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Cooling of PV Modules by Water, Ethylene-Glycol and Their Combination; Energy and Environmental Evaluation

Marzieh Lotfi [a*], Amir Hossein Shiravi [b], Tahereh Bahrami [a], Mohammad Firoozzadeh [b]

a *Department of Chemical Engineering, Jundi-Shapur University of Technology, Dezful, Iran*
b *Department of Mechanical Engineering, Jundi-Shapur University of Technology, Dezful, Iran*

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A B S T R A C T

Nowadays, the environmental crisis, due to the combustion of fossil fuels in thermal power plants has become a global issue. Application of renewable energies is the best strategy to overcome the crisis. The photovoltaic power plants are the most popular alternative for governments. As temperature rises in PV cells, a significant drop in their produced power is observed. Therefore, it is important to lower the cell temperature with an appropriate cooling method. In this paper, three types of cooling fluids; pure water, pure Ethylene-Glycol (EG) and mixture of water/EG with the same ratio, are experimentally investigated. Based on the results, application of pure water in the PVT system, shows better performance than other two fluids. While the conventional PV module has shown the surface temperature of higher than 70 ˚C, the proposed PV modules integrated with pure water, pure EG and water + EG have shown surface temperatures of 32.7 ˚C, 36.6 ˚C and 33.7 ˚C, respectively. The maximum temperature reduction of 37.3 ˚C compared to conventional PV module, increased the output power up to 51%. Accordingly, if conventional PV modules are used for commissioning a nominal 20 kW PV power plant, only 11.7 kW is attained, whereas, water cooled PV modules can improve the output power up to 17.7 kW.

Keywords: Photovoltaic, Renewable Energy, PVT, Energy Analysis, Environmental Evaluation

1. Introduction

It is well known that combustion of fossil fuels leads to a large amount of air pollutions release. As the air pollution, made by human activities, has increased rapidly and terribly around the world, so that the World Health Organization has repeatedly noticed in this regard [1]. Among all parts of pollutants, the energy sector, i.e. fuel combustion in traditional thermal power plants, have a chief portion of the greenhouse gas (GHG) emissions in the world. So that, up to 77% of the whole CO_2 and 48.7% of CH_4 emissions are relates to this section of activities, for some countries [2].

As a result, many countries are moving toward using renewable energies. Among the various renewable methods in generating electricity, photovoltaic (PV) power plants, have attracted the government's attentions around the world, due to its economy [3], availability [4, 5] and also ease of use. Although using PV power plants have many advantages, there are some weak-points, which leads to significantly drop in their output power [6, 7]. Temperature rise in the cells is one of the mentioned weak-points. So that, by each one-degree Celsius growth in temperature of the PV cells, their efficiency is decreased by 0.45% to 0.5% [8, 9]. So, it is necessary to keep the PV cell temperature as low as possible. Accordingly, various methods have been proposed to overcome the problem, e.g. application of phase change materials (PCMs) [10, 11], nanofluids circulation [12, 13], thermo-electric technology [14, 15], mounting metal fins [16, 17] and using artificial air flow [18, 19].

Joshi et al. [20] had an investigation on the performance of a PV system with water flow as a coolant. Thermal and electrical efficiencies for the considered system were reported as 55% and 8.5%, respectively. Pagodaripour et al. [21], used water spray on the photovoltaic panel in the summer climate of Kerman, Iran. The non-potable water was used in their experiments. Their system consisted of six 215 W poly-crystalline PV modules. It was found that the PV system integrated with cooling system had 16˚C lower temperature and accordingly, the efficiency of the system increased by 20%. Bhattarai et al. [22] performed an experimental study on cooling PV modules by water circulation system. Both electrical and thermal efficiencies were calculated, in accordance to the tests data. The novelty of that research was to present some mathematical relations, based on the experimental results, to calculate the efficiency in various ambient conditions. Their relations were compared with the tests output and had shown a proper agreement.

One of the benefits of PV systems is to use as electricity supply of a water pumping system. In order to enhance the output power of a PV/pumping system, cooling PV modules of a PV/pump system was proposed by Kordzadeh [23]. She had an experimental study on using a thin film of water as coolant of PV panels. Results show that the decrease in PV cells temperature, leads to increase in the output flow rate of the pump. So that at solar noon, when the considered PV modules (with and without cooling) met their maximum temperature difference of 25˚C, the PV/pump system integrated with a thin film of water, gave about 30 liters per hour more flow rate. In another similar research, Abdolzadeh et al. [24] performed water spray method as coolant of the PV modules of a PV/pump system. the water was sprayed with the flow rate of 15 L/h. Experimental results show that the output PV power was increased, when the mentioned cooling technique was accomplished. Accordingly, the increase of 3.1% in the electrical efficiency of the system was reported. Consequently, the output flow rate of the pumping system was improved by 34.4%.

Naghdbishi et al. [25] had an experimental research on application of multi-wall carbon nanoparticles in ethylene-glycol, as coolant of a PV module. the experiments were done in the climate of Qazvin, Iran. Both energy and exergy analysis had been performed. Accordingly, the thermal and electrical efficiencies were improved by 23.5% and 4.2%, respectively.

In this research, water, EG and combination of them with a same ratio are used as coolant of PV modules, experimentally. In order to compare the considered cases, an energy analysis is carried out. Moreover, since the PV systems are known as environmentally friendly, an environmental assessment for each case is accomplished, and reduction in CO_2 emission is calculated, too.

2. Experiment description

A 60 W polycrystalline photovoltaic panel made by Yingli Solar Company, China, has been used in this study. A 1 kW tungsten projector was used in order to simulate both irradiance and heat of the sun. An industrial pump was used to circulate the fluids through the system. Although the flow rate of fluids was adjustable, but the flow rate was not considered as a variable in this study, since its effect had been proved by many researchers [26]. Therefore, a constant flow rate of 0.4 lit/min was selected. A schematic view of the experimental set-up is depicted by Figure 1. Moreover, a complete characteristics of PV panel are listed in Table 1.

Table1: Main electrical and physical characteristics of the considered PV module

Module characteristics	Unit	Value
Power output ($\boldsymbol{P}_{max}$)	W	60
Nominal module efficiency ($\boldsymbol{\eta_m}$)	%	14.4
Voltage at $\boldsymbol{P}_{max}$ ($\boldsymbol{V_{mpp}}$)	V	18.47

Current at P_{max} (I_{mpp})	A	3.25
Open-circuit voltage (V_{OC})	V	22.86
Short-circuit current (I_{SC})	A	3.44
Operating temperature range	°C	-40 to +85
Dimension (*L /H/W*)	cm	66/63/2.5

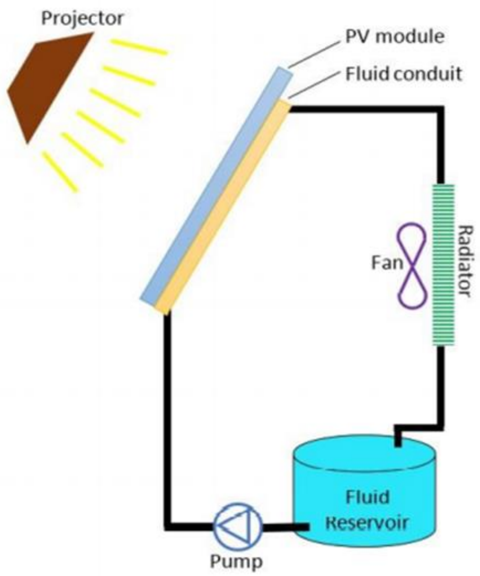


Figure1: Schematic of the experimental PV/T system

Since in this research, water, EG and a combination of them (1:1) were used, it is necessary to report their thermo-physical properties, as presented in Table 2.

Table 2: Thermo-physical properties of the considered fluids [27, 28]

Fluid	Specific heat capacity (J/kg K)	Density (kg/m^3)	Thermal conductivity (W/m K)
Water	4179	991	0.613
EG	2470	1113.2	0.528
Water +EG (50%+50%)	3509	1051	0.414

As the main aim of this study is to investigate the effect of temperature on the performance of PV modules, an accurate temperature measurement is necessary. So, four DS-18B20 thermal sensors with accuracy of 0.1 ˚C were used. Three of them are mounted at the back side of PV module (Figure 2), and one sensor is used to sense the ambient temperature. The technical specifications of the thermal sensors are presented in Table 3.

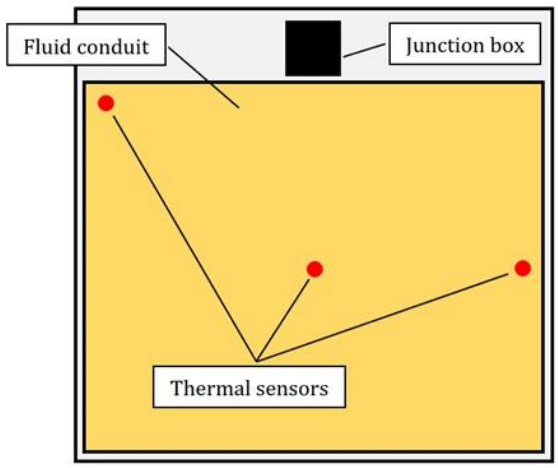


Figure 2: the thermal sensors position, at the back-side of PV module

Table 3: Temperature characteristics of the thermal sensors

Specification	Value
Quantity	4
Type	DS-18B20
Min. measurable temperature (°C)	-55
Max. measurable temperature (°C)	125
Accuracy (°C)	0.1

3. Governing equations

To calculate the electrical efficiency of a PV module, the input and output powers are defined by equation 1 and 2 respectively:

$$P_{in} = GA \quad (1)$$

$$P_{out} = VI \quad (2)$$

Where, V and I, are output voltage in (V) and output current in (A), respectively. Two mentioned electrical parameters are obtained from data-logger. Moreover, A is the module area in m^2 and G is the radiation intensity in W/m^2.

It is well known that the efficiency is defined as the output of any parameter to its input. Therefore, equation 3 can be used to calculate the electrical efficiency of a PV panel:

$$\eta_{PV} = \frac{P_{out}}{P_{in}} = \frac{VI}{GA} \quad (3)$$

But it is better to calculate the electrical efficiency of the whole system by considering the power consumptions, too. Here, pumping power (P_{pump}) is the only power consumption of the system. So, the following relation can be used:

$$P_{net} = P_{gen} - P_{pump} \quad (4)$$

Therefore, the net electrical efficiency of the considered system is:

$$\eta_{net} = \frac{P_{net}}{P_{in}} = \frac{P_{gen} - P_{pump}}{GA} \quad (5)$$

The dependency between PV cell temperature and electrical efficiency can be also calculated by the following numerical relation as [29]:

$$\eta_{e1} = \eta_0[1 - \beta(T_{cell} - 25)] \quad (6)$$

Where η_o is the panel's efficiency in standard test conditions, β is the silicon efficiency temperature coefficient which is reported in the panel's catalogue by the manufacturer and finally T_{cell} is the PV cells temperature under operating condition in Celsius. In addition, equations (7) and (8) are the two further relations which are less used by scholars [30, 31].

$$\eta_{el} = 0.1577 - 0.0009\, T_{cell} \quad (7)$$

$$\eta_{el} = 0.147 - 0.0008\, T_{cell} \quad (8)$$

4. Results and discussion

Experimental data were recorded at equal time intervals of 10 minutes. The effect of using pure water, pure EG and water + EG mixture as coolants of the photovoltaic system are experimentally investigated. In this section, the variations of temperature, electrical efficiency and output power of PV modules are reported and compared in considered cases.

4.1. Panel temperature variation

The main purpose of this research is to decrease the temperature of PV modules in order to increase their power and energy efficiency. The variations of temperature over time have been reported by Figure 3. In this diagram, it is obvious that after 2 hours, the surface temperature of all considered cases reaches to steady state temperature. In this condition, the surface temperatures of the photovoltaic panels for water, EG and water + EG are 32.7 °C, 35.6 °C and 33.7 °C, respectively, while the conventional PV module attained 71.6 °C. In another word, at least a temperature drops of 36˚C is achieved, when the fluids are used as coolants. Furthermore, it is found that water has the highest effect on the temperature of the PV module, due to its high specific heat capacity (refer to Table 2).

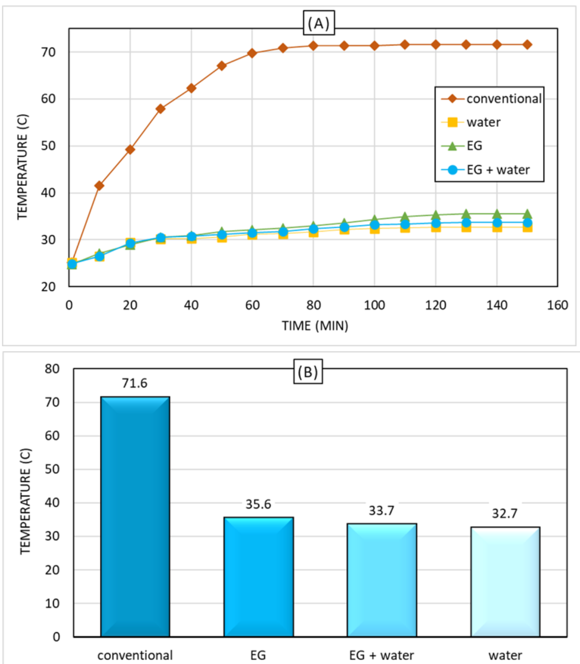
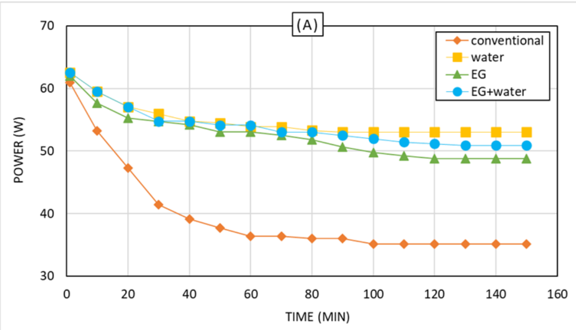


Figure 3: (A) Temperature variations over time, and (B) surface temperature at steady state condition

4.2. *Output power variation*

The output power of considered cases has been presented by Figure 4. It can be found that the output power of the conventional PV module drops by 41.4% compare with its nominal value. Here, the PV module integrated with pure water, clearly shows more power generation compared to the others.



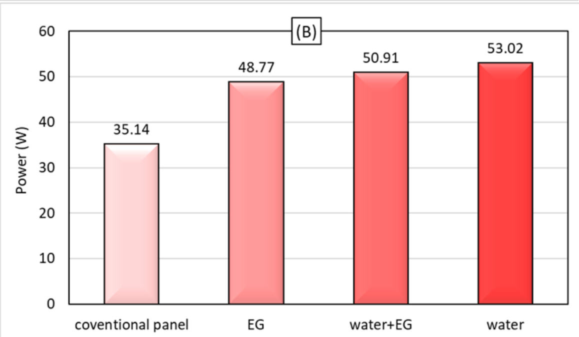


Figure 4: (A) output power vs time for all considered cases (B) output power in steady state

To extend a better mindset of the output power results, Figure 5 has been depicted. In this figure, a calculation of a 20 kW PV power plant is done for all of four considered cases. Accordingly, it is found that if the conventional PV modules are used for commissioning a PV power plant, only 11.7 kW is achieved in the output.

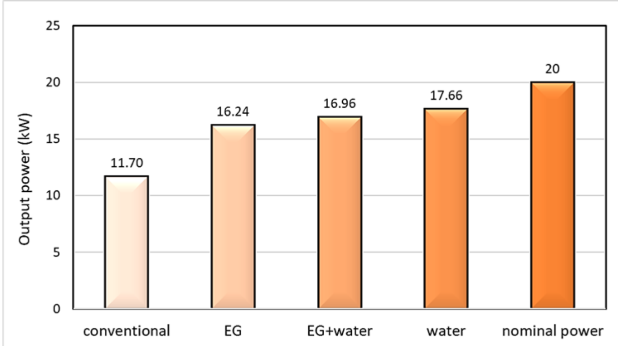
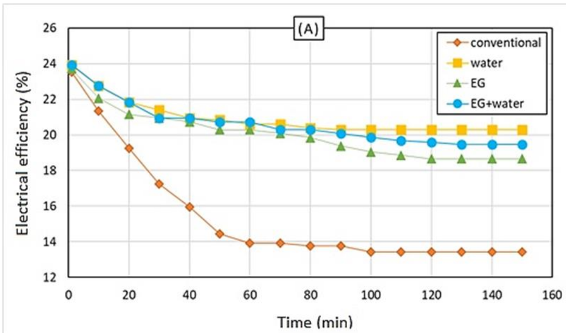


Figure 5: The output power of a 20 kW photovoltaic power plant, based on the all four considered cases

But when the fluids are used, a significant increment is seen. As expected, the PV power plant equipped with water had the utmost output power. This improvement is interesting for PV investors, because it leads to a remarkable reduction in return of investment.

4.3. *Electrical efficiency variation*

From Figure 3, the trend of electrical efficiencies is predictable as Figure 6 presents. After 120 minutes, pure water, water + EG mixture and pure EG as coolant fluids, have shown enhancements of 6.84%, 6.03%, 5.21% in electrical efficiency with respect to the conventional case, respectively.



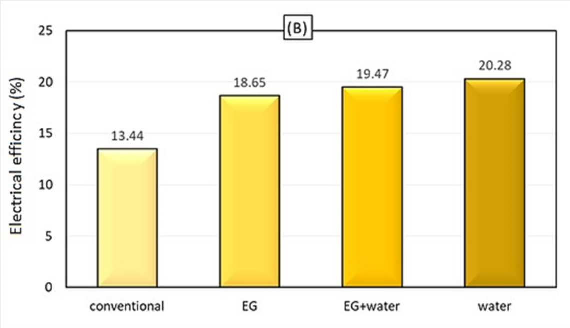


Figure 6: Electrical efficiency for all considered cases, (A) during time and (B) in steady state

The illustrated data in Figure 6, are based on the equation 3. In other word, this figure shows only the electrical efficiency of the PV module in various cases. But, as explained in section 3, it is better to consider the consumed pumping power in the calculations. Accordingly, Figure 7 is depicted. As clearly found, when the EG is used as coolant, the net electrical efficiency of the system is less than the conventional module.

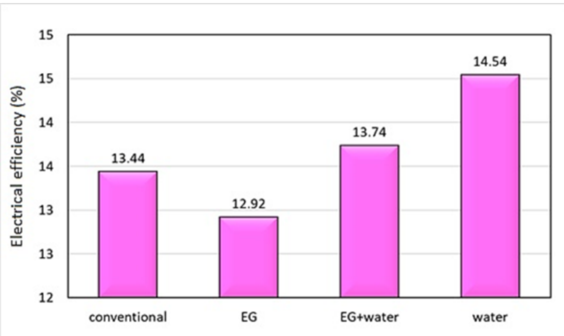


Figure 7: The net electrical efficiency for all considered cases, in steady state

4.4. *Environmental assessment*

In the past two decades, the governments around the world have moved towards using renewable energies. Nevertheless, more than 70% of the global electricity production is still generated in the thermal power plants, by sourcing fossil fuels [32]. The required electricity power in many oil-rich countries, is strongly relied on fossil fuels. For example; in Iran, the thermal power plants emit about 180 million tons CO_2, annually [33]. In this regard, a comprehensive assessment on the challenges of fossil fuel-based energy production and importance of investment in clean energy in Iran was done by Taheri [34]. According to the assessments, each kWh of electricity production by solar power plants, could prevent more than 700 g of CO_2 [33]. So, here, the environmental evaluation of a 20 kW PV power plant is done for the considered cases of this study. In this regard, the RETScreen software is used. The software was made by the government of Canada. The RETScreen is known as a powerful tool to perform both financial and environmental analyses of all kinds of power plants, either renewable or traditional.

In previous section the generated electricity power by means of all four considered cases were reported and discussed. Accordingly, here, the annual environmental effects of commissioning a 20 kW PV power plant are estimated and presented by Figure 8. In this figure, the considered cases are compared to a natural gas power plant. The criterion for environmental estimations is the emission factors of fossil-fuel based power plants. This factor has a specific value for each country, based on the applied technology level of the power plants, in that country. A list of emission factors for many industrial countries is presented by Stoppato [35]. From that paper, the Iran's emission factor for gas-based power plants was used. This factor is considered as 0.481 tCO_2/MWh [36]. More information about emission factor values and their remarks for different countries are available in [37-39].

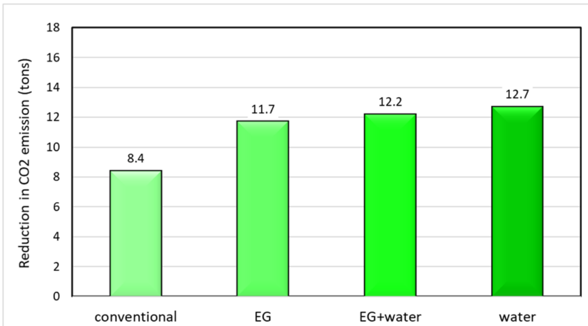


Figure 8: The estimated amount of annual reduction in CO_2 emission

Table 5 shows the environmental impacts of a 20 kW PV power plant for all considered cases, from different points of view. In this table, the

Table 5: Environmental impacts of proposed cases, compared with gas-based power plants

Environmental impacts	Conventional	EG	EG + water	Water
Liters of gasoline not consumed	3,613.9	5,016.1	5,238.5	5,454.8
Hectares of forest to absorb CO_2	0.8	1.1	1.14	1.2
Barrels of crude oil not consumed	19.6	27.1	28.4	29.5

annual reduction in CO_2 emission is transformed to some other quantitative parameters. It must be stated that the estimated data in both Figure 8 and Table 5, are the annual environmental impacts of the considered cases, for the first commissioning year. According to the research performed by Ito et al. [40], it was exhibited that PV systems have an annual reduction of 0.5% in their output power, due to depreciation caused in the equipment. Thus, if the purpose is to calculate the environmental evaluations of a PV power plant for its lifespan of about 25 years, the reduction percentage of 0.5% should be considered in the assessments.

5. Conclusion

In this research, the effects of using pure water, water/EG mixture and pure EG as coolants of PV panels was studied experimentally at indoor condition under controlled irradiation and environmental temperature. The main measured parameters of PV modules were the surface temperature, the electrical efficiency and the output power. The results revealed that the pure water as a working fluid, has the best thermal performance, compared to the pure EG and their mixture. Accordingly, a decrease of 37.3 ˚C in the surface temperature of PV module is observed, for pure water coolant in comparison with the conventional PV panel. This reduction caused to improve both output power and electrical efficiency by more than 50%. Therefore, the lifespan of PV modules could be enhanced and the energy payback time of the system could decrease. Moreover, the environmental assessments were accomplished installing a 20 kW PV power plant. It was shown that the power plant integrated with water has mitigates more than 4.3 tCO_2, annually, in comparison with the conventional one.

Nomenclature

A	*area (m^2)*
G	*solar irradiation ($W\ m^{-2}$)*
V	*voltage (V)*
I	*current (A)*
P	*power (W)*
PV	*Photovoltaic*
T	*temperature (°C)*
η	*energy efficiency (%)*
β	*PV efficiency temperature coefficient*
Subscript	
amb	*Ambient*
cell	*Cell*
in	*Input*
out	*Output*
el	*Electrical*
gen	*Generate*
net	*Net*
pump	*Pump*

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