Performance Appraisal of Photovoltaic Module Combined with Various Optical Filters: Experimental Investigation

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Abstract- The recent intensified structure of photovoltaic systems globally is a motivation to give a considerable attention for further efficiency improvement. The significant increase in surface temperature resulting from solar radiation is a major factor to the reduction in PV module power output. Currently, just ten to fifty five percent of the solar incident spectrum that hits a PV panel's surface today is converted to electrical power; the remainder is lost as heat. The thermal energy cumulation on the photovoltaic modules considerably reduces the electricity conversion efficiency. In the current study, five optical filters utilizing various working fluids are paired with a photovoltaic module and experimentally compared to the stand-alone photovoltaic module aiming to enhance its output and efficiency. In the current evaluation, the Monte Carlo technique is used to examine and compare the performance of the suggested optical filters. Glycerin, ethyl alcohol, oil, air, and water are the working fluids for the suggested configurations. The Monte-Carlo method indicates that the optical filter employing water has the maximum efficiency among the proposed working fluids. The consequences reveal that the electrical efficiency of the setup using water as a working fluid is the greatest, followed by structures using glycerin, oil, ethyl alcohol, air, and standalone PV modules, which have values of 7.74, 7.59, 7.51, 7.38, 7.19 and 5.17%, respectively.

Keywords- Photovoltaic module; optical filter; Monte Carlo; electrical efficiency.

1. Introduction

The prevalent use of renewable energy resources, such as solar energy, is a key strategy towards attaining carbon neutrality globally [1]. Utilizing solar energy can minimize the dependence on the traditional fossil fuels, save the environment, and decrease the climatic changes impact [2-4]. The primary solar energy conversion technique is the solar photovoltaic (PV) technology since it is reliable and adaptable for both local and remote power systems [5]. Worldwide over the last ten years, the installed capacity of photovoltaic modules has grown from roughly 14.8 to 150.8 TWh, sharing the same percentage with wind energy, both of which represent the major share percentage of renewable energy installations worldwide [6]. It should be realized that the simplicity of installation, low maintenance expenses, and no presence of moving parts are motivating factors for developing the sector of photovoltaic technology [7].

However, the major drawback of PV modules is that their output power is greatly influenced by the environmental factors including solar radiation and ambient temperature [8-10]. Whereas increasing ambient temperature boosts solar cell temperature, which drops the PV output voltage and diminishes the PV efficiency [11, 12]. The reason for this is that large number of photons whose energies are below the band gap of the PV cell semiconductor material are being inefficiently transformed leading to a huge thermal energy is lost besides the cell temperature elevation [13-15].

Rajanna [16] presents an alternative model developed to address the need for electricity that is necessary for many services. Any smart grid's main features revolve around efficiency, performance optimization, and dependability. As provided by Srikanth and Chandra [17], it also presents the grid connection for battery storage and MPPT technique optimization [18-21].

Furthermore, raising the cell temperature creates hot spots and develops great thermal stresses on the surface of PV module, shortening the PV cells lifetime [8]. Therefore, the full spectrum absorption of solar energy has not been attained by conventional photovoltaic cells. Accordingly, researchers are paying particular attention towards the spectrum-split technology for solar full-spectrum conversion as a promising technology to overcome this problem. Thus, the utilization of an optical filter encapsulated in a fluid between sunlight and the PV module surface is known as absorptive-based filters, and it is regarded as a reliable technique for spectrum beam splitting [22]. Recently, number of researchers have proposed different spectrum beam split configurations based on simultaneous photoelectric and photothermal conversion or photoelectric conversion only, where both techniques have proven their reliability in boosting the performance of PV cells. Different spectrum beam splitting techniques used for photovoltaic/thermal (PV/T) or PV systems were examined by Imenes and Mills [23] and Mojiri et al. [24].

The most commonly used spectrum beam splitting technique among these is the thin-film wave interference filter [25-28]. The utilization of thin-film wave interference filters in PV/T systems is a challenge, though, because of the huge costs associated with their production and operation [29]. Compared to the thin-film wave interference filter, spectrally selective liquid absorption is possible when the solar cell and the liquid filter are compatible filters, then it can be capable of providing a lower predicted cost as an spectrum beam splitting (SBS) in photovoltaic-thermal or stand-alone PV systems [22].

One of the first study on a fluid optical filter for solar power transference was conducted by Chendo et al. [30]. According to their research, cobalt sulphate salt could be a better alternative for PV/T systems that make use of silicon crystalline solar cells. With respect to, Rosa-Clot et al. [31] investigated the effectiveness of placing the PV module in water aiming to be compared with a third PV module that was put outside the pool and exposed to direct sunlight. Two PV modules were immersed under 4 cm and 40 cm of water in a pool. The experiment was conducted outdoors in Pisa, Italy. According to their findings, at a water depth of 4 cm, the average electrical efficiency increased by around 11%, while at a depth of 40 cm, it declines by about 23%. Similarly, Looser et al. [32] examined the resistance of various heat transfer fluids to ultra violet (UV) light exposure at 75 and 150°C. Through the fluids tested, industrial-grade propylene glycol with a chemically inert red dye proved to be the best filter. Moreover, the efficiency of a filter that uses both water and sustainable development goal (SDG) was evaluated by Mojiri et al. [33]. The results indicated that proctor and gamble (PG) remains to surpass water-SDG filters, with SDG possessing strong intake capacity at short wavelengths but further enhancement is required at longer wavelengths. Mojiri et al. also investigated a filter that combines a heat transfer fluid and a dichroic solid filter (SiO2/TiO2) [34]. The best spectral range for silicon cells was between 600 and 1125 nm. The remaining 54.5% of the concentrated light was transferred to the thermal absorber, which was then transformed into electricity in the cells to the extent of 26.1% by the filter. It was shown that a perfect fluid filter can increase a solar cell's efficiency by 30 to 40 percent of the solar radiation that the filter can absorb the thermal energy, according to computational work performed by Sabry et al. [35]. Likewise, a number of researchers have investigated the theoretical and experimental feasibility of Nano fluids as the SBS of PV/T or either the PV systems [36-39].

The main obstacle to integrating the liquid absorption filter into PV systems, however, the literature survey shows that the lack of non-degradable liquids with suitable optical properties. The devices under investigation with spectrally selective liquid absorption filters as a result still have a low efficiency [29]. Finding a liquid with the proper filtering characteristics to work with a PV module is really difficult. In order to achieve simplicity and convenience of integration with PV or hybrid PV/T systems, further study is needed to identify a suitable liquid filter with high efficiency, long-term consistency, and affordability. Hence, the rating of five several optical filters fitted with a PV module is compared and assessed using the Monte Carlo approach experimentally. The developed arrangements are formed such that the PV module is attached to a static working fluid that is encased between two layers of soda-lime optical glass, which serves as the optical filter. Meanwhile, the working fluids proposed in the current research are air, ethyl alcohol, glycerin, oil and water. In addition, the efficiency and power output of the proposed modules and the standalone PV module are compared.

2. Design of the System and Experimental Techniques

The explanation of the experimental framework, the commanding equations used in the present investigation, and the details of the recommended modules are all described in the current section.

2.1. System Description

The optical filter is placed directly above the PV panel to develop the intended structures. The optical filter is made of two layers of soda-lime glass, with the static fluids suggested in the current study are water, air, oil, glycerin, and ethanol filling the space between the layers. In the present study, a PV panel had boundary dimensions of (31.2 x 23.4) cm^2 is used, and the optical filter dimensions are the same as those of the PV panel located beneath it. The static fluid that fills the area between the two layers of glass, each layer of soda-lime glass is 6 mm thick, while fluid layer in between is 6 mm thick.

Additionally, the constituents of soda lime glass are SiO_2, Na_2O, K_2O, CaO, MgO, Al_2O_3, Fe_2O_3, and SO_3, with percentages of 71, 7, 7, 8.6, 4.4, 1.3, 0.1, and 0.3%, respectively. It should be mentioned that the configurations using water, air, oil, ethyl alcohol and glycerin are recognized as (PV-W), (PV-A), (PV-O), (PV-AL) and (PV-G), respectively. Whereas, the stand-alone PV module is named as (PV-S).

In the experimental set-up, as depicted in Fig. 1, a single 500W spotlight is used to produce a continuous radiation source from a tungsten halogen lamp. The radiation source is 30 cm above both the optical filter and the PV panel, which has a thickness of 16 mm, additionally, the bottom is where the 25 mm-thick PV panel is located. Also, it shows the three ways that an optical filter can affect incident solar flux: by reflecting, transmitting, or even by absorption.

2.2. Governing Equations

Optical filters have the capability to absorb a part of the incident spectrum in accordance with the Mie scattering theory, and by using the right base fluid, they may also be effective selective absorbers [40]. Remarkable heat absorption in incident solar spectrum zones that the PV cells are unable to capture is made possible by the fluid synergy. The spectrum percentage path through to both PV panel and optical filters can be calculated using the equations shown below [35, 36]:

$$G_{th}(\lambda) = G_{in}(\lambda) \,.\, \alpha_{OF}(\lambda) \quad (1)$$

$$G_{pv}(\lambda) = G_{in}(\lambda) \,.\, \tau_{OF}(\lambda) \quad (2)$$

$$Gr_{pv}(\lambda) = G_{in}(\lambda) \,.\, \gamma_{OF}(\lambda) \quad (3)$$

The effect of optical properties shown in the last equation that present the optical filter properties as absorptivity, transmittivity, and reflectivity with $\alpha_{OF}(\lambda)$, $\tau_{OF}(\lambda)$, and $\gamma_{OF}(\lambda)$ respectively. Presented in equation, that the specific energy of incident spectral distribution of AM1.5 as $G_{in}(\lambda)$. Moreover, $G_{th}(\lambda)$ represents the spectral percent absorbed by the thermal absorber, while $Gr_{pv}(\lambda)$ and $G_{pv}(\lambda)$ represents the spectral fraction reflected and transmitted to the PV cells respectively. It should be made clear that integrating $G_{th}(\lambda)$ with the spectrum range of 280–4000 nm can be used to determine the amount of solar energy absorbed by the optical filter.

The electrical energy and electric efficiency can be computed using the following equations [12, 14]:

$$\eta_{ele} = E_{ele} / E_s = \eta_{ref} \,.\, [1 - \delta_{sc} \,.\, (T_{sc} - T_{ref})] \quad (4)$$

$$E_{ele} = \eta_{sc} \,.\, A_{sc} \,.\, G_{sc} \,.\, [1 - \delta_{sc} \,.\, (T_{sc} - T_{ref})] \quad (5)$$

Where E_{ele} and η_{ele} are the amount of electricity produced and efficiency by the PV module, η_{sc} is the efficiency at the reference temperature of the PV panel, A_{sc} is the surface area of the PV cell, G_{sc} and E_s are the amount of solar radiation that enters the PV cell after hits the total PV module. η_{ref} is refers to the efficiency of the solar panel at reference temperature. The temperature coefficient for the c-si cell is also referred to as δ_{sc}. Moreover, T_{ref} and T_{sc} stand for the reference temperature and the temperature of the solar cell.

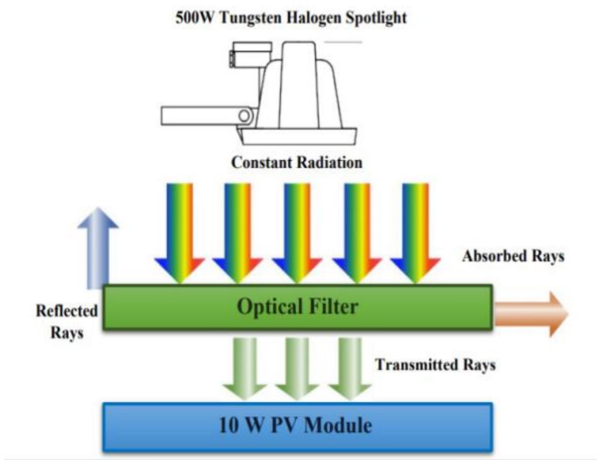

Fig. 1. Graphic representation of the suggested configuration.

2.3. Setup of Experimental Process

In order to compute the output electrical power and efficiency of a stand-alone PV module, as well as the explored layouts using water, oil, air, ethyl alcohol, and glycerin as working fluids, an experimental setup is developed aiming to measure the PV surface temperature.

As displayed in Fig. 2, a 500 W continuous radiation heat source is used and installed 30 cm above a 10 W PV panel M-Series SPM010P-R. The I-V and power curves provided by SOLARTECH Company are implemented in the current study. Also depicts the test rig configuration in its actual state.

2.4. Monte Carlo Approach

The Monte Carlo technique is a comprehensive class of computer methods that uses random sampling with periodicity to provide mathematical results. The underlying idea is to harness randomness to find solutions to issues that could theoretically be found.

Fig. 2. Test rig setup.

They are frequently employed to resolve numerically and physical problems, and they are more accurate when using several techniques to cases that would otherwise be challenging or impossible. The three issue types of numerical integration, drawing from a probability normal distribution, and optimization are where Monte Carlo equation are most frequently applied. The following section integration can be employed to assess the developed fluids effectiveness as a band-pass filter [43, 44]:

$$\eta_{OF} = [_{short\lambda}\int^{long\lambda} E_\lambda \, . \, T_\lambda \, d\lambda] \, / \, [_{short\lambda}\int^{long\lambda} E_\lambda \, d\lambda] - [_0\int^{short\lambda} E_\lambda \, . \, T_\lambda \, d\lambda] \, / \, [_0\int^{short\lambda} E_\lambda \, d\lambda] - [_{long\lambda}\int^{4\mu m} E_\lambda \, . \, T_\lambda \, d\lambda] \, / \, [_{long\lambda}\int^{4\mu m} E_\lambda \, d\lambda] \quad (6)$$

Where the value of E_λ, derived from Gueymard, denotes the sun irradiation per wavelength [45]. η_{OF} is refers of the optical filter efficiency depended on the sun irradiance and the variation of the transmittance with wavelength which refers as T_λ. A filter between short and long wavelengths that is totally transparent (T=1) and varies depending on the type of cell will have an efficiency of 1. As a result, filter optimization can be done using this objective function. In order to discover the best filter, the current work uses a straightforward Monte Carlo technique to produce volume fraction combinations at random [45]. This equation can be used to evaluate the efficiency based on the previously mentioned idea. It is important to understand that this equation was created using an ideal filter that captures the complete spectrum for distinct kinds of PV cells.

2.5. Error Analysis

The uncertainty analysis shows the impact of parameter measurement error on the results' uncertainty. Using the differential approach, a thorough examination of the numerous experimental parameters is performed [46].

The transmittance and absorbance measured by the JASCO V570 spectrophotometer had a coefficient of error of 1.76 percent, and measurements of temperatures, power, and efficiency had a coefficient of error of 0.9 percent. Since power and efficiency are calculated by adjusting the temperature, they have the same percentage of error.

3. Results and Discussion

The Monte Carlo method is applied in the current study to evaluate and compare the performance of five distinct optical filter arrangements used in combination with a PV module. Throughout the indicated arrangements, a static working fluid attached to the PV module is encased between two layers of soda lime glass, which acts as an optical filter. The working fluids for the proposed setups include glycerin, ethyl alcohol, oil, air, and water. The proposed modules electric output and efficiency are also compared to those of a PV unit without an optical filter experimentally. The surrounding temperature is 23°C at the start of the experiment and is elevated by about 2.5°C after passing 600 seconds.

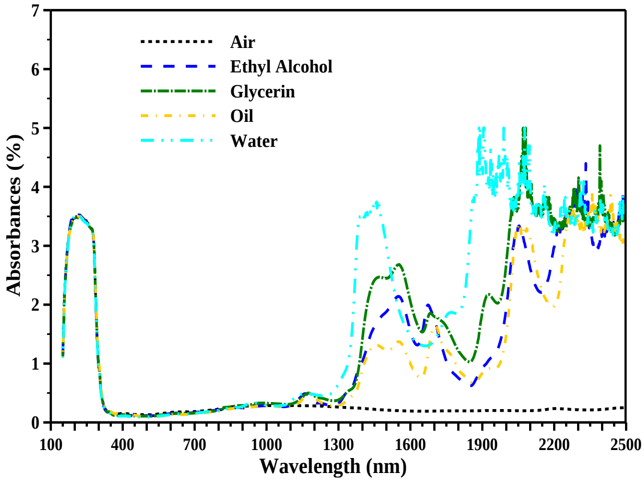

Fig. 3. The absorbance property of the proposed optical filters between 190 and 2500 nm.

3.1. The Optical Features Analysis of the Suggested Configurations

Figure (3) displays the variations in the absorbance percentages for the proposed optical filters throughout the spectrum frequency band of 190 to 2500nm. It is clearly shown that the optical filters utilized in the five configurations are capable of absorbing around 1.2 and 2 % of the spectral irradiance located in the wavelength range of 190 to 300nm which is a perfect absorbance for the UV spectrum because it could boost the temperature of the PV cell. Although there is a noticeable decline in wavelength between360 and 1200 nm, this range is appropriate for the generation of electricity from crystalline silicon PV cells. Additionally, it is demonstrated that, with the exception of the air filter, which has a lower range of absorbance due to its low specific heat capacity, the absorbance in the wave length range of 1200 to 2500nm rises gradually until it reaches its maximum value.

Figure (4) displays the changes of the transmittance for the investigated optical filters. According to this figure, the proposed working fluids have very low transmittance percen-

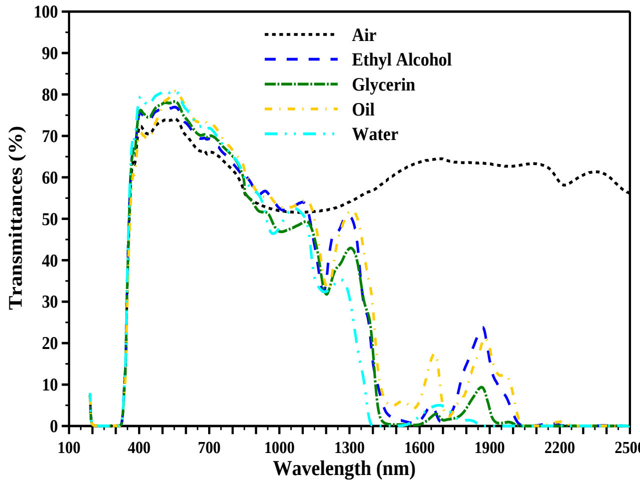

Fig. 4. Transmittances variations of the proposed optical filters between 190 and 2500 nm

-tages over the UV and IR regions that are significantly different from one another, except air that achieves a great transmittance. It is worth mentioning that both of these zones are undesirable since they vastly make the PV cell warmer. Except for the air filter, which has a higher range of transmittance due to its low specific heat capacity, it is revealed that the transmittance in the wavelength range of 1200 to 2500nm declines steadily until it reaches its minimum value.

Figure (5) clearly shows that the spectrum radiation power of the suggested filters is significantly less than the AM1.5 spectrum, with a slight difference between the suggested filters. This is due to the fact that the transmittance of the entire spectrum is one, whereas the transmittances of various filters fall short of one. It should be emphasized that in order to assess the effectiveness of the optical filters created in the current research, the optimum optical filter recommended by the Monte Carlo technique must be compared to each optical filter. The ability of the researched configurations to block undesirable wavelengths and let through beneficial ones for the PV cell, which is displayed across the visible and IR ranges, is shown in this picture. It should be mentioned that the air filter does not have the capacity to substantially reduce an undesirable spectral irradiance, however the rest of arrangements have proven their reliability and ability to extract huge part of the harmful irradiance, but with different ranges. Thus, the highest area under curve for the proposed filters along the wavelength range from 280 to 2500nm is achieved by air followed by oil, water, ethyl alcohol and glycerin with approximately 625, 591.2, 583.9, 578.5 and 570.8W/m^2, respectively.

3.2. Effectiveness Valuation

Figure (6) depicts the variation of PV module surface temperature with time for the investigated structures. This figure revealed that the temperature marginally increases with time for all modules. It can be dedicated that the PV surface temperature is minimized with absorbing the unfavorable band of spectrum irradiance through the emplo-

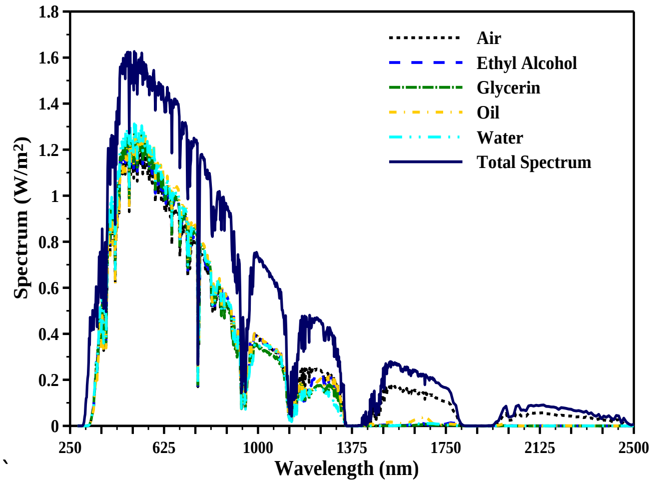

Fig. 5. The spectral power irradiance variation between the suggested filters and AM 1.5 total spectrum with range of 280 and 2500 nm.

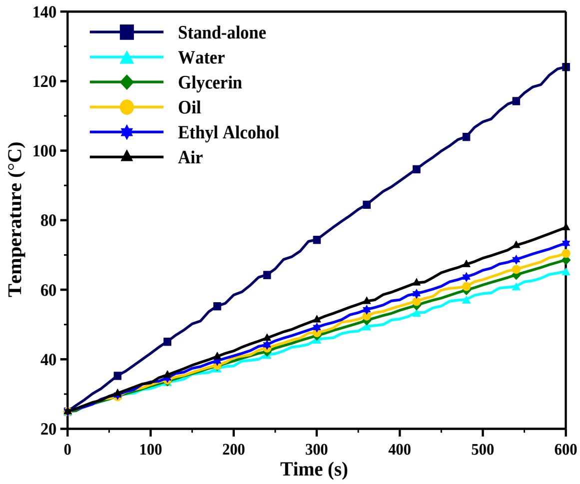

Fig. 6. The PV module surface of the analyzed layouts' changing temperatures over time.

-yed optical filter. After 100 seconds, the temperatures for the setups adopting optical filters are almost identical, but with substantially lower values than those offered by the stand-alone PV module. After passing 600 seconds, the lowest PV surface temperature is attained by (PV-W) followed by (PV-G), (PV-O), (PV-AL), (PV-A) and (PV-S) modules offering values of 65.3, 68.6, 70.5, 73.4, 77.9 and 124°C, respectively.

Figure (7) demonstrates the generated electrical power changes with time for the designed modules. It is clearly noted that the electrical power dramatically declines with enhancing the PV surface temperature. As the time passes the electrical power considerably reduces for the proposed modules because of the PV surface temperature elevation. Consequently, the lowest output electrical power is provided via the stand-alone PV unit followed by (PV-A), (PV-AL), (PV-O), (PV-G) and (PV-W) arrangements with the following values 1.9, 2.6, 2.70, 2.74, 2.77 and 2.83W, respectively.

As seen in Fig. (8), the electrical efficiency for all modules clearly declines with time. This is due to the substantial drop in the electrical power, as demonstrated in Fig. (7) for the earlier mentioned reasons.

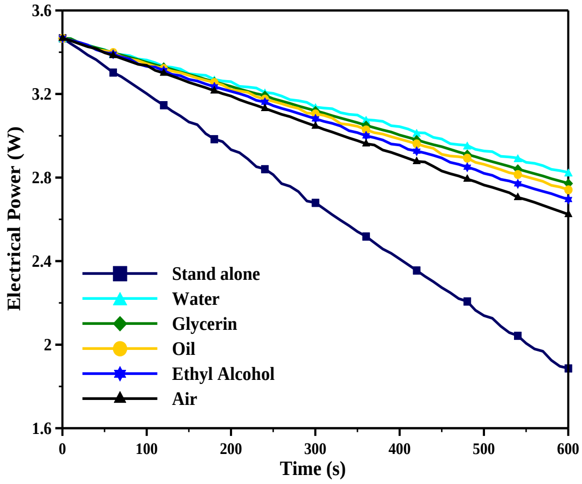

Fig. 7. The electrical power that is generated varies over time for the suggested setups.

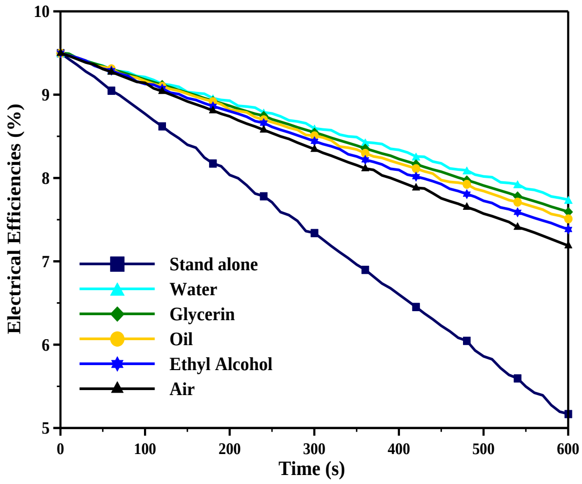

Fig. 8. The electrical efficiency change presented with time for all configurations.

Thus, the highest electrical efficiency is obtained by the (PV-W) followed by (PV-G), (PV-O), (PV-AL), (PV-A) and (PV-S) structures, respectively, with the following values 7.74, 7.59, 7.51, 7.38, 7.19 and 5.17%.

3.3. The Optical Features Validation

The attributes estimated empirically and the performance results obtained numerically were validated against theoretical work after the suggested system's performance was evaluated using the governing equation Eq. (2). While the performance results were validated against prior experimental work, the calculated properties were measured mathematically in earlier research that was done by S. Gupta and U. Bajpai and published in INPRESSCO international press cooperation [47]. The solar spectrum after filtering with a double soda-lime glass containing only pure water as an optical fluid was chosen as the property for certification which measured in the National Research Center labs.

Figure 9 depicts the relationship between wavelength and spectrum energy. It represents the verification of experimental data, namely the transmittance property effecti-

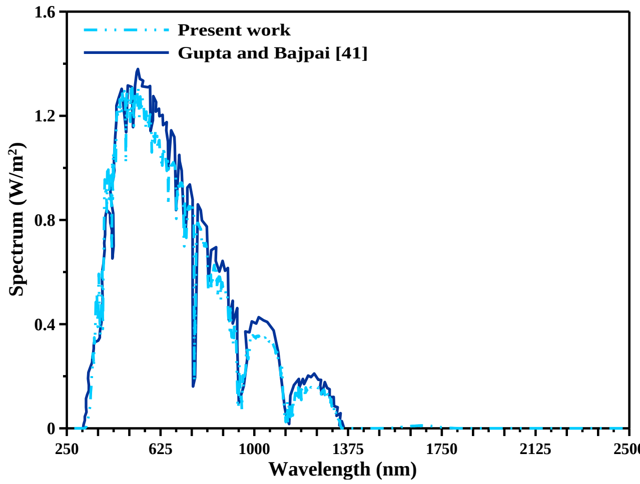

Fig. 9. The validation of the solar spectrum of double soda lime glass contained with water experimental against theoretical

-veness on incident spectrum as stated by Eq. (2) in opposition to Gupta and Bajpai mathematical strategy [41]. The theoretical model uses double soda lime glass that is 3 mm thick, while the experimental work preferred glass that is 6 mm thick. Additionally, the pure water thickness in the theoretical method was 5 mm while the experimental was 6 mm thickness. Therefore, there may be a slight variation with a maximum error value of 4.62%.

4. Conclusions

The objective of the current study is to discover ways to increase the power and efficiency of PV modules by using various types of operational optical fluids. The impact of placing an optical filter directly above the PV module is investigated, and its effects are contrasted with those of a standalone PV unit. By sandwiching a static working fluid between two layers of soda lime glass, the described designs are created. Other than that, ethyl alcohol, water, glycerin, oil, and air are the suggested working fluids. Additionally, the suggested layouts and the stand-alone PV module's electrical output, surface temperature, and efficiency are assessed. The following are the inferences that can be made:

- The Monte Carlo approach claims that the efficiency of the optical filter employing water is the highest among the proposed working fluids.
- Water as a static working fluid has the highest absorption percentage when compared to other working fluids in the IR spectrum.
- Optical filters employing water as a working fluid yield in the lowest PV surface temperature, which is then followed by glycerin, oil, ethyl alcohol, air, and the standalone PV module, which have values of 65.3, 68.6, 70.5, 73.4, 77.9, and 124 °C, respectively.
- The structure utilizing water as a working fluid has the greatest electrical efficiency, followed by the glycerin,

oil, ethyl alcohol, air, and stand-alone PV module structures offering values of 7.74, 7.59, 7.51, 7.38, 7.19 and 5.17%, respectively.

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