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CFD Analysis of Hybrid Photovoltaic Thermal (PV/Th) Solar Collector Efficiency Incorporating Ag-AL$_2$O$_3$/water Hybrid Nanofluids

Charafeddine Beldjani[1,*], Kamel Aoues[1], Noureddine Belghar[1,2], Yousra Boutera[3], Mohamed Aymen Kethiri[1,4]

[1]*Laboratoire de Génie Energétique et Matériaux, LGEM, University of Biskra 07000, Algeria*
[2]*Abbes Laghrour University of Khenchela, Algeria*
[3]*Laboratoire de Génie Mécanique, LGM, Université de Biskra, B.P145 R.P.07000 Biskra, Algeria*
[4]*Department of Architecture, Built Environment and Construction Engineering, DABC, Politecnico di Milano.*

ABSTRACT

The optimization of energy consumption is closely tied to enhancing the power output of photovoltaic panels. This study offers a numerical investigation of the utilization of hybrid nanofluids (Ag-Al_2O_3-water) as a cooling fluid in a hybrid photovoltaic thermal (*PV/Th*) collector, aiming to improve electrical performance by lowering the *PV* cells operating temperature. The hybrid *PV/Th* collector comprises a photovoltaic panel (*PV*) coupled with a thermal collector, including a heat sink equipped with rectangular ribs positioned at the bottom of the *PV* module. This research explores the impact of critical configuration parameters, such as inlet velocities of working fluid and nanoparticle volume fractions, on the *Nu* number, *PV* cell temperature, and both thermal and electrical efficiencies within steady-state operating conditions. The 3D numerical simulation to analyze the overall performance of a hybrid *PV/Th* collector was conducted using ANSYS Fluent software version 17.1. The numerical findings demonstrate that increasing the nanoparticle volume fraction elevates the cooling fluid's thermal conductivity, consequently enhancing the heat transfer by conduction. Furthermore, higher coolant velocities enhance heat transfer by convection, resulting in a more effective heat transfer rate within the *PV/Th* system. This, in turn, reduces the operating temperature and significantly enhances the hybrid *PV/Th* system's overall performance.

KEYWORDS

Renewable energy
Solar energy
Hybrid Photovoltaic-Thermal solar collectors
PV panel
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Heat and mass transfer

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1 Introduction

The majority of solar radiation absorbed by photovoltaic panels is not completely converted into electricity by the photovoltaic cells, which typically convert approximately 15 to 20% of solar radiation into electrical energy, while the residual solar radiation generates heat, thereby reducing the efficiency of *PV* cells [1]. This portion of solar radiation that is not converted increases the operating temperature of photovoltaic cells, which decreases output power efficiency by 0.4 to 0.5% for every 1°C than the rated temperature (which is typically 25°C). For this, cooling for *PV* panels becomes crucial [2].

Using a cooling method for *PV* modules effectively minimizes the high temperature of *PV* cells and enhances electrical efficiency [3]. This can be achieved by combining these *PV* panels, which transform light into electricity, with a thermal collector, which absorbs the remaining energy and eliminates waste heat from the *PV* panel, forming a hybrid photovoltaic-thermal collector (*PV/Th*) system. The Hybrid *PV/Th* collectors represent the most effective technology for converting sunlight into both thermal and electrical energy [4], which uses two or more power sources to produce electrical and thermal energy simultaneously.

Solar thermal collectors can be engineered to lower the *PV* cell's temperature by removing heat via a heat transfer fluid. Many different studies have been carried out utilizing air and water as cooling fluids for *PV/T* to minimize *PV* cell temperature and increase system efficiency [5-8], with higher performance than *PV* alone [9]. However, Conventional methods for cooling photovoltaic panels (such as cooling with water or air through natural or forced convection) are insufficient, due to the cooling fluid having low thermal conductivity [10], one of the recent popular methods for improving heat transfer at the photovoltaic cell is nanofluids which are used in different thermal applications due to their superior thermal conductivity and greater specific surface area relative to base fluids (water and air) [11, 12]. Hence, improving the performance of solar systems and increasing total efficiency. Where nanofluids have suitable properties for heat transfer and absorption [13, 14].

Researchers [15-18] have conducted both experimental and numerical studies to examine the impact of using nanofluids as a cooling fluid on *PV* panels and *PV/T* systems; they have used different types of nanoparticles, such as SiO_2, Al_2O_3, and TiO_2, as well as various values of solid particle volumes, whereas the results showed that the use of nanoparticles with high values of solid particle volumes helps to reduce the PV cell's temperature and enhance the thermal efficiency of *PV/T* collector. The evaluation of

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* Corresponding author. Charafeddine Beldjani (*C.* Beldjani)
E-mail : charafeddine.beldjani@univ-biskra.dz

energy efficiency of an un-glazed *PV/T* collector has been studied experimentally and numerically by Rejeb et all [19]. they floated different nanoparticles in various base fluids (water and glycols). They discovered that utilizing water and copper nanoparticles as the base fluid improved efficiency. The techno-economical evaluation of a grid-connected hybrid *PV/T* was presented theoretically and experimentally by Al-Waeli et al [20], by using different nanoparticles floated in water as the base fluid, they found that dispersing SiO_2 nanoparticles in water offers the best improvement in system performance over other nanoparticles. Their findings also revealed that the utilization of SiO_2-water lowered the *PV* panel's temperature from 49.8℃ to 44.92℃.

Khanjari et al [21] presented a CFD analysis on the *PV/T* system using *Ag*-water and *Al*-water as nanofluids with varying volumes of a fraction to examine the effect of utilizing nanofluids on *PV/T* system efficiency and to understand the system's behaviour. They discovered that using nanofluid with high amounts of volumes of friction ($\Phi = 5\%$) provides to increases the heat transfer coefficient and performance. Specifically, increasing the volume fraction (Φ) to 5% resulted in a 2% increase in the heat transfer coefficient for *Al*-water nanofluids at the inlet velocity. Meanwhile, *Ag*-water nanofluids exhibited a more significant increase in the heat transfer coefficient. The effects of the nanofluid *Cu*-water with various values of solid particle volumes and various Reynolds numbers on the temperature distribution and collector performance were analyzed numerically by Parvin et al. [22]. In their study, they discovered that as the solid particle volume increased, the fluid viscosity and heat transfer coefficient increased, and as the Reynolds number decreased, the heat transfer coefficient decreased.

The literature review reveals that considerable research has been dedicated to cooling systems, particularly solar systems and hybrid *PV/Th* systems, utilizing water, air, water-based nanofluids, and liquid-based nanofluids. Cooling *PV* cells with nanofluids is a crucial and compelling topic for improving their electrical efficiency. In addition, the nanoparticle mixture used in this study is distinct, as it incorporates various metallic particles with high thermal conductivity, creating a hybrid nanofluid (Ag-Al_2O_3-water). The current simulations aim to examine the impact of hybrid nanofluids on *PV* cell temperature and the electrical and thermal efficiencies of a *PV* module integrated with a thermal system employing a simplified combination of computational fluid dynamics approaches. The numerical simulation was conducted using ANSYS 17.1 Fluent software, and 3D modeling was performed to estimate the ideal operating temperature of the photovoltaic panel. Pure water and Ag-Al_2O_3-water hybrid nanofluid are served as working fluid to remove the absorber plate heat. The impact of hybrid nanoparticles (Silver and Alumina) on the overall thermal and electrical efficiency of a hybrid *PV/Th* system is evaluated under five different velocity inlet values calculated from Reynolds numbers ranging from 100 to 800 and various nanoparticle volume fractions values.

2 CFD simulation

2.1 Geometry Description

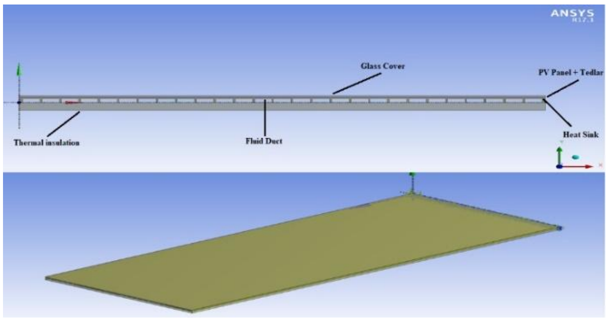

Fig.1. The geometry of the hybrid PV/Th solar collector.

Table 1. Hybrid *PV/Th* Solar collector dimensions.

PV/Th Panel Layers	Dimensions ($L \times W \times H$; [m^3])
Glass cover	1.2×0.5×0.003
PV Panel	1.2×0.5×0.0003
Tedlar (PVF)	1.2×0.5×0.0001
Heat Sink	1.2×0.5×0.002
Thermal insulation	1.2×0.5×0.03

Fig. 1 illustrates the model geometry of the hybrid *PV/Th* solar panel, which was realized with the ANSYS 17.1 Design Modeler. The various components of the *PV/Th* hybrid solar panel are: a photovoltaic panel and a copper heat sink equipped with rectangular fins attached to beneath the *PV* panel, a rectangular duct with a hydraulic diameter (D_h) of 0.0114 m was performed to ensure the flow of heat transfer fluid under these elements. The working fluid flows through the duct, removing the heat collected by the heat sink. Hence, the heat that is responsible for the heating of solar cells is transformed into useful energy. Thermal insulation (wood) is used on the border and base of the hybrid *PV/Th* solar collector to reduce energy waste. Table 1 shows the hybrid *PV/Th* solar collector dimensions.

2.2 Mesh generation

The ANSYS 17.1 ICEM CFD module was utilized to create a mesh for the hybrid PV/Th solar collector, after modeling its proposed geometry. The mesh was constructed with uniform mesh and was composed of very fine mesh-size quadratic elements to resolve the different governing differential equations. To achieve this, a 0.2 mm cell size was adopted, resulting in a total of 3,825,000 elements and 4,068,918 nodes. The final mesh output is shown in Fig. 2.

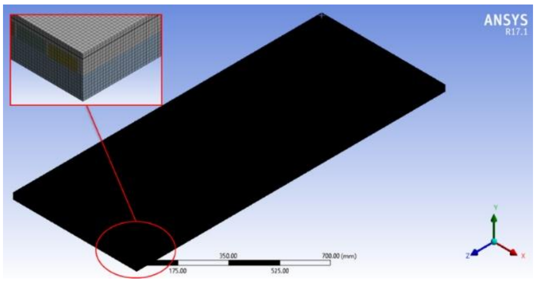

Fig.2. The Mesh of the hybrid PV/Th solar collector model.

2.3 CFD Modelling and operating parameters

The ANSYS-Fluent software enables the solution setup and calculation tasks. The governing equations, including continuity, momentum, and energy, are utilized for the CFD calculations. These equations are solved for volume control conservation to determine the velocity and temperature distribution of the heat transfer fluid flow in the channel and the *PV* cell's temperature. To predict the average *PV* cell temperature, a 3D numerical simulation was carried out under conditions of constant value of solar radiation (I) of 1000 W/m^2 on the top face of the *PV/Th* panel and steady-state. Different inlet velocities were calculated based on the Reynolds number, which ranged from 100-800. The working fluid was entered at 20°C, and various cases were examined by altering the volume fractions (Φ = 0, 0.02, 0.04, 0.06) of Ag-Al_2O_3 nanoparticles. For the CFD simulation, finite volume discretization was applied to convert the governing equations into algebraic equations. The semi-implicit method for pressure-linked equations (SIMPLE) was utilized to couple pressure and velocity, and the second-order upwind scheme [23]. The minimum convergence criteria are set as a relative residual of 10^{-6} for energy equations and 10^{-3} for pressure, velocity, and continuity equations. The different physical properties of materials, water, and nanoparticles used in CFD analysis are shown in Table 2 and 3 respectively.

Table 2. The physical properties of material used in CFD analysis [24].

PV/Th Panel Layers	ρ (kg/m^3)	Cp [$J/kg.°K$]	K ($W/m.°K$)
Glass cover	3000	500	1.8
PV Cell	2330	677	148
Tedlar (PVF)	1200	1250	0.2
Heat Sink (Copper)	8933	385	401
Thermal insulation (wood)	700	2310	0.173

Table 3. The thermophysical properties of water and nanoparticles used in CFD analysis [25].

PV/Th Panel Layers	ρ [kg/m^3]	Cp [$J/kg.°K$]	K [$W/m.°K$]	β [$°K^{-1}$]
Water (H_2O)	998.2	4182	0.6	21×10^{-5}
Alumina (Al_2O_3)	3970	765	40	0.85×10^{-5}
Silver (Ag)	10500	235	429	1.89×10^{-5}

The electrical efficiency of a photovoltaic panel is calculated by the following equation [5]:

$$\eta_{el} = \eta_{ref}[1 - \beta(T_c - \mathrm{T_{ref}})] \tag{1}$$

where, $\mathrm{T_{ref}}$ is the reference temperature (which is typically 25°C), η_{ref} is the PV panel efficiency at the reference temperature, $\beta = 0.0045 ℃^{-1}$ is the temperature coefficient, and Tc is the temperature of the PV cells obtained from the simulation.

The thermal efficiency of a thermal solar collector is calculated by the following equation [26]:

$$\eta_{th} = \frac{\dot{m} * Cp(T_o - T_{in})}{I * A_c} \tag{2}$$

where, $\dot{m}$ is the mass flow rate of working fluid which calculated from the Reynolds number, Cp is the specific heat capacity of working fluid [J/kg. °K], $T_{in} = 20°C$, T_o is the inlet and outlet temperature of working fluid [°C], respectively, *I* is the heat flux [W/m^2], and A_c is area of *PV/Th* solar collector.

$$Re = \frac{\rho * V * D_h}{\mu} \tag{3}$$

where:ρ is the working fluid density [kg/m^3], *V* is the working fluid velocity at the duct entrance [m/s]. D_h is the hydraulic diameter of the duct [m], and μ is the working fluid dynamic viscosity [kg/m s].

The total efficiency of the PV/Th hybrid solar collector (η_{Tot}) is calculated as the sum of two components: the thermal efficiency of the solar thermal collector system (η_{th}) and the electrical efficiency of the photovoltaic panel (η_{el}). This is expressed mathematically by the following equation [27]:

$$\eta_{Tot} = \eta_{th} + \eta_{el} \tag{4}$$

3 Results and discussion

3.1 Temperature distribution

The variations of the average temperature of *PV* cells with hybrid nanofluid cooling and water cooling are shown in Fig. 3, 4, 5, 6, and 7. The results showed a remarkable evolution in the average *PV* cells temperature at higher volume fractions of Ag-Al2O3 nanoparticles, which was also observed for an increase in Re number.

As shown in Fig. 3, the average temperature of *PV* cells with water cooling (Φ = 0) decreased from 60.11°C to 45.06°C at higher inlet velocities (high *Re* numbers). This reduction in temperature is due to heat absorbed by the water flowing beneath the heatsink layer and conductive heat flow across the various layers of the *PV* module. The dispersion of silver (*Ag*) and alumina (Al_2O_3) nanoparticles in the base fluid (water) creates a hybrid coolant fluid that enhances heat transfer from the PV module to the heatsink layer and the working fluid. To ensure effective cooling of the cell temperature, convection heat transfer was increased through forced circulation (with various *Re* numbers). In contrast, conduction heat transfer was improved by varying the volume fractions of nanoparticles.

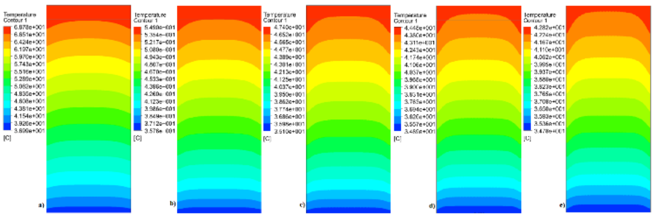

Fig.3. PV Cells Temperature distributions at Φ = 0 for cases: a) Re = 100, b) Re = 200, c) Re = 400, d) Re = 600, e) Re = 800.

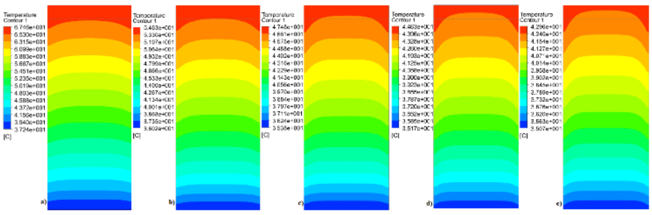

Fig.4. PV Cells Temperature distributions at Φ = 0.02 for cases: a) Re = 100, b) Re = 200, c) Re = 400, d) Re = 600, e) Re = 800.

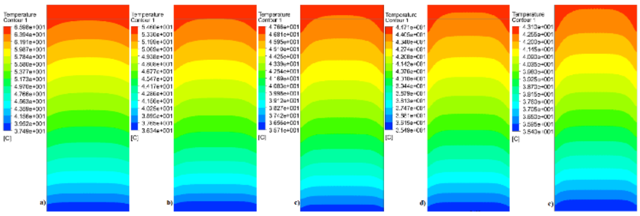

Fig.5. PV Cells Temperature distributions at Φ = 0.04 for cases: a) Re = 100, b) Re = 200, c) Re = 400, d) Re = 600, e) Re = 800.

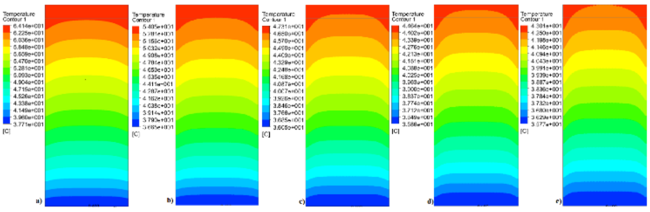

Fig.6. PV Cells Temperature distributions at Φ = 0.06 for cases: a) Re = 100, b) Re = 200, c) Re = 400, d) Re = 600, e) Re = 800.

According to Fig. 4, 5 and 6, it is clearly noted that the lowest average *PV* cells temperature was reached with hybrid nanofluid cooling at the highest *Re*=800. Furthermore, a more intense *PV* cell cooling was recorded when the higher volume fractions of nanoparticles ($Ag\text{-}Al_2O_3$) were used. with a value of 40.6 °C for Φ = 0.06, as compared to 41.6 °C and 43.6 °C for Φ = 0.04 and 0.02 respectively.

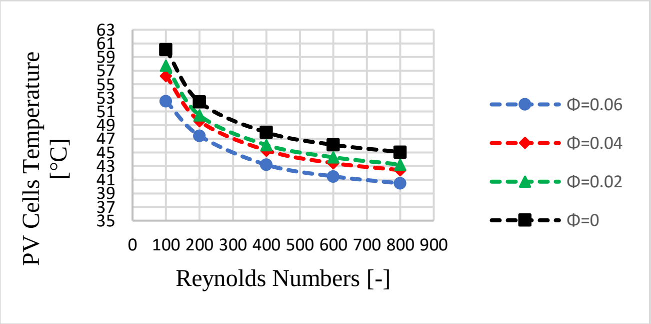

Fig.7. Variation of PV cells temperature for different Re numbers and at various volumes fractions.

As shown in Fig. 7, the results of the investigated cases are summarized in a graphic representation. Fig. 7 illustrates the variation in the average *PV* cells temperature of the photovoltaic module for different volumes fractions of the nanoparticles ($Ag\text{-}Al_2O_3$) for various *Re* numbers; the results indicate that the total temperature of the *PV* module surface diminishes with an increase in the *Re* number as well as with the increasing of the volumes fractions of the nanoparticle. The results demonstrate that the enhancement in heat transfer with hybrid nanofluids is most significant at higher volume fractions and *Re* numbers. Where, the addition of nanoparticles to the base fluid (water) increases its thermal conductivity, thereby improving heat transfer through conduction, while the rise in Re number enhances heat transfer through convection.

3.2 Velocity iso-contours

Fig. 8 shows the velocity contours of the hybrid nanofluids flowing through the cooling duct. The contours clearly show that the velocity values are decreased adjacent to the wall until reached to zero at the wall, whereas increase when directed towards the centre of the channel, it can be explained by the presence of frictional forces between the particles of nano-fluid and the walls of the channel, which are powerful in the case of the high-volume fraction of solid particles.

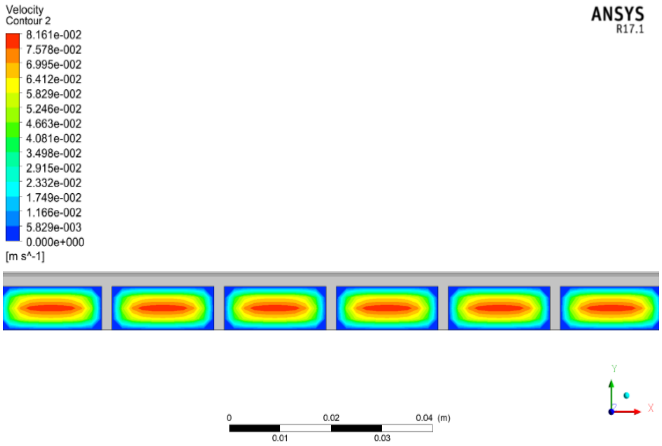

Fig.8. Velocity spectra of fluid flow inside the ducts (case Φ = 0.06 at Re = 800).

3.3 The Nusselt number

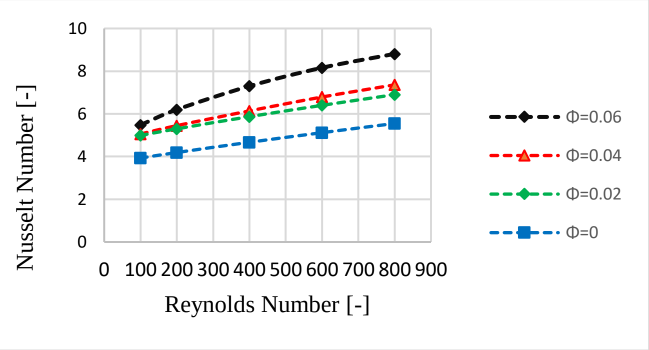

Fig.9. The Nusselt number's evolution at different volume fractions and Reynolds number.

The evolution of the Nusselt number as a function of the *Re* number for $Ag\text{-}Al_2O_3$-water hybrid nanofluid at different volume fractions (Φ = 0, 0.02, 0.04 and 0.06) is shown as a graphic representation in Fig. 9. This graphic representation clearly confirms the impact of the *Re* number on heat transfer. The average Nusselt values vary from 4 to 9. It appears that the increase in *Re* number improves the heat transfer, whatever the value of the volume fraction Φ following the strong velocity gradients generated by the increase in forces of inertia. It is found that there is a proportional relationship between the rate of heat transfer and the increasing values of the Re number and the concentration of the nanoparticles Φ, this is due to the fluid nanoparticles ($Ag\text{-}Al_2O_3$) which boost the thermal conductivity of the working fluid.

3.4 Thermal Efficiency of the collector system

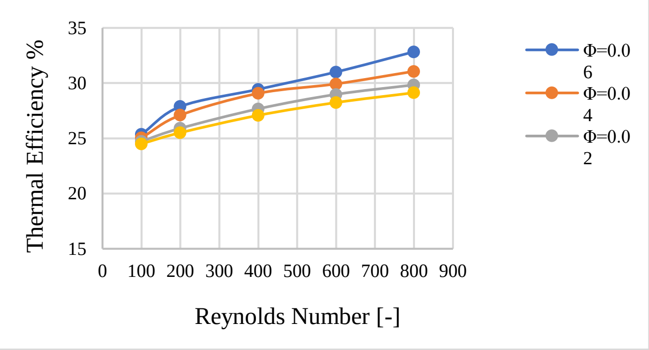

Fig.10. Thermal efficiency evolution at different volume fractions and Reynolds number.

As shown in Fig.10, The thermal performance of the thermal collector system is evaluated based on the variation in its thermal efficiency, which is affected by two main parameters: the *Re* number and the volume fraction of nanoparticles. The results indicate that at low *Re* numbers, the thermal efficiency of the system remains low for all volume fraction values. However, as the Reynolds number and the volume fraction of nanoparticles increase, the thermal efficiency increases proportionally. This suggests that a higher flow rate and a higher volume fraction of nanoparticles can enhance the thermal performance of the collector system. Additionally, the highest thermal efficiency value achieved at *Re* = 800 and Φ = 0.06 underscores the significance of optimizing these parameters for optimal thermal performance.

3.5 The electrical efficiency of Photovoltaic system

Fig. 11 displays the variations in the electrical performance of a *PV* module system for various *Re* numbers and different volume fractions of nanoparticles. The results indicate that the electrical performance increases with an increase in the Re number for four different volume fractions. This effect can be explained by the fact that higher volume fractions and Reynolds numbers lead to better heat dissipation from the photovoltaic panel, resulting in a decrease in the average PV module surface temperature and an increase in the electrical efficiency of the system. These findings are consistent with those presented in Fig. 7. the electrical efficiency value for a volume fraction of 0.06 is higher than that of 0.04, 0.02, and 0.

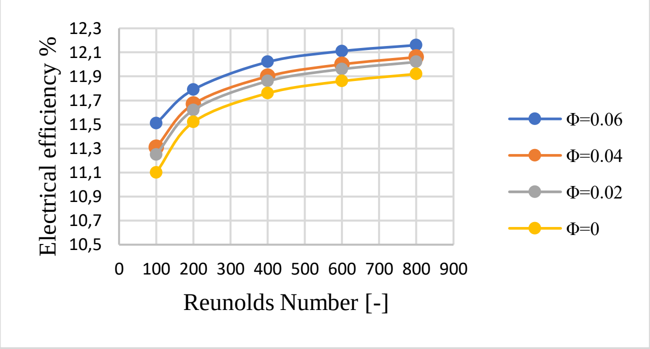

Fig.11. Electrical efficiency evolution at different volume fractions and Reynolds number.

3.6 The Total Efficiency of the PV/Th Hybrid Solar Collector

The evolution of the overall thermal and electrical effectiveness of the *PV/Th* hybrid solar collector as a function of the *Re* number and at different volume fractions is shown in Fig.12, the results demonstrate that the *PV/Th* hybrid panel's total efficiency is impacted by changes in the mass flow rate of the working fluid (indicated by variations in the Reynolds number) as well as alterations in nanoparticle volume fractions. An increase in both Reynolds number and nanoparticle volume fractions results in a rise in the total efficiency. The simulation yielded a maximum value of 44.7% for the total efficiency at a *Re* = 800 and a Φ = 0.06, while the minimum value obtained was 35.6% at a *Re* = 100 and a Φ = 0.

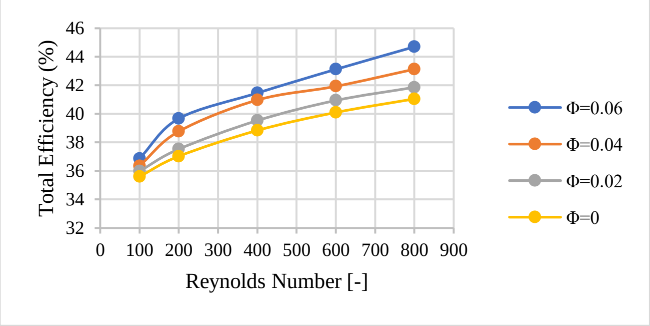

Fig.12. Total efficiency evolution at different volume fractions and Reynolds number.

4 Conclusion

The electrical efficiencies of the *PV* panels are severely dropped as the surface temperatures increase, as a solution, cooling the PV panel's surface is an effective way to avoid this reduction in efficiency. This can be achieved by combining two solar systems which are: a *PV* panel and a thermal collector, resulting in a hybrid photovoltaic-thermal solar collector. In order to improve the photovoltaic modules' cooling and enhance the overall thermal and electrical efficiency of the hybrid PV/Th system. A 3D numerical simulation is carried out by using ANSYS 17.1 software on cooling *PV/Th* system by using hybrid nanofluids ($Ag\text{-}Al_2O_3$-water) at different nanoparticles volume frictions values (Φ = 0, 0.02, 0.04, 0.06) and *Re* number. The obtained results illustrated that:

- The heat transfer boosts as the concentration of nanoparticles increases, due to the increase of the thermal conductivity which allows for enhancement in the heat transfer by conduction, as well as the increase of Reynolds number leads to the increase of the heat transfer by convection, which helps to reduce the temperature of the photovoltaic cells.

-The friction factor increases modestly with increasing nanoparticles volume fraction. Generally, higher nanoparticle volume fractions result in an increase in fluid viscosity, which in turn reduces fluid movement.

-The heat flux evacuated by a hybrid nanofluid ($Ag\text{-}Al_2O_3$-water) in the studied configuration, increases with the increase of the concentration of the nanoparticles and the velocity of the flow that is justified by the Nusselt number.

-The total efficiency of the hybrid *PV/Th* solar collector increases as the temperature of *PV* cells decreases, especially when using significant nanoparticles volume fractions values used in coolant fluids.

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