p/m* for ψ of 120º, and 150º. The values of solar radiation that used in theoretical calculations have been given in table (1).



(a)



(b)

Figure (3) : View factor Fr−c as a function of the relative dimensions of the collecting and reflecting surfaces. Adapted from Hamilton and Morgan (1952) [15].

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Table (1): Total solar radiation at normal incidence in Baghdad in January-15 [18]

Solar time	Total solar radiation I_{TN}
7.5 AM	229.46
8	366.12
8.5	495.23
9	592.61
9.5	663.29
10	713.94
10.5	749.40
11	772.86
11.5	786.23
12 AM	790.58
12.5 PM	786.23
13	772.86
13.5	749.40
14	713.94
14.5	663.29
15	592.61
15.5	495.23
16	366.12
16.5 PM	229.46

Experimental Setup

The theoretical assessment outcomes can be satisfactorily proven by validate the theoretical calculations against experimental data. In order to achieve this validation, a prototype PV concentrator is fabricated and examined its performance by using PV solar cell with dimensions ($15 \times 15 \ cm^2$) and it is provided by one and two plane reflector mirrors which put in the top and bottom side (y-dimension) of the solar cell to form a V-trough profile as shown in figures (4 to 6). the electrical output of the solar cell has been determined by using two avometers , the data acquisition system switched between measuring the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}) across the solar cell at 5-second intervals. From this it is possible to determine the output power of the solar cell without reflector, with one reflector and with two reflectors, respectively. The V-trough PV concentrator has been put at different tilt angles in order to evaluate its performance with different tilt angles.

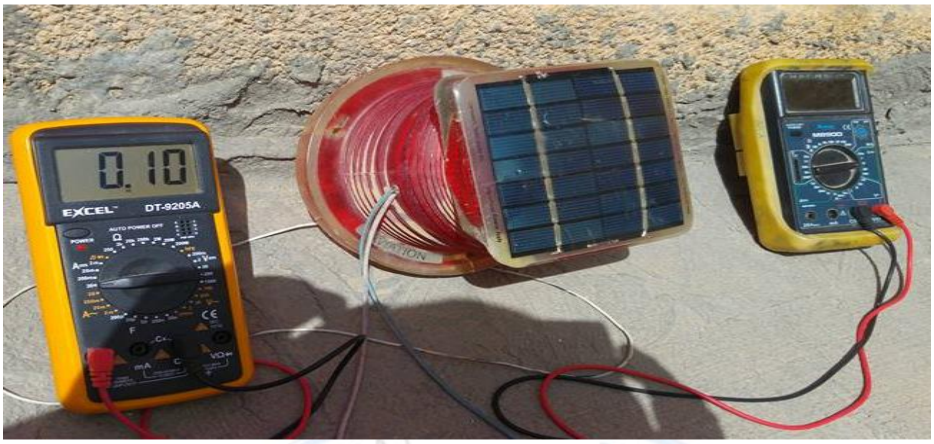

Figure (4): Solar cell without reflectors

Figure (5): Solar cell with one reflector

Figure (6): Solar cell with two reflectors

Results and Discussion

The performance of the V-trough PV system with one and two reflectors is evaluated for typical day of January, the total solar radiation falling on the Collector is function of reflector width, the PV collector width which effect on the view factor between PV collector and reflector (F_{r-c}). The angle between the PV collector and reflector and the tilt of PV collector are fixed at 120^o and 60^o, respectively. So the PV collector is at fixed orientation facing south, whereas reflector width and the PV collector width can be changed, in order to study the effect of the view factor between Collector and reflectors function of time the day of January are chosen. The view factor has been optimized of the ways that it can get the maximal insulation falls onto the PV collector. Variation of the total solar radiation received by the PV collector without reflector for horizontal surface, for normal surface, with tilt angle 60^o, with one reflector and with two reflectors for a selected day in 15-January during the time period from 7:30 AM to 4:30 PM for different view factor between the PV collector and reflector is shown in Figures 7 to 12. it is clear from these figures that the total solar radiation increase with time to get maximum value in the solar noon and then decrease to get minimum value in the last day for all curves which represent all case under study. The minimum insolation when the PV collector is horizontal without reflector and increase for tilt angle 60^o and normal incidence when tracking system has been used, but at solar noon the solar radiation has the same value for the last two cases. The solar insolation increase when the PV collector is provided with one and two reflectors, thus for F_{r-c} = 0.1 it increase from 786 W/m^2 for 60^o tilt angle and 790 W/m^2 for normal incidence to 990 W/m^2 when using one reflector and 1077 W/m^2 when using one reflectors which represent improvement about 26% and 37% for one and two reflectors, respectively. When F_{r-c} increase it has been more enhancement as shown in figures 5 to 9, thus for F_{r-c}=0.21 the solar radiation at solar noon when using one reflectors is 1265 W/m^2, in other words 61% enhancement. On the other hand, there is 120% enhancement of two reflectors system in comparison with horizontal surface without reflector. Figures 13 and 14 illustrate clearly the enhancement in the solar insolation for F_{r-c} when using one and two reflectors respectively.

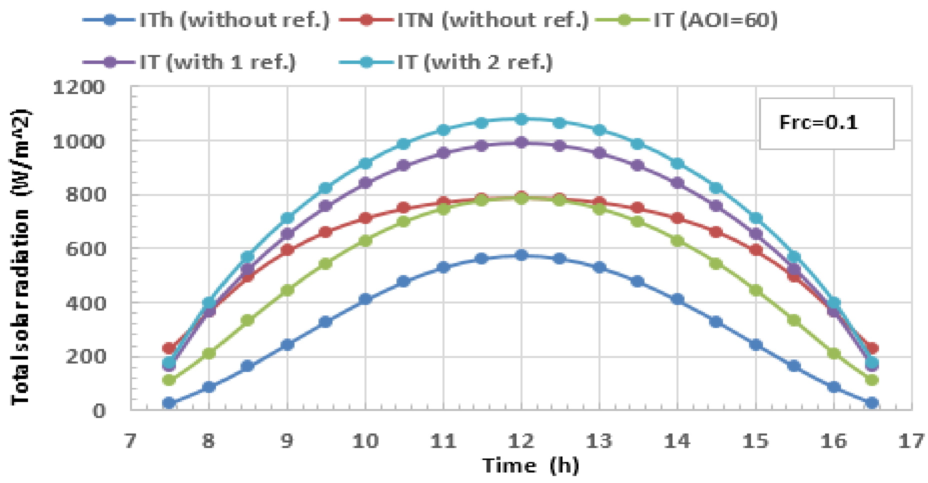

Figure (7) : Total solar radiation for horizontal, normal incidence and with incidence angle 60º without reflectors and with one and two reflectors for (F_{r-c} =0.1)

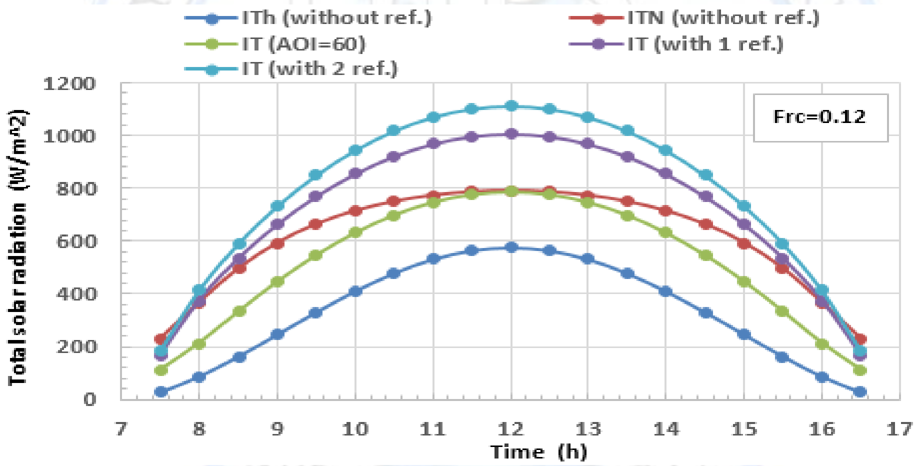

Figure (8) : Total solar radiation for horizontal, normal incidence and with angle of incidence 60º without reflectors and with one and two reflectors for (F_{r-c} =0.12)

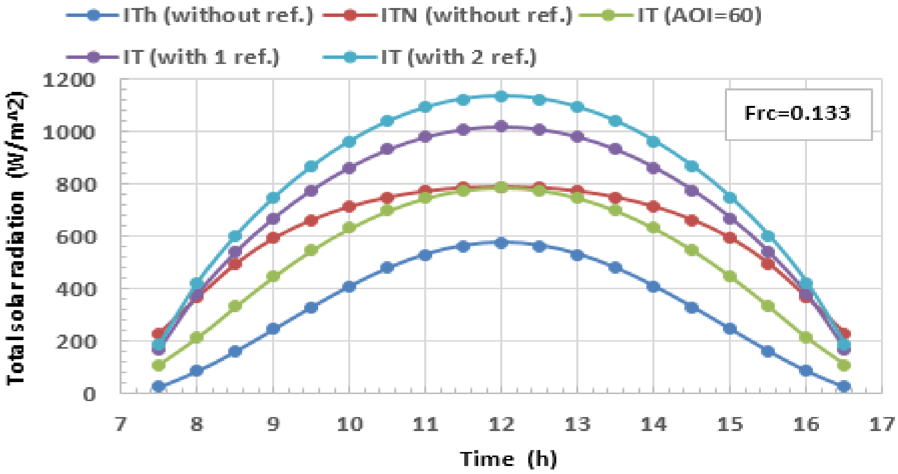

Figure (9) : Total solar radiation for horizontal, normal incidence and with angle of incidence 60º without reflectors and with one and two reflectors for (F_{r-c} =0.133)

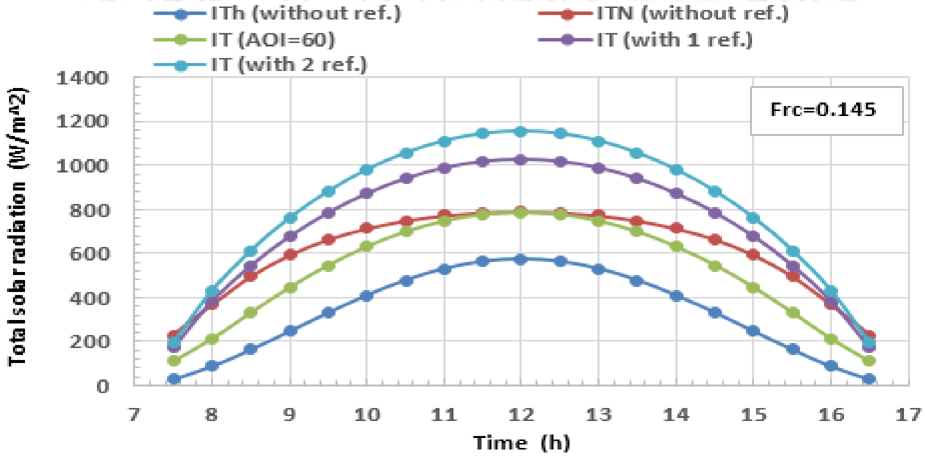

Figure (10) : Total solar radiation for horizontal, normal incidence and with angle of incidence 60º without reflectors and with one and two reflectors for (F_{r-c} =0.145)

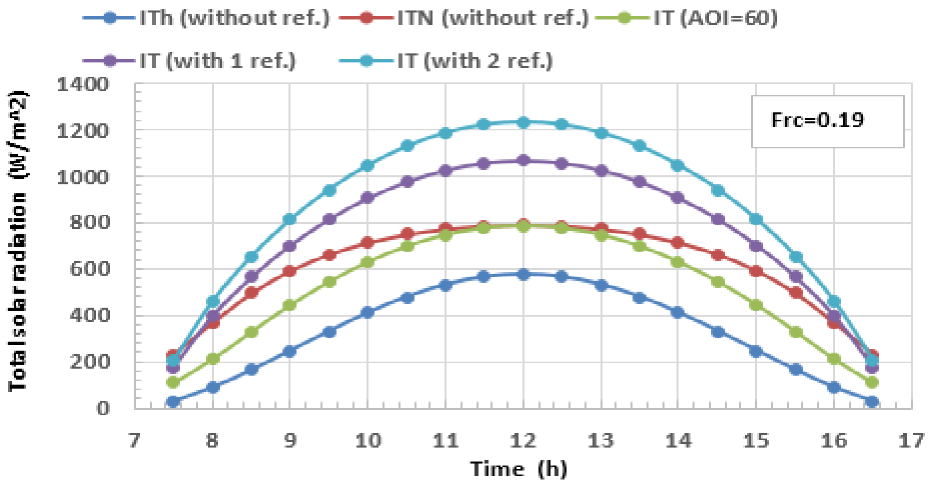

Figure (11): Total solar radiation for horizontal, normal incidence and with angle of incidence 60º without reflectors and with one and two reflectors for (F_{r-c} =0.19)

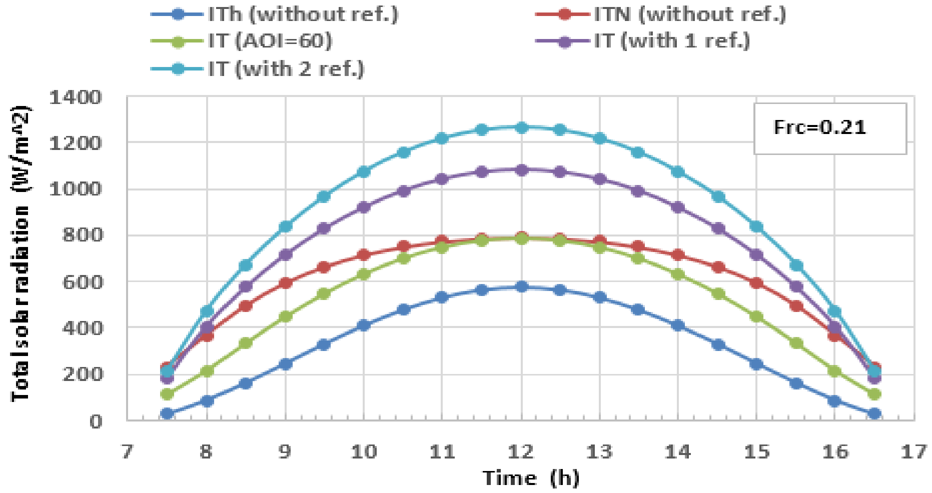

Figure (12): Total solar radiation for horizontal, normal incidence and with angle of incidence 60º without reflectors and with one and two reflectors for (F_{r-c} =0.21)

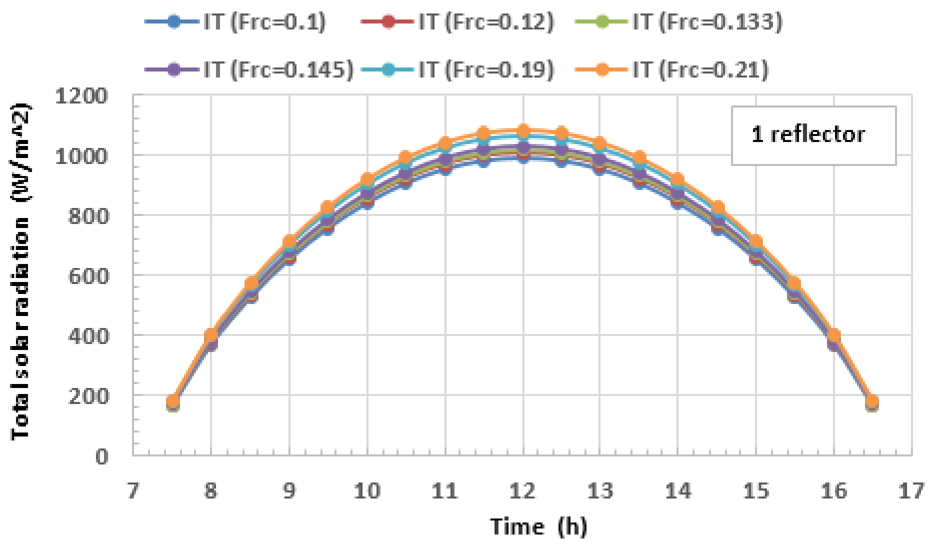

Figure (13): Increasing the input solar radiation to PV solar collector by using one reflector (W/m^2)

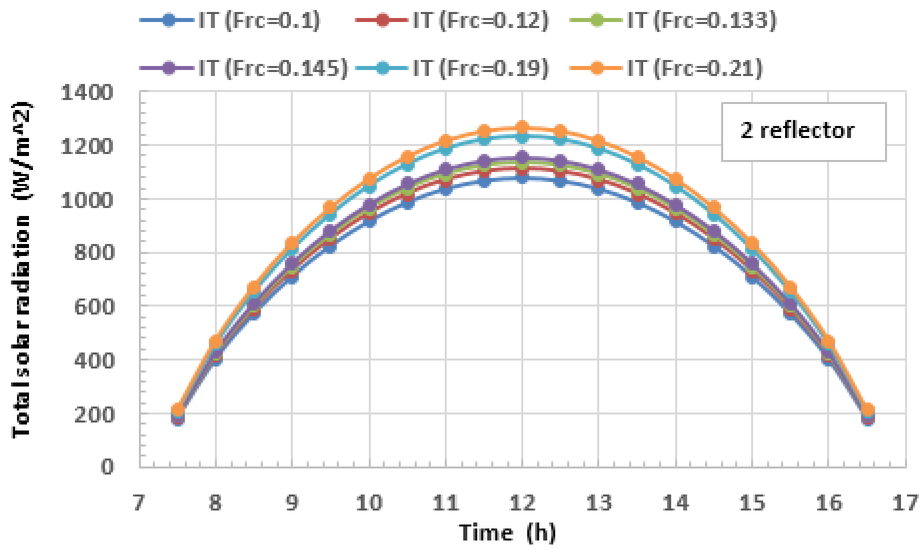

Figure (14): Increasing the input solar radiation to PV solar collector by using two reflectors (W/m^2)

The experimental result is shown in figures 15, 16, 17 and 18. Figure 15 shows the variation of short circuit current (Isc) with time for PV collector without reflector, with one reflector and with two reflectors. It is clearly seen from this figure that Isc at solar noon increase from 0.16 A for PV collector without reflector to 0.22 A for PV collector with one reflector which represent 37.5% enhancement and to 0.3 A for PV collector with two reflectors which represent 87.5% enhancement, while the open circuit voltage (V_{OC}) in figure 16 is less effected by using reflectors because it is less effected by increasing input solar radiation, thus it increase from 8.35 volt for PV collector without reflector to 8.43 volt with one reflector and to 8.4 volt with two reflectors. It is obviously that one reflector case give more V_{OC} because of the effect of increasing the solar cell temperature. Therefore the output power from PV collector is the same behavior of Isc as shown in figure 17 which have the values 1.06 W, 1.48 W and 2.01 W at solar noon for PV collector without reflector, with one reflector and with two reflectors, respectively. In order to study the effect of tilt angle of PV collector on its performance, different tilt angles from 0^o to 90^o have been tested and illustrated in figure 18. It can be seen from this figure that the optimum angle that get the maximum output power is 45^o for all three cases under study.

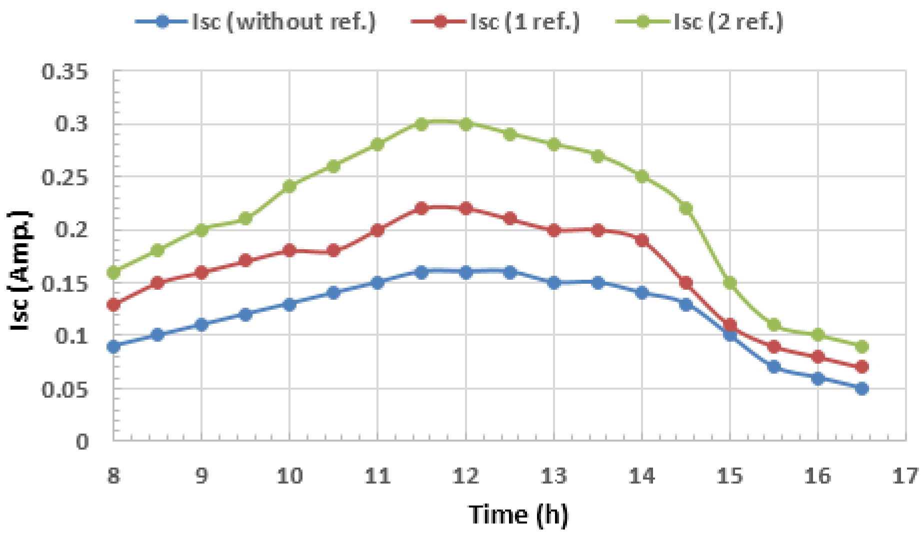

Figure (15): Experimental measurements of short circuit current with time without reflectors and by using one and two reflectors.

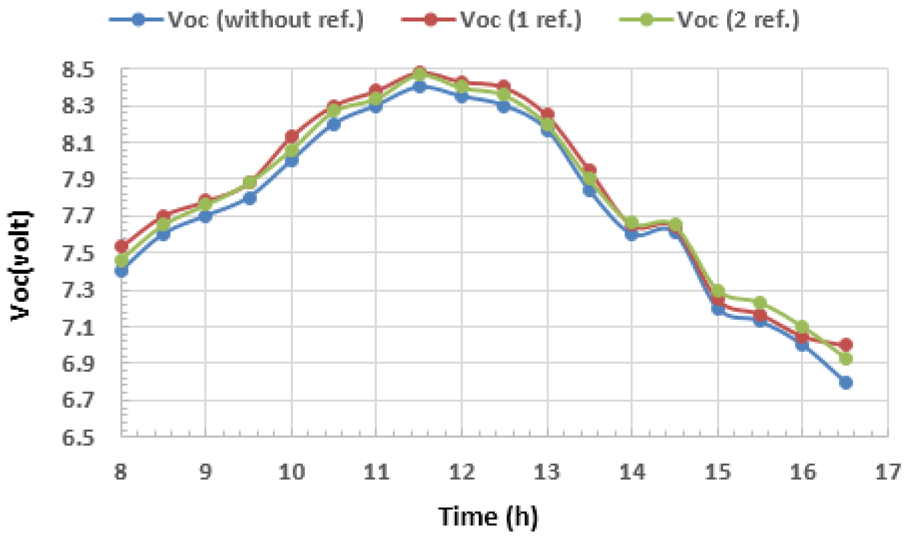

Figure (16): Experimental measurements of open circuit voltage with time without reflectors and by using one and two reflectors.

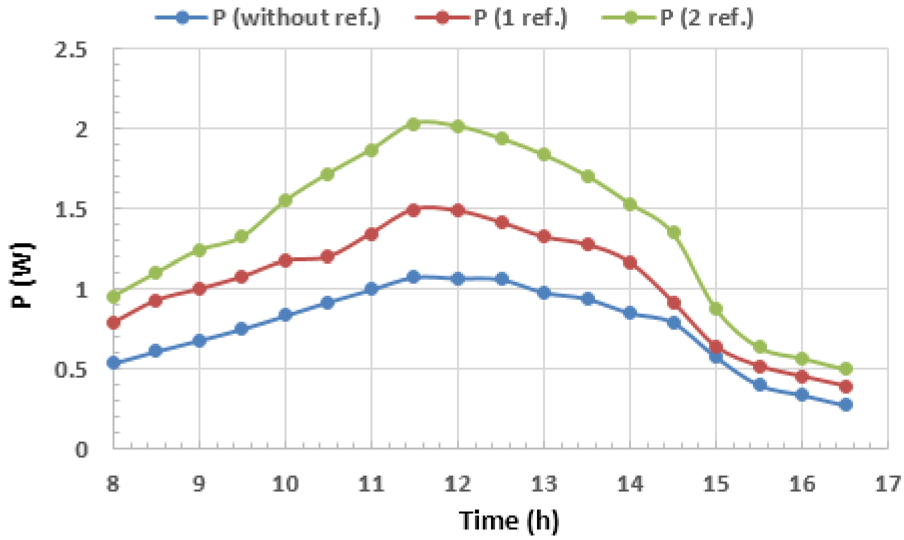

Figure (17): Experimental measurements of power with time without reflectors and by using one and two reflectors.

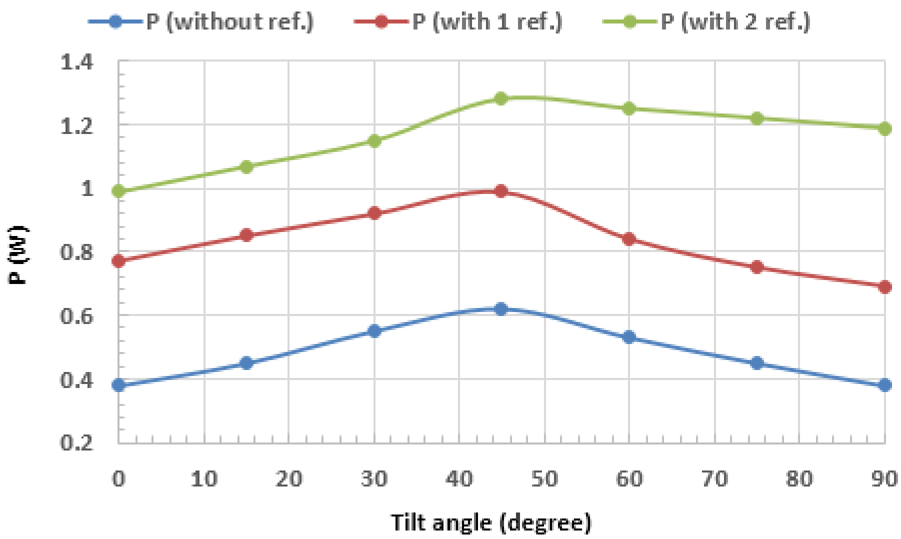

Figure (18): Experimental measurements of power with tilt angle of PV solar cell without reflectors and by using one and two reflectors.

Conclusions

1. The use of planer reflectors with fixed PV collectors improves its performance better than the use of solar trackers.
2. The planer reflectors are less expensive than solar trackers and do not require mechanical maintenance.
3. This design is not require to cooling system.

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