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V-TROUGH CONCENTRATOR ON A PHOTOVOLTAIC FULL TRACKING SYSTEM IN A HOT DESERT CLIMATE

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Abstract—A V-trough concentrator with a two-axis tracker system to increase the performance of photovoltaics was designed by the authors and installed on the roof-top of the building of the National Research Institute of Astronomy and Geophysics at Helwan in South Cairo. The V-trough concentrator system comprises two flat mirrors with dimensions 50 cm × 18 cm. They are fixed with the reflecting surfaces facing each other with a separation of about 11 cm, on a wooden table of 50 cm axis length. A sample of polycrystalline and amorphous silicon solar cells were fixed into the system, and similar solar cells of each type were fixed separate to the system, to estimate the electrical gain. The measurements were performed daily at different air masses for one complete year. The temperature of the solar cells in and out of the system were measured for comparison. Also, measurements for beam and global solar radiation and other meteorological conditions were recorded. The optical losses of the system were analyzed and details of collectable energy calculations are presented. The energy gain from the isolated contribution of the V-trough concentrators is also evaluated.

1. INTRODUCTION

Increasing the efficiency and reducing the cost are the two main targets in order to increase the competitiveness of PV energy. In order to reach that, the following points may be considered [1]:

(1) increase cell and module efficiency;
(2) use Sun-concentration modules;
(3) use one- or two-axis tracking system;
(4) minimize module mismatch losses;
(5) reduce cell temperature by cooling.

PV arrays are basically of two types, flat plate and concentrator. Since the active solar cell material is usually the most expensive component of an array, it is a sensible strategy to concentrate the insolation into the cell.

The concentration ratio C of a perfectly focused system is the ratio of the concentrator input aperture to the surface area of the cell. In practice, energy concentration reaches 80–90% of this geometric factor. Low C systems ($C \leqslant 5$) do not have to be oriented through the day to follow the Sun and so make use of some diffuse as well as direct insolation. Increased C systems have to track the Sun, and are only sensible in places with a large proportion ($>70\%$) of direct insolation.

There is a wide variety of concentrator systems based on lenses, mirrors and various novelties such as internal prism reflection [2].

V-trough cavities used in conjunction with commercial photovoltaic cells can be an effective way to reduce the cost of the energy produced by photovoltaic panels. The walls of the cavity, being plane, enable the use of low cost, good quality mirrors with the benefit of a high optical efficiency. If at the same time the V-trough concentrator can be built at a moderate cost, the use of photovoltaic panels coupled to V-trough concentrators can result in a favourable cost–benefit ratio [3].

The advantage of V-trough concentrators over high concentrators is that no cooling techniques are required, since the loss of voltage is not very high.

2. V-TROUGH CONCENTRATOR CAVITY

2.1. *V-trough optics*

A V-trough concentrator can be characterized by two parameters (as shown in Fig. 1); the trough separation angle 2θ, and the geometric concentration ratio C defined as the ratio of the aperture area to the absorber area.

The uniform illumination of the PV module in a V-trough requires that the incident rays undergo at most one reflection before reaching the absorber. This implies the relation [4]:

$$C \geqslant 1+2(\cos 2\theta), \quad \theta < 45. \tag{1}$$

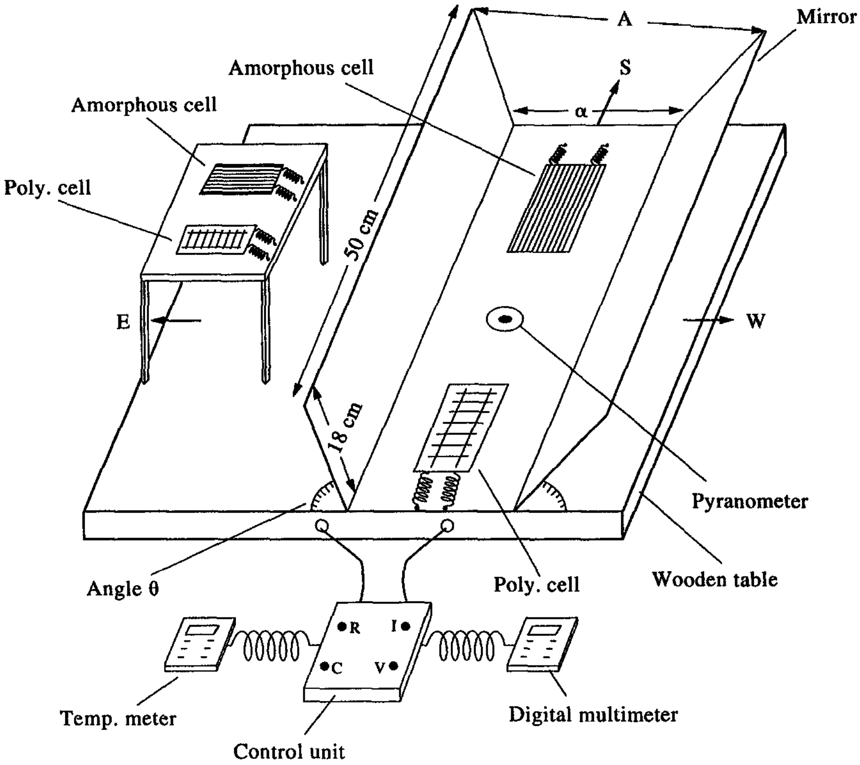

Fig. 1. Schematic diagram of the V-trough concentrator.

For incident radiation, there are three types of rays:

(i) direct hitting beams;
(ii) incident beams after one reflection;
(iii) diffuse radiation due to sky scattering.

The first type is the part of radiation which is incident on the absorber directly, the second type is the radiation incident on the mirrors which is then reflected onto the absorber, while the third type is the radiation hazard which may be neglected for two reasons: first, the system is fully tracking to the Sun, so the major part of the radiation is direct radiation, and second, the diffuse radiation represents a small percentage of the total radiation, especially for clear sky days.

For the first and second types, we have the equations of the collected energy:

$$G_i = I_n \times \cos(\theta_i) \times K(\theta_i) \tag{2}$$

and

$$G_r = I_n \times \cos(\theta_r) \times K(\theta_r) \times \rho_{\text{mirror}}, \tag{3}$$

where I_n = normal beam intensity; θ_i = incidence angle of the radiation on the absorber without reflections; θ_r = incidence angle of radiation after one reflection from the mirrors; $K(\theta_i)$, $K(\theta_r)$ = incident angle modifiers [5]; and ρ_{mirror} = reflectivity of the mirrors.

2.2. *V-trough system description*

The system was installed at the top of the building of the Institute at Helwan which is a hot desert city to the South of Cairo. The system consisted of two mirrors facing each other; Fig. 1 is a schematic diagram representing the system dimensions. Figure 2 is a relation between the effective measured concentration and half the angle between the two mirrors; it also shows the dust accumulation on the cavity walls and its effect on the concentration ratio; the mirrors were left for only three days in real environmental conditions. The optimum concentration at which the homogeneous illumination falls on the absorber area and covers it is about 1.7, corresponding to an angle of about 20° and geometric concentration of about 2.6. The difference between the geometrical and the real concentration is due to the optical losses such as reflectivity of the mirrors ($\rho \cong 85\%$ for commercial

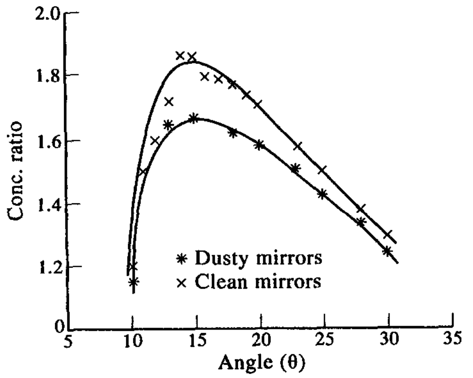

Fig. 2. Variation of concentration ratio vs half angle; and the effect of dust on the concentration.

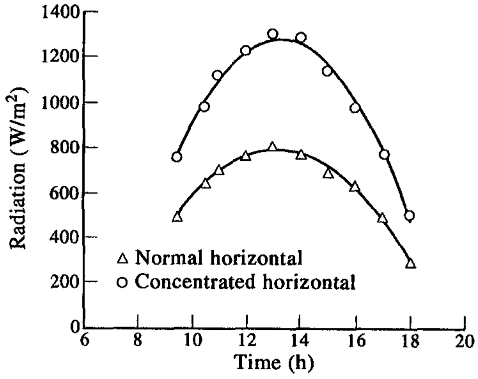

Fig. 3. Horizontal radiation in and out of the V-trough concentrator.

mirrors) and also the perturbation in the tracking system. Inside the cavity, there are two cells, one amorphous type and the other a polycrystalline Si solar cell, inside the cavity. Two other cells of the same types and dimensions were fixed outside the cavity for comparison. The system is fully tracking and the irradiance inside the cavity was measured using a pyranometer.

The short-circuit current and open-circuit voltage of each cell was measured every hour in the daylight together with the back surface temperature of each cell using a thermocouple attached to the back surface of each cell to see the effect of cell temperature on performance, beside other meteorological parameters like humidity, ambient temperature, and horizontal global and direct radiation.

3. SYSTEM PERFORMANCE AND POWER GAIN

This section will discuss first the radiation intensity and concentrator efficiency; second the behaviour of current, voltage and power for amorphous Si solar cells. Also the behaviour of polycrystalline Si is shown.

3.1. *V-trough efficiency and orientation modes*

There were four possible orientations for the V-trough to operate:

(1) totally horizontal with the cavity axis aligned to the E–W direction;
(2) fixed with the place declination angle aligned with the E–W direction;
(3) axially (one axis) tracking system;
(4) fully tracking the Sun.

The first two modes have the advantage that they don't use any external devices such as the tracking system, but give less output.

Tracking modes (axially or fully tracking) have relatively higher outputs, but need auxiliary tracking systems which demand some energy. For a specific area, deciding to work on a specific mode must come after some field tests. Also, dimensions and the concentration ratio of the V-trough and the ratio between the whole gain of the system and the energy delivered by the tracker must be known. For the present system, Fig. 3 shows the gain in solar insolation for concentrated and normal radiation over the day giving a gain of about 58%. The comparison between concentrated horizontal and tracking radiation is shown in Fig. 4 with a gain of about 23% between full tracking and the horizontal tracking mode. For the full tracking mode, the gain of insolation with the concentrator is about 62% as shown in Fig. 5.

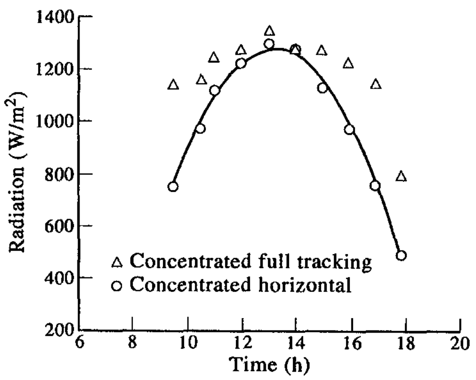

Fig. 4. Concentrated radiation for the horizontal and fully tracking modes.

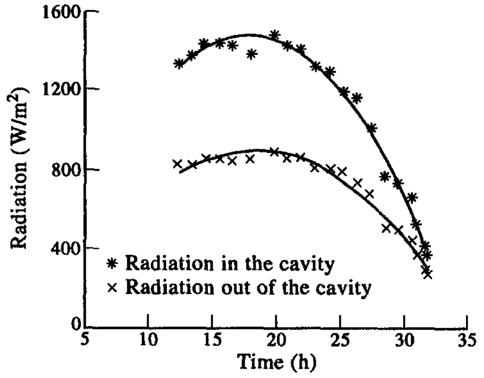

Fig. 5. Fully tracking solar radiation in and out of the V-trough concentrator.

The variation of concentration ratio over the full day for the full tracking mode is shown in Fig. 6 and will be dealt with in the next section.

3.2. *Amorphous solar cell power gain*

The current gain of amorphous Si solar cells, as shown in Fig. 7, equals about 42% as an average over the day, with a peak gain about 47% at noon. Regarding the voltage loss of the solar cell due to the increased temperature of the cell which, reaches 60°C on summer days in the cavity with an increase of about 15–20°C over the cell out the concentrator, the voltage drop is shown in Fig. 8 with the maximum decrease around noon. The highest value of the loss is about 4%, which is a relatively small value.

Finally, the gain in the power of the amorphous solar cell due to solar radiation concentration is shown in Fig. 9 and equals about 40% as a day average, which is a quite high value, and may be applied very widely.

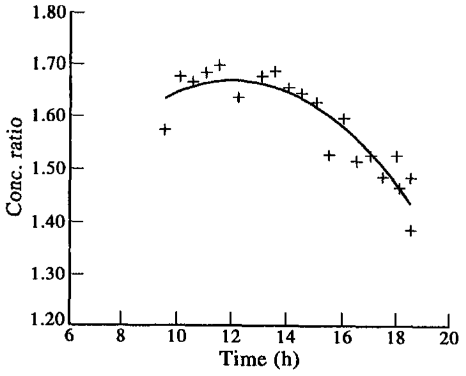

Fig. 6. Variation of concentration ratio over the full day.

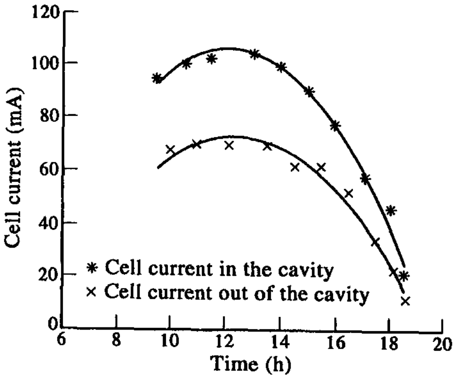

Fig. 7. Amorphous cell current in and out the V-trough concentrator.

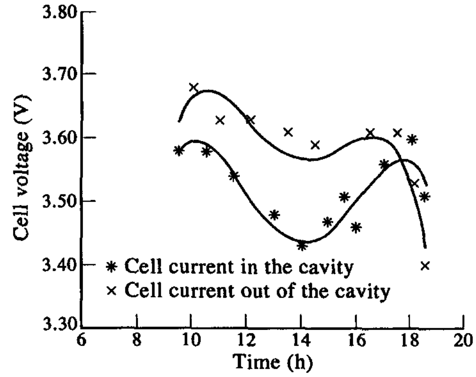

Fig. 8. Voltage drop for the amorphous cell in and out the V-trough concentrator.

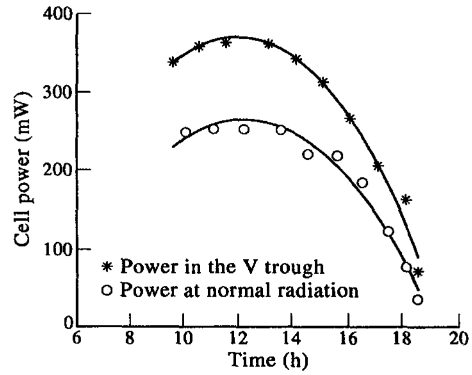

Fig. 9. Cell's power in and out the V-trough concentrator for the amorphous type.

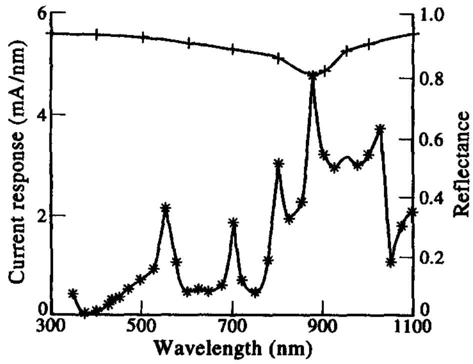

Fig. 10. Aluminium reflectance superimposed with the current response of the polycrystalline cell.

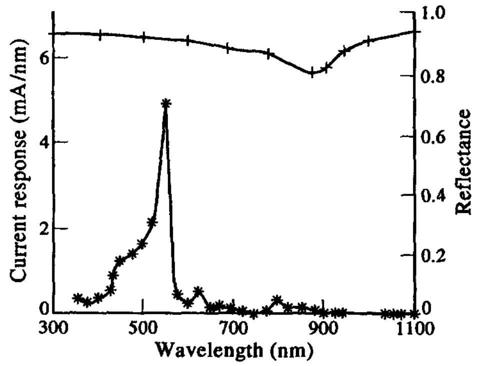

Fig. 11. Aluminium reflectance superimposed with the current response of the polycrystalline cell.

3.3. *Polycrystalline solar cell power gain*

The current gain of the polycrystalline Si solar cell is quite a lot less than the amorphous type. Figure 10 shows the reflectivity of the commercial mirrors [6] which are used in the V-trough superimposed with the polycrystalline Si solar cell's spectral response curve. The mirror's back surface is coated with a thin layer of aluminium; the aluminium's reflectivity drops around the wavelength 900 nm, which is the highest peak for polycrystalline solar cells. So the current gain is low, especially at sunset and sunrise which correspond to the highest percentage of total radiation. In contradiction, the spectral response of the amorphous cell is mainly around 550 nm which corresponds to the highest percentage of the visible radiation which is at a maximum at noon as shown in Fig. 11.

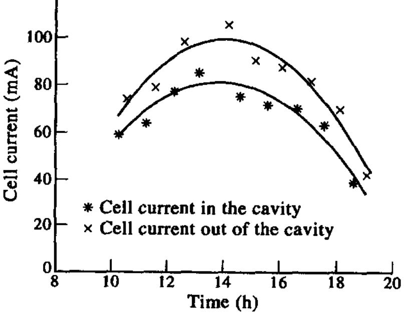

Fig. 12. Current gain of the polycrystalline type in and out the V-trough concentrator.

The current gain of the polycrystalline type is shown in Fig. 12 with a gain of about 25%.

For the voltage loss of the polycrystalline type, the drop is increased for the cell in the cavity compared with the outer cell without the concentrator due to the temperature increase. The difference in temperature for the polycrystalline cells in and out of the cavity reaches 3–7°C. The open-circuit voltages of the cells in and out of the concentrator are shown in Fig. 13, with a loss of about 6% at noon. Finally, the power gain equals about 22% as an average on the day for the cell in the concentrator over the outer cell with a curve very similar in shape to that of the current curve.

4. CONCLUSION

From the present work on the V-trough solar radiation concentrator on photovoltaic solar cells, it can be shown that:

(1) the V-trough solar concentrator is a very effective

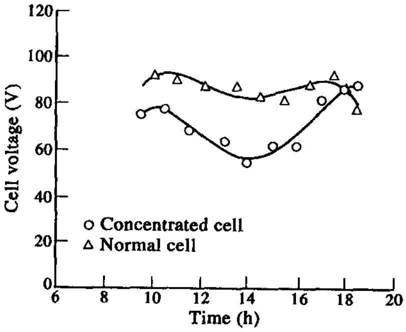

Fig. 13. Voltage drop for polycrystalline type in and out the V-trough concentrator.

method to concentrate insolation with a good concentration ratio (about 1.6) considering its cost and the simplicity of its materials;

(2) for applications of the system to amorphous Si solar cells whose effective wavelength is mainly in the visible band (centered at 550 nm) it gives relatively high gain in the cell's power which is about 40% more than the cell without a concentrator which makes that system effective and may be used commercially;

(3) for applying the system to the polycrystalline Si solar cell, a gain less than the expected is obtained. The reason is that the commercial mirrors coated with aluminium have their lowest reflectivity around 900 nm, which is the centre of the effective wavelength required for the polycrystalline solar cell. So, that system may not be very useful commercially.

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