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Experimental and Analytical Study on Enhancing Efficiency of the Photovoltaic Panels Using Polyethylene-Glycol 600 (PEG 600) as a Phase Change Material

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A B S T R A C T

Paper mill producing several type papers has a wastewater treatment plant with an aerated lagoon system to remove their pollutants. But the removal efficiency of this system is still low so that the effluent is still not complying with the Indonesian of effluent quality standards yet. It needs pre-treatment plant before aerated lagoon. In an effort to improve the performance of wastewater treatment plant, study of wastewater characteristics, wastewater treatment, the establishment of treatment systems and equipment design have been carried out. After construction of pre-treatment plant, the field trial of wastewater treatment plant using wastewater originated from several type of paper produced was conducted. Result of laboratory-scale experiment showed that the paper mill needs a wastewater treatment with physical-chemical system before aerated lagoon treatment. Field trial of wastewater treatment showed that the removal of suspended solids (TSS) of 97%, COD of 88%, BOD5 of 85%, and a pH of 6.2 to 7.7 could be obtained using 5 - 10 % NaOH solution at doses of 50-240 mg/L and 0.1% cationic polyelectrolyte (PE) solution as flocculants at dose of 1.0 to 1.5 mg/L. Application of physical-chemical treatment plant can lighten the load on an aerated lagoon treatment. Effluent quality of aerated lagoon discharged into environment has met the Indonesian of effluent quality standard.

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INTRODUCTION

In recent years, research on new energy sources is one of the most important and most popular topics in the field of energy science. Many of these studies have been focused on optimizing and increasing the efficiency of electricity production at renewable power plants. Since the sunlight is almost available at all areas of the planet, power generation by photovoltaic power plants is being done in many parts of the earth. Studies in PV field has a wide range e.g. Initial cost of solar power plants [1], greenhouse gas emission reduction by renewable energy [2, 3], energy payback time of PV power plants [4], innovation in PV installation technology [5], economical assessment of grid connected systems [6]. One of the problems that exists in the photovoltaic industry is the panel surface temperature rising, which decreases the panel efficiency.

Different methods have been used to reduce the surface temperature of photovoltaic panels. Among these methods, the use of PCMs, have been studied more by researchers due to the very wide variety of usable materials, being economic no need for maintenance and no need to consume energy for cooling. Except using PCMs, cooling by Nano fluids [7-9], cooling by using water [10-12], air blowing [13, 14], and thermoelectric cooling [15, 16] are other ways to keep the photovoltaic panels cool.

Some scholars focused their studies on measuring the efficiency difference of crystalline silicon PV cells as a result of rising temperature [17, 18]. They concluded that each one degree Celsius increasing the panel temperature, causes about 0.45 to 0.5% decreasing the efficiency. Increasing the PV panel temperature, in addition to reducing the power output, also reduces its lifetime. If the PV panel is maintained under the thermal stress for a long time, it will cause permanent damage in its structure [19].

Nassar and Salem [20], reported the maximum PV operating temperature of 125°C in Libyan climate, which caused to a reduction of 69 % in nominal power of PV modules. In order to increase the thermal conductivity in the phase change material, Japs et al. [21] used graphite in a PCM and showed that due to enhanced thermal conductivity in the material, it performs better than the non-graphite state. In addition, Atkin and Farid [22] also showed that the addition of graphite to RT40 caused thermal conductivity of RT40 increase from 0.25 to 16.6 W/mK.

Indartono et al. [23] reported a 21.6% in efficiency increasing of solar PV panels using Petroleum jelly (Vaseline) as a PCM

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in Indonesia's climate. In their work, they used two 10 W panels. Mahamudul et al. [24], used RT35 in the climate of Malaysia. They showed that the material, while the ambient temperature was about 53°C, kept the panel's temperature at about 42°C for about 4 hours.

Huang [25] also compared the use of GR40 and RT25 as PCMs and showed that these materials will keep the panel temperature below 32 and 51°C for about 150 minutes, respectively. In that study, instead of the light and heat of the sun, a 1000-watt projector was used that caused an irradiation of about 750 W/m^2.

Hasan et al. [26] showed that with using capric palmic acid and $CaCl_2$, the photovoltaic panel surface temperature can be reduced by 18°C for about 30 minutes, and if only the $CaCl_2$ used behind the panel, for about 5 hours, 10°C decrease was observed.

Hachem et al. [27] did an experimental investigation for comparison the electrical efficiency of three prototype cases: reference panel without any changed on it, panel with pure PCM (White petroleum jelly) and another panel that has combined PCM (white petroleum jelly, copper, and graphite). They concluded that the electrical efficiency of photovoltaic panels has increased about 3 and 5.8% when pure PCM and combined PCM was used, respectively.

Stritih [28] conducted experimental and numerical studies on the use of phase change material behind the panel to increase panel efficiency. Their research was located in Ljubljana, the capital of Slovenia. In their study, RT28HC was used as PCM and two 250 watt mono-crystalline panels. The results showed that the highest temperature difference between the panels with and without PCM was 36.5°C.

Nouria and Sammouda [29] were done a numerical study of the process of charging and discharging of PCM for passive cooling of PV panels, in Tunisian climate. They showed that the inappropriate selection of material (from viewpoint of melting point), due to not re-freezing at night, could not have the desired effect on cooling.

The main purpose of this study, is to perform a comparison between three various states of photovoltaic panels; a conventional panel, a panel with PCM behind it, and a panel by PCM and a number of fins. This experimental set-up was tested in an indoor condition in order to control temperature and irradiation.

Phase change material selection

A phase change material (PCM) refers to a material that has good potential to store heat through its latent heat. Salts hydrates, fatty acids, paraffins, hydrocarbons, sugar alcohols, and nitrates are just part of materials that have been used as a PCM. Each of these materials has its own thermo-physical and chemical properties. Therefore, choosing a material, needs to consider a lot of things that will be mentioned below.

The first step in selecting a substance, is to know the temperature range of the operating condition. The second determinant factor that leads to the exclusion of a number of candidates is the latent heat of melting materials. A material with higher latent heat of fusion, has a higher potential for heat storage. Paraffin is one of the most commonly used materials as a phase change material in researches.

As 25°C is often introduced as the best operating temperature for photovoltaic panels, a list of materials with a melting point of around 25°C is shown in Error! Reference source not found.. Polyethylene glycol 600 (PEG-600) was selected and it's solid and liquid phases are shown in Figure 1. Its thermo-physical property is shown in TABLE 2.

PEGs shows many unique natural features of a would-be biomaterial, such as being non-irritating and immunogenic, having good biocompatibility and biodegradability, being soluble in water and many organic solvents (ethanol, acetone, etc.) [40, 41].

PEGs are non-toxic, colorless, odorless, low vapor pressure and have various industrial applications such as application in adhesives, ceramics, dough and paper, electroplating metals, lubricants, agriculture and detergents.

PHOTOVOLTAIC TECHNOLOGY

Semiconductors

Solar cells are made from a variety of semiconductor materials and coated with special additives. Semiconductor materials are those elements or compounds that have conductivity intermediate to that of conductors and insulators [42].

Therefore, photovoltaic cells are semiconductor systems that transform some part of the light received from the sun directly into electricity. There are many variations on cell material, design, and methods of manufacture. Polycrystalline silicon (Si), cadmium sulfide (CdS), gallium arsenide (GaAs), and some other semiconductors are common to use for cells [43].

Mathematical formulation

The efficiency value written in panel's catalogue is measured according to the Standard Test Conditions (STCs), which are defined as: solar irradiance of 1000 W/m^2, cell temperature of 25°C and air mass AM=1.5. In order to find the amount of variations in the efficiency of the panels, it is necessary to use the electrical data include V_{mp} and I_{mp}, received from the data-logger, with the parameters mentioned in TABLE 3. Finally the efficiency of the photovoltaic panel (η) is calculated from Equation (1):

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{oc}\, I_{sc}.FF}{A\,G} \quad (1)$$

Figure 1. PEG 600 in solid and liquid phases

TABLE 1: Candidate materials and their thermo-physical characteristics for this research

Material	Melting point (ºC)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m.K)	Density (kg/m^3)	Ref.
n-Octadecane	28	243.5	0.358 (solid) 0.148 (liquid)	865 (solid) 770 (liquid)	[30]
$CaCl_2$. $6H_2O$	29	188.34	0.540 (@38.7ºC)	1562 (@38ºC)	[31]; [32]
Mystric acid (34%) + capric acid (66%)	24	147.7	0.164 (@39.1ºC)	888 (@25ºC)	[33]
Polyethylen glycol 600	22	127.2	0.189 (solid) 0.187 (liquid)	1.126 (@25ºC) 1.232 (@4ºC)	[32]; [33]
$Mn(No_3)_2$. $6H_2O$	25.8	125.9	2.34 (solid)	1800 (@20ºC)	[34]
Coconut oil	22-24	103.25	0.321	916	[35]; [36]
Paraffin C13, C14	22-24	189	0.21	900	[37]
RT25	22-26	170	0.2	880 (solid) 760 (liquid)	[38]
RT28HC	28	245	0.2	-	[39]

TABLE 2: Thermo-physical properties of Polyethylene glycol 600

Property	Value
Melting point (℃)	23-26
Density (kg/m^3)	1128
Heat of fusion (kJ/kg)	146
Specific heat (kJ/kg.ºC)	1318.2
Kinematic viscosity (m^2/s)	10.8
Moderate molecular weight (gr/mol)	570-630

Where A is the area of PV panel in (m^2). This equals to 0.415 m^2 for the current study and G in (W/m^2) is irradiation of sun, which is constant in this research, supplied by three projectors were used instead of light and heat of the sun. Another parameter in Equation (1) that should be introduced, is Filled Factor. This is defined as:

$$FF = \frac{V_{mp}\, I_{mp}}{V_{oc}\, I_{sc}} \tag{2}$$

Where V_{oc} is open-circuit voltage in (V) and I_{sc} is short-circuit current in (A). At open-circuit condition the current is zero and at short-circuit condition the voltage is zero.

As already mentioned, when temperature rises in a silicon based photovoltaic cells, the efficiency, falls down. This decreasing in efficiency can be calculated by the following equation:

$$\eta = \eta_0[1 + \beta(T_{cell} - 25)] \tag{3}$$

Where η_0 is the panel's efficiency in STCs, β is the silicon efficiency temperature coefficient which mentioned in the panel's catalogue by the manufacturer and finally T_{cell} is the cell's temperature under operating condition in Celsius.

Experimental setup

A series of three identical polycrystalline panels has been tested in the photovoltaic laboratory of Jundi-shapur University of Technology, Dezful. Each panel has maximum power of 60 watts. These panels are made by Yingli Solar Company (China). TABLE 3 shows the full electrical and physical characteristics of the panels. As is shown in Figure 3, in order to observe the effect of using PCM and fins, three prototype cases were studied as follows:

Prototype 1: Normal panel, no change was made.

Prototype 2: A panel that PEG 600 was used as a PCM behind it.

Prototype 3: In addition of the PEG 600, some fins are used behind the panel due to increasing heat exchange between the panel and the PCM

In prototypes 2 and 3, behind each panel, there is a container for inserting PCM. In each prototype, 8.5 kg of PEG 600 has been added and no leakage was seen. Because the experiment was carried out in winter, the ambient temperature was much lower than the melting point of the PCM, and the research was carried out in a room with adjustable temperature and light conditions, to simulate the desired conditions. Figure 2 illustrates a schematic of integrating PCM and insulator on backside of PV module.

In some studies, it was observed that part of the phase change material behind the panel remained at solid state until the end of the charging process [44]. This phenomenon means that the total material capacity is not

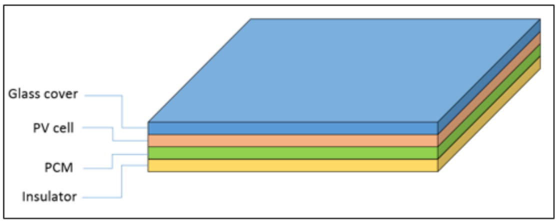


Figure 2. A shematic of using PCM on backside of photovoltaic module

used to absorb the heat of the panel. Therefore, the idea of using fins was presented in order to absorb the maximum heat from the panel surface. The reason for not melting a part of the PCM, is due to the low thermal conductivity of most PCMs, thus a part of the material remains in solid state.

In the third prototype, 10 longitudinal 4 cm width fins were used behind the panel. The fins were made of aluminum with a thermal conductivity of 204 W/mK. Figure 4, represents photos with and without fins panels. Silicon adhesive has been used to ensure that the edge of the fins stick to the back of the panel. This adhesive has a high thermal conductivity coefficient, which fills the narrow gap between the fin and the panel.

Three tungsten projectors were used instead of light and heat of the sun. Each of them has 1000 W power. The advantage of doing experiment in this method is that by changing the projector's distance from the panel, the test can be performed with different lighting and temperature conditions. In this experiment, the projectors were set up at a vertical distance of 50 cm and 60 cm from the surface of the panels. Figure 3, illustrates the experimental setup of this research. Panels, data-logger and projectors can be observed in this photo.

TABLE 3. Main electrical and physical characteristics of the considered modules

Module characteristics	Value
Module name	YGE 60
Power output ($\boldsymbol{P_{Max}}$) [W]	60
Power output tolerances ($\Delta\boldsymbol{P_{Max}}$) [%]	+/- 3
Module efficiency ($\boldsymbol{\eta_m}$) [%]	14.4
Voltage at $\boldsymbol{P_{Max}}$ ($\boldsymbol{V_{mpp}}$) [V]	18.47
Current at $\boldsymbol{P_{Max}}$ ($\boldsymbol{I_{mpp}}$) [A]	3.25
Open-circuit voltage ($\boldsymbol{V_{OC}}$) [V]	22.86
Short-circuit current ($\boldsymbol{I_{SC}}$) [A]	3.44
Dimension (L /W//H) [mm]	660/630/25
Weight [kg]	4.97

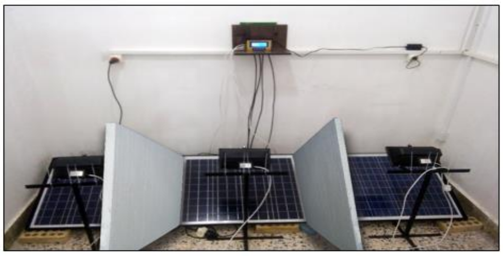


Figure 3. Experimental set-up

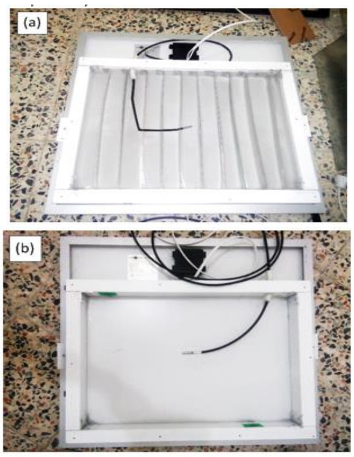


Figure 4. Panels (a) with fins and (b) without fins

In order to measure the amount of radiation emitted to the panel surface, TES-132 solar power meter was used. It was determined that for 60 cm and 50 cm vertical distance of the projectors from the panels, 420 and 630 W/m^2 radiation and the temperature of 65 and 85 °C can be achieved, respectively.

The DS-18B20 digital water proof thermometer sensors are used. The central unit converts the pulses received by the sensor to the number, which is the temperature, shown on its display. These sensors are embedded behind the panels. Additional information related to the sensors is given in TABLE 4. The exact position of sensors is shown in Figure 5. As shown in Figure 2, behind the panels of prototypes 2 and 3, in order to heat insulation, glass-wool with a thermal conductivity of K=0.038 W/mK (@23 °C) [45] was used. Therefore, the PCM, absorb and remove heat solely through the surface of the panel.

TABLE 4. Specifications of the temperature sensors used

	Quantity	Type	Minimum measurable temperature (°C)	Maximum measurable temperature (°C)	Accuracy (°C)
Value	4	One-wire DS-18B20	-55	125	0.5

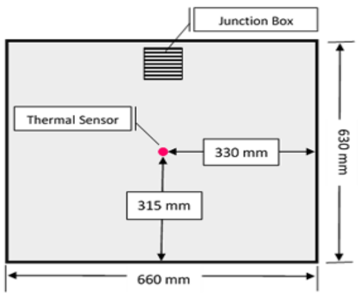


Figure 5. Exact position of thermal sensor

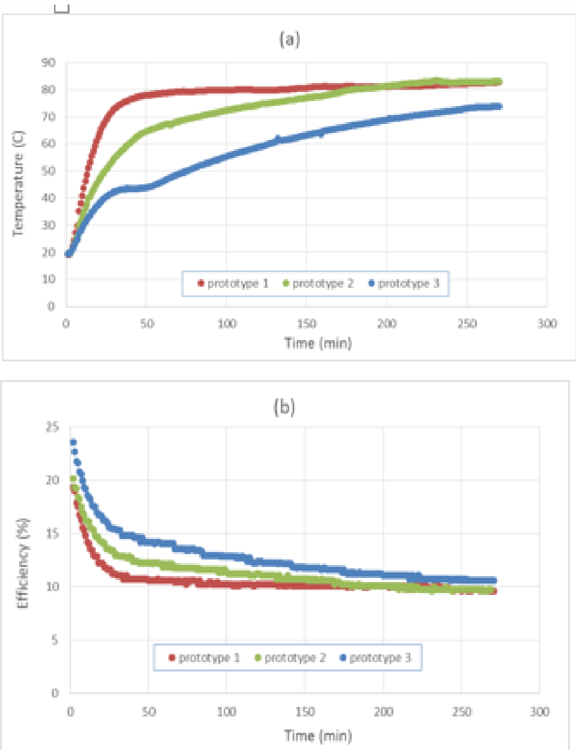
RESULTS AND DISCUSSION

In this experimental research, comparison between three different modes of photovoltaic panels were performed. In the previous sections, describing the test conditions and how to calculate and extract the results were expressed. The duration of all tests was 270 minutes (4.5 hours), and each test was repeated three times to ensure the accuracy of the obtained data.

In Figure 6, the temperature, efficiency and power charts are plotted versus time for two irradiations of 630 and 420 W/m^2. At these irradiations, the temperature created at the panel's surface by the projectors are 85 and 65 °C, respectively. The purpose of performing the experiment at two different irradiations is to evaluate the performance of the panels in two different temperature and light conditions.

Surface temperature

In Figure 6 (a, d), it has shown that after a period of time from the start of the experiment, we have almost reached to steady state condition and there is not significant change in temperature. Figure 7 shows a better illustration of the positive effect of prototypes 2, 3 in comparison with prototype 1. As shown in Figure 7a, for irradiation of 630 W/m^2, the maximum temperature differences created by prototypes 2 and 3 were 18.6 and 34.1 °C, respectively.



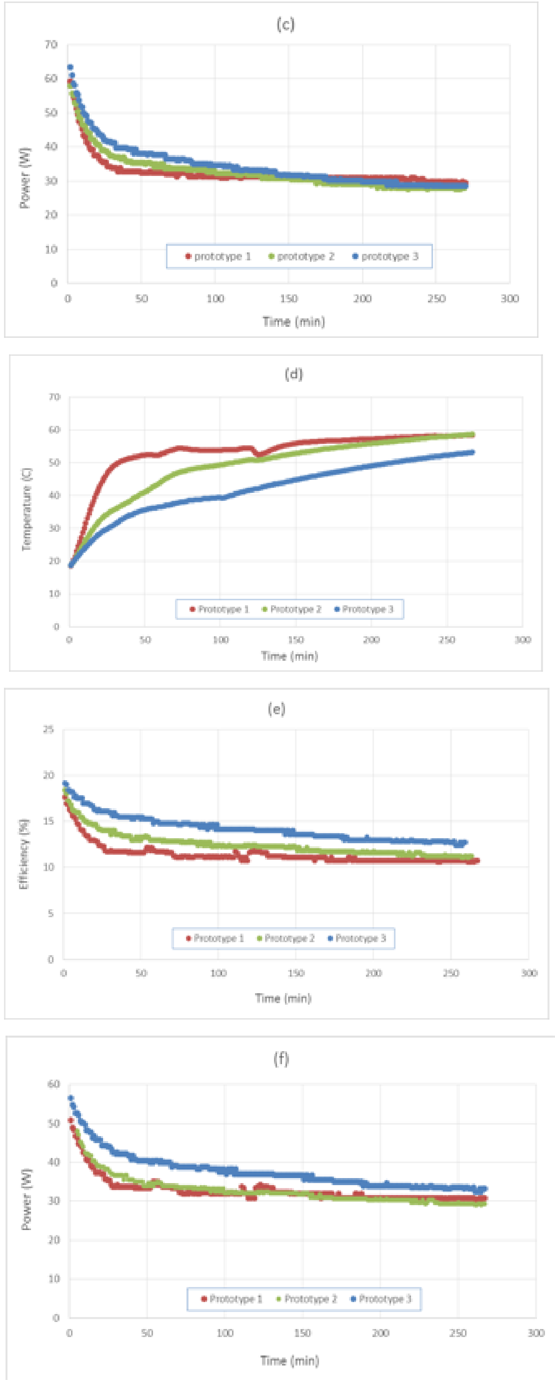


Figure 6. Measured or calculated of (a) temperature, (b) efficiency and (c) power output for 630 W/m^2 and (d) temperature (e) efficiency and (f) power output for 420 W/m^2, for three prototypes

Prototype 2, after about 200 minutes from the start of the experiment, has reached almost the same temperature as prototype 1, while the prototype 3, even in 20 minutes of the end of experiment could keep temperature difference of about 9 °C with prototype 1.

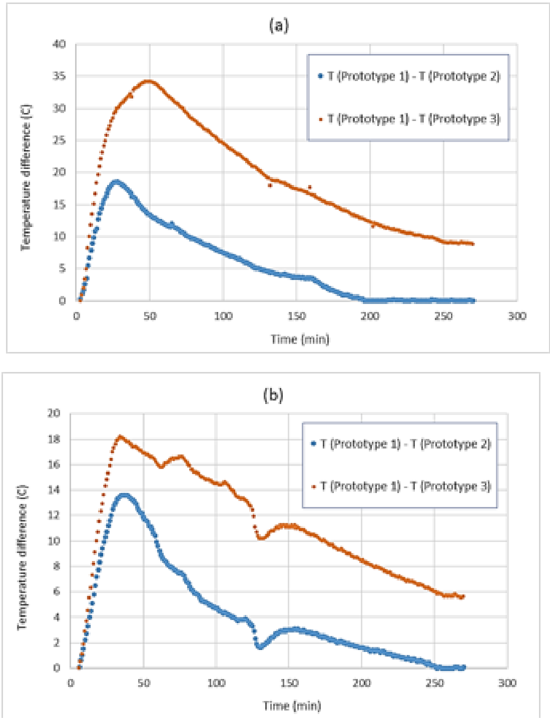


Figure 7. Temperature difference between prototype 2 and prototype 3 with prototype 1 for the case of (a) 630 W/m^2 and (b) 420 W/m^2

Similarly, in Figure 7b for irradiation of 420 W/m^2, the maximum temperature difference created by prototypes 2 and 3 were 13.6 °C and 18.2 °C, respectively. In addition, prototype 2, after about 250 minutes from the start of the experiment, had the same temperature with prototype 1, while prototype 3 also maintained the temperature difference of 5.6 °C until the end of the test.

Electrical efficiency

In Figure 6 (b and c), the graph of efficiency variations is plotted over time. As expected, with the passage of time and increasing the temperature of the panels, their efficiency reduces. Similar to part 5.1, where the temperature difference graph was plotted, in this part, the efficiency difference graph is plotted in Figure 8, to show that, over the duration of test, how much difference in electrical efficiency between prototypes 2 and 3 with prototype 1, was reported.

As shown in Figure 8a, for the case of 630 W/m^2, the maximum efficiency difference value between the prototypes 1 and 2 was 2.45% and between the prototypes 1 and 3 was 4.65%. Furthermore as illustrated in Figure 8b for 420 W/m^2, the maximum efficiency difference value between the prototypes 1 and 2 was 2.43% and between the prototypes 1 and 3 was 4.75%.

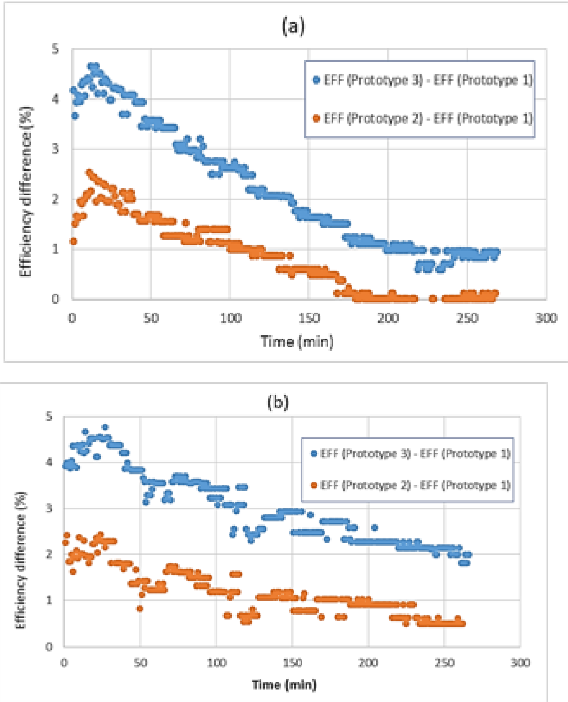


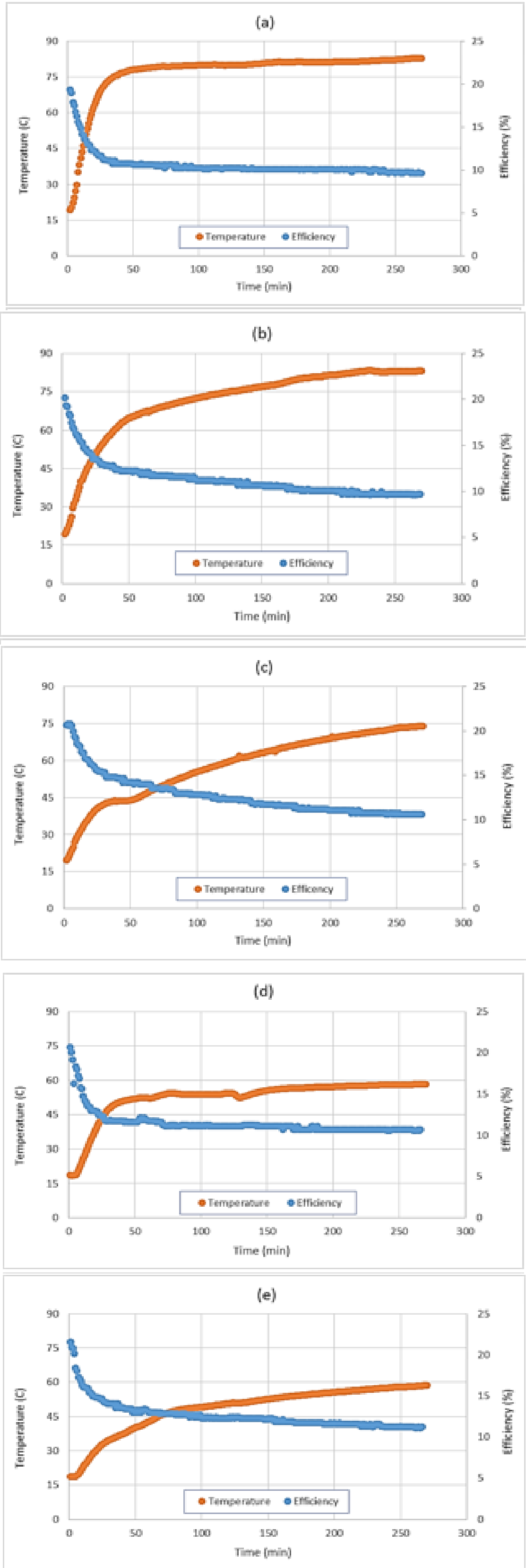
Figure 8. The electrical efficiency difference in case of (a) 630 W/m^2 and (b) 420 W/m^2

Power output

As it is clear in Figure 6 (b, c, e and f), the power and efficiency curves are quite similar to each others. The reason for this similarity is that the numerator of formula for calculating the efficiency, is output power of the panel and denominator of that formula is also constant for a given amount of radiation.

As shown in Figure 6c, after about 170 minutes from the start of the test, the power output of the three panels is almost half of nominated value of panel capacity. From this time until the end of experiment, based on Figure 6a, the average surface temperature of panels for prototypes 1 and 2 was about 81 °C and for prototype 3 was about 72 °C. Similarly, for irradiation of 420 W/m^2, there is a significant decrease in output power, as shown in Figure 6f. In this case, it was also observed that, after about 120 minutes from the start of the test, output power of the prototypes 1 and 2, dropped to about 30 watts and for prototype 3 dropped to about 34 watts. This huge decreases in output power means that in these temperature conditions, only half of the nominated capacity of the panel was used, which was considered very unpleasant economically.

Efficiency and temperature dependency



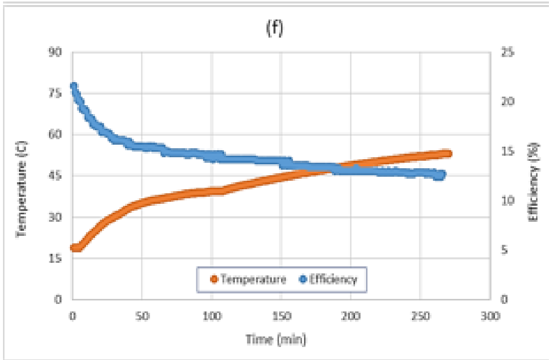
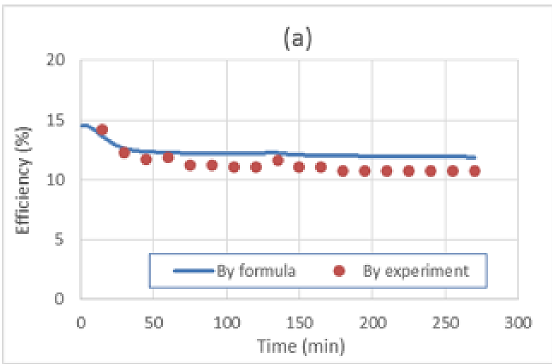


Figure 9. Efficiency and temperature dependency for irradiation of 630 W/m^2 for (a) Prototype 1 (b) Prototype 2 (c) Prototype 3 and Irradiation of 420 W/m^2 for (d) Prototype 1 (e) Prototype 2 (f) Prototype 3

The main purpose of this paper is to demonstrate the effect of using PEG 600 with fins on the efficiency of photovoltaic cells, in high temperatures. In Sections 5.1 to 5.3, changes in temperature, efficiency, and power were plotted over time. In order to illustrate the relationship between temperature and efficiency, In Figure 9, these two parameters are plotted over time in a graph. The slope of six parts of Figure 9, is completely in agreement with the results of Tiwari et al. [46], research. Another point that can be understood from the slope of these graphs is that the slope of the graph of prototype 1 is faster than prototypes 2 and 3 to be steady horizontal. In Figure 9 (c and f), even up to the end of the test, the curves are not horizontal yet, indicating the positive effect of the changes made to the panel.

Experimental and analytical results comparison

In order to compare the measured efficiency from the test data, with calculated efficiency from Equation (3), which described in section 3.2, Figure 10 is depicted. This figure shows a good agreement between these results.



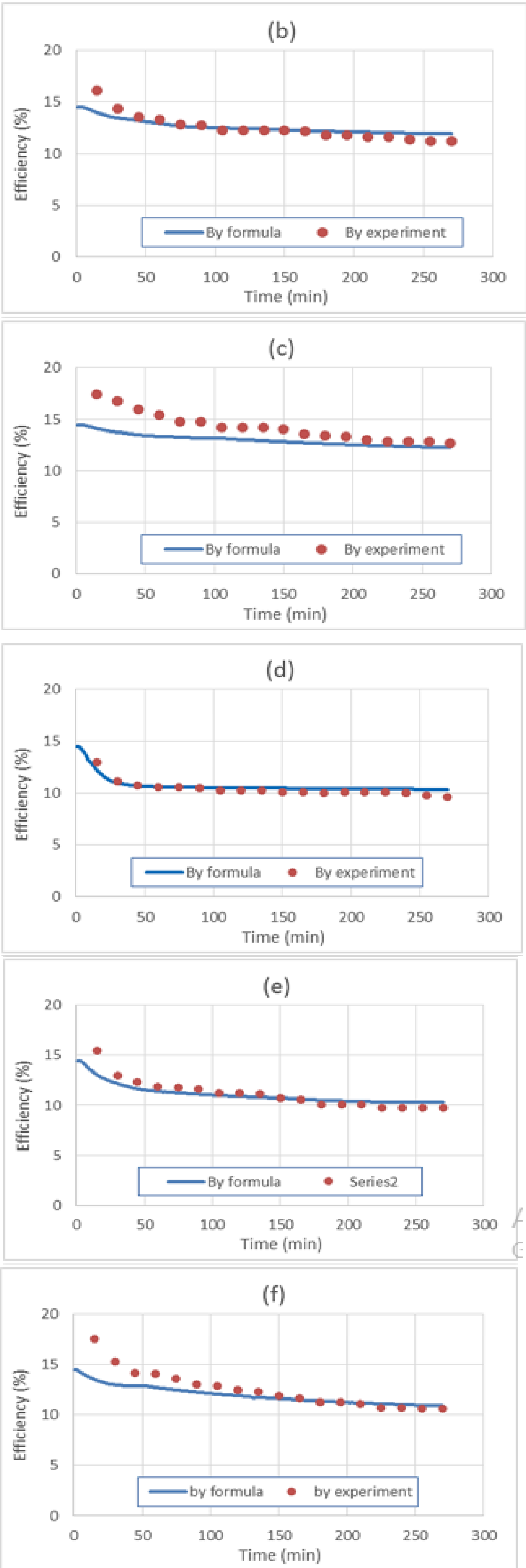


Figure 10. Experimental and analytical comparison of 630 W/m^2 for (a) Prototype 1 (b) Prototype 2 (c) Prototype 3 and 420 W/m^2 for (d) Prototype 1 (e) Prototype 2 (f) Prototype 3

CONCLUSIONS

In this study, the effect of using phase change material and the role of the fin on reducing the temperature of photovoltaic panels to enhance their efficiency was experimentally conducted. Since 25 °C is the best operating temperature for photovoltaic panels, Polyethylene glycol 600 with melting point in the range of 23-26 °C was used as PCM.

Based on the data obtained from tests and calculation of efficiency, the positive effect of using Polyethylene glycol 600 with fin in controlling temperature and increasing the efficiency of photovoltaic panels was proved. The results of this research can be summarized as follows:

1. In the prototype 3, which PCM and fin used together, because the heat from panel surface could penetrate to the depth of PCM, the photovoltaic cell's temperature dropped and thus the efficiency increased.

2. In the case of 630 W/m^2 irradiation, the maximum temperature differences between prototypes 3 and 2 with prototype 1 were 34.1 and 18.6 °C, respectively. For irradiation of 420 W/m^2, the maximum temperature differences between prototypes 3 and 2 with prototype 1 were 18.2 °C and 13.4 °C, respectively.

3. For irradiation of 630 W/m^2, the maximum efficiency differences between prototypes 3 and 2 with prototype 1 were 4.65 and 2.45 %, respectively, and for irradiation of 420 W/m^2, this efficiency differences between prototypes 3 and 2 with prototype 1, were 4.75 and 2.43 %, respectively.

4. For surface temperature over 75 °C, the output power had a huge decrease to almost half of its nominated power. In addition to having a negative effect on the life-time of the panel, this fact also has strong effect on decreasing the power generation, which is economically unpleasant.

5. Experimental data and analytical calculation are in good adaptation.

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Persian Abstract

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چکیده

تولید برق از منابع تجدیدپذیر به سرعت در حال رشد است. استفاده از پانل های فتوولتائیک یکی از محبوب ترین روش های تولید انرژی تجدید پذیر است که در اکثر نقاط جهان در دسترس است. یکی از مشکلات موجود در این صنعت، افزایش دما پانل ها در طول روزهای گرم سال است؛ که قدرت خروجی آنها را کاهش می دهد. استفاده از مواد تغییر فاز (PCMs) یک راه برای جلوگیری از افزایش سریع دمای پانل ها است. در این مقاله، پلی اتیلن گلیکول ۶۰۰ (PEG 600) در پشت پانل به عنوان یک PCM استفاده می شود. این ماده، بخشی از حرارت پانلی را جذب می کند و باعث می شود که دمای پانل کاهش یابد. به منظور افزایش گرما جذب شده توسط PEG600، تعدادی از باله ها نیز در پشت پانل نصب می شوند و نتایج با حالت غیر غوطه ور مقایسه می شود. نتایج نشان داد که در ابتدا ۱۵۰ دقیقه از آغاز آزمایش، تفاوت دما بین پانل با هر دو PCM و ورق در مقایسه با پانل معمولی بین ۱۸ و oC34.1 است. علاوه بر این، حداکثر کارایی پانل با هر دو PCM و پره با پانل معمولی ۴٫۶۵٪ است. برای پانل با PCM و غیر پره، با پانل معمولی ۲٫۴۵٪ است. در نهایت، مقایسه هر دو روش تجربی و محاسبات تحلیلی انجام شد.