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IMPROVING THE EFFECTIVENESS OF A PHOTOVOLTAIC WATER PUMPING SYSTEM BY USING BOOSTER REFLECTOR AND COOLING ARRAY SURFACE BY A FILM OF WATER*

H. TABAEI[1] AND M. AMERI[2**]

[1,2]Dept. of Mechanical Engineering, College of Engineering, Shahid Bahonar University of Kerman, Kerman, I. R. of Iran
[1,2]Energy & Environmental Engineering Research Center, Shahid Bahonar University of Kerman, Kerman, I. R. of Iran
Email: ameri_mm@uk.ac.ir

Abstract– The increase of cell temperature with increased irradiance is probably the most significant disadvantage of using Photovoltaic modules equipped with booster reflectors. The aim of this study is to investigate the possibility of improving the performance of a photovoltaic water pumping system by using a booster reflector and to keep the temperature of PV panels at a low level by cooling PV panels with a film of water. The water required for covering the cells is fed by the pump itself. By applying the modifications on the photovoltaic water pump system, significant improvement in the output power from PV panels, and therefore in the pump flow rate, is displayed in the experimental results.

Keywords– Photovoltaic water pump, Booster reflector, Aluminum foil, water film, performance

1. INTRODUCTION

Solar energy is the most interesting and promising source that plays a vital role in meeting the increasing energy demand and saving the depleted fossil fuel resources. The rapid consumption of fossil fuels to meet the increasing energy demand leads to environmental pollution and lack of fossil fuels is prompting the search for alternative energy resources to achieve sustainable development [1, 2]. Photovoltaic panels have been used widely around the world in the last two decades due to the lack of energy resources (coal, oil, etc.) and environmental problems. Photovoltaic panel is a semiconductor device that can directly convert solar radiation into electricity. One of the main problems with generating electricity from photovoltaic panels is that its costs are still many times higher than the cost of producing electricity from the conventional power generations. Silicon, which contributes significantly to the cost of the photovoltaic systems, is used as a base material for the production of photovoltaic panels. Thus, an effective way to lower the cost of the electricity generated by a photovoltaic system is to reduce the use of photovoltaic cells for a given power demand. However, using booster reflectors is a promising way to reduce the use of high-cost semiconductor material and greatly reduces the cost of producing photovoltaic modules and electricity generation cost of photovoltaic systems. It is well known that the output power from the photovoltaic panels is proportional to the amount of the incidental solar radiation and photovoltaic cell temperature. It is evident that increasing the incidental solar radiation on a PV module leads to an increase in the PV module's power output. The use of booster reflectors is a promising solution to raising the intensity of incidental irradiance on the PV panel surface. Several researchers investigated the effects of booster reflectors on solar systems' performance. Tabor [3] studied solar collectors equipped with a

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**Corresponding author

stationary mirror. He investigated the range of concentration ratios obtainable with different shapes of targets for circular and parabolic cylindrical concentrators of stationary type requiring seasonal adjustments. It was found that a useful concentration can be obtained from a mirror which has no diurnal movement but whose tilt is adjusted at certain periods of the year. Use of solar collectors and booster reflectors under non-stationary conditions for high latitudes was reported by Perers[4]. He 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. Ronnelid et al. [5] investigated the performance of photovoltaic modules with planar booster reflectors with variable length and tilts for Swedish conditions. They reported that a flat stationary booster reflector can increase the annual output of the module in the order of 20-25 percent. Matsushima et al. [6] used commercial PV modules and low concentration planar reflectors. The concentrating module described in their paper, increased generation power density and is expected to increase electricity delivered by 1.5 compared to conventional modules. Ahmad and Hussein [7] studied PV modules with and without a tilted plane reflector. They indicated that the planar booster reflectors can improve the yearly energy output of PV modules by about 22%. Sangani et al. [8] developed a V-trough concentrator system for different types of tracking modes: seasonal, one axis north-south, and two axes tracking. Kostic et al. [9] investigated photovoltaic thermal (PV/T) collector without reflectors and with reflectors. They showed that energy saving efficiency for PV/T collector without reflectors is 60.1%, which is above the conventional solar thermal collector, whereas the energy-saving efficiency for PV/T collector with reflectors in optimal position is 46.7%, which is almost equal to the values for conventional solar thermal collector.

The use of photovoltaic panels as the power source for pumping water is one of the most promising areas in photovoltaic applications. Photovoltaic water pumping systems are particularly suitable for water supply in villages and remote locations where no electricity supply is available. Optimizing the photovoltaic pumping system to improve the system efficiency and reduce the installation costs has been the subject of many research papers. Various studies have been done on the choice of the drive system to suit photovoltaic generation, types of pumps to use, and ways to control and optimize the water pumping system. Roger [10] reported that a DC motor driving a centrifugal pump represents a well-matched load for a PV array because this system utilizes most of the available DC power generated by the array. Anis et al. [11] reported that a load composed of a DC motor driving a centrifugal pump represents a non-matched load to PV array. This is because the motor driving a volumetric pump requires an almost constant current for a given head, apart from the starting current which tends to be higher. This condition does not match the PV array characteristics where the current varies almost linearly with solar irradiance. Appelbaum [12] studied directly coupled PV systems, Dc motors, and water pumps. He reported that permanent magnet motor driving a centrifugal pump is the best candidate, as it provides the best match between PV and dc motor. Different optimization strategies have been proposed to improve the overall system efficiency, such as maximum power tracking or MPPT. The maximum power point tracking (MPPT) is usually used as an on-line control strategy to track the maximum output power operating point of the photovoltaic generator for different operating conditions of insolation and temperature. Yao et al. [13] have indicated a maximum power point tracking (MPPT) inverter and a variable frequency controller to improve the slip and the efficiency of the motor under low isolation conditions. They concluded that a constant optimum value of motor efficiency can be assured by adjusting the proper inverter frequency. Koner [14] showed that to minimize capital costs, it is necessary to match the load characteristics with the PV array characteristic. This can be achieved either by including a maximum power point tracker in the system or by an appropriate selection of the motor constants, based on optimizing the system output as an optimal combination of parallel and series cells. Abdolzadeh et al. [15] investigated the effects of an operating head on the performance of photovoltaic water pumping systems. They showed that there is a maximum power corresponding to each head. So when the modules' power exceeds that maximum point, the remaining power is wasted. They also found that when the array power is more than the maximum power corresponding to the head, more water is pumped during the day. Tabaei and Ameri [16] investigated the effects of booster reflectors on the photovoltaic water pumping system performance. They pointed out that concentrating solar radiation on the PV cells increases the main PV cells output power and consequently, increases water pump main flow rate. However, the application of booster reflector increases the photovoltaic cells temperature.

It is well known that the performance of PV panels will drop when the cell temperature increases. By increasing the cell temperature 0.4-0.5 %/^{o} C, a decrease in the output power for single and multi crystalline silicon solar cells is detected. However, the increase of cell temperature as a result of the increasing intensity of solar radiation on the PV panel is, without a doubt, the largest negative effect of using photovoltaic modules augmented with the booster reflectors. Therefore, it is necessary to keep the temperature of the Photovoltaic module at a low level to achieve satisfactory performance. Several theoretical and experimental studies are done in the passive and active PV cooling systems. Royne et al. [17] present a critical review on cooling photovoltaic cells under concentrated illumination. Krauter [18] investigated the effects of cooling photovoltaic panels with a flowing film of water on the power generated by the array. Due to the quick flow of the water, there should be only a minimal increase in water temperature. Additionally, the evaporating water should further decrease the temperature and therefore, result in increased electrical yields. Krauter showed that by using this modification, the increase of the electrical energy yield measured over a whole day was 10.3%. Lanzafame et al. [19] investigated the electrical and thermal performances of a single-crystalline submerged photovoltaic solar panel. They showed that, in shallow water, an increase of 10-20% in efficiency will be achieved. Abdolzadeh and Ameri [20] investigated the possibility of improving the performance of a photovoltaic water pumping system by spraying water over the top surface of PV array, experimentally. They pointed out that the efficiency of photovoltaic water pump system can be increased by spraying water over the front of PV array.

The effects of booster reflectors and spraying water over the top surface of PV array on the photovoltaic water pumping system performance have been studied [16, 20]. The aim of this paper is to study the effect of booster reflector on photovoltaic water pumping set with array surface covered by a continuous film of water. The water required for covering the cells is fed by the pump itself. A film of water improves the operation of the system by decreasing cells reflection and temperature.

2. SYSTEM DESCRIPTION AND DATA COLLECTION

In order to quantify the efficiency of the photovoltaic water pump prototype coupled with booster reflector, an experimental outdoor system is set up. The experimental setup consists of three PV modules (3×45W) equipped with booster reflector (Fig. 1). The size of each solar panel is 960×460×30 mm. The booster reflector has been made of aluminum foil because of its high reflectivity characteristics. The booster reflector height is selected to be equal to the PV module height in order to receive more uniform distribution of the solar radiation on panel surface. The photovoltaic panels are positioned east-west. The panels tilt angle is set to 30^o with respect to the horizon, which is the local latitude of Kerman (Latitude 30^o 17´ and longitude 57^o 50´), Iran, so as to face the south direction. The panels are connected to the water pump system through Maximum Power Point Tracker (MPPT). One positive displacement surface water pump with a permanent magnet DC motor (Model PS150 Boost, Positive displacement, 1000 L/h flow rate maximum, 45 m head maximum) is being used to pump water from the tank. A film of water flew permanently over the cells to decrease cells' reflection and temperature. The water required for covering the cells is fed by the pump itself. To produce a film of water over the photovoltaic cells, a tube with small holes on top of the photovoltaic array has been used (Fig. 2).The experiments were done during clear days at solar energy laboratory at Shahid Bahonar University of Kerman, Iran. A sensor (model PT100) installed at the back of the array measured the actual temperature as the temperature in front of the array surface was about 2^{o} C higher than the temperature at the back. Irradiance was measured by a pyranometer (model BM 6 Kip&Zonen) installed parallel to the surface, at the same incident plane of the array. The pump flow rate was measured by a digital flow meter. Measurements have been performed in three weeks during June and July, and data were recorded every 15 minutes.

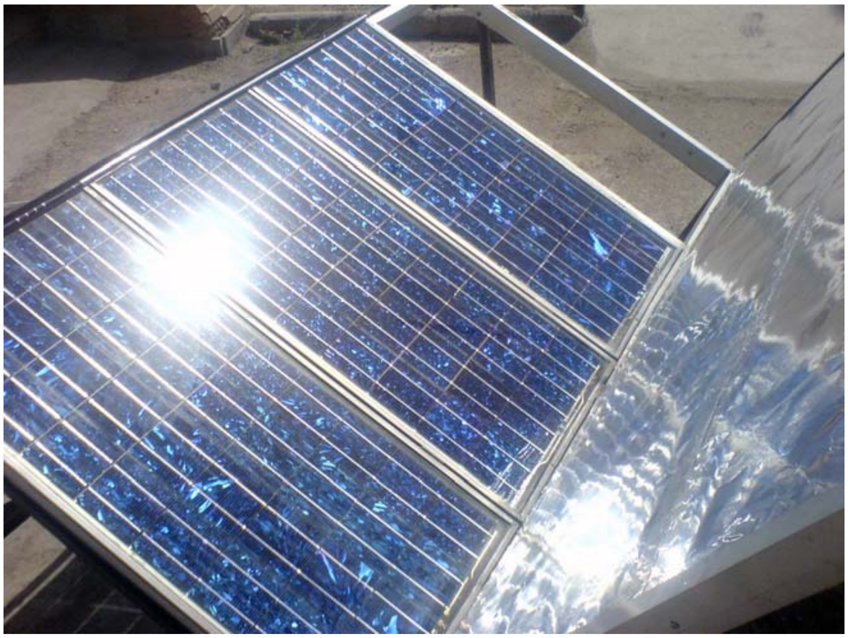


Fig. 1. The experimental setup consists of PV modules equipped with Aluminum foil booster reflector

Fig. 2.Transmitting water from the pump over the cells front

3. EXPERIMENTAL RESULTS

At first, the optimal inclination angle of the booster reflector for the experimental location, Kerman was determined by measuring the power generation of three PV modules (3×45 W) equipped with booster reflector. A rheostat was used as a load resistance to obtain the optimal inclination angle of the booster reflector. The booster reflector was mounted on the PV panels with a changeable position in relation to PV Panels. Variation of the solar radiation received by the photovoltaic cells without concentrator for a selected day during the test period is shown in Fig. 3. In order to obtain the highest solar radiation intensity on PV panels, inclination angle of the reflector was changed. Variation of the output power of three PV panels at different positions of the booster reflector is presented in Fig. 4. Based on the measurement results of the output power during the day, for different positions of the reflector in relation to PV panels, it is clear from the figure that an optimal position for the reflector is where the booster reflector position is 45^o with respect to the horizontal plane (Fig. 5). It should be noted that the authors do not claim that this angle is the best choice for the whole year, but results show that this incline angle of booster reflector leads to greater increase in the system power generation in summer.

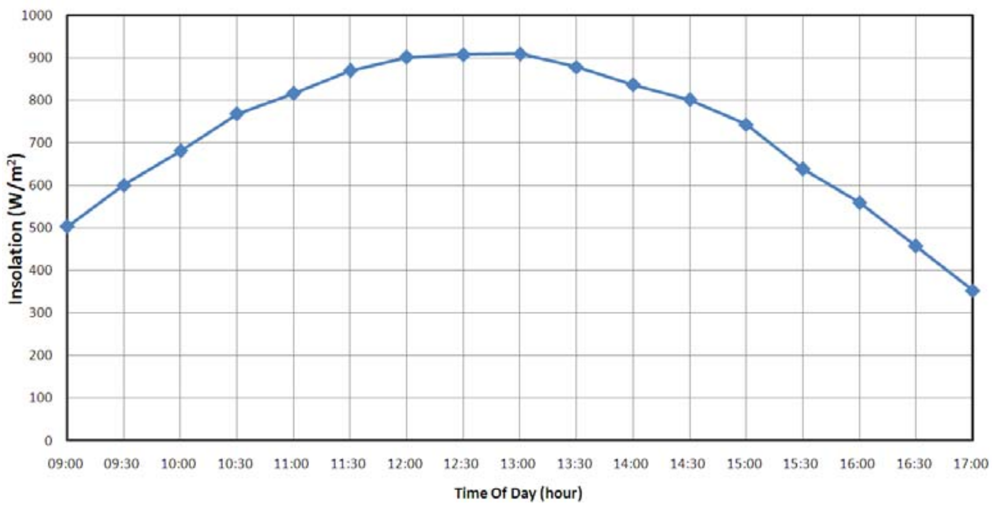


Fig. 3.Variation of insolation during a test day

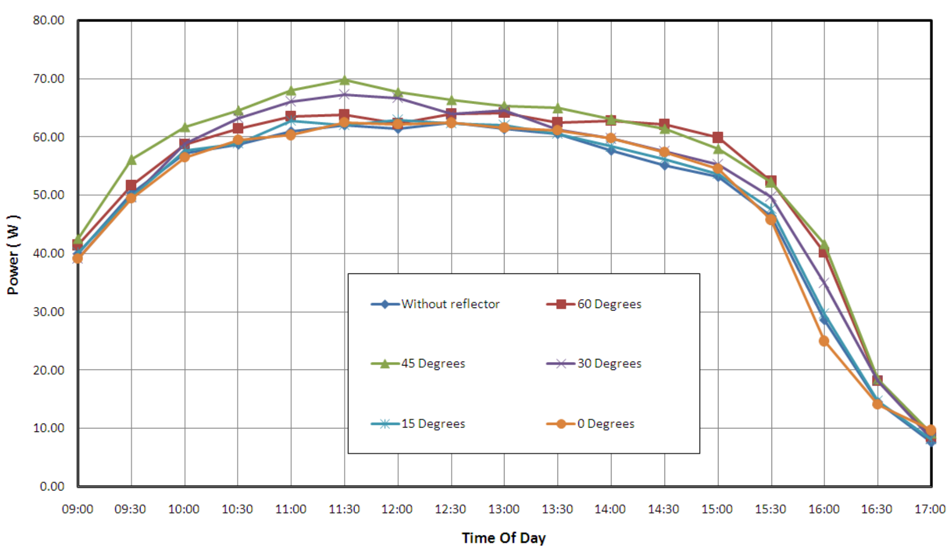


Fig. 4. Comparison of total output power with three modules (135 w) depending on the reflector position in respect to the horizontal plane

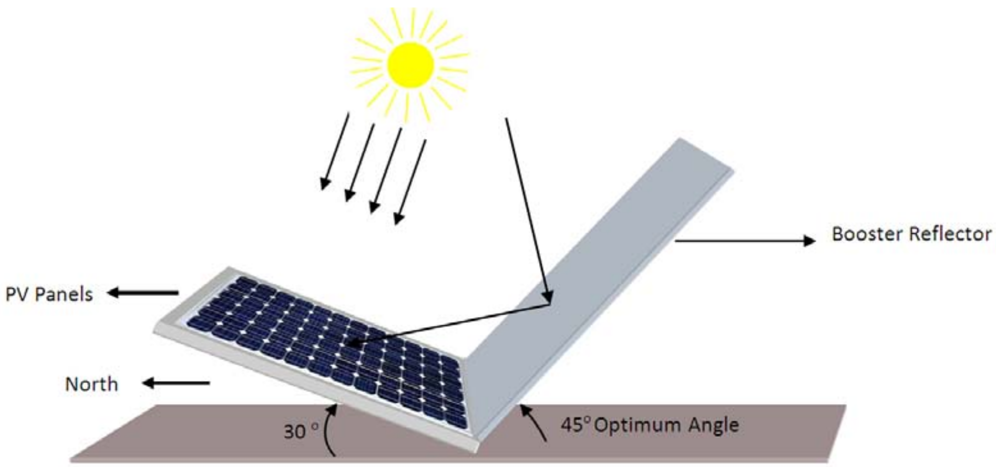


Fig. 5. Schematic diagram of the PV panels with the solar reflector

After determining the optimal position of the reflector, the effect of the booster reflector and the water film over the cells on the power generation of the photovoltaic panels and the flow rate of the water pump was investigated. Two of the three panels are used as the power source for the water pumping system. The reason behind this choice is that using all three panels together satisfies the water pump's required energy, and this leads to the concealment of the booster reflector and the water film's impact.

To investigate how the booster reflector and water film over the cells' front simultaneously affect the PV water pumping system performance, a 16-meter-head has been chosen. Experiments have been done in the following conditions: without reflector, with water film, with reflector, and with reflector and water film simultaneously. Figure 6 shows the output power of the photovoltaic array in different situations. The average output power for PV panels with aluminum foil reflector and water film concurrently is 77.6 watt. Therefore, one can see 50% improvement in power generation for the case of using reflector and water film concurrently at h=16m. As it can be seen, using a booster reflector with a water film over the photovoltaic cells strongly improves the electrical power output. A comparison of the electricity generated by PV panels in different conditions is demonstrated in Table.1. In addition, variations of photovoltaic pump flow rate are illustrated in Fig. 7. It is obvious from this figure that using booster reflector and cooling PV array with a film of water leads to significant increase in the flow rate of the photovoltaic water pump. As the daily pump flow rate improves about 18% for the case of using aluminum foil reflector, the volume of water gained in the case of using booster reflector and water film was about 48% more than conventional panels. This means that using a film of water over the cells which is equipped with booster reflector, extremely reduces the installation costs of utilizing photovoltaic water pumps in remote locations. A flowing film of water practically absorbs the heat generated by the array and reduces the cell reflections during the daytime. As it is seen in Fig. 8, using a film of water over the cells significantly decreased the cells temperature. On a sunny day, with a main ambient temperature of 35^{o} C, the main temperatures for the PV array without reflector, with water film, with reflector, and with reflector and water film simultaneously are 59^{o} C, 36 ^{o} C, 71^{o} C, and 39^{o} C, respectively. Moreover, the maximum temperatures for these cases are 65^{o} C, 41^{o} C, 84^{o} C, and 42^{o} C. As it was mentioned before, using booster reflectors leads to the extreme increase of cell temperature, which is its greatest disadvantage. Due to the film of water and additional cooling by evaporation, the cells' operating temperatures were significantly reduced in comparison to a module equipped with booster reflector and without a film of water. It can be found that the temperature reduction exceeds 40^{o} C at solar noon and temperature graph is very close to the ambient temperature. Effective reduction in the cell temperatures and cell reflections can be achieved by this method. Variations of output voltage and current of the array are presented in Fig 9. It is clearly seen that by increasing the light intensity by the use of the booster reflector, the voltage begins to drop while the current increases. This reduction of output voltage is due to the rising of the operating PV cells temperature. It can be seen that because of the presence of a film of water on the modules surface equipped with a plane reflector, a noticeable improvement in the output voltage of the temperature-dependant system can be seen. Experimental results indicate that the current of the panels which are temperature independent increases due to the existence of the reflector and film of water. In most panels, glass with a refraction index of n=1.53 is used to shield the PV active material. An intermediate layer of water with n=1.33 reduces the reflected fraction of an incoming perpendicular ray from 4.4% to 2.0% and therefore, improves the optical transmittance of the PV cells [18]. Using a water film over the photovoltaic panels can be useful in most photovoltaic water pumping applications which are operating at high temperature in hot climates. Moreover, the flow of purified water over the cells results in cleaner cells.

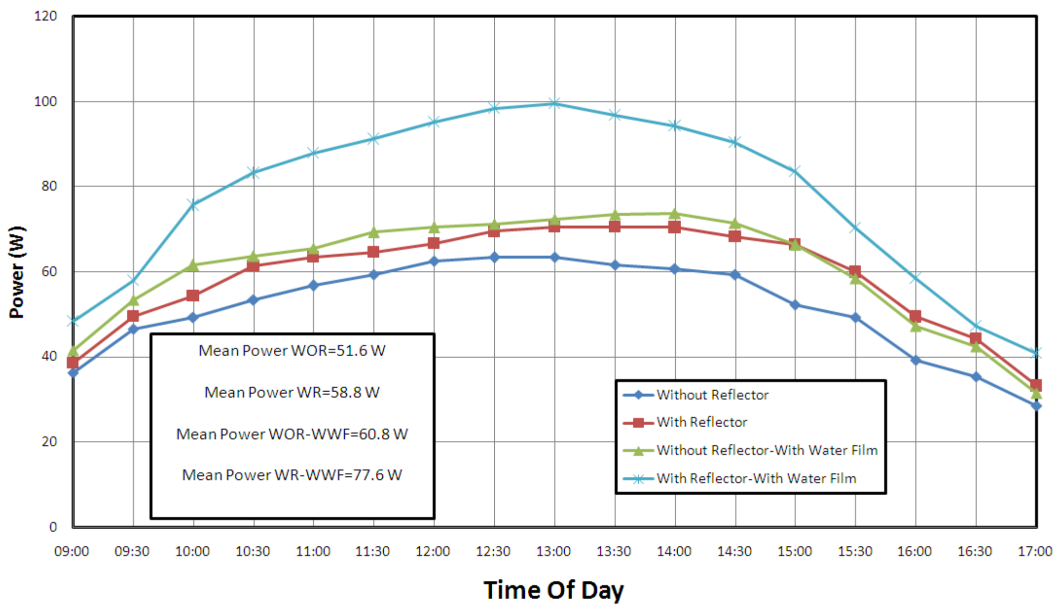


Fig. 6.Comparison of output power of the cells in different situations at h=16 m

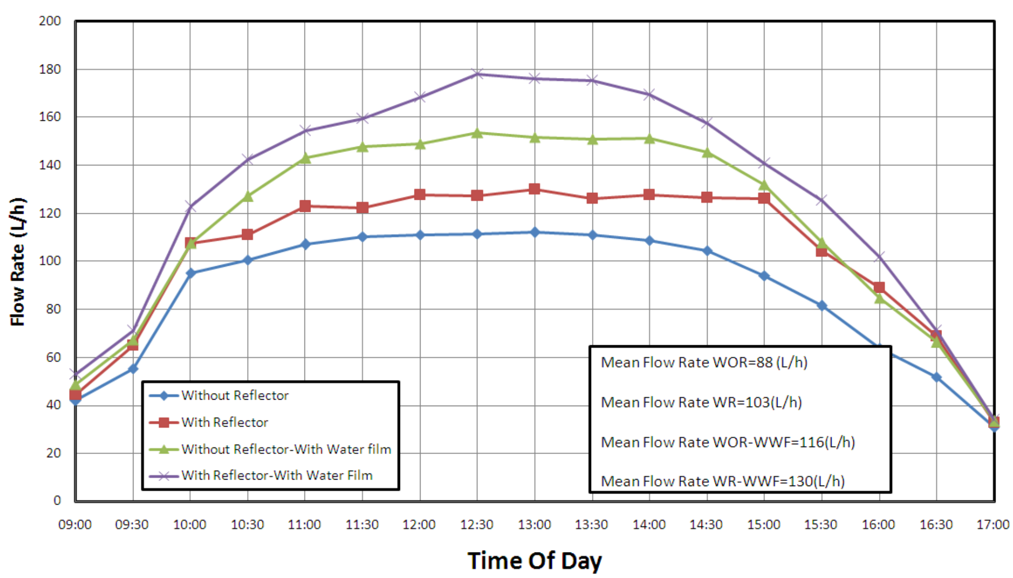


Fig. 7. Comparison of pump flow rates in different situations

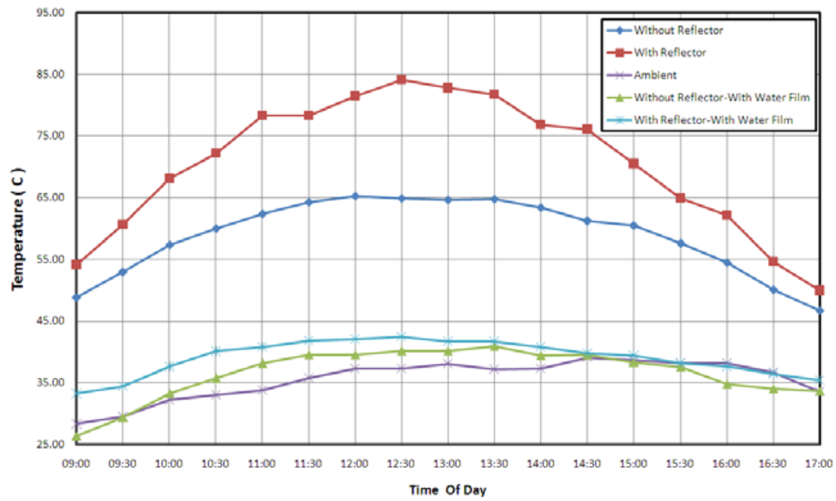
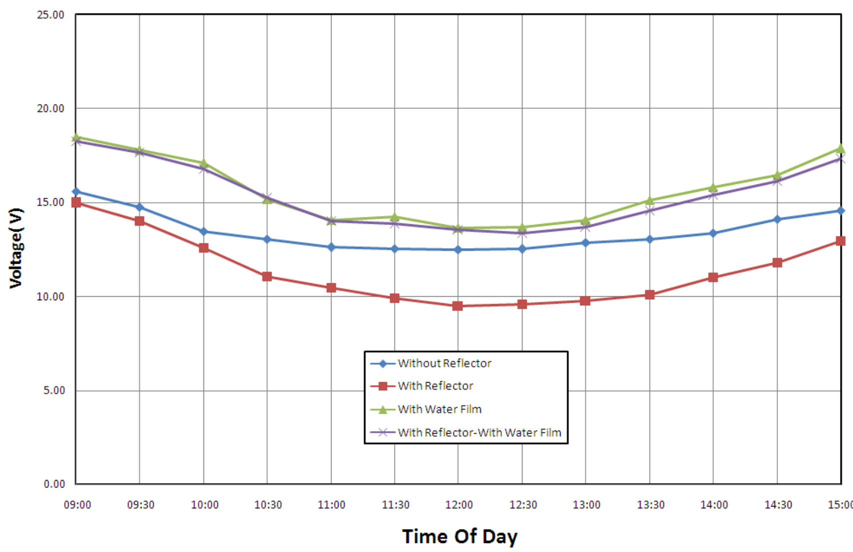
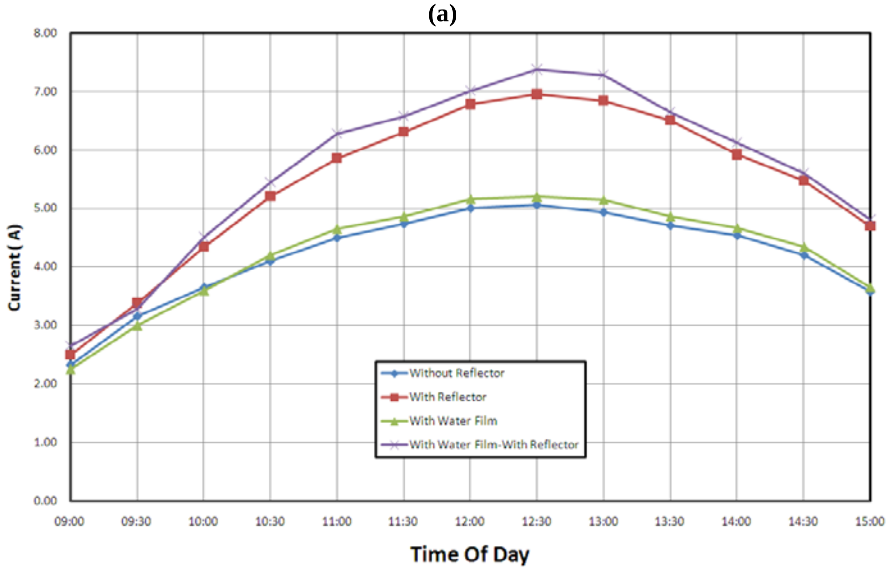


Fig. 8. Comparison of array temperature in different situations



(a)



(b)

Fig. 9. Variations of output (a) voltage and (b) current of the array

Table 1. Variations in panels output power due to the use of booster reflector and a film of water over the cells

	Conventional panels	With Reflector	With Water Film	With Reflector-With water Film
Mean Daily Power(watt)	51.6	58.8	60.8	77.6
Improvement		14.0 %	17.80 %	50.4 %

Figure 10 shows the output power of the photovoltaic array at h=6m. For this case, the improvement in the output power is 42%. As it can be seen, the effect of booster reflector and water film over the cells on the system performance is more in higher heads than in lower heads. This variation is mainly due to a system design criteria where system output is not further increased when maximum pump speed is reached. This speed corresponds to a certain value of input power. Higher input power will not be utilized by the pump.

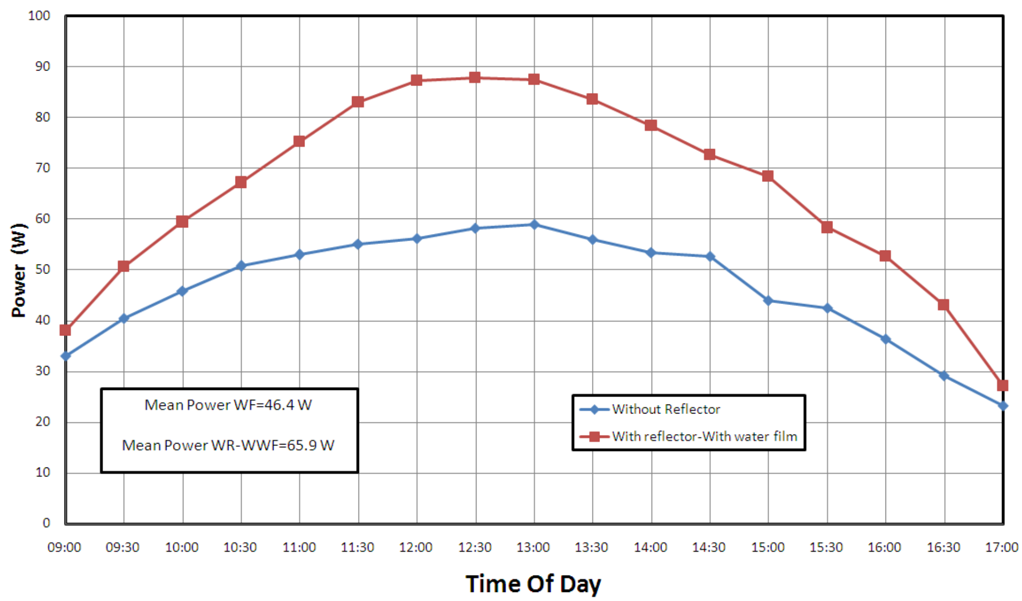


Fig. 10. Comparison of output power of the cells in different situations at h=6 m

4. CONCLUSION

The performance of a Photovoltaic water pump system coupled with booster reflector and panel cooling with a film of water has been presented in this work. Extra solar radiation on the PV panels due to the use of booster reflector leads to a significant increase in the cells' temperature. It is well known that the increase in the cells' temperature will result in a decrease of the panels' power output.In order to improve the performance of the modules equipped with concentrator, passive and active cooling systems have been proposed. Cooling the panels by covering the cells' surface with a film of water is one of the ways to improve the photovoltaic systems which are operating in high temperature. It is shown that using a booster reflector and covering the photovoltaic panels' surface with a film of water strongly improve the power generated by the array. These improve the whole system's efficiency and therefore, the pump flow rate of the system. Decreasing the cell's temperature and reflection loss can also reduce the threshold radiation of the starting motor pump torque on the hot days and result in the increase of customer requirement in the early morning.

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