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Research Article

Thermal Profile of a Low-Concentrator Photovoltaic: A COMSOL Simulation

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With the gradual reduction of fossil fuels, it is essential to find alternative renewable sources of energy. It is important to take advantage of substitutes that are less expensive and more efficient in energy production. Photovoltaic concentrators (CPVs) are effective methods through which solar energy can be maximized resulting in more conversion into electrical power. V-trough concentrators are the simplest types of low-CPV in terms of design as it is limited to the use of two plane mirrors with a flat photovoltaic (PV) plate. A consequence of concentrating more solar radiation on a PV panel is an increase in its temperature that may decrease its efficiency. In this work, the thermal profile of the PV plate in a V-trough system will be determined when this system is placed in different geographical locations in Saudi Arabia. The simulation is conducted using COMSOL Multiphysics software with a ray optics package integrated with a heat transfer routine. The 21st of June was chosen to conduct the simulation as it coincides with the summer solstice. The employment of wind as a cooling method for V-troughs was investigated in this work. It was found that with the increase in wind speed, the PV panel temperature dropped significantly below its optimum operating temperature. However, due to the mirrors' attachment to the PV panel, the temperature distribution on the surface of the panel was nonuniform. The temperature gradient on the PV surface was reduced with the increase of wind speed but not significantly. Reducing the size of the mirrors resulted in a partial coverage of solar radiation on the PV surface which helped in reducing the temperature gradient but did not eliminate it. This work can assist in testing numerous cooling models to optimize the use of V-troughs and increase its efficiency especially in locations having high ambient temperatures.

1. Introduction

Recently, researchers have shown an increased interest in renewable energy sources such as solar, wind, and biomass energy [1]. Photovoltaic (PV) cells are one of the attractive and safe solutions for energy production as they can convert solar energy into electrical energy through semiconductor materials. They are simple and reliable and can be provided everywhere. PV cells use sunlight during the day, producing fewer than 3 kW on average from one cell. Despite the current advantages of PV cells, it cannot be used as a substitute for fossil fuels for power generation due to its low efficiency and high industrial manufacturing cost [2, 3]. As a solution to reduce its manufacturing costs, concentrator photovoltaic (CPV) is being used. The idea of CPVs depends on the collection of sunlight, whether direct or scattered beams, and focusing it on the solar cell using optical devices. Based on a factor known as the concentration ratio (CR), the CPVs can be divided into three categories, high (HCPV), medium (MCPV), and low concentration (LCPV), that have ranges of 300-2000 suns, 40-300 suns, and less than 40 suns, respectively. LCPVs are simpler in design compared to HCPV. It is important to emphasize two conditions for the success of utilizing an LCPV system. The first is that the optical devices used to focus the radiation on the PV cell must be cheaper than the cost of the PV cells used. The second is that the solar cell efficiency should not be reduced by the concentration of radiation on it [4, 5].

Researchers have suggested different optical designs for LCPV to focus light on a focal point or on a line. The linear concentrators involve troughs (V-type, cylindrical, and compound parabolic concentrators (CPC)) and Fresnel concentrators. These linear concentrators are utilized to irradiate a linear array of PV cells, while the point-focus concentrator focuses the parallel sunlight in a focal point, which makes it reach high concentration ratios. However, this is not suitable for illuminating flat-plate PV panels and therefore, it is not used commercially [6, 7]. Amanlou et al. [5] conducted a comprehensive review of different designs of linear LCPVs from the point of view of solar illumination uniformity since nonuniformity in the illumination results in several problems in the performance of the CPV system. It is currently agreed that a V-trough gives the best uniform irradiation pattern at mirror inclination angles of 60° with a concentration ratio equal to 2 suns [5]. Çalık and Fırat [8] investigated theoretically a simple-designed CPV system incorporated with linear Fresnel reflectors (LFR). They found that the power produced by this system would be about seven times higher than a bare PV system under direct sunlight. Wang et al. [9] conducted a theoretical and experimental study of a LFR concentrator. Both studies showed that the concentration uniformity of the suggested solar concentrator is relatively high. Moreover, Li et al. [10] compared two different-scale CPC-PV cell modules at the same CR. The results showed that the average output power of CPC-PV cells of a small size was 424,960 mW, which is slightly higher than that of a larger size which gave 420,713 mW. Also, the experimental study on a new model of CPC with a flat-plate PV was considered by Abd et al. [11]. They found that the CPC area greatly influenced the collector performance.

The main focus of this work is to simulate the simplest form of an LCPV, a V-trough. This type of light concentrator is built using mirrors or reflectors that are composed in a V-shape configuration [5, 12] (Figure 1). The combination of V-trough concentrators with commercial PV panels can be considered an efficient way for reducing the costs of PV systems. The trough's walls, being plane mirrors, allow the use of low-cost and high-quality mirrors, hence having the advantage of high optical efficiency [13]. There is a long history of utilizing flat reflective elements to raise the amount of radiation incident on a PV panel [14–16]. However, there are only few studies that focused on the heat balance of the PV panel. The heat balance refers to the amount of heat absorbed by the panel and lost due to natural convection. Hermenean et al. [17] developed a model to evaluate the temperature on a PV surface of a fixed V-trough under wind speed of 2 m/s. They found an increase in the temperature of the V-trough to be about 30-40°C, whereas the daily energy lost as heat from the system was approximately six times greater than the energy from an unconcentrated system. Palaskar et al. [18] conducted an experimental study on the thermal performance of a V-trough placed in Mumbai with a continuous tracking system. They found that the highest registered temperature of the V-trough was 66°C while it was 52.2°C for a simple PV module at an ambient temperature equal to 33°C. Sant'Anna et al. [19] constructed a prototype of a V-trough and simulated it using the SunPlot 3D program to investigate its performance. They concluded that the average temperature on a PV surface was 52.20°C compared to 49.20°C for a PV panel without a concentrator. They also found that the nonuniformity of the temperature of the PV model contributed to the reduction in the efficiency of the tested prototype. Kasim et al. [20] investigated experimentally a V-trough that was located in Baghdad. Their results showed that there was a double increase in the temperature of the PV module compared to the ambient temperature (30°C-40°C over the daylight). Due to this, there was a drop in the open-circuit voltage.

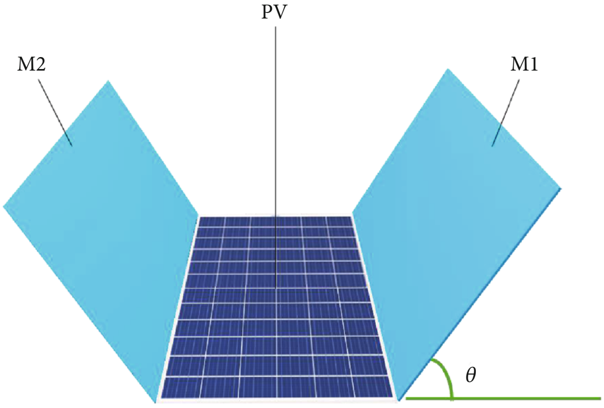


Figure 1: Schematic diagram of V-trough [5].

The PV cell temperature increases due to the rise of the CR. When more photons are made to fall on the PV panel and are absorbed, the more energy is received by the panel causing its temperature to increase. The main disadvantage of the increase in PV temperature is that it will result in the reduction of the PV efficiency and its lifetime. The problem of temperature rise in CPVs can be solved by using suitable cooling techniques [21]. Some of these techniques involved the employment of continuous aluminum sheets for heat dissipation as in the work of Solanki et al. [12]. They designed and fabricated six V-trough channels with continuous aluminum sheet. Their results showed that the PV temperature of the V-trough system, with the aluminum sheets, was 60°C which is the same temperature of a flat-plate PV module. However, without the aluminum sheets, the temperature of the PV cells in the V-trough system reached 80°C under an irradiance of 750 W/m^2. Other workers suggested the use of water as a cooling element [22, 23]. For example, Bahaidarah et al. [22] modelized theoretically a V-trough system with a water cooling process and confirmed experimentally the optical, thermal, and electrical performance during two specific days in the year: 13th of March and 16th of September. They observed that, by using two planar reflectors, the power output of the PV panel was enhanced by 34.6% and 37% in March and September, respectively. Likewise, Elminshawy et al. [23] used the buried water heat exchanger (BWHE) for cooling a V-trough system. They studied the performance within flow rates ranging from 0.01 kg/s to 0.04 kg/s. Their results showed that the cooling system reduced the temperature of the PV cell. Furthermore, there was a rise in the electrical power when compared to the uncooled PV panel. This work will focus on using wind as a cooling method.

Building different geometrical designs of CPVs and investigating their performance through simulation can assist in determining key factors affecting their efficiency prior to manufacturing. Moreover, incorporating information on the sites where the CPV systems will be installed can provide a better understanding of its overall operation and total efficiency. Such site information includes the geographical location parameters and weather conditions. Hence, mimicking CPV systems through simulation can help in saving time, effort, and money and in addition determine, in advance, the optimum conditions for obtaining maximum efficiency. There are many simulation programs that can be used to build a physical model and then study and analyze its data mathematically. One of these simulation programs is COMSOL Multiphysics [24]. COMSOL allows for building the geometries of the model, choose the properties of the materials used, enter the geographical location information, incorporate the weather conditions surrounding the model, and then link the required physics laws to it. This is followed by solving the space and time-dependent partial differential equations (PDEs) of the physics problem using the finite element method (FEM). More explanation of this procedure will be given in Methodology.

As mentioned above, one of the main problems in using CPVs is the elevation of PV panel temperature due to increased CRs. This problem is magnified if the CPV systems are place in locations having high ambient temperature such as locations in Saudi Arabia where it could reach 50° during summer months. The purpose of this work is to use COMSOL software to study the thermal profile of an LCPV system. This includes the investigation of the rise in PV temperature and the temperature distribution across the surface of the PV panel. Moreover, determine the effectiveness of using wind power as a cooling method to maintain the PV temperature below its optimum operating value. The simulation will be carried out assuming the LCPV system is situated in five different locations in Saudi Arabia to investigate the effect of different climates and ambient temperatures on the overall performance of the system. The chosen locations are Riyadh, Sharurah, Aljawf, Dhahran, and Jeddah which covers central, south, north, east, and west of Saudi Arabia, respectively.

The results obtained in this work can aid in making sound decisions regarding the use of LCPV systems as a cost-effective solution in harvesting solar energy. Moreover, it can help in determining the best geographic locations and the facilitation of free wind power in cooling LCPV systems to maintain its efficiency in locations having high ambient temperatures.

2. Methodology

COMSOL is a platform for simulation that is based on FEM. The basic concept behind FEM is simplifying a complex problem and finding its solution. Usually, physics problems that are space- and time-dependent are described by PDEs. These PDEs cannot always be solved using analytical methods and instead are solved by numerical techniques, such as the FEM [25]. In general, the simulation is carried out in COMSOL software by following some essential steps. In the beginning, the space dimensions, physics involved, and study type are selected. All required parameters and variables are defined. The geometries of the model are built, and the properties of the used material and mesh generator types are chosen. The required physics laws are then linked to the simulation problem where the governing PDE equations are solved using FEM. A description of the PDEs and the FEM method can be found in literature [26].

Two cases of V-trough design were constructed via COMSOL software. The first case is the double coverage design where the width of the mirrors is double the width of the PV panel. Hence, the whole PV surface is swept completely by the reflected radiation from both mirrors. The second case is a partial coverage design, where the reflected rays from each mirror cover only part of the PV surface. In this design, the width of the mirrors is the same as that of the PV panel. Since the PV module temperature is influenced by the amount of solar radiation intensity falling on it, the temperature of the system will be calculated at the highest amount of ray's power. This coincides with the middle of the day for an altitude angle equal almost to 90°. In a previous work [27], the optimum inclination angle (θ) of the mirrors at solar noon time was determined for both double and partial coverage. In this work, the inclination angles of the mirrors were fixed at $\theta = 70^\circ$ for the double coverage case and $\theta = 65^\circ$ for the partial coverage case as reported in [27].

The solar energy that is absorbed by the PV cell and is not converted to electrical power is manifested in the form of thermal energy. Hence, the PV cell acts as a source of heat. The operating temperature of a PV module is reached when equilibrium is established between the heat produced by the solar cell and the heat lost through conduction, convection, and radiation to the surrounding environment [28]. To investigate the thermal performance of the system, COMSOL enables the coupling of the heat transfer (ht) in a solid interface with the geometrical optics (GOP) interface. Therefore, a simultaneous study of the thermal and optical performances can be conducted by adding some boundary conditions related to the heat transfer in a solid interface. These conditions consider the power that is deposited on the PV surface from solar radiation and assign it as a heat source. Then, the heat transfer in the system can be studied due to the three basic mechanisms: conduction, convection, and radiation.

2.1. Thermal Simulation Assumptions and Parameters. In the combined optical and thermal models, the assumptions made are that all material properties are regarded to be isotropic and temperature independent. In addition, the initial temperature of the PV module is taken to be 25°C. Also, the ambient temperature is assumed to be equal in all areas of the system that are exposed to the environment. Concerning the exchange of heat radiation, the front and back of the PV module are facing the sky and ground, respectively. The temperature of both sides is expected to be equal to the ambient temperature [29]. Normally, the back of the PV module is not cooled to the same degree as the front. Hence, it is presumed that the convective heat transfer at the back surface is half that at the front. The study is selected as a time-dependent problem since the steady state of the PV panel temperature cannot be justified during the periods of constantly fluctuating irradiance [30].

The values of the ambient temperature, wind speed, solar noon, and altitude angle (α), for each geographical location on the 21st of June, are listed in Table 1; these data were taken from reference [31]. For the purpose of studying the effect of wind speed, the highest values of wind speed during the month of June are also incorporated in Table 1 [32]. After defining the parameters in the simulation program, the thermal performance of the system for each geographical location at solar noon can be found.

2.2. Temperature of a V-Trough. The thermal performance of a PV panel is found before and after applying the mirrors to investigate the effect of the concentrators. To enable COMSOL to calculate the effect of heat on the boundaries of the system, the option of "using principal curvatures and ray power" will be selected in the GOP interface. In the ht interface, the three mechanisms of heat transfer will be defined as follows:

(1) Conduction: the various amounts of heat that the module components absorb and their thermal conductivity give rise to transmission of heat in the form of conduction. The conduction heat transfer is calculated by default on all the domains of the V-trough geometry using the Fourier heat conduction law [33]:

$$q_{\text{cond}} = -k\nabla T, \tag{1}$$

where q_{cond} is the conductive heat flux, k is the thermal conductivity, and ∇T is the temperature gradient

(2) Convection: the convective heat transfer in PV systems is due to the flow of winds over the surface of the module. Irrespective of the specific nature of the convective heat transfer method, a suitable rate equation can be determined by Newton's law of cooling [33]:

$$q_{\text{conv}} = h\left(T_{\text{mod}} - T_{\text{amb}}\right), \tag{2}$$

where q_{conv} is the heat flow due to convection; T_{mod} and T_{amb} are the module surface temperature and the ambient temperature, respectively; and h is the convective heat transfer coefficient, which depends on the wind speed (v). For the front surface, h can be found through Notton's equation [34]:

$$h = 5.82 + 4.07v. \tag{3}$$

For the back surface, h is presumed to be half that of the front surface

(3) Radiation: the PV module is not an ideal blackbody, and to calculate the radiation power density (q_{rad}) for nonideal blackbodies, the following equation is applied [28]:

$$q_{\text{rad}} = \varepsilon\sigma\left(T_{\text{mod}}^4 - T_{\text{amb}}^4\right), \tag{4}$$

where σ is the Stefan-Boltzmann constant and ε is the emissivity. The emissivity of the PV panel is assumed to be 0.8 as suggested by Gerber et al. [35]. The radiative heat transfer relationship holds true if the temperature around the PV modules can be regarded as equal to the ambient temperature [28].

As mentioned above, this study is a time-dependent problem. Hence, the thermal performance will be measured in a 30 min time interval at solar noon. The temperature on the PV panel will then be estimated with or without mirrors. In order to examine the effect of wind speed on the module temperature, the value of v will be varied from its lowest value (1 m/s) to its highest as registered in the month of June for the selected geographical locations (Table 1).

3. Results

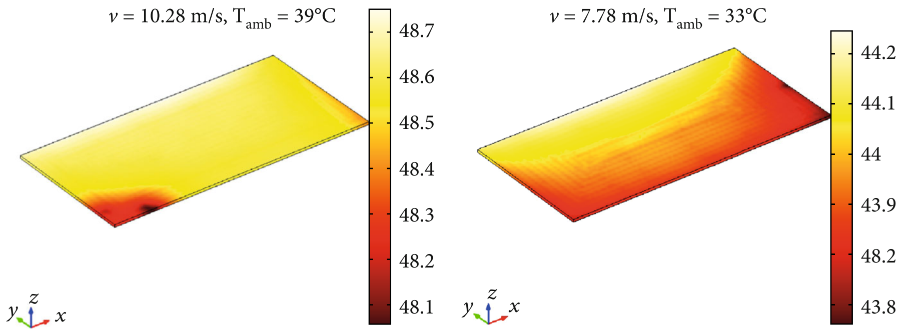
When rays falling on the PV surface increase, the temperature of the module increases. The temperature on the PV surface was calculated at the maximum amount of irradiance in the day, that is, at solar noon. Figures 2 and 3 show the thermal profile of the PV panel without and with mirrors, respectively, for the double coverage case under the climate conditions of each city on the 21st of June. In Figure 2, two features can be noticed. Firstly, during the 30 min simulation interval, the temperature of the PV panel increased by 10°C, approximately, for all locations. Secondly, the temperature is uniformly distributed on the surface of the PV surface with a temperature gradient not greater than 1°C across the area. On the other hand, when mirrors are attached, it can be seen from Figure 3 that the PV temperature increased tremendously as more radiation is collected by the mirrors. For example, for Jeddah's location, the addition of the mirrors increased the temperature of the PV panel by 17°C reaching a temperature of 76°C. The increase in temperature when attaching the mirrors seems to not depend on the ambient temperature surrounding the system. Another point worth noticing is the effect of wind speed on the temperature increase when adding the mirrors. As winds help in cooling the PV panel, it can be noticed that cities with low wind speed, such as Jeddah and Sharurah, had the greatest increase in temperature when mirrors were attached. On the contrary, a decrease in PV temperature occurs when wind speed increases as in Dhahran and Aljawf.

The temperature distribution across the PV plate after the attachment of the mirrors is an important point for the PV efficiency. By examining the temperature distribution on the PV surface of the V-trough as illustrated in Figure 3, it can be seen that it is not uniformly distributed. The PV experienced a temperature gradient between 4°C and 8°C in the cases studied. This is a clear indication of the effect of mirrors in limiting equal exposure to the incident rays. An additional indication that the mirrors are the main cause for the nonuniformity of the temperature distribution is the partial coverage case shown in Figure 3(f). By comparing Figures 3(e) and 3(f) for the same location and wind speed,

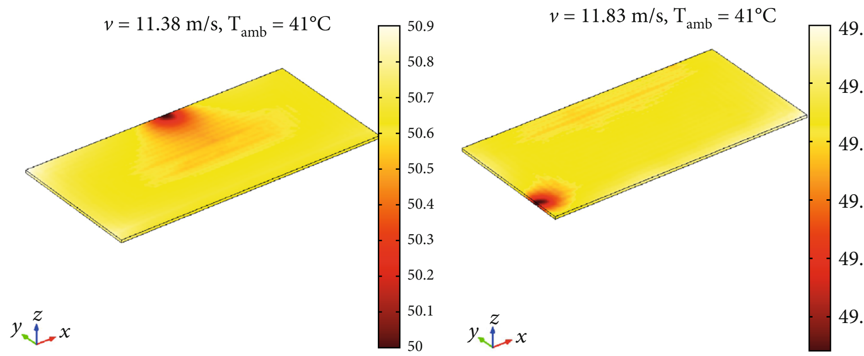
Table 1: Thermal model parameters for the geographical locations.

City	Ambient temperature (°C)(a)	Wind speed (m/s)(a)	Solar noon time(a)	Altitude angle (°)(a)	Peak wind speed in June (m/s)(b)
Riyadh	39	10.28	11:54	89	15.7
Sharurah	33	7.78	11:53	84	19.2
Aljawf	41	11.38	11:43	87	19.7
Dhahran	41	11.83	11:41	87	13.1
Jeddah	47	9.17	12:25	88	20.3

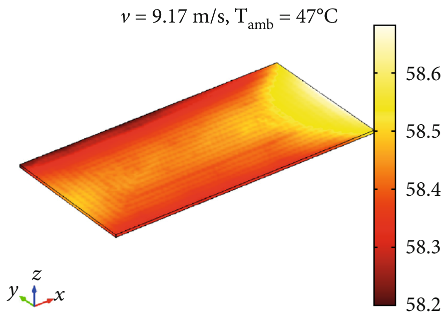
(a)Reference [31]. (b)Reference [32].



(a) Riyadh (b) Sharurah



(c) Aljawf (d) Dhahran



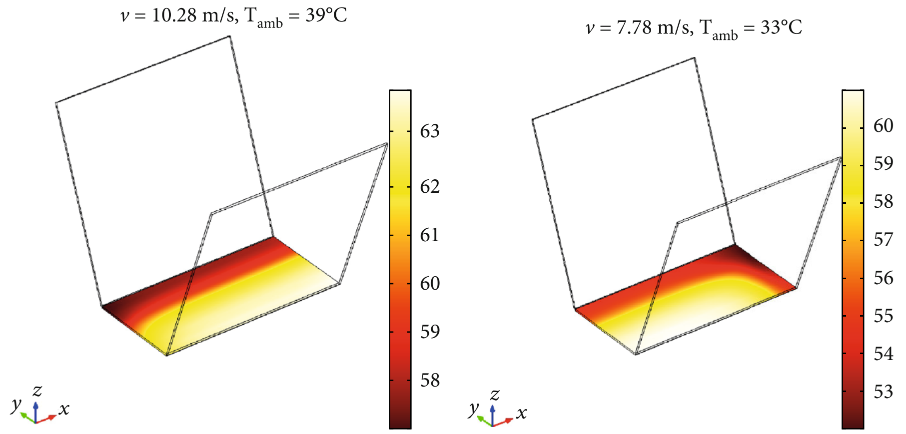
(e) Jeddah

Figure 2: Temperature distribution of a PV plate at noon.

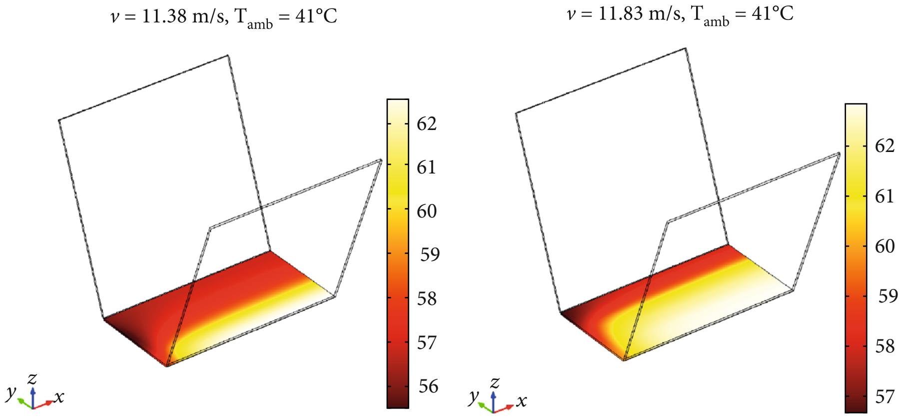
it can be seen that the partial coverage case did produce a nonuniform temperature distribution but to a lesser extent than the double coverage case. The temperature gradient in the partial coverage case was around 4°C, approximately.

A question has been raised about the effect of wind speed as a cooling method for PV concentrators. To examine this effect, the temperature of a V-trough was calculated at different wind speed values and then, the results were compared with those of a simple PV plate. Figure 4 illustrates the average temperature for each city for a simple PV and a V-trough at different wind speeds during the 30 min simulation period.

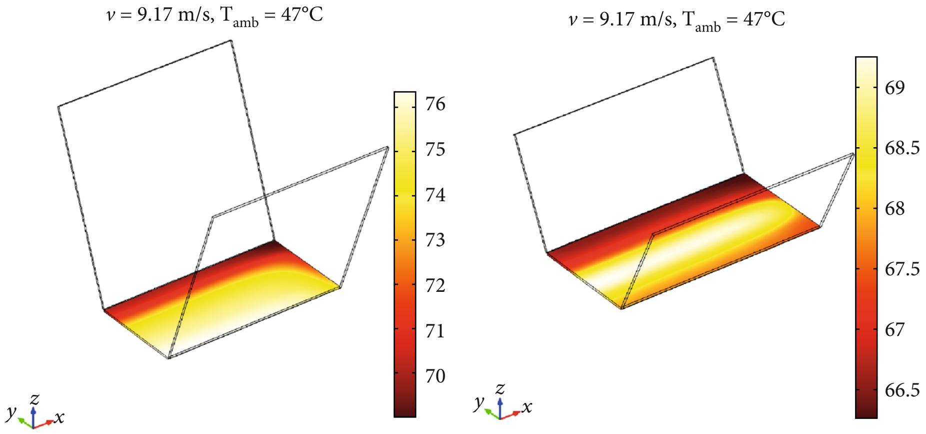
It can be seen from Figure 4 that at a wind speed equal to 1 m/s, an increase in temperature was found for both a PV plate and a V-trough during the 30 min radiation



(a) Riyadh (b) Sharurah



(c) Aljawf (d) Dhahran

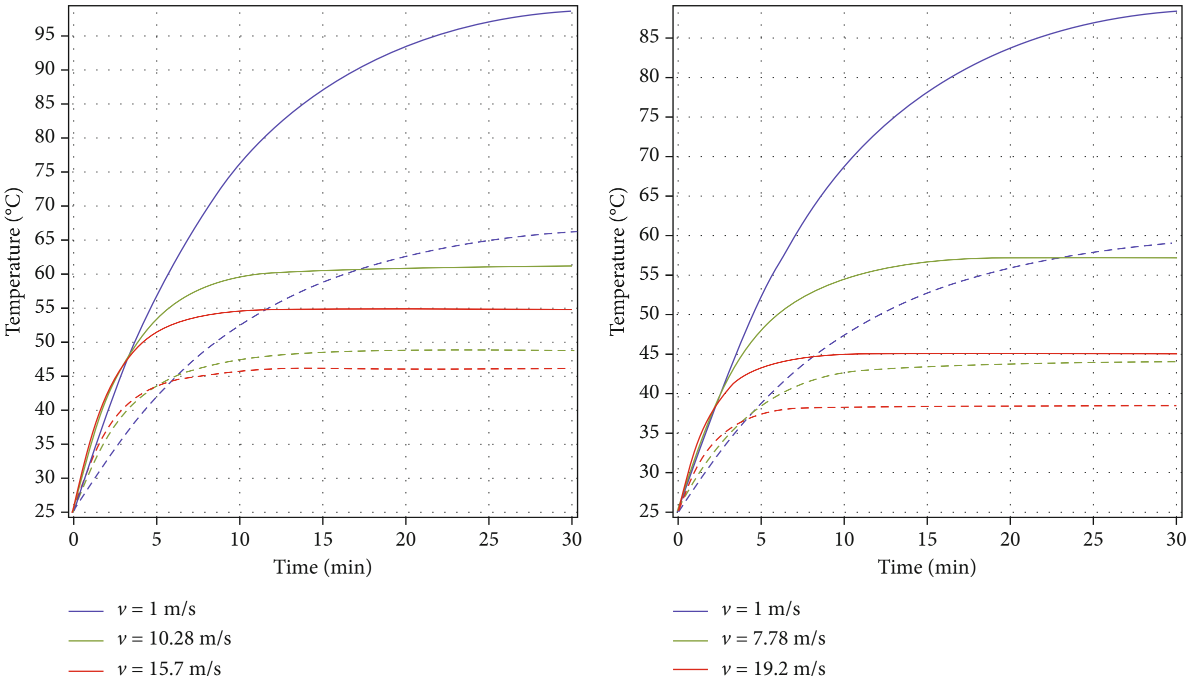


(e) Jeddah (f) Jeddah

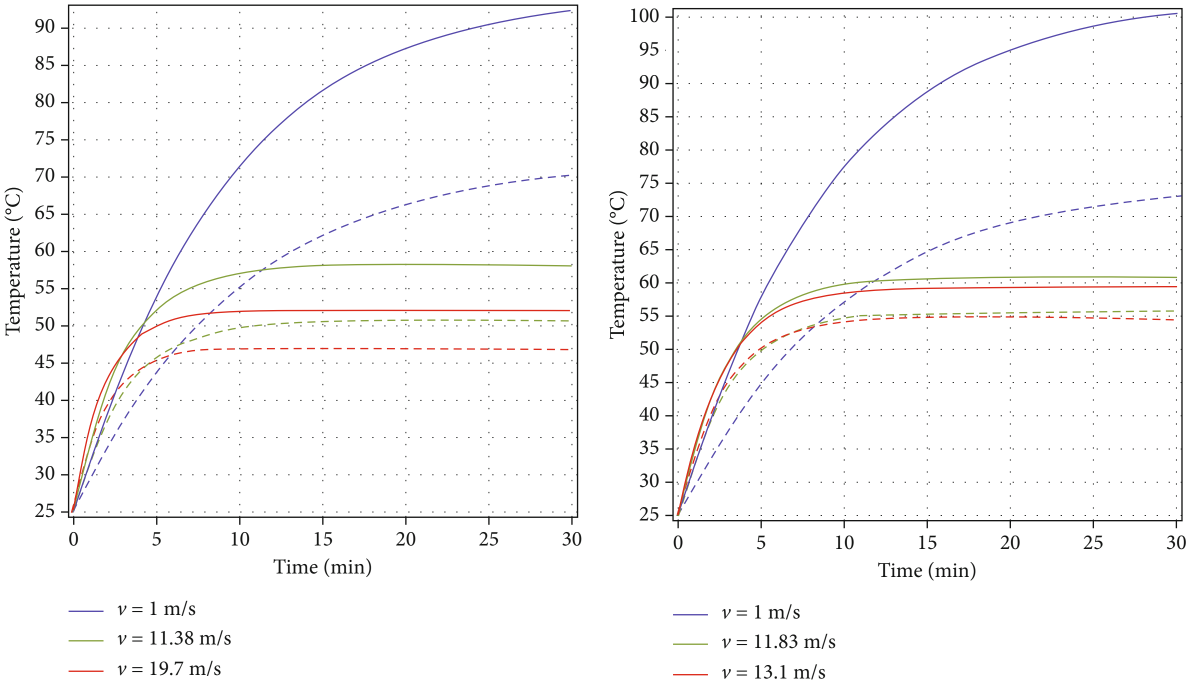
Figure 3: Temperature distribution of a V-trough at noon for (a–e) double coverage and (f) partial coverage.

accumulation. However, for a V-trough, the temperature increased considerably and exceeded 100°C. On the other hand, although the plain PV plate experienced a temperature increase at low wind speed values, it remained under 80°C, which is the optimal operating temperature of a PV cell. The attachment of the mirrors raised the PV plate temperature, on average, an additional 30°C. Such an increase could damage the PV cell or decrease its efficiency greatly.

The effect of using free wind as a cooling method for V-troughs was observed in this study as follows. When the wind speed increased, the PV cell temperature dropped significantly. Furthermore, it was found that the PV cell temperature stabilized and reached a steady-state value after a time period of 10 min, approximately. The drop in temperature was observed to be proportional to the wind speed. The maximum drop in temperature of a V-trough system was around 50°C, where the temperature was reduced from 112°C to 61°C, when the wind speed in Jeddah was 20.3 m/s (the highest wind speed registered in June for Jeddah). Hence, the wind speed alone was able to cool the V-trough system and

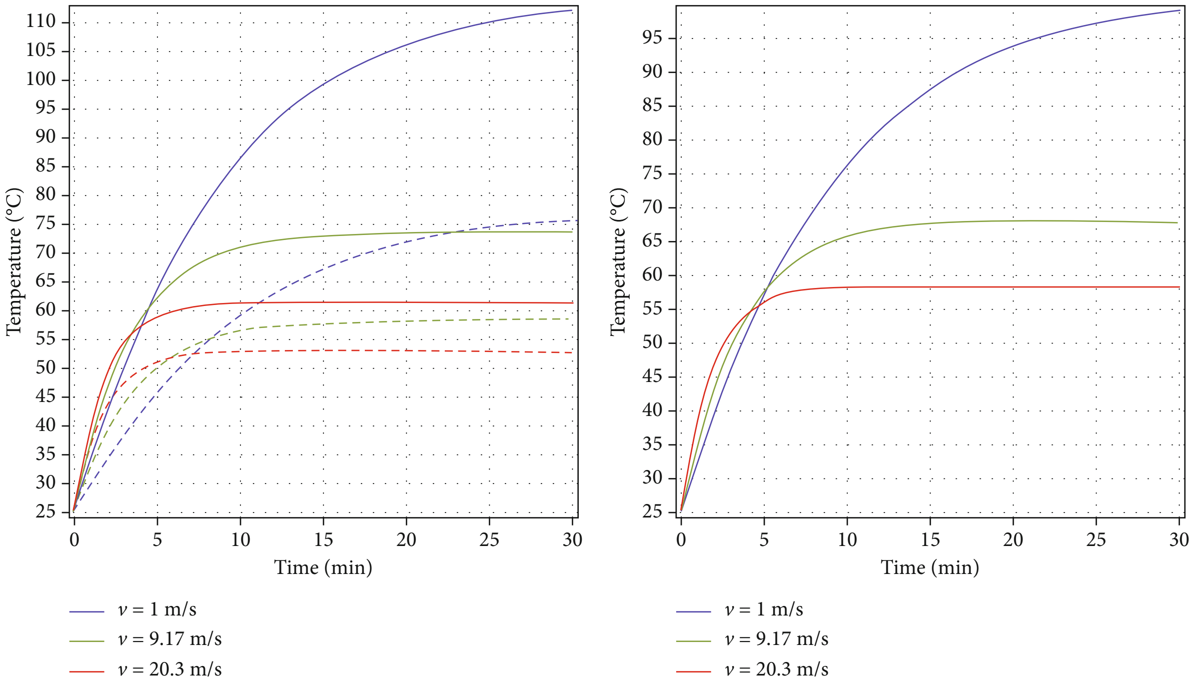


(a) Riyadh (b) Sharurah



(c) Aljawf (d) Dhahran

FIGURE 4: Continued.



(e) Jeddah

(f) Jeddah

Figure 4: Average temperature of a PV panel at noon for different wind velocities; without mirrors (dashed) and with mirror (solid) for (a–e) double coverage case and (f) partial coverage case.

protect the PV panel from damage due to excess heat. It is worth noting here that the increase of wind speed to lower the temperature of the PV panel in the V-trough did not change nonuniformity in temperature distribution on the PV surface.

Lastly, to investigate the effect of wind speed for cooling the different geometrical designs of V-troughs, a comparison between the double and partial coverage cases can be conducted. By studying Figures 4(e) and 4(f), for the double and partial coverage cases for the city of Jeddah, respectively, it can be concluded that the temperature drop for the double coverage case was greater than that for the partial coverage. However, the final temperature after 30 min at a speed of 20.3 m/s was relatively similar for the two cases. The final temperature being equal, the selectivity between double and partial coverage will depend on the preference between obtaining more electrical energy output in the double coverage case vs. more uniform temperature distribution in the partial coverage case.

4. Conclusion

The thermal performance of a V-trough system was found using COMSOL software. This investigation is important since V-troughs cause an increase in the temperature of a PV panel as more solar radiation is made to fall on it. The temperature increase due to a V-trough is further raised for location having high ambient temperatures. The simulation was conducted for solar noon on the 21st of June for different geographical locations in Saudi Arabia where temperatures could reach up to 50°C in summer months. It was found that by attaching mirrors to a PV panel, an increase in the panel's temperature reached 30°C, on average, compared to the case of a PV panel without mirrors attached. The double coverage case resulted in the highest increase in temperature to an extent that it exceeded the optimum operating temperature of the PV panel. Without cooling a V-trough system, PV panels are at risk of damage or deteriorated efficiency. Our results found that using wind as a cooling method assisted in lowering the temperature of the PV panel in a V-trough system. The maximum drop in temperature, after cooling with wind, was around 50°C. Even moderate wind speed reduced the temperature of a V-trough to below the optimum operating temperature of a PV panel. The major disadvantage of a V-trough is the production of nonuniformity in the temperature distribution across the PV panel surface. This nonuniformity of the temperature distribution is found to be unaffected by the wind speed but solely related to the size of the attached mirrors. This work was limited to the investigation of the thermal performance of a V-trough system and the application of wind as a cooling element. A more thorough investigation may be performed by integrating the electrical aspects of the system to the simulation model. This will provide insights of the effect of the optical and thermal performance of a V-trough system on the overall electrical output of the PV panel. This work recommends studying and testing different heat-sink models to reduce the temperature of PV panels in V-trough systems especially in high-temperature geographical locations.

Data Availability

The simulation graphs and data files used to support the findings of this study are available from the corresponding author upon request (corresponding author: Entesar A. Ganash, eganash@kau.edu.sa).

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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