An Experimental Study on the Performance of Concentrated Photovoltaic System with Cooling System for Domestic Applications

A. Benuel Sathish Raj, S. Praveen Kumar, G. Manikandan, P. Jerry Titus

Abstract: ***Concentrated photovoltaic (CPV) system helps in focusing the direct solar radiation on the photovoltaic module. The CPV systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. As the Concentrated Solar radiation reaches the PV panel system, the temperature increases rapidly and because of this increase in temperature, the output efficiency will be decreased. In order to reduce the temperature and to increase the output efficiency, the Cooling System is used. It has been found that the electrical output of the water cooled CPV is 4.7 to 5.2 times more than the PV module (without concentration and cooling). The cooling system has a heat pipe filled with Acetone. The performance of the CPV module with cooling system based on voltage output and temperature were evaluated and verified with the help of an experimental setup. The electrical energy from the CPV panel is stored in the battery and it is converted to AC supply by using inverter and then used for the residential lighting.***

Keywords-Concentrated Solar Photovoltaic (CPV); Cooling System; Pulsating Heat pipe.

I. INTRODUCTION

Majority of the world population are away from the grid and do not have proper access to the electricity. Extending power lines from centralized sources to rural areas is often not yet economical, and so, decentralized power sources, such as the photovoltaic (PV) system, are a promising alternative. Concentrated photovoltaic (CPV) system helps in focusing the direct solar radiation on the PV module. In CPV, optical lenses are used to concentrate direct solar radiation on the PV module and hence the CPV module produces more output. But due to concentrated incident direct solar radiation on the PV module, the operating solar cell temperature also increases and therefore the solar cell efficiency decrease and the also the life time of the PV module decreases[1][7]. It is important to include proper cooling system in the CPV system for increasing the efficiency of solar cell by reducing the operating cell temperature[3].

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The Australian National University has developed a concentrating solar PV-thermal system by using the parabolic mirror and very encouraging results have been reported and they are: under typical operating conditions the thermal efficiency has been around 58% and electrical efficiency around 11%, therefore a combined efficiency of this system has been 69% [2]. Concentrated solar power plants require high direct solar irradiance to work and are therefore a very interesting option
for installation in the Sun Belt region (between 40 degrees north and south of the equator). This region includes the Middle East, North Africa, South Africa, India, and the Southwest of the United States, Mexico, Peru, Chile, Western China, Australia, southern Europe and Turkey [8].

II. CONCENTRATED PHOTOVOLTAIC (CPV) SYSTEM

After years of slow progress, concentrated PV solar is gaining momentum and installations will grow at double-digit percentages annually through 2020, according to a new IHS report. CPV technology employs lenses or mirrors to focus sunlight onto solar cells. While this allows for more efficient PV energy generation, the use of additional optics for focusing sunlight has also driven up the cost of CPV compared to conventional PV installations, limiting the acceptance of concentrated solar solutions. Concentrating photovoltaic has been an established science since the 1970s, but is only now reaching commercial viability. It is the newest technology to enter the solar Sector. CPV systems can be thought of as telescopes, trained on the suns position and feeding the concentrated light to the cell. The magnification ratio used in different CPV system designs varies so widely that three classes of systems have developed:

- Low concentration (LCPV), where the magnification ratio is less than 10X
- Medium concentration (MCPV), between 10X and 150X;
- High concentration, where the ratio lies above 150X, but is usually less than 1000X.

Concentrating photovoltaic technology offers the following advantages:

- Potential for solar cell efficiencies greater than 40%
- No moving parts
- No intervening heat transfer surface
- Near-ambient temperature operation
- No thermal mass; fast response
- Reduction in costs of cells relative to optics
- Scalable to a range of sizes.

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III. EXPERIMENTAL SETUP

An experimental setup was developed to evaluate the performance of the CPV system with cooling system. The block diagram of the same is explained below. The sunlight is reflected to the solar panel by using a reflecting mirror and a cooling system is placed at the back side of the solar panel in order to get high output efficiency. The Solar panel is fixed on the main stand and the mirror structure connected with it has a single axis tracking to reflect the maximum amount of sunlight to the panel. The electrical energy from the solar panel is stored in the battery and it is converted to AC supply by using inverter and then the supply is used for the residential lighting.

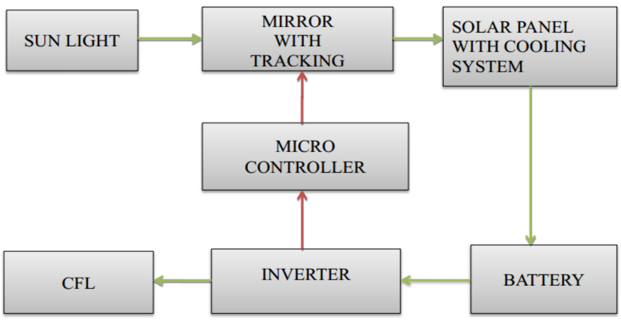

Fig. 1 Block Diagram of the Experimental Setup

The structure is well designed and welded with the iron bars and pipes. This structure consists of a main fixed stand which is of 54mm inner diameter and 60mm outer diameter respectively. The PV Panel is placed at the top of it and in the center of this main stand, a pipe is placed in which two ball bearings are made to fit in it for smooth rotation for tracking. From the pipe, in which bearings are fitted, another pipe is extended for the mirror structure. And in the mirror frame, four mirrors of size 55cm height and 60cm length each were placed. This mirror structure is made to rotate in single axis in the direction of the sunlight. The Cooling system is placed below the Solar panel for cooling the panel. The cooling system consists of pulsating heat pipes filled with acetone is placed just behind the PV panel. The pipes extend beyond the PV panel to dissipate the heat to the surrounding. The fans are placed on those extended areas to wipe away the heat from the cooling pipes. A wiper motor which is of 70rpm is fixed at the stem of the main stand and gears are connected with chain for tracking. Another motor is fixed near the mirror structure for tilting it. The electrical output power generated from PV panel is stored in the battery and the DC is converted to AC by using and inverter and then it is utilized for the residential lighting. Based on the battery backup and inverter the load can be decided.

IV. CONCENTRATOR AND ITS TRACKING

The flat mirrors are used for concentrating the sunlight to the solar panel in this setup. Four mirrors of the following specification are placed on the mirror structure so as to concentrate the solar radiation with a concentration ratio of 2:1. A microcontroller is programmed to rotate this structure every half an hour to reflect the solar radiation on to the PV panel.

A. Mirror Specification

Height - 60 cm (each)
Width - 30 cm (each)
Thickness - 5.0 mm (each)
Maximum withstanding temperature - 90°C
Reflecting ratio - 90 %

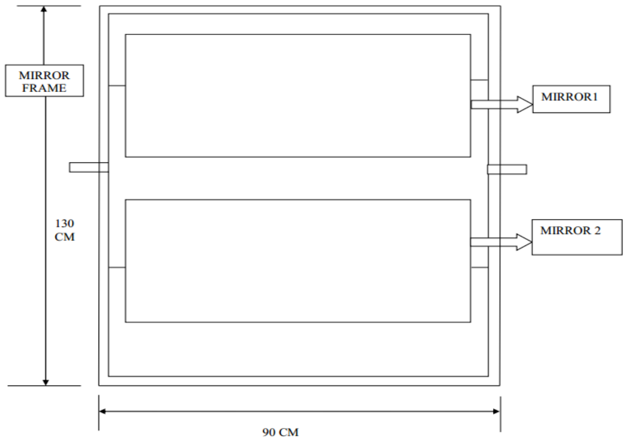

Fig. 2 Structure of the Concentrator

In concentrated photovoltaic (CPV) and concentrated solar thermal (CSP) applications, trackers are used to enable the optical components in the CPV and CSP systems. The optics in concentrated solar applications accepts the direct component of sunlight light and therefore must be oriented appropriately to collect energy. Tracking systems are found in all concentrator applications because such systems do not produce energy unless pointed at the sun. Tracking is one of the major aspects we have to consider for continuous concentration of solar energy. Manual and automatic methods are involved in tracking. But due to cost and simplicity of the system, mechanical tracking system is used. Normal gear arrangements are normally used to track solar radiation. The single axis mirror tracking system was done in the experimental setup with the help of two DC motors. One motor is used to rotate the entire concentrator about the vertical axis from east to west and vice versa to focus the concentrator on to the PV panel during forenoon and afternoon. Another motor is used to tilt the mirror concentrator about the tilted axis every half an hour until noon under the action of a bidirectional DC(wiper) motor. During afternoon, the first motor rotates and the concentrator goes to the otherside(East) to focus the solar radiation from west side.

Fig. 3 CPV System with Tracking Arrangements

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V. DESIGN OF COOLING SYSTEM

The concentrated solar energy is delivered to the solar cell at 20 to 75 W/cm2. The energy that is not converted to electricity must be dissipated to prevent excessive cell heating and to maximize efficiency. Therefore, solar cell cooling is an integral part of the CPV design. First, the solar cell efficiency is a function of cell operating temperature and lower temperatures result in higher efficiencies. Second, the solar cell must be kept below the melting point of the die and interconnect attach materials that are used to manufacture the multi-junction cell receiver package to prevent immediate cell failure. And third, the reliability of the receiver is a function of the number of thermal cycles and the magnitude of the thermal excursion. Some experts claim that reliability or life expectancy is doubled for every ten-degree reduction in thermal excursion.

A. Pulsating Heat Pipe

Pulsating heat pipes/oscillating heat pipes (PHPs) are a passive two phase heat transfer devices, which are special type of wickless heat pipe. Due to its excellent features, such as high thermal performance, faster response to high heat load, simple design, light weight and low cast, PHP has been considered as one of the promising technologies for electronic cooling, heat exchanger, cell cryopreservation and space application, etc. The PHP operation can be explained briefly as follows. In the heated section, evaporation takes place causing the pressure in the vapour bubbles to increase. This increase in pressure in the vapour bubbles causes pressure differentials across some of the liquid plugs. Due to these pressure differentials across some of the liquid plugs will move. In the cooled section, condensation takes place causing the pressure to decrease in the vapour bubbles. These decreases in pressure also causing pressure differentials across some of the liquid plugs causing those plugs to move as well. Due to the fact that all the liquid plugs and vapour bubbles are interconnected by a single tube the movement of any plug will cause neighboring liquid slugs to move as well, causing all the liquid plugs to oscillate in an irregular a periodic manner. The heat is transferred to the atmosphere through forced convection. A 12V Dc fans are placed to remove the heat from the heat pipe at the top. The total length of the heat pipe is 15m and it is bended and made as shown in the fig. The spacing between the bended portions is 3cm and the gap left for each tube is 2cm. The heat pipe is well covered all over the solar panel at the back side and 10cm length of heat pipe is left in free space and above it, the fans are placed for cooling the solar panel . When the temperature ranges to 40 degree the cooling tube reacts and the vapour will go to the top and the liquid(Acetone) will come down , this process is called as recycling process.

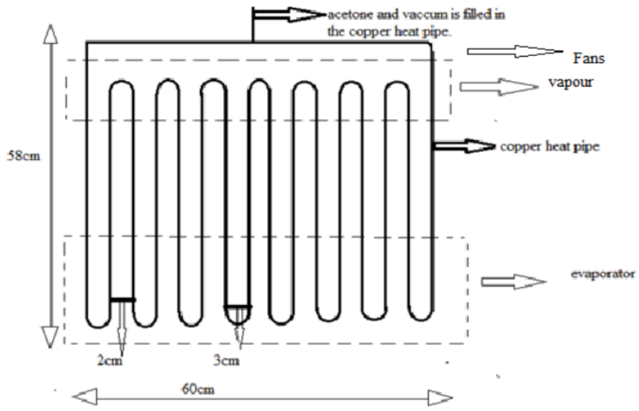

Fig. 4 Pulsating Cooling Pipe Arrangement

B. Choice of Working Fluids

The heat pipe working fluid chosen depends on the operating temperature range of the application. Working fluids range from liquid helium for extremely low temperature applications (-271°C) to silver (>2,000°C) for extremely high temperatures. The most common heat pipe working fluid is water for an operating temperature range from 1°C to 325°C. Low temperature heat pipes use fluids like ammonia and nitrogen. High temperature heat pipes utilize cesium, potassium, NaK and sodium (873–1,473°K).

C. Desirable Working Fluid Properties

- High specific heat: is desirable, sensible heat is playing the major role in heat transfer in the pulsating mode of PHP operation
- Low latent heat: is more beneficial, aiding quick bubble generation & collapse
- High Surface tension: It increases maximum allowable tube diameter
- Low viscosity: It generates lower shear stress
- High values of (dPsat/dT): a small change in T generates a large corresponding P_{sat} inside the generated bubble which aids in the bubble pumping action of the device. The same is true in reverse manner in the condenser.

Table 1 Choice of Working Fluids

Heat Pipe Working Fluid	Operating Temperature (°C)	Heat Pipe Shell Material
Mid Range Heat Pipe Working Fluids		
Acetone	**-48 to 125**	**Aluminum, Stainless Steel**
Ammonia	-75 to 125	Aluminum, Stainless Steel
Ethane	-150 to 25	Aluminum
Methanol	-75 to 120	Copper, Stainless Steel
Methylamine	-90 to 125	Aluminum
Pentane	-125 to 125	Aluminum, Stainless Steel
Propylene	-150 to 60	Aluminum, Stainless Steel
Water	1 to 325	Copper, Monel, Nickel, Titanium

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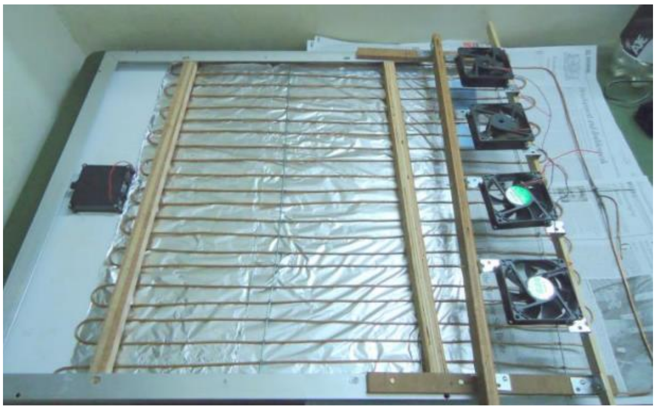

Fig. 5 Pulsating Cooling Pipe Arrangement on the Rear Side of PV Panel

VI. INVERTER & CHARGE CONTROLLER

An Inverter is an electronic device or circuitry that changes direct current (DC) to alternating current (AC). The input voltage, output voltage and frequency, and overall power handling, are dependent on the design of the specific device or circuitry. There are two different types of power inverters:

- Modified sine wave
- Pure (true) sine wave inverters

A charge controller or charge regulator is basically a voltage and/or current regulator to keep batteries from overcharging. It regulates the voltage and current which is got from the solar panel to the battery. Most of the "12 volt" panels voltage is about 16 to 20 volts so if there is no regulation, the batteries will be damaged due to overcharging. Most batteries need around 14 to 14.5 volts to get fully charged. The charge controller is connected directly to the 12 V, 26Ah battery which stores the energy and discharges to the load. The load what we used is a 40W Compact Fluorescent lamp. The results shows that enough power is being generated to power the load although the day.

VII. RESULTS AND DISCUSSION

Experiments were conducted on the set up to determine the voltage generated by the PV panel for the following conditions:

1. PV Output without concentrator and cooler
2. PV Output with concentrator and without cooler.
3. PV Output with concentrator and cooler.

The output voltage of the PV panel was noted from morning 06.00 Hrs to evening 18.00 Hrs. Along with the voltage, temperature of the PV panel was also noted at the rear side of the PV panel. This experiment was conducted on the setup for the above mentioned conditions. It was found that the output voltage of the PV panel reached the maximum value of 21.03V at 13.00 Hrs when neither concentrator nor cooling system is employed. The corresponding temperature at that time is 31.08ºC.

Table 2 PV Output without Concentrator and Cooler

S.No	Time (Hrs)	Output Voltage (V)	Temperature (^oC)
1	06.00	11.01	22
2	07.00	12.56	23.8
3	08.00	12.75	26.4
4	09.00	12.90	28.3
5	10.00	12.23	29.4
6	11.00	15.42	30.23
7	12.00	19.23	31.42
8	13.00	21.03	31.48
9	14.00	19.03	30.32
10	15.00	15.30	26.22
11	16.00	15.22	25.32
12	17.00	14.00	24.00
13	18.00	12.12	22.24

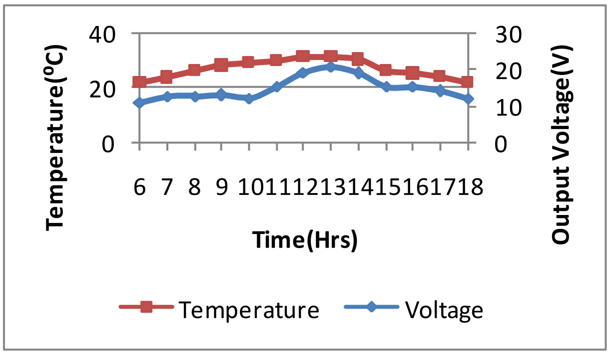

Fig. 6 PV Output without Concentrator and Cooler

Table 3 PV Output with Concentrator and without Cooler

S.No	Time (Hrs)	Output Voltage (V)	Temperature (^oC)
1	06.00	12.23	21.08
2	07.00	13.09	24.7
3	08.00	13.42	26.4
4	09.00	16.09	28.3
5	10.00	16.43	29.4
6	11.00	18.42	30.23
7	12.00	20.23	33.4
8	13.00	23.03	34.26
9	14.00	19.03	34.32
10	15.00	16.03	30.22
11	16.00	15.22	28.32
12	17.00	13.21	26.23
13	18.00	12.42	22.43

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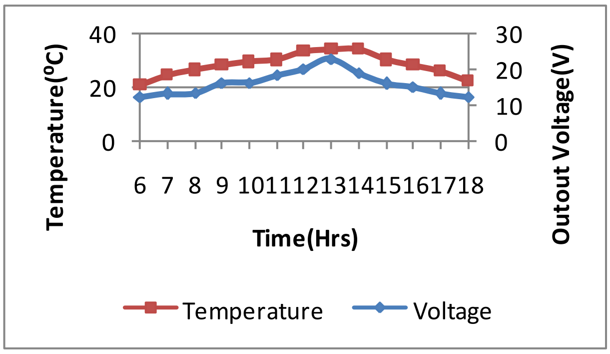

Fig. 7 PV Output with Concentrator and without Cooler

When the concentrator with a concentrating ratio of 2 and without any cooling system is being employed, the temperature goes to a peak of 34.32°C at 14.00 Hrs. It was observed that the output voltage of the PV panel at that time is not the peak voltage but the maximum voltage was generated an hour before. When compared to the system without concentrator, the output voltage of the PV panel has increased by a marginal of 2V.

Table 4 PV Output with Concentrator and Cooler

S.No	Time (Hrs)	Output Voltage (V)	Temperature (°C)
1	06.00	12.23	22.23
2	07.00	13.32	23.23
3	08.00	13.42	24.42
4	09.00	14.09	25.32
5	10.00	15.23	26.42
6	11.00	17.42	27.21
7	12.00	22.23	29.13
8	13.00	20.43	29.26
9	14.00	20.03	30.32
10	15.00	19.03	28.22
11	16.00	17.22	26.32
12	17.00	16.43	25.23
13	18.00	15.34	21.23

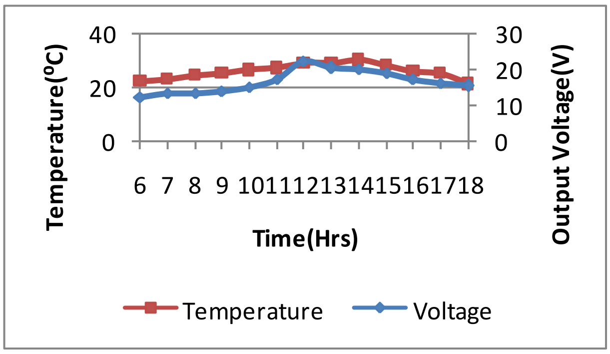

Fig. 8 PV Output with Concentrator and Cooler

It had been observed that the output from the CPV with cooling system is much more than that from the fixed PV module. The maximum voltage that was generated was 22.23V at exactly 12.00 Noon. But substantially the peak temperature measured was only 30.32°C with the concentrator. Since the fans were installed on the top of the Pulse heating pipe, more amount heat were extracted from the CPV module and it can help in reducing the cell temperature and hence in increasing the cell electrical efficiency. So, it was found that when the temperature of the PV panel is reduced by some means the efficiency is being increased automatically.

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