Performance analysis of the solar photovoltaic thermal system using phase change material

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Abstract. This study presents the experimental analysis of photovoltaic thermal system and calculations for percentage electrical efficiency gained and thermal energy. Photovoltaic cells are sensitive to temperature and its performances decrease with increasing temperature. To increase the performance of the photovoltaic panel, a phase change material cum water heating arrangement is attached to the photovoltaic panel. To reduce the cell temperature, paraffin wax (phase change material) is used in the experiment as a heat storage medium. A copper tube is attached to the containment box filled with phase change material. Water is heated through paraffin wax when it flows through the copper tube. The photovoltaic thermal system has a dual benefit over photovoltaic system i.e. it improves electrical efficiency and produces thermal energy simultaneously. It was concluded from the experimental work that percentage of electrical efficiency gained from the photovoltaic thermal system is 1.12% in comparison with polycrystalline silicon photovoltaic panel of model DDS50M at ambient temperature. The maximum reduction in cell temperature and the average thermal energy produced is 8.5°C and 25.45 J/min respectively.

1. Introduction

Solar energy is the most available alternative energy source and also a green and clean energy. It is the main source of non-conventional energy striking to the surface of the Earth which is used as input for secondary sources. Solar flux striking the upper layer of the atmosphere every year is about 5.6 x 10²⁴ J [1]. Energy is the fundamental aspect of a living; it may be in the form of solar energy, wind energy, and other non-conventional energy sources. In the past few decades, most of the countries are dependent on the conventional energy source such as coal, oil and fossil fuels for power production. Due to this, carbon emission is increasing and causing an adverse effect on the environment which increases earth’s temperature.

India is a fast-developing country in the solar power sector. India has increased its solar power generation in recent years. Photovoltaic (PV) modules and flat plate collectors are good technology to
harness solar energy [2]. But the efficiency of PV cells decreases when the cell operating temperatures increases due to the effect of solar intensity and ambient temperature [3], [4]. Photovoltaic thermal (PV/T) system has a dual benefit, it converts solar radiation into thermal and electrical energy separately or simultaneously as per need [5]. The electrical efficiency, thermal efficiency and total efficiency of the PV/T module decreases with the increasing inlet water temperatures, and increase with increasing mass flow rates [6]. There is another method, an active cooling which has an 8 % conversion efficiency of PV panel [7]. The electrical efficiency of PV panel decreases by about 0.4 %/°C for crystalline silicon panels for an increase of temperature beyond a certain range generally 25 °C [8]. Through PCM, a reduction in the temperature of the panel by 15 °C can be achieved [9]. Polycrystalline-Si PV panel has about 13-18 % electrical energy conversion efficiency [10]. Increasing the temperature of the PV cells has an adverse effect on the cells which results in the decline of cell efficiency (-0.5 % per °C) [11]. Thermal, optical and electrical properties also affect the thermal and electrical efficiency of PV cells [12]. Few researchers have used water circulating channel, concentrated PV panel for cooling by using heat pipes [13], [14]. Heat storing materials (PCMs) have been used by researchers to cool the PV cells [15], [16], [17], [18].

2. Materials and Methodology

Two 50 W polycrystalline silicon solar panels were used in the experiments having same property i.e. maximum efficiency of 11 % under standard condition (cell temperature 25 °C, solar irradiation 1000 W/m²) and an area of 0.4158 m². Both the panels were established in the south direction with a tilt angle of 26°. PV/T system consists of a box filled with paraffin wax and attached to the PV panel as shown in figure 1. Water flowed from the water tank to the PV/T system. A rubber pipe was used to join input and output points. The rotameter was used to measure flow rate as seen in figure 1. Phase change material was introduced for the thermal part of a PV/T system. A serpentine copper pipe arrangement was attached to a rectangular box (made of stainless steel) of dimensions 0.533 m × 0.457 m × 0.025 m as shown in figure 2. This box was filled with PCM (paraffin wax) with a volume allowances of 4 % of containment box and adhered to the rear side of the PV module. Silicone sealant was used to avoid any leakage. Copper pipe has seven passes submerged into paraffin wax having a serpentine configuration for flow channel. In this experiment, the serpentine flow channel was designed in such a way that offers a large coverage area with simplicity. The pipe has a circular cross-section with nominal diameter 0.0095 m. The bend is made in arch-shape with a radius of 0.035 m. The total flow length is 3.9 m.

| Table 1: Specifications of Paraffin wax |
|----------------------------------------|
| Parameter                             | Value       |
| Density                               | 0.869 g/cm³ |
| Thermal conductivity                  | 0.21 W/mK   |
| Melting point                          | 44.7 °C     |
| Freezing point                         | 48.2 °C     |
| Thermal expansion coefficient          | 3.41 x10⁻⁵ |
| Thermal limit of supercooling         | 2.27 x10⁻⁵ |

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| Description               | Specification |
|--------------------------|---------------|
| Melting point            | 36.7 °C       |
| Boiling point            | 370 °C        |
| Liquid density           | 900 kg/m³     |
| Solid density            | 856 kg/m³     |
| Specific heat capacity   | 2.14-2.19 J/gK|
| Heat of fusion           | 198 kJ/kg     |

Table 2: Parameters of the PV module

| Description                     | Specification |
|---------------------------------|---------------|
| Power                           | 50 W          |
| Open circuit voltage            | 22.14 V       |
| Short circuit current           | 2.89 A        |
| Nominal operating cell temperature | 47 ±2         |
| Maximum system voltage          | 1000 VDC      |
| Maximum series fuse rating      | 10 A          |
| Cell technology                 | Poly-Si       |
| Weight                          | 5.40 kg       |
| Dimension                       | 540 mm x 770 mm x 30 mm |
| Operating temperature           | -40 ºC to +85 ºC |
| The voltage at $P_{max}$ ($V_{mp}$) | 18.5 V       |
| Current at $P_{max}$ ($I_{mp}$)  | 2.70 A        |
The place where the experiments are carried is Sultanpur which is located at geographical coordinates 26°17’ 17.41”N and 82°4’ 58.44”E. It is situated at an altitude of 93 m from average mean sea level in India. It has a typical climate with hot summers and cold winters. Sultanpur climatic characteristics are as follows: during the cold winter months (November to February), the temperature is the lowest and the wind speed is low. During the hot summer months (April to August), the temperature is the highest and the wind speed is relatively slow. The average monthly global horizontal irradiance (GHI) is 264 W/m² and direct normal irradiance (DNI) 175 W/m² [Source: SRRA].

There are various parameters which affect the performance of a photovoltaic cell. Some of the parameters are material, cell size, solar irradiation availability, and direction or weather condition in which
two parameters; current and voltage are the most important to evaluate the output condition of the PV module whether it has good performances or poor power output.

2.1. Voltage (V)
Voltage is the important parameter in measuring the power of the PV module. Voltage is inversely proportional to the temperature. Hence, the power output of the photovoltaic cell decreases as the temperature rises more than its optimum temperature value.

\[ V \propto \left( \frac{1}{T} \right) \]  

where \( T \) stands for temperature.

2.2. Current (I)
Current is the flowing variable which slightly increases with increase in the temperature. Current increases when there is an increase in a number of cells of PV module. As a number of cells increases, the area of PV panel increases and therefore, cells temperature increase.

\[ I \propto T \]  

From the above discussion, increase in temperature of PV panel results in a decrease in voltage as compared to the current’s slight increment. Hence, the overall power of the PV panel decreases as clear from equation (3)

\[ P = V \times I \times t \]  

where \( P \) stands for power and \( t \) stands for time.

3. Results and Discussions
To find the factors, that improve the performance of the PV panel, parameters are measured, such as the air velocity, atmospheric air temperature, top and back side temperature of panels, the photoelectric conversion efficiency and rise in water temperature. The photoelectric conversion efficiency is calculated \[19\] as

\[ \eta(T) = \eta(25) \left[ 1 - \beta(T - 25) \right] \]  

\[ \text{efficiency gain} = \eta(25) \left[ \beta \times \Delta T \right] \]  

From the above expressions, it is observed that an increase in temperature beyond 25 °C, the efficiency of PV panel decreases, hence it is required to be cooled in order to increase its efficiency. The quantities \( \eta(25) \) and \( \beta \) are usually specified by the manufacturer but they can also be calculated by flash a test. Substituting the values of temperature obtained from the experiment in the equation 5. The thermal energy was calculated from the equation

\[ Q = m \times c \times \Delta T \]  

where \( m \) stands for mass flow rate, \( c \) stands for specific heat capacity and \( \Delta T \) stands for the difference in the water temperature.
3.1 Temperature reduction in top surfaces of PV/T system with respect to PV panel

Figure 3 shows variation in the temperature of the top surfaces of the PV panel (T_1) with respect to the time. All the value of temperature were recorded during the experiment from 10:00 am to 5:00 pm at a 60 minute interval. It could be seen from the figure that the maximum increase in temperature (T_1) occurred on 7/6/2018 about 58.7 °C. A digital temperature sensor was attached to the top surface of the PV panel to collect the values of temperature.

Figure 4 shows the variation of top surface temperature (T_a) of the PV/T system with respect to time. The temperature of the top surface of the PV/T system depends on the solar irradiation, hence the temperature could increase or decrease from 10:00 hours to 17:00 hours. The drop in temperature on 8/6/2018 was due to the low intensity of solar irradiation because of cloudy weather.

**Figure 3:** Temperature variation on the top surface of PV on different days
It can be concluded from the figures 3 and 4 that temperature of the top surface of a standalone PV panel is much higher than the temperature of PV/T system with PCM during the daytime. The temperature on the PV panel and the PV/T system during the experiment was recorded at 58.7°C and 50.2°C respectively at 14:00 Hrs. The maximum reduction in temperature is 8.5°C.

3.2 Temperature reduction in back sides of the PV/T system with respect to PV panel

Figure 4: Temperature variation on the top surface of PV/T on different days

Figure 5: Temperature variation on the back side of PV
Figure 6: Temperature variation on the back side of PV/T

Figure 5 shows the variation of backside temperature ($T_2$) of the PV panel with respect to time. It was observed that temperature increases as solar irradiation increases and the temperature decreases as solar irradiation decreases.

In figure 6 temperature variation on the back side ($T_3$) of photovoltaic thermal (PV/T) system with respect to time is shown. The temperature on PV/T increases from 10:00 hours to 12:00 hours. It can be observed from the figure that temperature increases as solar irradiation increases and vice-versa.

From figures 5 and 6, it is clear that the temperature of the back side of standalone PV panel is higher than the temperature of the PV/T system with PCM during the daytime. The temperature on the PV panel and the PV/T system during the experiment was recorded at 50.5 °C and 44.4 °C respectively at 14:00 hrs. The maximum reduction in temperature is 6.1 °C.

3.3 Variation of thermal energy

In the PV/T system, the thermal part is calculated by water heating. Thermal energy is the additional energy from the PV/T system which may be used in households. The thermal energy was collected by the means of heat collected from the PV/T system. In figure 7, the amount of thermal energy during five days data is plotted. The variation in thermal energy depends on the change in the temperature of the water from the inlet temperature to outlet temperature and flow rate of flowing fluid. The average thermal energy obtained per day is 25.45 J/min. water flows naturally and flow is 2LPM.
Figure 7: Thermal energy collected on different days

Figure 8 shows the percentage of electrical efficiency gained with respect to the time. The improvement in electrical efficiency from standalone PV is done by fabricating a PV/T system with PCM. The maximum percentage of electrical efficiency gained is 1.12 % of the PV/T system over PV panel.

Figure 8: Percentage of electrical efficiency gained with time on different days
4. Conclusions

In this study, the experiments were performed in Sultanpur to find parameters which affect PV module and followings conclusions were drawn:

1. It was observed that the temperature of the panel increases as solar irradiation increases and the temperature of the panel decreases as solar irradiation decreases.
2. The average thermal energy obtained per day is 25.45 J/min.
3. The temperature of the top surface of the PV/T system depends on the solar irradiation; hence the temperature could increase or decrease.
4. The temperature of the top surface of a standalone PV panel is much higher than the temperature of the PV/T system with PCM during the daytime. The maximum reduction in top surface temperature is 8.5 °C.
5. The temperature of the back side of standalone PV panel is higher than the temperature of the PV/T system with PCM during the daytime. The maximum reduction in back surface temperature is 6.1 °C.
6. The maximum difference in percentage electrical efficiency gained was 1.12 % between PV and PV/T system.

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