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Comparative Modeling of Photovoltaic Thermal (PV/T) Collector Performance Using Two Different Heat Transfer Fluids Under the Same Weather Scenario

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Photovoltaic thermal, Solar collector, Efficiency, Modeling, Air, Water, Performance.

ABSTRACT

In this paper, a detailed investigation of the energetic characteristics of a photovoltaic thermal collector taking into consideration water and air as heat transfer fluids, circulating through the flow channel at the collector under examination. The present research takes as its main purpose the evaluation of the differences in performance between both tested transfer flows and to identify the impact of each fluid on energy efficiency. A mathematical model governing heat transfer between the principal elements of the investigated device is defined.

The numerical resolution of this model is carried out using MATLAB software, taking into consideration air and water as heat transfer fluids, with similar flow conditions and meteorological parameters. The numerical model allowed us to make a detailed evaluation of the energy properties of the analyzed system. The findings obtained showed significant differences between both coolants examined. The cooling effect of water demonstrated superior heat transfer capacity, with higher heat transfer rates and better overall energy efficiency than air, and a positive effect on electrical efficiency was observed. The use of water demonstrated a better overall energy efficiency of around 67.84%, compared with the case of air, which was no more than 57%.

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نمذجة مقارنة لأداء مجمع حراري كهروضوئي (PV/T) باستخدام وسطين مختلفين لنقل الحرارة في ظل نفس الظروف المناخية

محمد احلوتي، ربيع العثماني، خالد قندوسي، امحمد بوطاوس.

ملخص: في هذه الورقة، تم إجراء دراسة مقارنة لأداء الطاقة لمجمّع حراري كهروضوئي باستخدام الهواء والماء كسوائل لنقل الحرارة، يتم عبور السوائل عبر قناة التدفق في المجمّع قيد الفحص. والهدف الرئيسي من هذه الدراسة هو تقييم الاختلافات في الأداء بين سائلي نقل الحرارة وتحديد تأثير كل سائل على المردود الطاقي للمجمع الشمسي المدروس. تم تحديد نموذج رياضي يحكم انتقال الحرارة بين مختلف الطبقات المكونة للمجمع محل الدراسة. تم تنفيذ الحل العددي لهذا النموذج الرياضي باستخدام برنامج MATLAB، مع الأخذ في الاعتبار الهواء والماء كسوائل لنقل الحرارة، مع ظروف تدفق ومعلمات أرصاد جوية متشابهة. سمح لنا النموذج العددي بإجراء تقييم مفصل للأداء الكهربائي والحراري الذي يميز النظام المدروس. أظهرت النتائج التي تم الحصول عليها اختلافات كبيرة بين استخدام الهواء والماء كسوائل لنقل الحرارة، حيث تبين أنه لاستخدام الماء قدرة فائقة على نقل الحرارة، و ذلك بالتحصل على معدلات نقل حرارة أعلى وكفاءة طاقة إجمالية أفضل مقارنة باستخدام الهواء كناقل للحرارة، ولوحظ أيضا تأثير إيجابي على الكفاءة الكهربائية للنظام الشمسي المدروس. وتم أيضا التوصل إلى نتيجة أنه لاستخدام الماء كفاءة طاقة إجمالية أفضل بنسبة 67.84 % تقريبا، مقارنةً بحالة استعمال الهواء التي لم تتجاوز قيمة هذه النسبة عندها 57%.

الكلمات المفتاحية الحرارية الكهروضوئية، المجمع الشمسي، الكفاءة، النمذجة، الهواء، الماء، الأداء.

1. INTRODUCTION

With electricity consumption on the rise, Moroccan energy policy aims to significantly enhance the proportion of renewable energy sources in national electricity production, and made a goal of over 50% of the country's electrical capacities supplied by renewable energies by 2030. One of the main factors influencing the energetic return of a PV/T device is the type of coolant employed, several types of fluid were examined by scientists to analyze the yield of different PV/T devices.

Ong [1] has examined four configurations of single-flow air collectors intending to examine the transmission of thermal energy between the circulating air and the various components of the configurations examined. In Farshchimonfared et al. [2] study, an unglazed single-pass PV thermal air collector was examined pertaining to channel depth and inlet mass flow. Tonui and Tripanagnostopoulos [3] investigated the influence of a number of geometric parameters and the inlet air flow on the yield and power generated for numerous air PV/T devices. Slimani et al. [4] have implemented an assessment of a double-pass PV/T system, they sought to develop the collector examined for integration into an indirect solar dryer. Tiwari et al. [5] have measured the total yield of a hybrid air system based on the variation in the incoming air velocity, they have also examined the operation of the analyzed system by determining the optimum length and depth. Tiwari and Sodha [6] have reviewed various designs of glazed and unglazed PV/T air systems, and they also analyzed the influence of the tedlar layer on the energy efficacity of the solar systems studied. Aste et al. [7] have carried out an analysis of the yields of an uncovered water PV/T system at three different Italian sites. An experimental study by Nualboonrueng et al. [8] of a single-glazed photovoltaic thermal system under the effect of the weather characteristics of a Thailandian location, they also discussed the energetic behaviors of different PV thermal systems depending on multicrystalline silicon and amorphous silicon. A detailed numerical investigation by Lämmle et al. [9] to determine the effect of a selective coating on the thermal behavior of a flat glass PV/T water collector.

Dimri et al. *[10]* have conducted a comparative examination of a PV/T system combined with a thermoelectric system, considering air and water as operating fluids, they found that the thermal productivity in the water case is 21.8% higher than in the air case. Senthilraja et al. *[11]* have assessed the energy effectiveness of water and air-based PV thermal systems for hydrogen production, their findings demonstrated that the highest reduction in PV cells temperature was almost 20% for the PV/T-water system. Daghigh and Khaledian *[12]* experimentally evaluated the thermal yield of a bi-fluid (water, air) hybrid collector under cold Iranian climate. In the study by El Manssouri et al. *[13]* a comparative evaluation of thermal behavior was carried out between a basic PV/T system and a bi-fluid hybrid collector, their results indicate that the bi-fluid collector improves thermal efficiency compared with a PV thermal system cooled only by water. In another study by Zabihi Sheshpoli et al. *[14]*, an investigation of four different configurations of PV/T tube collectors was performed, their results revealed that electrical performance was improved by around 7.3% using the serpentine tube configuration when compared to the uncooled collector.

In the study *[15]*, an experiment was carried out on a PV/T collector supplied by heating pipes allowing water circulation, the experiment was carried out at three sites with different climatic characteristics to evaluate the effect of water cooling on the thermal specifics of the studied solar configuration. Yuan et al. *[16]* have compared the energy yield of a hybrid solar panel using water pipes against a conventional photovoltaic panel, their findings indicate that daily electrical efficiencies are 10.2% and 8.2% respectively for the two systems compared. Assoa et al. *[17]* have developed a PV/T prototype designed specifically for rooftop integration. Their study focused mainly on a parametric analysis aimed at optimizing the performance of the configuration studied. Another study providing an experimental reviewing of the energy performance of two flat-plate PV/T devices is included in Ref. *[18]*, the authors carried out tests on both hybrid systems exploiting numerous absorber types.

The main focus of this research is to carry out a comparative study of the performance of two PV/T devices using water and air separately as heat transfer fluids. The aim is therefore to assess and measure the energy features of the two solar systems reviewed under the same weather operating conditions; the first system exhibits an air-cooled PV/T panel, while the second shows a water-cooled PV/T panel. As this study focuses on highlighting the benefit of using each cooling fluid on the energy characteristics of both systems, considering that the two systems have the same geometric dimensions and the same physical specifications, exposed to an identical external environmental factor. The only difference between the two studied systems is the type of fluid that would work to cool the solar systems under investigation.

2. DESCRIPTION OF SOLAR SYSTEMS

The solar collector investigated in this work is a device designed to capture and convert the solar energy received into heat and electricity simultaneously (see Figure. 1), it comprises a glazing layer specially incorporated to maximize the transmission of solar radiation.

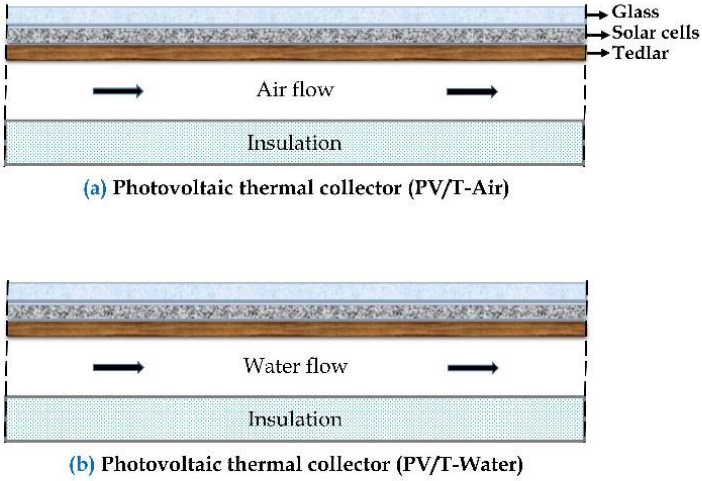

Figure 1. Schematic illustration of solar collectors examined: (a) PV/T-Air, (b) PV/T-Water.

In addition, it features a rectangular channel to ensure fluid flow, with the aim of minimizing the temperature at which photovoltaic cells operate; the main features of the solar device under examination displayed in Table 1. It should be noted that air and water are assumed to have the same flow rate as they pass through the rectangular channel inlet section, and also that the temperature of the inlet coolant is equivalent to the ambient air temperature. In addition, the fluid velocity considered constant during the performance test of each investigated collector.

Table 1. Primary specifications of the examined hybrid solar device [19], [20].

Properties	Value
Collector area, A_c	2 m^2
Collector width, W	1 m
Collector length, L	2 m
Duct thickness, l_f	2 cm
Packing factor, β	0.89
PV module efficiency, η_{ref}	18 %
Temperature coefficient, β_T	0.405 %/K
Conversion factor, C_f	0.36
Insulation thickness, l_{is}	5 cm
Solar cells absorptance, α_c	0.89
Glass emissivity, ε_g	0.93
Solar cells conductivity, k_c	0.035 W/m.K

3. MATHEMATICAL MODELING

In this work, the energy conservation principle has been applied to the two solar collectors examined, while the energy balance used enables to identify the temperature at which photovoltaic cells operate, as well as the fluid temperature traversing the rectangular channel.

For the glass layer *[20]*:

$$m_g Cp_g \left(\frac{dT_g}{dt}\right) = A_c(\alpha_g G - h_{rd,g}(T_g - T_k) - h_{v,a}(T_g - T_a) - h_{c,g-c}(T_g - T_c)) \quad (1)$$

where:

$h_{rd,g}$ refers to the exchange parameter by irradiation relating the top layer to the external surround, formulated by the following formula *[21], [22]*:

$$h_{rd,g} = \varepsilon_g \sigma (T_k + T_g)(T_g^2 + T_k^2) \quad (2)$$

The convective parameter due to wind speed V_w can be defined as follows *[23], [24]*:

$$h_{v,a} = 2.8 + 3V_w \quad (3)$$

For the solar cells layer *[20]*:

$$m_c Cp_c \left(\frac{dT_c}{dt}\right) = A_c(\tau_g \alpha_c \beta G - h_{c,g-c}(T_c - T_g) - h_{c,c-t}(T_c - T_t)) - Q_{el} \quad (4)$$

Where: T_c, T_g and T_t refer to the temperatures of solar cells, top cover and tedlar layer respectively.

$h_{c,g-c}$ and $h_{c,t-c}$ correspond to the parameters of conduction exchange connecting the PV cells layer to the glass cover, and the one that relates the tedlar and PV cells layers, respectively; these two parameters are expressed as follows *[25], [26]*:

$$h_{c,g-c} = \frac{1}{\left(\frac{l_c}{k_c}\right) + \left(\frac{l_g}{k_g}\right)} \quad (5)$$

$$h_{c,c-t} = \frac{1}{\left(\frac{l_c}{k_c}\right) + \left(\frac{l_t}{k_t}\right)} \quad (6)$$

For the fluid flow through the channel *[20]*:

$$m_f Cp_f \left(\frac{dT_f}{dt}\right) = A_c \left(h_{cv,f}(T_t - T_f) - h_{cv,f}(T_f - T_{is})\right) + \dot{m} C_{pf}(T_{in} - T_{out}) \quad (7)$$

By calculating the average fluid temperature based on Eq. (7), the outlet temperature of the duct that ensures the displacement of the operating fluid can be determined as follows:

$$T_{out} = 2T_f - T_{in} \quad (8)$$

Where:
T_f and T_{is} refer to the mean temperature of working coolant and the insulator temperature, respectively; T_{in} indicates the temperature of the fluid as it enters the duct of collector.

The convective parameter of the fluid flows in the channel:

$$h_{cv,f} = \frac{Nu \cdot k_f}{d_h} \tag{9}$$

Where: The Nusselt number (Nu) is regarded as a dimensionless measure that characterizes the convection regime of a fluid. It is defined as the ratio of heat flux by convection to heat flux by conduction. Therefore, a higher Nusselt number indicates more efficient convection, hence, a higher convective parameter ($h_{cv,f}$), resulting in an acceleration of heat transfer between the fluid and the collector channel. The correlations that describe the Nusselt number vary depending on the nature of the coolant flowing through the channel, and can be expressed as follows;

In the case of air flow *[27], [28]*:

$$Nu = 0.023 \cdot Pr_f^{0.4} \cdot Re_f^{0.8} \tag{10}$$

In the case of water flow:

$$Nu = 0.023 \cdot Pr_f^{0.33} \cdot Re_f^{0.8} \tag{11}$$

with: Re_f and Pr_f represent the Reynolds and Prandtl number of the operating fluid.

$$Re_f = \frac{\rho_f \cdot d_h}{\mu_f} v_f \tag{12}$$

While: The Reynolds number (Re_f) is a crucial dimensionless parameter that helps characterize the flow regime describing the fluid circulation around the collector channel. It depends on the fluid's inlet velocity (v_f), and is inversely proportional to the fluid's dynamic viscosity (μ_f). In general, an increase in the Reynolds number leads to enhanced convective heat transfer. As shown in Table 2, it is notable that the Reynolds number is less pronounced for water flow due to its higher viscosity compared to air.

Table 2. Main thermophysical factors of the cooling fluids investigated [20], [26].

Properties	Water	Air
Heat capacity, Cp (J/kg.K)	4180	1004
Thermal cond, k_f (W/m.K)	0.6	0.025
Density, ρ_f (kg/m^3)	997	1.18
Dyn. viscosity, μ_f (Pa.s)	$6.5 \cdot 10^{-4}$	$18 \cdot 10^{-6}$
Prandtl number, Pr_f (-)	4.48	0.74
Mass flow, $\dot{m}$ (kg/s)	0.023	0.023
Reynolds number, Re_f (-)	69.4	$2.4 \cdot 10^3$

The electrical yield could be determined in that manner *[29], [30], [31]*:

$$\eta_{el} = \eta_{ref} \cdot \left(1 - \beta_T(T_c - T_{c,r})\right) \tag{13}$$

Based on Eq. (12), the electrical power generated can be expressed as follows *[32], [33]*:

$$Q_{el} = \eta_{el} \cdot G \tag{14}$$

For evaluating the appropriate thermal behavior of the investigated system with regard to the effect of air and water separately, the thermal yield is used as a performance metric, which is expressed by the following formula *[20]*:

$$\eta_{th} = \frac{Q_{util}}{A_c \cdot G} = \frac{\dot{m}_f Cp_f (T_{out} - T_{in})}{A_c \cdot G} \quad (15)$$

Where: Q_{util} stands for the recoverable thermal energy by the PV/T collector, whereas A_c signifies the collector surface.

The overall efficiency of each photovoltaic thermal collector under investigation can be defined by the following relation *[34], [35], [36]*:

$$\eta_{ov} = \frac{\dot{m}_f Cp_f (T_{out} - T_{in})}{A_c \cdot G} + \frac{\eta_{el}}{C_f} \quad (16)$$

4. CLIMATIC CHARACTERISTICS

4.1. Site climate description

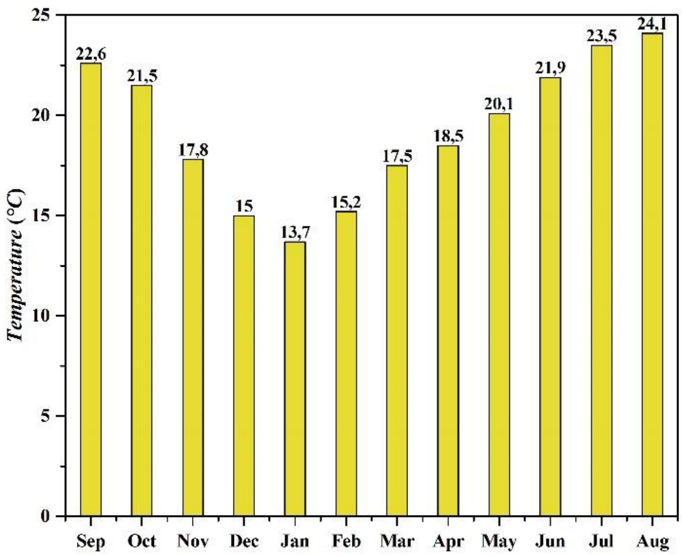

Figure 2. Monthly temperature variations in Agadir city [37].

The city of Agadir, part of the Souss-Massa region, is a coastal city located in west-central Morocco, on the edge of the Atlantic Ocean, the area examined exhibits a latitude of 30.4° North, a longitude of -9.6° East and an elevation of 23 meters. It lies close to the Anti-Atlas Mountains and has a Mediterranean climate. The summer in Agadir is known for its high temperatures and dry climate, where temperatures can exceed 30°C. Winters are generally mild, with temperatures averaging around 15°C. The region's temperature variations are mainly related to the changing seasons (see Figure. 2). In August, the highest level of monthly temperature variation is recorded, reaching 24.1°C, while the lowest monthly value is observed in January, with 13.7°C.

The examined area benefits from significant insolation that is abundant throughout the seasons (see Figure. 3), with an annual total of around 3032 hours of sunshine. The peak of sunshine hours is observed in May, with 296 hours, while the minimum of 219 hours is recorded in November.

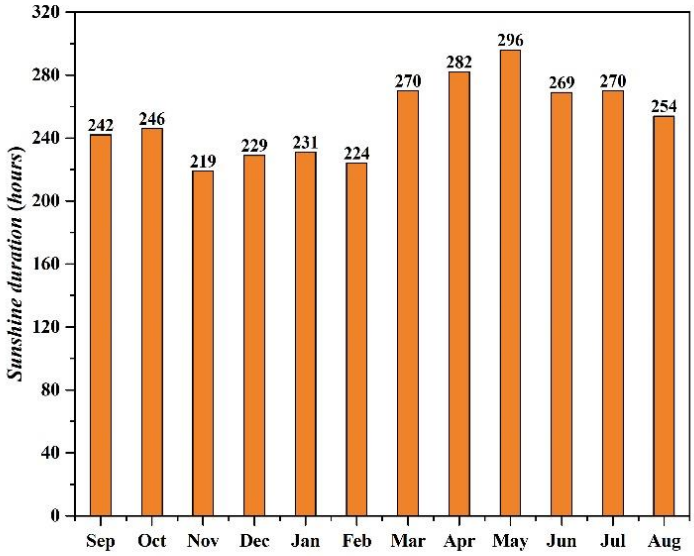

Figure 3. Monthly variations of sunshine duration in Agadir city [37].

4.2. Meteorological data

For this study, a clear, sunny summer day is taken as the reference for examining the operation of both examined solar collectors. The meteorological data used are from Agadir, presented according to surrounding temperature and received irradiation. The hourly variation in the weather parameters of the selected day that have been used in the tracking of the energy productivity of the solar collector are presented in Figures. 4 and 5.

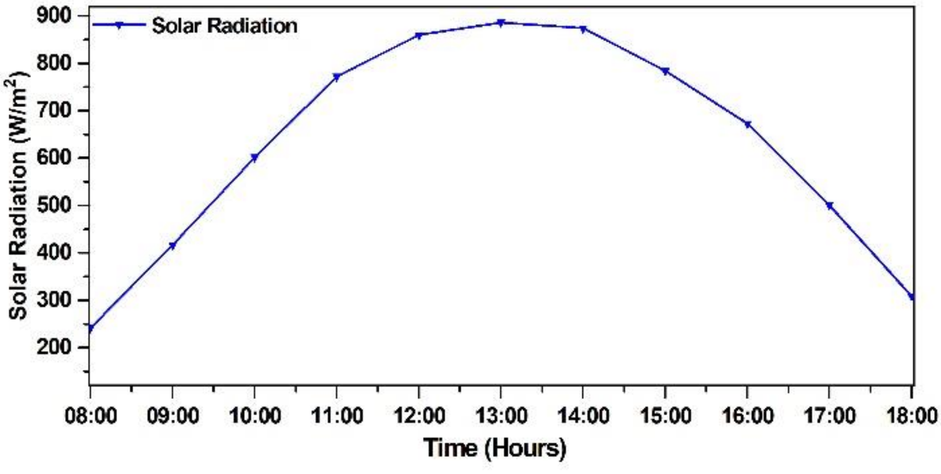

Figure 4. The daily variability of incoming irradiation for the tested day [37].

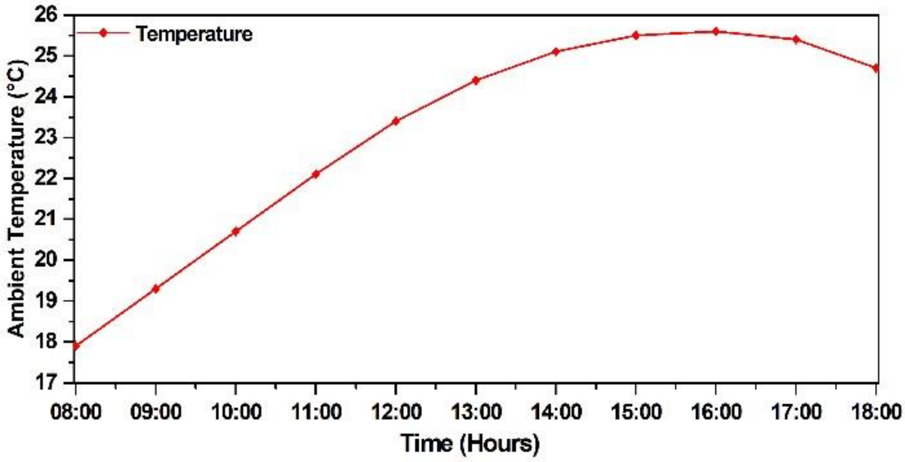

Figure 5. The daily variability of ambient temperature for the tested day [37].

The comparative analysis of the energetic effectiveness of the two hybrid collectors is founded on the heat balance that combines the various components of each solar configuration, the procedure for the numerical resolution of the used heat balance was implemented in MATLAB environment. The hourly meteorological parameters of the selected day, which range from 8h00 to 18h00 (see Figs. 4 and 5), are used as inputs during numerical solving, while the wind speed parameter is taken as an average of 1 m/s over the test period. The geometrical characteristics and the primary specifications of the tested solar device are denoted in Table 1, accompanied by the principal thermophysical parameters of both cooling agents used are indicated in Table 2.

5. Results and discussions

5.1. Solar cells temperature

The temporal evolution of solar cells temperature for both photovoltaic thermal collectors examined is presented in Figure. 6; we can clearly distinguish that there is a significant difference between both temperature profiles, which strongly demonstrates the resultant of the operating fluid type on the solar collector working temperature.

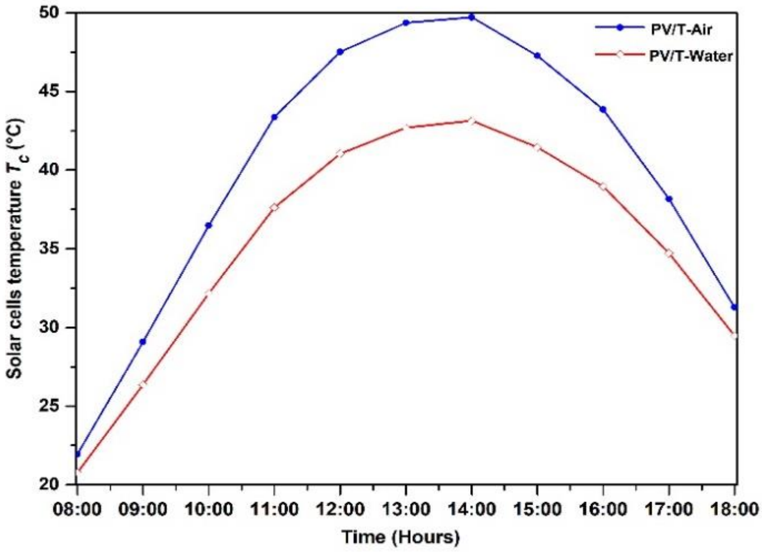

Figure 6. The temporal evolution in temperature of solar cells for the selected day.

At 14h00, the solar cell temperature reaches its maximum values by: $49.7\ °C$ and $43.1\ °C$ for both the air and water hybrid solar collector, respectively. In addition, by using water as an operating fluid, it is possible to increase the cooling rate by 12.7% compared with the use of air.

5.2. Operating fluid temperature

Figure. 7 depicts the hourly evolution in the mean temperature of the operating fluid over the selected day for the two collectors examined. It can be noted that this temperature depends on the type of fluid used; also, it is viewed that the fluid temperature in the water-cooled hybrid collector is lower throughout the daytime than in the air-cooled PV/T collector. At 14h00, the fluid temperature reaches its maximum value: $29.85\ °C$ and $27.4\ °C$ for the case of the studied air and water PV thermal collector, respectively.

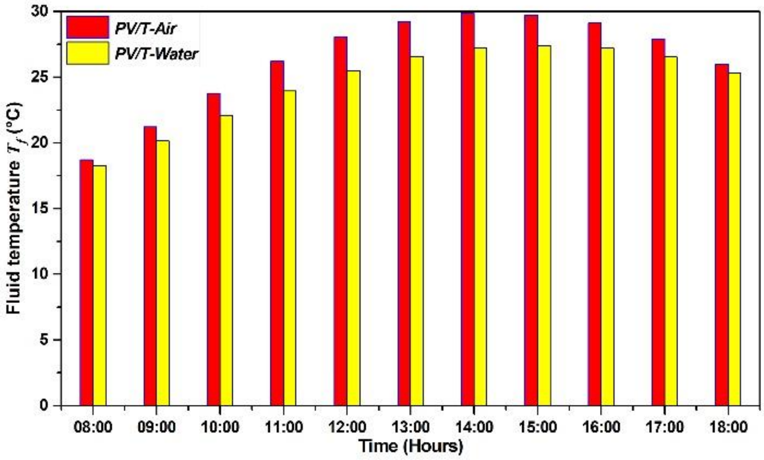

Figure 7. Daily variability of the mean temperature of each working fluid.

5.3. Electrical efficiency

The temporal variation of the electrical productivity for both hybrid solar collectors studied is depicted in Figure. 8. In both types of collectors tested, there was a clear decrease in electrical efficiency at midday, which can be attributed to the warmer operating temperature at this period of the day (see Figure. 6).

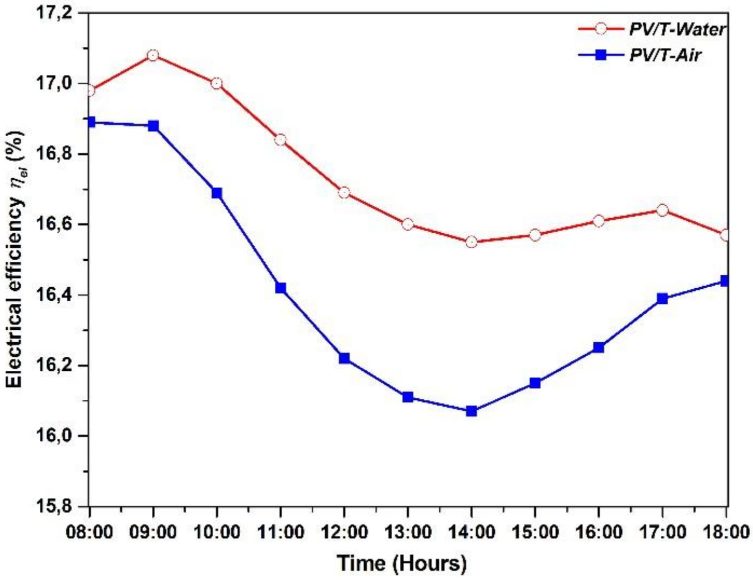

Figure 8. The daily fluctuations in electrical yield for the selected day.

The mean electrical yield is 16.74% for the water-based PV/T collector, while this average is around 16.41% for the air-based collector. As a result, we can conclude that using of water in the role of a coolant provides a beneficial effect on the energy yield of the hybrid solar panel under examination, allowing us to enhance the electrical efficacy by a percentage of 2.05% compared with the case of applying air as the operating fluid.

5.4. Thermal efficiency

Figure. 9 provides a comparative illustration of the cooling effect of each coolant on the thermal behavior of the investigated collector. The comparison utilizes the daily variation of thermal yield as a performance metric under the same operating conditions. From the graphical representation in Figure. 9, it is evident that the water-cooled collector exhibits a more effective thermal yield, reaching a maximum value of 23.6%, whereas the air-cooled collector does not exceed 12.55% at its maximum. The findings indicate that using water as a coolant offers a more efficient capability to convert the dissipated heat from the collector into usable heat. This advantage of using water as a coolant can be attributed to its significantly higher specific heat capacity, which is nearly 4 times larger compared to that of air (See Table 2).

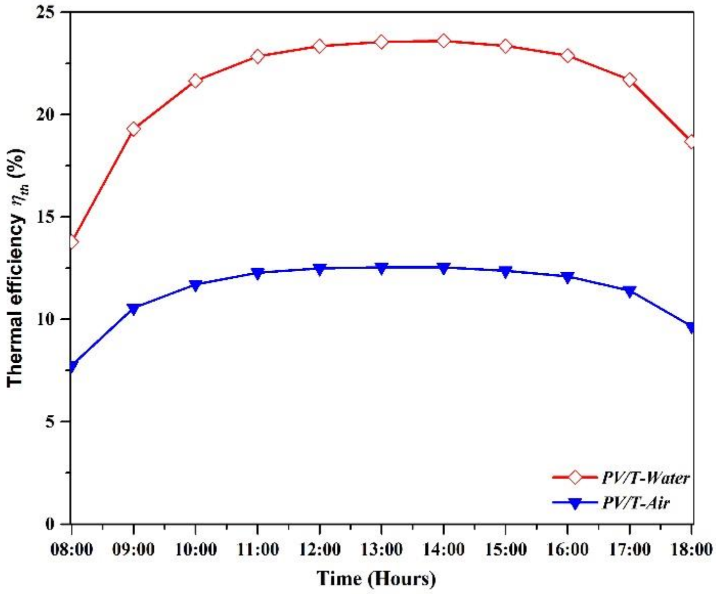

Figure 9. The hourly variation in thermal yield for the selected day.

5.5. Overall efficiency

The daily evolution of the overall yield that characterize both studied hybrid solar collector is illustrated in Figure. 10. From the two variations, it is clearly deduced that the PV/T configuration with water cooling offers a considerable advantage in terms of overall efficiency, with a daily average of 67.84%, while this average remains below 57% for the hybrid configuration cooled by air. Due to this, it obviously demonstrated that the use of water as a heat transfer fluid optimizes overall efficiency by around 19% compared with the air collector.

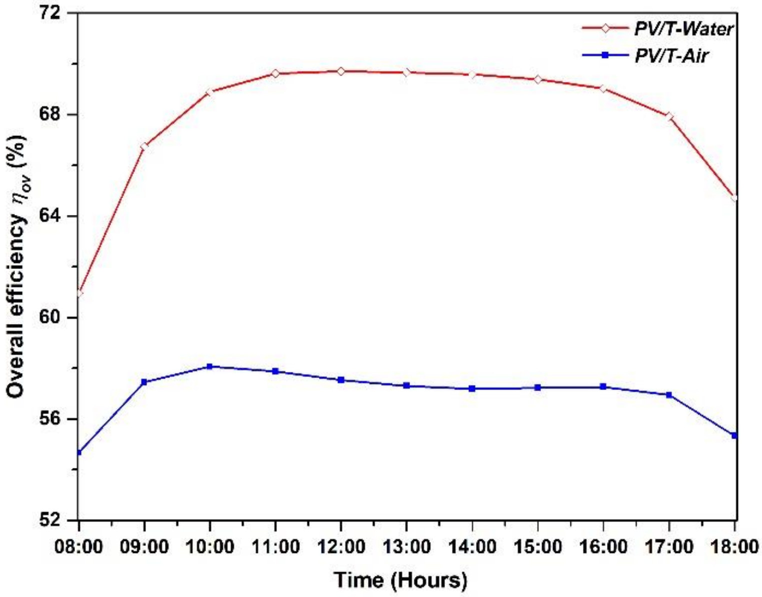

Figure 10. The hourly variation in overall efficiency for the selected day.

5.6. Energy efficiency

A comparative illustration of the energy efficiencies of the two collectors examined is shown in Figure. 11. The observation drawn from the comparison reveals that the PV/T collector cooled by water carries a significantly greater energy efficiency than the air-cooled collector; this remarkable superiority in energy efficiency due to the use of water could be explicated by its significant thermal conductivity and density, which enables more efficient heat extraction than air.

Using water as a liquid to extract the dissipated heat energy in a solar hybrid collector offers an average thermal efficiency of 21.34%, while that of air averages just 11.4%; this means an 87% improvement in thermal yield from water in comparison with air.

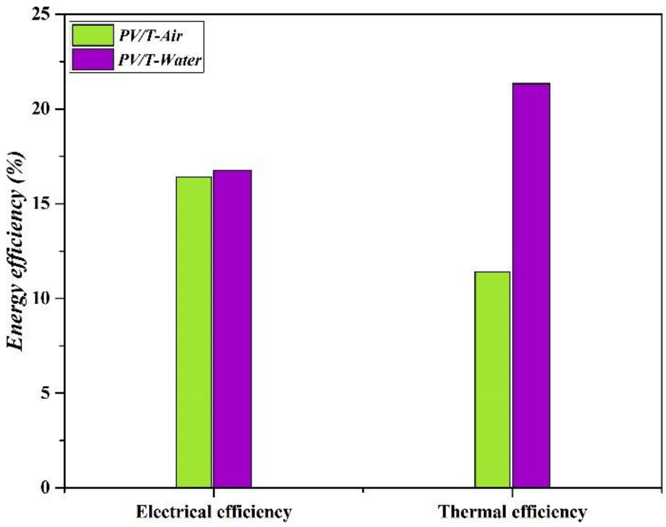

Figure 11. Comparative representation of average thermal and electrical yields for the two hybrid configurations examined.

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Using water as a liquid to extract the dissipated heat energy in a solar hybrid collector offers an average thermal efficiency of 21.34%, while that of air averages just 11.4%; this means an 87% improvement in thermal yield from water in comparison with air.

6. Conclusion

In this paper, a comprehensive modeling of the energizing behavior of a hybrid PV/T design utilizing air and water in the role of working coolant is realized within the framework of the effect of same weather properties. In this context, several characteristics that define the behavior of the reviewed hybrid PV/T configuration with respect to energy generation have been taken into consideration, including electrical yield, overall yield, also the functioning temperature during the day under investigation. The cooling rate for each type of working fluid has been defined, and their impact on energy efficiency has been discussed in detail.

According to the comparative study conducted through this work, several conclusions can be derived from this research, which may be outlined in this manner:

- The water PV/T device exhibits smaller daily average solar cell temperature ($35.31\ °C$) than the air PV/T device ($39.83\ °C$).
- The hybrid collector cooled by water presents a higher daily average electrical efficiency (16.74%) than the one cooled by air (16.41%).
- The overall efficiency when water is used as a coolant in the hybrid system examined averages about 67.84%, which is significantly higher than using air as a coolant (56.99%).
- The studied water hybrid solar collector increases the cooling rate by 12.7% compared to the air hybrid collector, and consequently an improvement in electrical efficiency of about 2.05%.
- In terms of daily average of energy efficiency, utilizing water in the role of a cooling liquid resulted an optimization of around 19% versus employing air in a coolant role.

Finally, we can consider that this study has already answered in a detailed way the question of how to amend the production capacity of PV/T systems by cooling the solar panels by water and air under real climatic factors. Hence, as a perspective for the future works, the results of this paper can be used to further investigate the possibility of incorporating other heat transfer fluids in solar panels to increase energy efficiency and to maximize the benefits from the incoming irradiance by photovoltaic thermal devices.

Author Contributions: Conceptualization, M.A.; Methodology, all authors; Validation, M.A. and R.EO.; Formal analysis, M.A.; Supervision, R.EO.; Investigation, M.A.; Resources, all authors; Data curation, M.A.; Original draft preparation, M.A.; Writing-reviewing and editing, M.A. and R.EO.; All authors have endorsed the conclusive draft of the manuscript for publishing.
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Data Availability Statement: Not applicable.
Conflicts of Interest: The authors declare that they have no conflict of interest.

Nomenclature

PV/T-air	*Air photovoltaic thermal*
PV/T-water	*Water photovoltaic thermal*
Symbols	
C_p	*Heat capacity* ($J/kg.K$)
C_f	*Conversion factor*
G	*Incoming irradiance* (W/m^2)
d_h	*Hydraulic diameter (m)*
k	*Thermal conductivity* ($W/m.K$)
m	*Component mass (kg)*
$\dot{m}$	*Mass flow* (kg/s)
Q_{el}	*Electrical power* (W/m^2)
T	*Temperature*
t	*Time*
Greek symbols	
α	*Absorptance*
η	*Efficiency*
τ	*Transmittivity*
l	*Thickness (m)*
ε	*Emissivity*
Subscripts	
c	*solar cells*
el	*electrical*
f	*fluid*
g	*glass*
in	*inlet*
is	*insulator*
out	*outlet*
ov	*overall*
r	*reference*
t	*tedlar*

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