A cascade nanofluid-based PV/T system with optimized optical and thermal properties

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ABSTRACT
In recent years, nanofluids have been proposed as efficient coolant fluids and as a means to filter sunlight for PV/T systems. In the present study, a new, cascading nanofluid-based PV/T configuration with separate channels is proposed, where one channel controls the optical properties while the other enhances heat removal from the PV cells. That is, the first nanofluid, optical nanofluid, acts as a liquid optical bandpass filter above the PV cells while the second, thermal nanofluid, removes heat from the back of the PV cells. Both nanofluids have been designed to work together to improve the overall electrical and thermal performance of the PV/T hybrid system. The proposed PV/T system has been investigated for two designs — with separate channels (D-1) and with a double-pass design (D-2). In addition, these designs were simulated for both GaAs- and Si-based PV cells at various concentration ratios. The simulation results show that the best nanofluid-based optical filter can transmit ~82% of the desired spectrum to GaAs or Si PV cells. In concentrated systems it was found that the separate channel system (D-1) outperformed the double-pass design (D-2) by ~8.6%, in terms of the electrical efficiency of GaAs (at C = 45) and Si (at C = 30). The overall efficiency of the D-1 system with GaAs (at C = 160) and Si (at C = 100) have been improved by ~5.8% and ~4.6%, respectively, by increasing the volume fraction of the thermal nanofluid from 0.001 to 1.5%. Overall, it was found that the proposed PV/T configuration with separate channels has potential for further development in high-concentration (C > 100) solar systems.

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1. Introduction

Prior to the industrial revolution, humanity was almost entirely dependent on renewable energy resources (biomass, wind, solar, and hydro) to supply energy for a majority of human activity (e.g. heating, cooking, and transportation). After the massive expansion in coal, oil, and natural gas usage over the last 150 years, many economies are planning (and investing in) a return to renewable energy. According to the Renewables 2015 Global Status Report [1], renewable energy represented approximately 59% of net addition to global power capacity in 2014. Solar energy, which is by far the most abundant type of renewable energy, can be used to generate heat and electricity — and could potentially be used to meet a majority of total energy demand.

Photovoltaic (PV) cells are able to convert sunlight directly into electricity by exciting the electrons of semiconducting materials. However, because only a portion of the solar spectrum has enough energy to excite the electrons, PV cells have limited efficiency. The efficiency of well-designed silicon cells can exceed 50% for incoming light between 700 nm and 1100 nm, but is low or zero at shorter or longer wavelengths, respectively [2,3]. Absorbed light outside 700–1100 nm becomes heat, which could reduce the efficiency of the cell or, in the extreme, cause damage.

Solar thermal collectors, on the other hand, can utilize the entire solar spectrum through a black absorber. Conventional thermal absorbers consist of a solid surface with a heat transfer fluid flowing over them to remove heat. In recent years, advanced volumetric absorbers have been proposed as a means to absorb the light directly inside the working fluid, saving a heat transfer step and (potentially) losses incurred from having the highest
temperature on the outer boundary [4,5]. Even with these advancements, heat is still much less fungible and transportable compared when to electricity.

Considering the aforementioned limitations of using PV and thermal solar technologies, scientists and engineers have long sought to bring them together with hybrid PV/T technology [6]. The hybrid PV/T collector is more efficient than stand-alone PV or thermal systems [7] because it can be designed to utilize nearly 80% of the incoming solar energy [8]. The interested reader can peruse the large body of work on PV/T collectors in the review papers published by Chow [8], Michael et al. [9], and Al-Shamani et al. [10]. Overall, it can be concluded that researcher have put a lot of effort into optimizing the working fluid(s) inside the system.

The efficiency of PV cells decreases when the cell temperature increases as a result of the absorption of photons at energy levels below the cell band gap [11]. The combination of PV and thermal systems can prevent the increase of the PV cell temperature, while at the same time harvesting another useful output. Standard PV/T systems can prevent the increase of the PV cell temperature, while this system, they can operate at significantly different temperature.

Pure fluids can serve as ‘selective’ filters [19,20] and coolants [21] in PV/T systems [9], but recent advancements in nanomaterials have provided a means to substantially improve upon conventional pure fluids. In particular, nanofluids [22] promise tenability of optical properties [23–26] and more attractive thermal properties than pure fluids [27,28].

Zhao et al. [29] presented the ideal nanofluid for a hybrid double-pass PV/T solar collector. In Zhao’s work the same nanofluid was used as both an optical filter and a coolant fluid. The theoretical results show that increasing the mass flow rate improves the thermal efficiency of the thermal unit, and the electrical efficiency of the PV cells is not influenced by variations in the mass flow rate. At high solar concentration, this does not hold true because decreasing the mass flow rate increases the working fluid temperature. This leads to an increase in the solar cell temperature, which consequently decreases the electrical efficiency.

Taylor et al. [30,31] conducted a theoretical study on the optimization of nanofluid-based optical filters in PV/T systems and investigated the various combinations of base fluids, nanoparticle materials, nanoparticle shapes, and volume fraction to discover a set of potential nanoparticle-based fluid filters. The optical properties were numerically modeled for optimal performance in five PV cell materials, namely Si, Ge, InGaP, InGaAs, and CdTe. The results show that nanofluid-based optical filters can achieve the same level of control as conventional optical filters, although the some of the materials may be difficult to fabricate with the necessary geometric tolerances. To obtain the desired optical properties, very low volume fractions (on the order of 0.001%) were found to be for optimum PV/T filters, which makes nanofluids potentially
inexpensive spectrally selective optical filters.

Otanicar et al. [11] applied the resulting nanofluid-based optical filters developed by Taylor et al. [30] to concentrated PV/T systems and compared the output performance with different conventional thin-film-based optical fluid filters. The results demonstrate that nanofluid-based filters have a slightly lower overall efficiency than conventional thin-film filters. Otanicar et al. [11] did not consider the heat removed from the PV cells in calculating the overall efficiency of the PV/T system — an unexploited source of thermal energy.

Cui and Zhu [32] experimentally explored the effect of nanofluids in a PV/T system. In their study, MgO-water nanofluids were used as a coolant and applied to the top of a silicon photovoltaic panel to cool down solar cells and collect heat. The results show that the increase of both particle volume fraction and nanofluid film thickness decreases the transmittance of visible light, which leads to a reduction in the output power of solar cells in the PV/T system.

After reviewing references [29,33–36], the authors have found that a gap exists in the literature in that no studies have investigated the use of separate nanofluids for the optical filtering and for the cooling process. In fact, using the same nanofluid for optical filtering and cooling in PV/T systems is disadvantageous since it imposes conflicting requirements in the particle volume fractions and materials, as is shown in Fig. 1b. Increasing the volume fraction of the nanoparticles will enhance the thermal conductivity of the nanofluid and promote heat transfer between the nanofluid and PV cells, but will considerably degrade the optical properties of the nanofluid filter. Similarly, a good nanofluid-based optical filter is obtained at a low volume fraction and no measurable change is possible in the thermal properties. Therefore, a new PV/T design is proposed herein which uses two different nanofluids as shown in Fig. 1a. The first nanofluid — the ‘optical nanofluid’ — is optimized to obtain the best liquid optical filter (high transmittance at the visible spectrum and high absorbance at the UV–IR spectrum). The second nanofluid — the ‘thermal nanofluid’ — is designed to enhance heat removal from the PV cells. To verify the benefit of the proposed PV/T system configuration, a comparative analysis is conducted between a separate and a double-pass channel configuration. Overall, this study presents a rigorous study of an improved PV/T design — a design which opens up a new approach for hybrid solar collectors.

2. Methods

A detailed numerical model of the proposed PV/T system was developed herein which included the physical optical, thermal and electrical coupling of the system. A systematic study of the salient operational parameters and the physical geometry were investigated to determine the performance of the proposed two-nanofluid PV/T system relative to a more conventional design. Overall, the mathematical tools used to evaluate the performance can be considered a push forward from previous physical PV/T models in the literature.

2.1. Physical model of PV/T system

Fig. 1a shows the optical and thermal flows of proposed PV/T design as compared to the double-pass design presented in literature Fig. 1b. Solar radiation reaches the PV cells after crossing the cover glasses and the nanofluid filtration channel. After the nanofluid channel only the radiation within the spectral response of the PV cells remains. The choice of the nanoparticle material type, base fluid, size, and volume concentration for the optical nanofluid depends on the bandgap of the PV cells and the thickness of the channel. The function of air gaps 1 and 2 is to reduce heat loss by conduction and convection, and to enable the optical nanofluid thermal receiver to operate at significantly higher temperature than the PV cells.

The metal plate on the rear side of the PV module acts like a heat sink. The heat generated by the PV cells is removed by the thermal nanofluid in the second channel. The thermal nanofluid contains metal nanoparticles at a concentration on the order of 0.001%–1%, and is designed to have high thermal conductivity to enhance the extraction of heat from the PV cells.

To show the advantages of the PV/T system with separate channels, a comparative study was conducted between the systems presented in Fig. 1a and b — e.g. separated channels and a commonly employed double-pass channel. In this paper, the notations D-1 and D-2 refer to the systems presented in Fig. 1a and b, respectively.

2.2. Mathematical model

The general numerical model presented below was used to predict system temperatures, electrical performance, and efficiencies, if the optical and thermal properties are known. In the following sub-sections, a brief description of this model is given, based on how it relates to the pertinent literature.

2.2.1. Thermal model

The mathematical model used in the present study was derived by applying the first law of thermodynamics (i.e. the energy balance equation) for each element of the PV/T collector. For one-dimensional heat transfer, the general energy balance equation is given by:

\[ \frac{\partial U}{\partial t} = Q_{in} - Q_{out} + Q_{g} \]  

(1)

where \( \partial U/\partial t \) is the change in the internal energy, \( Q_{in} \) is the heat transfer rate into the system, \( Q_{out} \) is the heat transfer rate out of the system, and \( Q_{g} \) is the heat generation rate into the system.

To simplify the model, a set of assumptions are made and presented in Table 1:

- Before any energy balance equation is provided for the parts of the collector, the method in which heat is transferred from one element to another should be understood. Starting from top (cover glass 1) to bottom (insulation), the different heat transfer modes involved in the system are resumed in Table 2.

  - The temperature variation along the flow direction is considered. Therefore, a backward scheme for the spatial coordinate (x) is adopted to discretize the derived thermal energy balance equations for each element of the PV/T collector. The resulting discretized equations are summarized in Table 3.

2.2.2. Electrical model

In the present study, two types of photovoltaic materials, Si and GaAs, are investigated. The electrical model to evaluate them at different temperatures are based on references [11,42–45].

The dark saturation current \( J_{00} \) in the cell is calculated as follows [43]:

\[ J_{00} = K T_{p}^{3} n^{3} m^{2} \exp \left( \frac{-E_{g}}{mK T_{p}} \right) \]  

(10)

where \( K, n, \) and \( m \) are empirical constants. \( E_{g} \) is the energy gap that corresponds to the PV cells.

The short circuit current \( J_{sc} \) can be computed from Ref. [11]:
where $\lambda_g$ is the wavelength of solar radiation, which corresponds to the band-gap of the PV material, $e$ is the electron charge, and $F_i$ is the photon flux. $\text{EQE}_i$ is the PV cell’s quantum efficiency, which is wavelength-dependent and were adapted from Refs. [46,47].

Considering the AM1.5 spectral range, $\tau_{\text{sys},\lambda}$ is the spectral transmittance of the thermal unit ($\tau_{\text{sys},\lambda} = \tau_{11} \tau_{21} \tau_{31} \tau_{\lambda,11}$) in the transmission window between 0.28 μm – $\lambda_g$.

The open-circuit voltage $V_{oc}$ is then calculated as follows [11]:

$$V_{oc} = \frac{J_{sc}}{I_{sc}}$$

The open-circuit voltage $V_{oc}$ is then calculated as follows [11]:
The final step is the expression of the electrical efficiency of the PV cells, which can be calculated by Refs. [11,43]:

$$\eta_{el} = \frac{V_{oc}\eta_{FF}}{G}$$

(16)

To account for the spectral filtering assured by the nanofluid, an expression for adjusted electrical efficiency is proposed [11] as follows:

$$\eta_{*} = \frac{V_{oc}\eta_{FF}}{\tau_{c1}\tau_{c2}\tau_{c3}\int_{0.25\mu m}^{2.5\mu m} \tau_{j,n_i}G_j}$$

(17)

2.2.3. Overall efficiency of PV/T

The interdependence of the different temperatures and the efficiency of the PV cells requires a coupled iterative method between the electrical and thermal models. In other words, Eqs. (2)–(17) should be solved simultaneously. In the present study, the overall thermal efficiency of the system is the sum of the thermal efficiency of the first and second channels. In Refs. [11], the thermal energy in the second channel is considered as lost energy. In the strategy described in Refs. [11], the thermal efficiency analysis does not enable one to directly calculate the thermal energy extracted from the second channel, the authors believe this could be considered as useful energy source.

When all the unknown temperatures have been computed, the thermal efficiency of the PV/T can be calculated by adding the useful energy obtained from both channels, defined as:

$$\eta_{th} = m_{n_1}C_{PN1}(T_{n1, out} - T_{n1, in}) + m_{n_2}C_{PN2}(T_{n2, out} - T_{n2, in})$$

(18)

The overall efficiency of the PV/T system can be calculated using Eq. (19) as follows:

$$\eta_{ov} = \eta_{el} + K \sum_{i=1}^{2} \left( \frac{1 - \frac{T_{T_{0,i}}}{T_{n_i}}} \right) \eta_{th,i}$$

(19)

where $i = 1$ is the first channel and $i = 2$ is the second channel. $(1 - \frac{T_{T_{0,i}}}{T_{n_i}})$ is the Carnot efficiency, and $K$ is the fraction of thermal energy converted to electrical output and assumed to be 0.5 [11,42,48]. The quantity $K \sum_{i=1}^{2}(1 - \frac{T_{T_{0,i}}}{T_{n_i}}) \eta_{th,i}$ might be considered as a thermal exergy efficiency as well.
2.3. Optical properties and thermal conductivity determination of nanofluid

2.3.1. Optical properties of nanofluid as optical filter

Achieving the desired optical properties is critical in creating a nanofluid optical filter. In general, the choice of nanoparticles and their volume fraction essentially depends on the type of PV cell materials and the collector geometry. The aim, of course, is to design the nanofluid-based optical filter to transparent across spectral response curve of the PV cells. Moreover, the nanofluid should highly absorb the undesired sunlight to obtain a high quality output.

In the present study, silver (Ag) nanoparticles suspended in Therminol VP-1 was chosen to design two nanofluid-based optical filters. Therminol VP-1 is a High Temperature Fluid (HTF) suitable at high working temperature application, and it will be used to absorb the long wavelength whereas the silver nanoparticles to absorb shorter wavelengths.

The radiative transfer equation is used to determine the intensity distribution of the incoming solar radiation in the first channel as follows:

$$\frac{\partial I_1}{\partial y} = - (\sigma_{n1,\lambda} + \beta_{n1,\lambda}) I_1 = -\rho_{n1,\lambda} I_1$$

where \(I_1\) is the spectral solar irradiance. AM1.5 Global (ASTM G-173) [49] for solar spectra is used in the present study, and its range is from 0.28 \(\mu\)m to 2.5 \(\mu\)m, which has an integrated power of 992 W/m².

\(\sigma_{n1,\lambda}, \beta_{n1,\lambda}\), and \(\rho_{n1,\lambda}\) are the linear absorption, linear scattering, and linear extinction coefficients of the nanofluid, respectively. The aforementioned coefficients have been determined based on references [30,31,50], and using Mie theory, as described in Ref. [51].

Then, the extinction coefficient of the nanofluid is determined, and the spectral transmittance of the nanofluid is calculated using the Beer–Lambert–Bouguer law as follows [52]:

$$\tau_{n1,\lambda} = \frac{I_1}{I_0,\lambda} e^{-\sigma_{n1,\lambda} \beta_{n1,\lambda}}$$

where \(I_1\) is the transmitted irradiation, \(I_0,\lambda\) is the incident irradiation (AM1.5 Global [ASTM G-173]), and \(\sigma_{n1}\) is the fluid thickness of the optical nanofluid in the first channel. The extinction coefficient in Eq. (21) formally includes scattering, but, the loss of solar energy by scattering is ignored herein because the nanoparticles are extremely small (~10 nm).

The total transmittance of the nanofluid-based optical filter in the first channel is then calculated by performing the following integral:

$$\tau_{n1} = \int_{0.28\mu m}^{2.5\mu m} \tau_{n1,\lambda} I_0,\lambda \, d\lambda$$

2.3.2. Thermal conductivity determination of nanofluids

One of the objectives of the present study is to demonstrate that using two different nanofluids improves system efficiency for both optical filtering and cooling processes. In this case, each of the two nanofluids could be optimized for its designated purpose. Low volume concentration is needed to achieve a good nanofluid-based optical filter (channel 1 in Fig. 1a), whereas a good nanofluid-based coolant (channel 2 in Fig. 1a) needs to have relatively high particle volume concentration to improve its thermal conductivity. This approach is currently missing in the literature. Therefore, this represents a straightforward, yet novel contribution to the field.

In this study, silver (Ag) nanoparticle of diameter 10 nm suspended in water was chosen to design the thermal nanofluid in the second channel for the PV/T collector type D-1. Water base fluid was selected due to its good performance in thermal cooling application. To optimize the nanofluid used as a coolant in the second channel, a new correlation, previously developed by Hassani et al. [53], is used for the thermal conductivity of the nanofluid. The correlation is suitable for metal and oxide metal nanoparticles.

3. Results and discussion

3.1. Electrical model validation

Before the set of equations presented in Table 3 can be solved, the accuracy of the electrical model should be verified. Using the different parameters indicated in Table 5, the simulation results for different outputs of Si and GaAs PV cells at 25 °C and 1 sun are compared with experimental data reported in various studies [54] and summarized in Table 4.

As indicated in Table 4, the present model agrees with the experimental data. Moreover, at 25 °C, 117 and 92 suns, the predicted electrical efficiency for GaAs and Si cells are 30.65% and 28.8%, respectively. These results are comparable to the value of 29.1 ± 1.3% for GaAs and 27.6 ± 1.2% for Si reported in Ref. [54].

In addition, Fig. 2 depicts the evolution of the electrical efficiency normalized to its standard value at 25 °C of Si and GaAs PV cells at a different temperature. Fig. 2 shows that the predicted data obtained by the present model agree well with the experimental results. The electrical efficiency of Si cells decreases more that GaAs with increases of temperature, which is correctly predicted by the present model.

3.2. Optimized nanofluid-based optical filters

The nanofluid-based optical filters designed in the present work corresponding to GaAs and Si PV cells are optimized to match the ideal filter suggested by Taylor et al. [30] for Si and Russo et al. [55] for GaAs. To find the best volume fraction of nanoparticle and filter thickness (thickness of the first channel), an optimization algorithm is used to solve Eqs. (20)–(22). Since the PVT system is expected to run at high solar concentration, a high temperature fluid is needed. Therminol VP-1 was selected to be used as a base fluid for the optical nanofluid. The optical properties of Therminol VP-1 and Ag nanoparticles, along with the real and imaginary parts of the index of refraction, were adapted from Refs. [56] and [57], respectively. The resulting optical properties of the optimized nanofluid-based optical filters are summarized in Table 6.

To understand the behavior of the solar radiation spectrum within the nanofluid-based optical filter (first channel), Eq. (20) is numerically resolved using the finite difference scheme. The simulation results are presented in Fig. 3. Approximately, 81.3% and 82.1% of the sunlight energy within the interval of the high spectral

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Comparison of different outputs obtained by the present model and experimental data.</th>
<th>Mod.</th>
<th>Exp.</th>
<th>Mod.</th>
<th>Exp.</th>
<th>Mod.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\eta_{in}(%))</td>
<td>(J_{sc}(mA/cm^2))</td>
<td>(V_{oc}(V))</td>
<td>FF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>24.96</td>
<td>25.6</td>
<td>41.652</td>
<td>41.8</td>
<td>0.7455</td>
<td>0.74</td>
<td>0.7976</td>
</tr>
<tr>
<td>GaAs</td>
<td>27.37</td>
<td>28.8</td>
<td>30.17</td>
<td>29.68</td>
<td>1.1254</td>
<td>1.122</td>
<td>0.8</td>
</tr>
</tbody>
</table>

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[References]


The response of Si (750–1100 nm) and GaAs (550–875 nm) is transmitted to the PV cells, respectively. Roughly, both nanofluid-based optical filters are able to absorb the desired UV and near UV spectra completely. Fig. 3a shows that the UV spectrum at wavelength 500 nm backward is absorbed within 1.95 cm from the top in the case of the PV/T with Si, as opposed to 3.8 cm for GaAs at wavelength 325 nm backward, as shown in Fig. 3b. At the transmission window corresponding to the spectral response of Si and GaAs, the solar radiation intensity is estimated to be almost transmitted to the PV cells. For instance, at wavelength of 1050 nm for Si and 850 nm for GaAs, the radiation intensity after crossing the path length of the filter is slightly reduced from 654 W/m² μm to 593 W/m² μm, and from 894 W/m² μm to 837 W/m² μm, respectively.

The nanofluids based optical filters absorb partially the IR spectra, and this is due to the optical properties of the base fluid, Therminol, which is not a good absorber of long wavelength. The simulation result show that ~34% of the IR spectra at 875 onward was absorbed by the optical nanofluid in the case of GaAs, as opposed to ~45% for Si at wavelength 1100 nm onward.

The energy in IR region is not a useful energy for the PV cells, therefore once it is absorbed by the PV will be transferred to the heat and then will be removed by the thermal nanofluid under the PV module.

Overall, both nanofluid-based optical filters designed for PV/T with Si and GaAs PV cells are able to absorb 57.7% and 42% of the total incident radiation, respectively.

The volume fraction of the nanoparticles and the thickness of the filter are determined precisely because the performance of the PV modules significantly depends on these two parameters. For example, increasing either of these two parameters reduces the solar radiation intensity that reaches the PV cells and leads to considerable deterioration of the PV module performance. From this simulation, one can conclude that both nanofluid optical filters are optimized to absorb the maximum unconvertible energy to electricity, which increases the output of the thermal unit, and to enable the transmission of the maximum convertible energy to electricity.

### 3.3. Electrical and thermal performance of PV/T collector

After the electrical model is validated, the next step is to check the electrical and thermal performance of the present PV/T design (D-1) as illustrated in Fig. 1a, and to compare its performance to those of the PV/T with double pass channel (D-2) as illustrated in Fig. 1b. For this, a MATLAB code was built to simultaneously resolve Eqs. (2)–(9). In the code, the temperature distribution along the flow direction is considered in the present analysis.

Fig. 4 shows the evolution of the electrical efficiency as a function of solar concentration. It can be seen that, when the solar concentration increases, the mean electrical efficiency in D-2 decreases sharply than in D-1. For instance, at C = 45 for the GaAs PV cells, the electrical efficiency is 13.8% for PV/T type D-1, whereas the electrical efficiency in D-2 decreases from 13.8% to 8.5%.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>1 m²</td>
</tr>
<tr>
<td>l</td>
<td>1 m</td>
</tr>
<tr>
<td>D_{h1}</td>
<td>0.04 m for PV/T with Si; 0.095 m with GaAs</td>
</tr>
<tr>
<td>D_{h2}</td>
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</tr>
<tr>
<td>ε_{s1}</td>
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<tr>
<td>Δε</td>
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<td>r_{s}</td>
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<td>Δε_{s2}</td>
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<td>r_{s2}</td>
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<tr>
<td>K</td>
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<tr>
<td>m</td>
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</tr>
<tr>
<td>n</td>
<td>0.96</td>
</tr>
<tr>
<td>Δ</td>
<td>0.99 for Si, 1.1 for GaAs</td>
</tr>
<tr>
<td>k</td>
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<tr>
<td>R_{p}</td>
<td>5.71 × 10^{-6} K/W</td>
</tr>
<tr>
<td>T_{amb}</td>
<td>298 K</td>
</tr>
<tr>
<td>v_{amb}</td>
<td>1 m/s</td>
</tr>
</tbody>
</table>

### Table 5

Values of the different parameters and coefficients used in this study.
rate is 4.8% for D-2. Similarly, for Si PV cells at C = 30 the electrical efficiency is 9.2% for PV/T type D-1, whereas this is 0.63% for type D-2. In this case, the electrical efficiencies in PV/T type D-1 are boosted by ~8.6% compared with those in D-2.

The optimum value of the solar concentration, C, depends on the desired electrical or thermal performance. In present analysis the maximum value of C is determined so that the hottest cells of the GaAs and Si PV modules must operate with a local electrical efficiency greater or equal to 10% and 5%, respectively. The maximum attainable value of C satisfying this condition is obtained from Fig. 5.

Fig. 5 shows the variation of the electrical efficiency of the PV cells (Si and GaAs) along the flow direction in PV/T collector types D-1 and D-2. The electrical efficiency, in both cases, decreases when collector length increases. This phenomenon is due to the temperature of the PV panel, which increases along the direction of flow caused by the temperature of the volumetric absorber in the first channel. The present model confirms the suggestion in Ref. [58] that the non-uniformity in temperature within the PV panel can cause a reduction in the PV current, which consequently leads to a reduction in the electrical efficiency.

In addition, the electrical performance of the D-2 design is lower than D-1 as solar concentration increases, and the optimum value of the solar concentration, corresponding to the minimum requirement on electrical efficiency, is much lower in D-2 compared to D-1. The simulation results presented on Fig. 5 shows that system D-1 can run at C = 132 and that GaAs cells still deliver electricity at 10% efficiency. In contrast, the maximum value of C in system D-2 maintaining the GaAs efficiency at 10% is reached at C = 22. Similarly for Si cells, in D-1 the optimum C achieves a Si cell efficiency of 5% at C = 96, but this can be achieved at C = 15 for system D-2.

PV cells are highly sensitive at an elevated temperature; thus, the system in D-2 is poorly cooled compared to D-1. Although the double-pass design in D-2 helps the working fluid to increase in temperature, the higher temperature limits the PV module performance. Moreover, the working fluid in the second channel is similar to that in the first channel in the collector type D-2, which is only designed to be applied as an optical filter. Thus, it can be concluded that the low volume fraction of nanoparticles in PV/T type D-2 results in poor thermal conductivity of the nanofluid. This leads to a reduced cooling during the first pass of the nanofluid under the PV module.

In the PV/T collector type D-1, the system uses different nanofluids in two separate channels. The slow decrease in electrical efficiency in D-1 (as shown in Figs. 4 and 5) is due to the high thermal conductivity of the nanofluid in the second channel, which perfectly accomplishes its cooling function.

In Fig. 5, in the case of the D-1 system, it can be seen that at very high values of solar concentration (C > 80) the electrical efficiency of the PV cells has an optimal value along the flow direction of the nanofluids. Indeed, in the second channel the nanofluid cools down the PV cells until it reaches a point of thermal saturation where the solar heat received by the cells is greater than that removed by the thermal nanofluid in the second channel. In order to increase the heat removal from the solar cells, the volume fraction and/or mass flow rate of the thermal nanofluid in the second channel needed to be increased further. However, this solution has its limitations,

### Table 6

<table>
<thead>
<tr>
<th>PV cells</th>
<th>Nanoparticles</th>
<th>Diameter (nm)</th>
<th>Volume fraction (%)</th>
<th>Filter thickness, (e_{11}) (mm)</th>
<th>(1_{1})</th>
<th>(a_{11})</th>
<th>(\pi_{11})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>Ag</td>
<td>10</td>
<td>0.003</td>
<td>20</td>
<td>0.813</td>
<td>0.577</td>
<td>0.601</td>
</tr>
<tr>
<td>GaAs</td>
<td>Ag</td>
<td>10</td>
<td>0.0002</td>
<td>50</td>
<td>0.821</td>
<td>0.420</td>
<td>0.451</td>
</tr>
</tbody>
</table>

\(1_{1}\) and \(a_{11}\) are the boundaries of the ideal filter corresponding to each PV cell.
because the increase in volume fraction and/or mass flow rate involves a significant increase in pumping power which reduces the overall efficiency of the system.

Figs. 6 show the variation of electrical and thermal exergy output performance for both D-1 and D-2 as a function of solar concentration. At a lower solar concentration, the PV/T collector type D-2 outperforms D-1 in terms of thermal exergy output. Notably, the Carnot efficiency in D-2 is higher than that in D-1, but
due to the minimum requirement performance imposed to the PV cells ($\eta_{el, GaAs} \geq 10\%$, $\eta_{el, Si} \geq 5\%$), the PV/T collector type D-1 can run at higher solar concentration than D-2. Consequently, the electrical and thermal exergy rates in D-2 will be significantly lower in magnitude compared with those in D-1. Overall, it is clear that the PV/T hybrid system type D-1 is more suitable at high solar concentration based on the results shown in Figs. 4–6.

To emphasize the advantage of the separate channel design and its positive effect on the electrical and thermal performances of a PV/T hybrid system at high solar concentrations, a numerical simulation is conducted by the variation of the volume fraction of the thermal nanofluid in the second channel. The volume fraction of the optical nanofluid in the first channel should remain constant because it is optimized only to act as a liquid optical filter. The simulation results are shown in Fig. 7 and summarized in Table 7.

It can be concluded that the increase in the volume fraction, from 0.001% to 1.5%, for the thermal nanofluid has a significant positive effect on the electrical performance enhancement of PV/T type D-1 with GaAs PV cells (shown in Fig. 7a) and of D-1 with Si PV cells (shown in Fig. 7b). In this instance, the efficiency of GaAs cells has been improved from 3% to 11%, and that of Si cells from 0.8% to 6.2%. Similarly, the overall efficiency of the system D-1 with GaAs and Si cells has been improved from 24.2% to 30%, and from 19.8% to 24.4%, respectively.

Table 7 shows that the electrical efficiencies of GaAs and Si PV cells are enhanced by 9% and 5.6% by increasing the volume fraction from 0.001% to 1.5%, respectively. Moreover, this increase in volume fraction causes a sharp decrease in PV module temperature. For instance, the mean GaAs cell temperature decreases from 254.8 °C to 254.4 °C, whereas that of Si decreases from 298.2 °C to 159.3 °C. The thermal efficiency of the first and second channels decreases marginally because of the effect of the cooling process. This reduction in thermal efficiency is negligible and does not affect the overall efficiency of the system, which is enhanced by 5.8% and 4.6%, respectively. In this case, it can be concluded that the overall efficiency is more sensitive to the electrical performance than to the thermal performance.

Furthermore, at high temperature, the GaAs PV cells are more efficient than the Si PV cells, which confirms the experimental results reported in Ref. [45]. Therefore, GaAs is more suitable at high solar concentrations.

In addition to the thermal conductivity of the nanofluid in the second channel, the mass flow rate is a key parameter that significantly contributes to the alteration of overall efficiency. Fig. 8 depicts the variation of the performance of the PV/T collector type D-1 as a function of mass flow rate and solar concentration. According to Fig. 8, the overall efficiency decreases when the mass flow rate increases. This drop in overall efficiency is essentially due to the decrease in the Carnot efficiency. Based on the fundamental definition of Carnot efficiency, the latter is proportional to the temperature of the system. Increasing the mass flow rate reduces the output temperature of the working fluid, which is the principal factor that causes the reduction of overall efficiency. Each value of solar concentration has its own optimum operating point of mass flow rate corresponding to the maximum value of overall efficiency. For example, at $C = 30$ the optimum mass flow rate is 0.009 kg/s whereas it has been found equal to 0.015 kg/s at $C = 60$. The peaks in Fig. 8 define the maximum overall efficiency operating point – a point which varies when the solar concentration mass flow rate change. In real life, the operating mass flow rate depends essentially on the desired output performance of the PV/T application.

4. Conclusions

In this study, a new configuration of a PV/T hybrid system using two separated nanofluids is proposed. The optical nanofluid is designed to achieve high performance of a liquid optical filter, whereas the thermal nanofluid is designed to act as a coolant fluid under the PV module.

The main conclusions based on the results of the present study are summarized as follows:

a) In PV/T collectors with both GaAs and Si cells, the nanofluid-based optical filter absorbs practically all the desired UV and partially the IR spectra.
Fig. 7. Electrical efficiency of (a) GaAs and (b) Si PV cells and overall efficiency of PV/T hybrid collector type D-1 as a function of volume fraction of the thermal nanofluid in the second channel, under the following conditions: $m_{n1} = m_{n2} = 0.08 \text{ kg/s}$, $C = 160$ for GaAs and $C = 100$ for Si, $G = 992 \text{ W/m}^2$.

Table 7
Influence of volume fraction of the thermal nanofluids in the second channel on different parameters of the PV/T hybrid system.

<table>
<thead>
<tr>
<th>Design</th>
<th>$C$</th>
<th>$\phi_{nf2}(%)$</th>
<th>$T_{h1}(\degree C)$</th>
<th>$T_{h2}(\degree C)$</th>
<th>$T_{pv}^* (\degree C)$</th>
<th>$\eta_{h-1}$</th>
<th>$\eta_{h-2}$</th>
<th>$\eta_{el}$</th>
<th>$\eta_{inv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1 with GaAs PV cells</td>
<td>0.001</td>
<td>402.7</td>
<td>206.7</td>
<td>541.0</td>
<td>0.502</td>
<td>0.386</td>
<td>0.029</td>
<td>0.242</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>400.3</td>
<td>207.8</td>
<td>529.0</td>
<td>0.498</td>
<td>0.387</td>
<td>0.032</td>
<td>0.245</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>378.1</td>
<td>214.6</td>
<td>365.6</td>
<td>0.454</td>
<td>0.383</td>
<td>0.078</td>
<td>0.276</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>369.3</td>
<td>225.3</td>
<td>254.8</td>
<td>0.437</td>
<td>0.368</td>
<td>0.109</td>
<td>0.300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>334.6</td>
<td>120.6</td>
<td>298.2</td>
<td>0.601</td>
<td>0.325</td>
<td>0.006</td>
<td>0.198</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>334.1</td>
<td>121.0</td>
<td>293.1</td>
<td>0.599</td>
<td>0.325</td>
<td>0.007</td>
<td>0.199</td>
<td></td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>328.0</td>
<td>122.1</td>
<td>218.8</td>
<td>0.583</td>
<td>0.314</td>
<td>0.035</td>
<td>0.221</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>325.8</td>
<td>123.1</td>
<td>180.3</td>
<td>0.577</td>
<td>0.302</td>
<td>0.053</td>
<td>0.235</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>324.8</td>
<td>125.4</td>
<td>159.3</td>
<td>0.575</td>
<td>0.295</td>
<td>0.062</td>
<td>0.244</td>
<td></td>
</tr>
</tbody>
</table>

(*) Mean temperature.

Fig. 8. Overall efficiency of PV/T hybrid collector type D-1 with GaAs cells as a function of solar concentration and mass flow rate of the thermal nanofluid (second channel) under the following conditions: $m_{n1} = 0.08 \text{ kg/s}$, $\phi_{nf2} = 0.01$, $G = 992 \text{ W/m}^2$. 

Table 7
Influence of volume fraction of the thermal nanofluids in the second channel on different parameters of the PV/T hybrid system.
b) To determine the advantage of the proposed PV/T hybrid system, the performance of the PV/T with separate channels (D-1) was compared with the double-pass channel (D-2). The results demonstrate that the electrical efficiency of GaAs (at C = 45) and Si (at C = 30) can be improved by –8.6% in PV/T type D-1, compared with that in PV/T type D-2.

c) The simulation results prove that, at these solar concentration ratios, the PV/T with separate channels is more suitable than that with a double-pass channel.

d) The use of two different nanofluids gives a significant boost to the PV/T hybrid collector. Based on the results of the present study, increasing the volume fraction of the nanofluid-based coolant, yield enhanced electrical efficiencies for the GaAs and Si PV cells by 9% and 5.6%, and overall efficiency of the system by 5.8% and 4.5%, respectively.

The present study proposes a new approach to the efficient use of solar energy in PV/T hybrid systems. The optimized PV/T hybrid system is a reliable solution to electrify remote off-grid regions at a low cost and to provide a potentially large supply of useful thermal energy.

Acknowledgment

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Appendix A

This Appendix presents the coefficients and parameters used in the present paper.

\[ h_{eq}(c_{1-am}) = h_{r_{1-am}} + h_{c_{1-am}} \]  
(A.1)

\[ h_{r_{1-am}} = \frac{\sigma \varepsilon_{1-c} (T_{c1}^4 - T_{sky}^4)}{T_{c1} - T_{am}} \]  
(A.2)

where \( T_{sky} \) is the sky’s temperature evaluated using Daguenet’s formula [59]:

The correlations for the Nusselt numbers \( Nu_{c_{1-am}}, Nu_{c_{1-c}}, Nu_{c_{2-am}}, Nu_{c_{2-c}} \) and \( Nu_{am} \) were taken from Refs. [60,61].

The nanofluid flow regime in this study is limited to a fully developed laminar flow with a Reynolds number \( Re_{c1} < 2300 \).

The radiation heat transfer coefficients in a participating medium (channel 1) have been developed using the fundamental literature of the thermal radiation heat transfer available on the Ref. [52]:

\[ h_{r_{c2-c3}} = \frac{\epsilon_{c2} \varepsilon_{c3} (1 - \pi) \sigma (T_{c2}^2 + T_{c3}^2) (T_{c2} + T_{c3})}{1 - (1 - \epsilon_{c2})(1 - \epsilon_{c3})(1 - \pi)^2} \]  
(A.3)

\[ h_{r_{c3-n1}} = \frac{\epsilon_{c3} \varepsilon_{n1} (1 - \pi) \sigma (T_{c3}^2 + T_{n1}^2) (T_{c3} + T_{n1})}{1 - (1 - \epsilon_{c2})(1 - \epsilon_{c3})(1 - \pi)^2} \]  
(A.4)

\[ h_{r_{c3-pv}} = \frac{\sigma \varepsilon_{c3} \varepsilon_{pv} (T_{c3}^2 + T_{pv}^2) (T_{c3} + T_{pv})}{\varepsilon_{c3} + \varepsilon_{pv} - \varepsilon_{c3} \varepsilon_{pv}} \]  
(A.8)

Note: The heat transfer correlations used are given in the Appendix A. All other parameters and coefficients involved in solving Eqs. (2)–(9) are presented in Table 5.

References


