Article

Utilization of H₂O/CuO and Syltherm 800/CuO Nanofluids in a Concentrating Solar Collector with Photovoltaic Elements

Theodoros Papingiotis, Dimitrios N. Korres *, Irene Koronaki and Christos Tzivanidis *

School of Mechanical Engineering, National Technical University of Athens, 157 80 Athens, Greece; thpapingiotis@mail.ntua.gr (T.P.), koronaki@central.ntua.gr (I.K.)

* Correspondence: korres@central.ntua.gr (D.N.K.), tzivan@central.ntua.gr (C.T.)

Abstract: This study examined the performance of a concentrating solar collector with an asymmetric reflector. Two receivers were investigated, differing in the presence of photovoltaic cells. The first one was equipped with cells on both sides while the other was without cells. The analysis was performed using a numerical model that integrates a combination of three-dimensional optical and thermal analyses developed in COMSOL. The investigation included studying the influence of CuO/water and CuO/Syltherm 800 nanofluids on the thermal performance for the receiver without photovoltaic elements, as well as on both thermal and electrical efficiencies for the hybrid receiver. Two volumetric concentrations of CuO in water and Syltherm 800, 3% and 5%, were explored with varying inlet temperatures, ranging from 20 °C to 80 °C for the hybrid solar unit and from 20 °C to 140 °C for the thermal solar unit. The outcomes of the examination were compared between the nanofluids and the pure base fluid. Properly pressurized water was considered in the case without photovoltaic elements.

Keywords: hybrid solar collector; concentrating collectors; nanofluids; optical-thermal simulation

1. Introduction

The increasing demand for renewable energy has elevated solar collectors to a prominent position in sustainable technologies due to their ability to harness solar radiation. Two primary classifications of solar collectors exist: flat plate and concentrating collectors [1]. To enhance the efficiencies of solar collectors, various receiver and/or concentrator geometries have undergone comprehensive examination. Apart from different concentrator geometries, photovoltaic–thermal (PV/T) solar receivers [2], integrating photovoltaic cells with thermal absorbers, have been proposed to enhance energy conversion efficiency.

In the pursuit of optimizing solar technologies, extensive research, including both numerical simulations and experimental studies, has been undertaken to assess the impact on efficiency through the utilization of nanofluids as heat transfer fluids. Nanofluid technology introduces an enhancement of thermal conductivity [3] even at a very low volume fraction. This augmentation in thermal conductivity, surpassing that of the base fluid, elevates the heat transfer coefficient in the flow.

The use of nanofluids on flat-plate solar collectors has been studied extensively in the literature. Geovo et al. [4] developed and validated a mathematical model to simulate the performance of a flat-plate solar collector using MgO-water nanofluid as the heat transport medium. They showed that the use of MgO-water nanofluid with a concentration of up to 1% significantly improved the thermal efficiency. Ashour et al. [5] compared the use of water based ZnO and CuO nanofluids with water utilizing a three-dimensional fluid dynamics model. They concluded that CuO achieved the highest thermal efficiency increase. Akram et al. [6] experimentally examined the thermal performance of a non-concentrating collector utilizing nanofluids derived from carbon and metal oxides. They found that 0.1wt% functionalized carbon nanopleatelets enhanced the performance by 17.45% in comparison with water.
Mouli et al. [7] conducted an experimental analysis of a flat-plate collector with multi-walled carbon nanotube nanofluids with water as the based fluid. The peak thermal efficiency of the transient analysis surged from 27.78% with the base fluid to 56.69% with a thermal fluid of 0.3vol% concentration with nanofluid, accompanied by an exergy efficiency rise from 0.5% to 2.67%. Mostafizur et al. [8] numerically analyzed the energy and exergy efficiencies of a flat-plate solar collector utilizing four different nanofluids compared to water. They concluded that CuO nanofluid-operated collectors exhibit higher efficiencies, surpassing those operating with water.

Regarding flat-plate hybrid PV/T solar collectors, the use of nanofluids has been studied extensively. Rejeb et al. [9] conducted an experimental and numerical assessment of a PV/T collector using nanofluids, employing a validated two-dimensional model to examine the impact of nanofluids on electrical and thermal performance. Studying concentration, nanoparticle types, and base fluids (pure water and ethylene glycol), the research identified pure water as superior to ethylene glycol and highlighted Cu/water as the most efficient configuration. Elangovan et al. [10] experimentally examined the effect of TiO2/water nanofluid on the electrical efficiency of a PV/T collector. They concluded that the nanofluid increased the efficiency of the PV.

Nasrin et al. [11] studied, both numerically and experimentally, the performance of a PV/T using water/multi-walled carbon nanotube nanofluids. The system demonstrated an increase of approximately 3.81% and 4.11% in numerical and experimental outcomes, respectively, when utilizing the nanofluid compared to water. Sardarabadi et al. [12] performed an experimental investigation focused on assessing the impact of employing nanofluid as a coolant on the thermal and electrical efficiencies of a PV/T. They observed a maximum increase of 12.8% for the thermal efficiency by using the nanofluid.

Nanofluids are also used as a medium for spectral splitting PV/T collectors. When employing this technique, the solar spectrum is divided into different wavelengths. The PV cells capture the specific range utilized for electrical production, and the thermal absorber harnesses the remain spectrum and converts it into heat. Xiao et al. [13] integrated an affordable and uncomplicated nanofluid containing carbon quantum dots (CQD) with superior stability and specific spectral absorption capabilities into PV/T systems. Xiao et al. [14] assessed the stability, optical characteristics, and filtering performance of a novel hybrid nanofluid comprising ATO and CuO nanoparticles as a spectral splitting fluid in PV/T systems.

In the literature, there are many articles reporting on the impact of nanofluids on the thermal performance of concentrating solar collectors. Among the available studies, the main focus has been on parabolic collectors, whereas investigations into the thermal performance of compound parabolic concentrator (CPC) collectors are notably constrained. Furthermore, the studies exploring the combined CPC/PV/T systems are even more scarce in comparison.

Dou et al. [15] employed numerical methods to explore the impact of Cu nanoparticles in combination with two distinct base fluids on the thermal performance of a parabolic trough solar collector (PTC). The findings indicate that under various operational conditions, synthetic oil/Cu nanofluids can enhance the convective heat transfer coefficient. However, this improvement comes at the expense of increased pumping work due to an elevated pressure drop. The maximum thermal enhancement observed was 7.99%, with Syltherm 800 as the base fluid. Ghasemi and Ranjbar [16] implement a Computational Fluid Dynamics (CFD) model to model the thermal performance of a PTC with CuO-water and Al2O3-water nanofluids. They concluded that the application of water/CuO led to a greater enhancement in the heat transfer coefficient compared to water/Al2O3.

Korres et al. [17] numerically examined the thermal enhancement of Syltherm 800/CuO nanofluid with a concentration of 5vol% in comparison to Syltherm 800 at a CPC. They observed an enhancement of 2.60% in exergy efficiency and 2.76% in overall performance. Arora et al. [18] examined the performance of partially covered PVT-CPC
collectors which utilize single-wall carbon nanotubes (SWCNTs) and multiwall carbon nanotubes (MWCNTs)-water based nanofluids.

The cited articles demonstrate the effectiveness of the integration of nanofluids into solar collectors to boost thermal efficiency. Despite this, the literature review reveals a notable gap, as few studies have examined the effect of nanofluids on CPCs with or without photovoltaic cells. According to the previous studies mentioned, the nanoparticle CuO demonstrated a substantial impact on the performance indices of solar collectors. Consequently, the authors opted for CuO in their selection. The main aim of this study was to investigate, through a 3D combined thermal and optical numerical analysis, the performance of a solar collector with an asymmetric reflector. The impact of CuO/water nanofluid on thermal performance in the absence of a PV for the receiver, and on both thermal and electrical efficiencies for the hybrid receiver, are studied. Various concentrations of CuO and inlet temperatures are systematically examined, with a focus on laminar flow conditions. The results are contrasted between the use of a nanofluid and pure water.

Conducting this analysis through CFD simulations aids in pinpointing the collector’s efficiency and effectiveness across diverse operating temperatures, configurations, and heat transfer fluids. The insights gained into the performances, electrical and thermal, of each of the heat-transfer medium provide valuable knowledge for refining the design of these systems.

2. Materials and Methods

2.1. The Solar Collector and Key Characteristics

This study examined asymmetric CPC with a concentration ratio (C) of 1.414 and an aperture (A_s) measuring 1.064 m². The collector under consideration was examined by the authors in Ref. [19]. Table 1 encompasses the primary dimensions and information relating to the studied solar collector.

### Table 1. Collector dimensions and characteristics [20,21].

<table>
<thead>
<tr>
<th>General Characteristics</th>
<th>Symbols</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>L</td>
<td>2290 mm</td>
</tr>
<tr>
<td>Width</td>
<td>W</td>
<td>464.52 mm</td>
</tr>
<tr>
<td>Absorber width</td>
<td>w_abs</td>
<td>157 mm</td>
</tr>
<tr>
<td>Absorber height</td>
<td>h_abs</td>
<td>6.50 mm</td>
</tr>
<tr>
<td>Number of elliptical channels</td>
<td>n</td>
<td>8</td>
</tr>
<tr>
<td>Radius of the circular geometry of reflector</td>
<td>R_0</td>
<td>144.86 mm</td>
</tr>
<tr>
<td>Focal length of the parabolic geometry of reflector</td>
<td>f_0</td>
<td>144.86 mm</td>
</tr>
<tr>
<td>PV temperature dependence</td>
<td>\beta_PV</td>
<td>0.64%/K</td>
</tr>
<tr>
<td>PV nominal efficiency</td>
<td>\eta_{PV}</td>
<td>18.7%</td>
</tr>
<tr>
<td>Glass transmittance</td>
<td>\tau</td>
<td>0.95</td>
</tr>
<tr>
<td>Glass emissivity</td>
<td>\varepsilon_g</td>
<td>0.95</td>
</tr>
<tr>
<td>Concentrator reflectance</td>
<td>\rho</td>
<td>0.94</td>
</tr>
<tr>
<td>Concentrator emissivity</td>
<td>\varepsilon_c</td>
<td>0.05</td>
</tr>
<tr>
<td>Solar cell absorbance</td>
<td>\alpha_PV</td>
<td>0.93</td>
</tr>
<tr>
<td>Solar cell emissivity</td>
<td>\varepsilon_PV</td>
<td>0.90</td>
</tr>
<tr>
<td>Receiver absorbance</td>
<td>\alpha_rec</td>
<td>0.92</td>
</tr>
<tr>
<td>Receiver emissivity</td>
<td>\varepsilon_rec</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The collector’s reflector is formed by merging a parabolic and a circular geometry. The transition point between the two geometries is perpendicular to the collector’s cover. The focal point of the parabolic segment aligns with the center of the circular section. The receiver is positioned on the circular side of the concentrator, and the thermal fluid runs through 8 elliptical channels. Figure 1 shows the geometry of the solar unit.
As solar radiation reaches the absorber, PV cells on both sides generate electricity. However, a significant portion of the solar energy is transformed into heat, causing the PV cell temperature to rise and reducing the electrical efficiency. To address this, water is used to cool the cells, lowering their temperature and enhancing efficiency, all while generating a valuable thermal output.

![Image](57x535 to 275x675)

![Image](286x539 to 538x675)

(a) (b)

Figure 1. The examined solar collector: (a) the concentrator, (b) 3D view of the collector and the absorber.

2.2. Mathematical Modeling of the Analysis

In this subsection, the mathematical equations utilized for the thermal analysis are presented.

The useful heat transferred to the heat transfer fluid is calculated as [17]:

\[ Q_u = \dot{m} \cdot C_p \cdot (T_{out} - T_{in}) \]  

(1)

where \( \dot{m} \) is the mass flow rate, \( C_p \) the specific heat capacity of the medium, and \( (T_{out} - T_{in}) \) the temperature difference between the outlet and inlet.

The thermal efficiency is determined as [17]:

\[ \eta_{th} = \frac{Q_u}{A_u \cdot G} \]  

(2)

where \( A_u \) is the area of the aperture, and \( G \) the solar radiation.

The relationship between PV temperature and electrical efficiency is expressed by:

\[ \eta_{el} = \eta_{0, PV} \cdot \left( 1 - \beta_{PV} \cdot (T_{pv,m} - T_{0, PV}) \right) \]  

(3)

where \( \eta_{0, PV} \) represents the PV nominal efficiency, \( \beta_{PV} \) the coefficient of temperature of the PV, and \( T_{pv,m} \) and \( T_{0, PV} \) the mean temperature of the PV and the reference temperature, respectively.

Based on the electrical efficiencies calculated by the above equations for the top and bottom PVs, the respective electrical productions are calculated by:

\[ Q_{el,top} = A_{pv,top} \cdot G \cdot \eta_{el,top} \]  

(4)

\[ Q_{el,bot} = A_{pv,bot} \cdot G \cdot \left( \frac{A_{pv,\text{sum}}}{A_{pv,bot}} \cdot C - \frac{A_{pv,top}}{A_{pv,\text{sum}}} \right) \cdot \eta_{el,bot} \]  

(5)

where \( A \) is the area of the PV cells described by the subscripts; (bot) represents the PV at the bottom side of the receiver, and (top) represents the PV at the upper side, while (sum) is the sum of the top and bottom PVs. \( C \) denotes the concentration ratio of the solar collector.

The temperature of the sky is calculated by [22]:
\[ T_{sky} = 0.0552 \cdot T_a^{1.5} \] (6)

where \( T_a \) is the ambient temperature.

The energy balance of the solar collector at the hybrid operation is obtained by:

\[ Q_{abs} = Q_a + Q_{losses} + Q_{el} \] (7)

2.3. Thermal Property Analysis of Nanofluid

For an accurate simulation of nanofluids, it is essential to initially compute the required thermal properties. These encompass the thermal conductivity, dynamic viscosity, density, and specific heat capacity of the nanofluid.

For the following equations, the symbol for nanoparticles is \((n, \text{particle})\), nanofluids are denoted by \((n, \text{fluid})\), and the base fluid is represented by \((b, \text{fluid})\).

The calculation for the nanofluid's density, with regard to the volumetric concentration \( \phi \) of the nanofluid, is performed as follows [23]:

\[ \rho_{n, \text{fluid}} = \phi \cdot \rho_{n, \text{particle}} + (1 - \phi) \cdot \rho_{b, \text{fluid}} \] (8)

The calculation of the specific heat capacity is determined by [17]:

\[ C_{p,n, \text{fluid}} = \frac{\phi \cdot \rho_{n, \text{particle}} \cdot C_{p,n, \text{particle}} + (1 - \phi) \cdot \rho_{b, \text{fluid}} \cdot C_{p,b, \text{fluid}}}{\rho_{n, \text{fluid}}} \] (9)

The expression for the thermal conductivity is [24]:

\[ k_{n, \text{fluid}} = k_{b, \text{fluid}} \cdot \frac{k_{n, \text{particle}} + 2 \cdot k_{b, \text{fluid}} + 2 \cdot (k_{n, \text{particle}} - k_{b, \text{fluid}}) \cdot (1 + \beta)^3 \cdot \phi}{k_{n, \text{particle}} + 2 \cdot k_{b, \text{fluid}} - (k_{n, \text{particle}} - k_{b, \text{fluid}}) \cdot (1 + \beta)^3 \cdot \phi} \] (10)

Parameter \( \beta \) represents the ratio of the thickness of the nano-layer to the initial particle radius and is commonly assumed to be 0.1 [17].

This equation was selected as it was used in various studies that examined CuO as a nanoparticle [17].

The dynamic viscosity can be found as [17]:

\[ \mu_{n, \text{fluid}} = \mu_{b, \text{fluid}} \cdot (1 + 2.5 \cdot \phi + 6.5 \cdot \phi^2) \] (11)

2.4. Formulation of Numerical Model and Boundary Condition

The presented numerical model was created using the COMSOL 5.2 simulation tool [25], a frequently utilized software that has been employed in various investigations regarding solar collectors [26,27].

The designated boundary conditions and parameters for the numerical model are as follows. The ambient temperature remains constant at 20 °C across all the cases under consideration. To underscore the focus of this study, which is the effect of the nanofluid with different concentrations, in the thermal analysis of the solar collector, the solar irradiation \((G)\) was chosen to be constant and equal to 1000 W/m². This consideration appears, also, in study [17], in which the effect of a nanofluid was examined in a CPC. Additionally, based on the authors' prior optical analysis of the same reflector's geometry [19], an incident angle of 5° was adopted for the analysis, representing the angle that yields the maximum optical efficiency.

The heat transfer coefficient between the air inside the cavity and the inside surfaces of the reflector, receiver, and glass was consistently maintained at 5 W/m²K [19]. Also, the heat transfer coefficient between the outside surfaces and the ambient was estimated as constant and equal to 10 W/m²K.

The glass cover was represented as a semi-transparent surface, and the receiver was constructed with aluminum. The characteristics of the materials, including emissivity,
reflectance, transmittance, and absorbance, were assigned specified values as described in Table 1.

The system functions with a volumetric flow rate of 1 L/min, resulting in a laminar flow regime across all investigated scenarios.

As mentioned, the receiver was examined either equipped with a PV on both sides or without a PV. For the case with the PV, the system’s inlet temperature was selected to range from 20 °C to 80 °C with a step of 20 °C, and in the case without a PV, the inlet temperature varied from 20 °C to 140 °C with a step of 40 °C. By studying the collector’s behavior at different inlet temperatures, its design and operation can be optimized for enhanced performance in diverse environmental scenarios.

In Table 2, the fundamental information of the examined nanofluid is presented.

### Table 2. Fundamental information regarding the investigated nanofluid [17].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base fluids</td>
<td>Water, Syltherm 800</td>
</tr>
<tr>
<td>Nanoparticle</td>
<td>CuO</td>
</tr>
<tr>
<td>Specific heat capacity of CuO</td>
<td>532 J/kgK</td>
</tr>
<tr>
<td>Density of CuO</td>
<td>6320 kg/m³</td>
</tr>
<tr>
<td>Thermal conductivity of CuO</td>
<td>77 W/mK</td>
</tr>
</tbody>
</table>

For the combined optical and thermal simulation of the collector, a methodology developed by the authors was employed. This approach considers the air within the cavity for thermal analysis without explicit modeling, thereby reducing the time needed for the numerical solution to converge and the necessary computational resources. This is achieved by calculating the heat losses (both convective and radiation) from the exterior surfaces and the surfaces of the receiver for various internal air temperatures. As mentioned previously, the heat transfer coefficient remains constant for both cases. The air temperature at which the difference in heat losses (exterior and receiver) equals zero was selected as the temperature for the air in the simulation. The method is described in greater detail in Ref. [19]. Additionally, the reference contains validation of the method described with experimental results as well as a mesh-independence study.

### 3. Results

#### 3.1. Thermal Properties of Nanofluids

Initially, the effect of the nanoparticles on the thermal characteristics of the heat transfer fluid are examined. For the case of CuO/water, at temperatures approximately around 60 °C, the thermal conductivity of the nanofluid with a volumetric concentration of 3% CuO was 12.15% higher than the base fluid, while the nanofluid with a concentration of 5% exhibited a more substantial increase of 20.82%. Regarding heat capacity, the nanofluid demonstrated reduced values compared to the base fluid, with a decrease of 14.47% and 22.06% for nanofluids with concentrations of 3% and 5% CuO, respectively. Finally, the density of the nanofluids exhibited an increases of 16.28% and 27.14%, respectively, for the examined concentrations of 3% and 5%. Figure 2 illustrates the fraction between the density, the heat capacity, the thermal conductivity, and the product of density and heat capacity for each concentration of the nanofluid compared to the water.

The volumetric specific heat capacity, calculated by multiplying the density and specific heat capacity, indicates that in the case of CuO/water, the nanofluid can carry slightly less heat than the base fluid. However, the increase in the thermal conductivity seems to be the key difference in the nanofluid utilization, as is explained here in the results. More specifically, it is explained that at higher temperatures, the higher thermal conductivity of the nanofluids eradicates the effect of the lower volumetric specific heat
capacity. These explanations elucidate the results of the numerical simulations presented below.

Figure 2. Ratio of density, heat capacity, thermal conductivity, and the volumetric specific heat capacity of the nanofluid with water with regard to inlet temperature.

In the CuO/Syltherm 800 scenario, at 60 °C, the nanofluid’s thermal conductivity increased by 12.41% at a 3% concentration and significantly more at 21.27% for 5%. Concerning heat capacity, the nanofluid exhibited lower values, decreasing by 12.19% and 18.43% at 3% and 5% CuO concentrations, respectively. Finally, the density of nanofluids showed increases of 12.41% and 30.14% for the examined 3% and 5% concentrations. The volumetric specific heat capacity in this nanofluid was higher than the base fluid. This fact indicates that the addition of nanoparticles in this case leads to a combination that ensures higher amounts of absorbed heat considering the same temperature rise. Figure 3 visually illustrates the fractional differences in density, heat capacity, and thermal conductivity for each nanofluid concentration in comparison to Syltherm 800.
Figure 3. Ratio of density, heat capacity, thermal conductivity, and volumetric specific heat capacity of the nanofluid with Syltherm 800 with regard to inlet temperature.

3.2. Solar Collector with PV
3.2.1. CuO/Water Nanofluid

Initially, the solar unit featuring a PV on both sides of the absorber underwent examination using nanofluid with water as the base fluid. As depicted in Figure 4, it was apparent that at lower inlet temperatures, the nanofluid’s efficiency was slightly inferior to that of pure water for both concentrations. Lower thermal efficiencies when employing nanofluids in comparison to the base fluid are also presented Ref. [28], where an Al₂O₃/Water nanofluid was examined at a concentrating PV/T collector. However, as temperatures surpassed 60 °C, higher efficiencies became evident. For low temperatures, due to the lower volumetric specific heat capacity, the base heat transfer fluid has the capacity to transport a greater amount of heat. As the temperature rises, the higher thermal conductivity of the nanofluid seems to overcome the limitation of the volumetric specific heat capacity. Notably, a maximum enhancement of 0.28% was observed at 80 °C with the heat transfer medium at the higher concentration of CuO, particularly at 5%.
Figure 4. Thermal efficiency of solar collector with PV: (a) nanofluid 3% CuO/water, (b) nanofluid 5% CuO/water.

Figure 5 illustrates the impact on the electrical efficiency for both the top and bottom sides of the absorber when employing a nanofluid with a 3% concentration CuO. It is evident that the photovoltaic elements exhibited improved efficiencies with the utilization of the water-based nanofluid as the heat transfer fluid. However, these enhancements seem to be negligible.
Figure 5. Electrical efficiency for the (a) bottom and (b) top PVs of the solar collector with nanofluid 3% CuO/water.

Similar effects were noted when the nanofluid concentration was increased to 5%, as demonstrated at Figure 6. The solar collector exhibited superior performance compared to pure water, with enhancements more prominent at lower temperatures. As temperatures increased, the observed improvement lessened.
As evidenced by both thermal and electrical efficiencies, higher concentrations exhibited more substantial improvements in the performance indices of the solar collector, making them the preferred choice.

3.2.2. CuO/Syltherm 800 Nanofluid

Compared to the nanofluid based on water, the nanofluid based on Syltherm 800 demonstrated more remarkable enhancements in the thermal efficiency of the solar collector, particularly notable at elevated temperatures.

Figure 7 depicts the impact of varying the volumetric concentrations of a nanofluid on the thermal efficiency of the solar collector. The maximum enhancement observed for
the 3% concentration was 13.75%, while for the 5% concentration, it reached 25.74% at the
greater examined inlet temperature (80 °C). Sufficient nanofluid performances also
appeared at both low and medium temperatures with the enhancement of increasing
values up to 1.32%. It is remarkable, here, to notice that the 5% CuO/Syltherm 800
nanofluid ensured significantly higher enhancements than that of the 5% CuO/water,
comparing the base fluids in each case. However, the water and water-based nanofluids
seemed to provide higher thermal performances compared to the Syltherm 800 cases.

![Graph](image1)

(a)

![Graph](image2)

(b)

**Figure 7.** Thermal efficiency of solar collector with PV: (a) nanofluid 3% CuO/Syltherm 800, (b) nanofluid 5% CuO/Syltherm 800.

Figure 8 depicts the effect of the nanofluid with 3% concentration on the bottom and
top photovoltaic elements of the collector. The CuO/Syltherm 800 nanofluid exhibited a
more significant impact than the CuO/water counterpart. Particularly, at lower inlet
temperatures, the electrical enhancement was more pronounced, gradually declining as the inlet temperatures rose. The bottom PV had a higher enhancement compared to the top PV.

**Figure 8.** Electrical efficiency for the (a) bottom and (b) top PVs of the solar collector with nanofluid 3% CuO/Syltherm 800.

Similarly, Syltherm 800 infused with 5% CuO demonstrated heightened enhancement at lower input temperatures. In comparison to Syltherm 800 containing 3% CuO, the improvement was more substantial, with a maximum observed enhancement of 0.44%, as shown in Figure 9. Notably, no significant difference was observed between the top and bottom PVs in this scenario. It is remarkable to mention that the 5% CuO/Syltherm 800 nanofluid ensured higher enhancements in electrical efficiency than the 5%
CuO/water one, comparing the base fluids in each case. It deserves mentioning that the electrical efficiencies in the Syltherm 800 cases seemed to be very close to the corresponding one with water as a base fluid.

![Graph](image1)

**Figure 9.** Electrical efficiency for the (a) bottom and (b) top PVs of the solar collector with nanofluid 5% CuO/Syltherm 800.

Analyzing the data depicted in the preceding figures, it becomes evident that at elevated inlet temperatures, there is a slight decline in electrical efficiency when applying the nanofluids. This reduction in electrical efficiency corresponds to an increase in thermal performance, as anticipated by the heat balance outlined in Equation (7). This probably happens because the heat losses increment in absolute-value terms is lower than the
respective electrical efficiency reduction. Hence, it seems that the lost electrical power, due to the nanoparticles’ addition, is shared to both the useful power and the thermal losses.

3.3. Solar Collector without PV

The asymmetric reflector was further investigated with a receiver lacking a PV on both receiver sides to scrutinize the geometry and the influence of a heat transfer fluid at elevated temperatures. Previous findings clearly indicate that higher volumetric concentrations of the nanoparticle result in increased efficiencies. Consequently, only a concentration of 5% CuO was explored for this particular configuration of the solar collector.

As presented in Figure 10, the thermal efficiency profiles for both water and nanofluid exhibited comparable trends. A more significant enhancement was observed at higher inlet temperatures. The overall mean thermal efficiency enhancement was determined to be 2.16%, while the maximum observed increase was remarkably high at 7.09%.

![Figure 10. Thermal efficiency of the solar collector without PV for nanofluid 5% CuO/water.](image)

4. Conclusions

This research explored the utilization of a nanofluid as the operational fluid in an asymmetric CPC with and without a PV element. Two different base fluids were examined, Syltherm 800 and water, with two different volumetric concentrations of CuO, 3% and 5%, and the results were compared with each base fluid. The hybrid receiver was examined for both base fluids and both concentrations while the plain receiver (without a PV) was examined only with water as the base fluid. The investigation was carried out for varying inlet temperatures ranging from 20 °C to 140 °C, depending on the type of receiver used. To maintain laminar flow conditions in all cases, the inlet flow rate was held constant at 1 ltr/min. The analysis was conducted using a three-dimensional model encompassing optical and thermal aspects in COMSOL. The key findings presented in this paper include:

- Generally:
  - Higher nanoparticles’ concentrations lead to greater thermal efficiency.
  - The water-based nanofluid exhibited higher efficiencies compared to the Syltherm 800 cases.
The addition of nanoparticles leads to remarkably more significant enhancements in the Syltherm 800 case both in thermal and electrical performance.

Water case:

- The nanoparticles’ addition slightly reduced the thermal efficiency at low temperatures, and it increased it remarkably at higher ones. This happened due to the lower volumetric specific heat capacity and the higher thermal conductivity of the nanofluid compared to the base oil. The first parameter seemed to be more important in low temperatures, while the second one seemed to have greater impact at high temperatures by overcoming the limitation of the volumetric specific heat capacity.

- In the PV/T receiver case, the maximum thermal enhancement observed for the CuO/water nanofluid was 0.28%, while the maximum electrical efficiency increase was 0.04%.

- The enhancement in the electrical efficiency by the application of the nanofluid was negligible.

- In the receiver case without a PV, the maximum enhancement was remarkably high at 7.09% for the operating temperature of 140 °C.

Syltherm 800 case:

- The nanoparticles’ addition significantly enhanced the collector’s thermal efficiency for the entire temperature range examined.

- The thermal enhancement was observed to be up to 25.68% at high temperatures and up to 1.32% at low and medium temperatures, while the maximum electrical efficiency increase was 0.44%

**Author Contributions:** Conceptualization, T.P. and D.N.K.; methodology, T.P. and D.N.K.; software, T.P. and D.N.K.; validation, T.P. and D.N.K.; formal analysis, T.P. and D.N.K.; investigation, T.P. and D.N.K.; resources, I.K. and C.T.; writing—original draft preparation, T.P. and D.N.K.; writing—review and editing, I.K. and C.T.; visualization, T.P. and D.N.K.; supervision, I.K., C.T. and D.N.K.; project administration, I.K. and C.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Bodossaki Foundation (D.N. Korres).

**Data Availability Statement:** Data is contained within the article.

**Acknowledgments:** D.N. Korres would like to thank Bodossaki Foundation for its financial support in his post-doctoral research.

**Conflicts of Interest:** The authors declare no conflicts of interest.

**Nomenclature**

*General Parameter*

- **A** Surface area, mm²
- **Cp** Fluid specific heat, J/(kg K)
- **G** Solar radiation, W/m²
- **k** Thermal conductivity, W/m K
- **L** Length, mm
- **m** Mass flow rate, m³/s
- **n** Number of elliptical channels, -
- **Q** Energy rate, W
- **R** Radius, mm
- **r** Reflectance, -
- **T** Temperature, K
- **W** Width, mm
- **βpv** PV temperature dependence, %/K
- **ηpv** PV nominal efficiency, %
$\eta_{\text{th}}$  
Thermal efficiency, %

$\eta_{\text{el}}$  
Electrical efficiency, %

Greek symbols

$\alpha$  
Absorptance, -

$\beta$  
Ratio of the thickness

$\varepsilon$  
Emissivity, -

$\mu$  
Dynamic viscosity, Pa s

$\varrho$  
Density, kg/m$^3$

$\tau$  
Transmittance, -

$\varphi$  
Volumetric concentration, %

Subscripts

$a$  
Ambient

$\text{abs}$  
Absorber or absorbed

$b$  
Base

$\text{bot}$  
Bottom

$\text{fluid}$  
Fluid

$\text{in}$  
Inlet

$\text{losses}$  
Losses

$m$  
Mean

$n$  
Nano

$\text{out}$  
Outlet

$\text{particle}$  
Particle

$\text{PV}$  
Photovoltaic

$\text{rec}$  
Receiver

$\text{refl}$  
Reflector

$\text{sky}$  
Sky

$T$  
Perpendicular to aperture

$\text{top}$  
Top

$\text{water}$  
Water

Abbreviations

CPC  
Compound Parabolic Concentrator

MWCNT  
Multiwall Carbon Nanotubes

PTC  
Parabolic Trough Collector

PV/T  
Thermo-photovoltaic

SWCNT  
Single Wall Carbon Nanotubes

References


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.