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Numerical approach to nanofluid cooling of semiconductor-based electronic components based on maximum flux function, average velocity, temperature evolution, average Nusselt number and cell efficiency.

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Abstract

In this work, we use numerical simulation to study the cooling of a photovoltaic solar panel using a nanofluid as a cooler. The thermophysical properties of the nanofluid are assumed to be constant. The thermophysical properties of the nanofluid are assumed to be constant. In addition, the fluid phase and the nanoparticle phase are in a state of thermal equilibrium and flow at the same speed. The Bossiness approximation is valid. Thermal conductivity and dynamic viscosity are calculated from Maxwell's and Brinkman's models respectively. The permanent forms of the Navier-Stokes equations and the conservation of mass and energy equations are solved using the finite element method. The results obtained are presented in terms of velocity profiles and local and mean Nusselt numbers for different values of Reynolds number and volume fraction. Mathematical correlations of the numerical results are deduced. The solar panel is subjected to a hot temperature typical of the climate in the town of Béchar in south-west Algeria. The nanofluid (Al_2O_3-water) is introduced into the cavity at a constant horizontal velocity and subjected to the ambient (cold) temperature. The equations governing flow hydrodynamics and heat transfer are described by the Navier-Stockes and energy equations. The finite element method is used to solve the system of partial differential equations (PDE) based on the Galerkin method. We attribute the effect of solid volume fraction and aspect ratio for different Reynolds number values on results such as temperature, velocity, mean Nusselt numbers and solar panel efficiency.

Keywords: *Photovoltaic solar panel, nanofluid, forced convection, finite element method, Nusselt number,Introduction*

1. Introduction

Climate change, rising oil prices and other environmental factors in today's world are driving energy organizations to develop green energy technologies for the commercial and residential markets. One of these technologies was invented in 1894 by Charles Fritts and is called the photovoltaic cell [2]. Photovoltaic cells convert sunlight into electricity, which can be harnessed and fed into the grid. The first photovoltaic cell created by Fritts had an efficiency of only 1%; however, modern single-junction solar cells have efficiencies of up to 23% [3]. New photovoltaic technologies such as multijunction cells, optical frequency shifting and concentrated photovoltaic (CPV) systems have been shown to improve the efficiency of energy use; However, these technologies have high acquisition and maintenance costs and therefore are not widely adopted on a large scale at present [4]. In commercial and residential applications, photovoltaic cells are assembled into modules, which are then assembledin panels. The photovoltaic panels are then assembled to form grids. The most suitable regions for the use of photovoltaic panels are environments with high exposure to the sun, which are often regions with a warm climate.The surface temperature of the photovoltaic panels increases due to the low efficiency of converting solar energy into electricity, because not all the energy absorbed by the photovoltaic cells can be converted into electricity. To satisfy the law of conservation of energy, the remaining solar energy must be converted into heat. The efficiency of photovoltaic cells is also reduced when installed in hot weather environments (i.e. high ambient temperature),becausethe heat dissipation of the panels is reduced. Therefore, it is important to develop cooling methods of PV cells to increase the output efficiency. Nelson, Jenny [1] Basic Physics of Semiconductors in Photovoltaic Devices covers physical models of solar cell operation; the characteristics and design of common types of solar cells; and approaches to increase the efficiency of solar cells. The text explains the terms and concepts of solar cell physics and shows the reader how to formulate and solve relevant physics problems.Jaewon Oh et al. [2] found that poorly ventilated photovoltaic panels in high ambient temperature environments can reach temperatures above 90 degrees Celsius. These conditions are not only dangerous, but also reduce the efficiency and life of the panels. Active and passive cooling methods of photovoltaic panels have been studied and analyzed to date. These studies have allowed us to conclude that the control of the temperature rise of the photovoltaic panels results in benefitsproduction of electricity from panels. In many of these studies, thermal energy extracted from photovoltaic panels was used for various low-temperature applications (e.g. domestic water heating, floor heating, swimming pool heating, etc.). These systems are called hybrid photovoltaic-thermal (PV/T) systems.Teo et al. [3] studied an active cooling system for PV panels, in which the panels were cooled by forced convection, with air as the heat transfer fluid. This system resulted in an increase in electrical efficiency of 4 to 5%.Fontenault, B et al. [4] Researchers studied the cooling of a photovoltaic-thermal solar panel combined with water. This was achieved by solving the PDE system numerically using the finite element method. The increase in electrical efficiency of the panel at different operating temperatures is calculated based on the thermal coefficient of the PV cells.This study is based on the work already done [4], using identical properties of PV/T sheet and thermal adhesive. However, the study used a thin rectangular tank through which water flows, drawing heat away from the panel. This is a cooling tank attached to the back of the panel with thermal paste of a uniform thickness of about 0.3 mm on the entire interface surface of the PV panel with the tank. The walls of the tank are approximately 1 mm thick and are made of aluminum. Aluminum was chosen as the material for the container of the tank because of its high thermal conductivity, which promotes the transfer of heat through its boundaries, its availability, and its relatively low cost compared to other conductive metals such as copper.Practical applications of PV/T systems have recently been installed in the United States. The largest installation of PV/T solar panels in the United States was commissioned in February 2012 at the Katherine Moran Coleman Aquatic Center at Brown University in Rhode Island. In this application, 168 patented PV / T panels were installed on the roof of the center, which, in direct sunlight, can provide enough electricity to power the building and heat the million-gallon swimming pool [8] .Our focus in this work is based on previous research conducted by Bradley J. Fontenault et al. [4]. This work derives from Yang et al. [36], using the same properties of the PV/T panel and the thermal adhesive (Figure 1), but replacing the water with nanofluid. A thin rectangular reservoir through which the nanofluid will flow and remove heat from the panel will be analyzed as shown in Figure 1, instead of the copper-FGM tube model. This will be performed using the finite element software COMSOL Multiphysics. The increase in electrical efficiency of the panel at different operating temperatures will be calculated based on the thermal coefficient of the PV cell. The objective of this study is to improve the performance of an installation of photovoltaic solar panels in an arid region such as the city of Béchar, located in the southwest of Algeria. To achieve this goal, a nanofluid is used to cool the solar panel. The setup used in this study is shown in Figure 1.

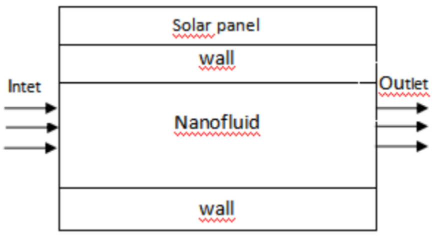

Figure1: Physical model

2. Mathematical Formulation

The flow of the nanofluid in the cooling line and the heat transfer between the panel and the nanofluid are governed by the mass, momentum and energy conservation equations.To solve the system of partial differential equations (PDEs), we adopt the following simplifying assumptions:- The physical properties of the nanofluid are constant.- The flow is laminar and bidimensional.Using a Cartesian coordinate system and taking into account the simplifying assumptions, the system of equations takes the following forms: In nanofluid zone

- Continuity equation: nanofluid zone
- Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} = 0 \quad (1)$$

- Equation of momentum following x:

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho nf}\frac{\partial p}{\partial x} + \frac{\mu nf}{\rho nf}\left(\frac{\partial^2 u}{\partial^2 x} + \frac{\partial u^2}{\partial^2 y}\right) \quad (2)$$

- Equation of momentum following y :

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho nf}\frac{\partial p}{\partial y} + \frac{\mu nf}{\rho nf}\left(\frac{\partial^2 v}{\partial^2 x} + \frac{\partial^2 v}{\partial^2 y}\right) \quad (3)$$

- Energy equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial Y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}\right) \quad (4)$$

- In solid zones:

$$\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial y^2}=0 \quad (5)$$

With:

$$\alpha_{nf}=\frac{k_{nf}}{(\rho_{cp})_{nf}} \quad (6)$$

$$\rho_{nf}=(1-\emptyset)\rho_f+\emptyset\rho_s \quad (7)$$

$$\mu_{nf}=\frac{\mu_f}{(1-\emptyset)^{2.5}} \quad (8)$$

$$k_{nf}=\frac{(2-2\emptyset)k_f+(1+\emptyset)k_s}{(\rho_{cp})_{nf}(2+2\emptyset)k_f+(1-\emptyset)k_s} \quad (9)$$

$$(\rho_{cp})_{nf}=(1-\emptyset)(\rho_{cp})+\emptyset(\rho_{cp})s \quad (10)$$

- Dimensionless equations:

Inlet	*U=1; V=0; θ=0*
Outlet	*P=0; Convective flux*
Nanofluid-wall interface	*U=V=0; Continuity*
Wall-solar panel interface	*U=V=0; Continuity*
Top wall	*U=V=0; T=1*
Bottom wall	*U=V=0, Adiabatic*

Equations (1) to (5) can be converted to the dimensionless forms by using the following parameters:

$X=\frac{x}{D}$	$Y=\frac{y}{D}$	$U=\frac{u}{U_0}$
$V=\frac{x}{U_0}$	$P=\frac{p}{\rho_{nf}U_0^2}$	$\theta=\frac{T-T_c}{T_h-T_C}$

Therefore using the above parameters leads to dimensionless forms of the governing equations as below:

- In nanofluid zone:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (11)$$

In solid zones

Where figure the following dimensionless numbers and ratio:

$$Pr=\frac{\mu_f}{\rho_f\alpha_f},\ Re=\frac{UD_f}{\mu_f},\ R_\rho=\frac{\rho_s}{\rho_f},\ R_k=\frac{k_s}{k_f},\ R_{(\rho C_P)}=\frac{(\rho C_P)s}{(\rho C_P)f} \quad (12)$$

The table below includes the boundary conditions used to solve the above system of equations:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=\frac{\partial P}{\partial x}+\frac{1}{[(1-\emptyset+\emptyset R_\rho)(1-\emptyset)^{2.5}]}\frac{1}{R_e}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \quad (13)$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial V}{\partial Y}=\frac{\partial P}{\partial y}+\frac{1}{[(1-\emptyset+\emptyset R_\rho)(1-\emptyset)^{2.5}]}\frac{1}{R_e}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right) \quad (14)$$

$$U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial Y}=\frac{2-2\emptyset+(1+\emptyset)R_k}{2+\emptyset+(1+\emptyset)R_k}\frac{1}{P_rR_e}\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right) \quad (15)$$

$$\frac{\partial^2\theta}{\partial^2 X}+\frac{\partial^2\theta}{\partial^2 Y}=0 \quad (16)$$

3. Results and discussion

The finite element method is used in our model to discretize the governing equations ((10) to (13)) and the boundary conditions. We tried several meshes and chose a mesh consisting of 40,000 elements. To describe the flow structure in the cavity, we set the following parameters of the nanofluid (Al_2O_3-water):

$Pr=7$, $R_\rho=3.885$, $R_k=60$, $R_{(\rho Cp)}=0.71$

3.1. Maximum Stream function

Figure 8 shows the evolution of the maximum current function as a function of the form factor for different values of the volume fraction and Reynolds number.

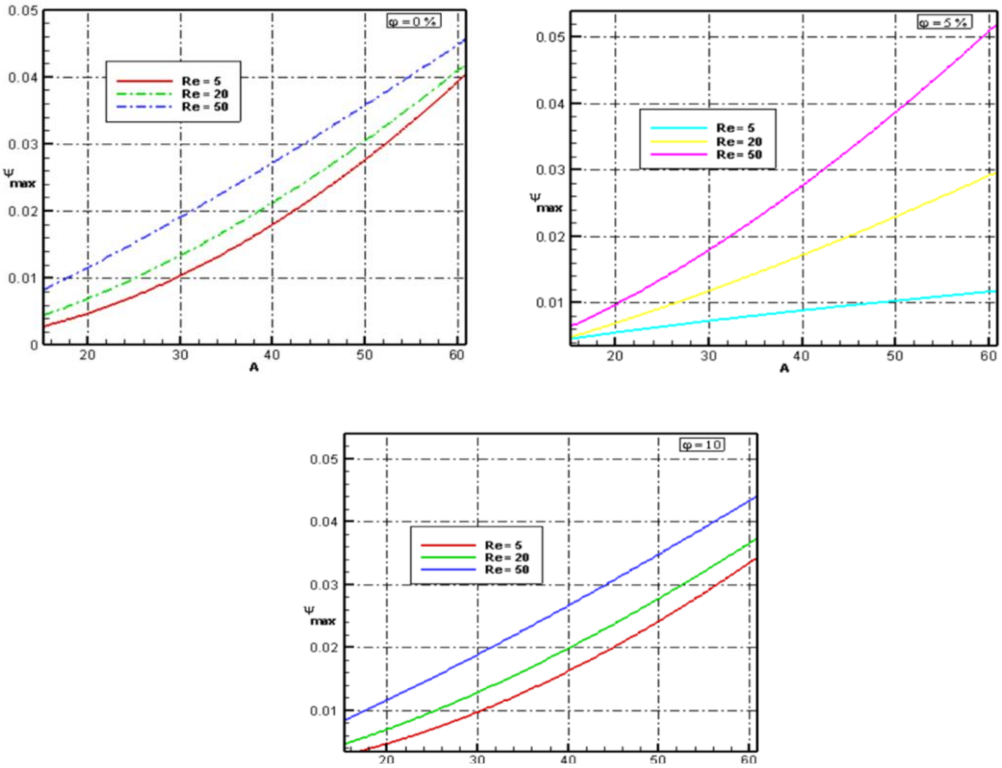

Figure 8: Stream function vs aspect ratio

By fixing the value of the shape factor (A), the value of the tip stream function increases with increasing Reynolds number.For a constant volume fraction and whatever the value of the Re number, the peak current function increases with increasing form factor.Fixing the geometric characteristics of the setup and for a constant flow of the nanofluid, the peak flow function decreases with increasing nanoparticle volume fraction.

- **Average velocity**

Figure 9 shows the evolution of the average speed U_{avg} as a function of the Reynolds number Re for different values of the shape factor A and ϕ varying between 0% and 10%.

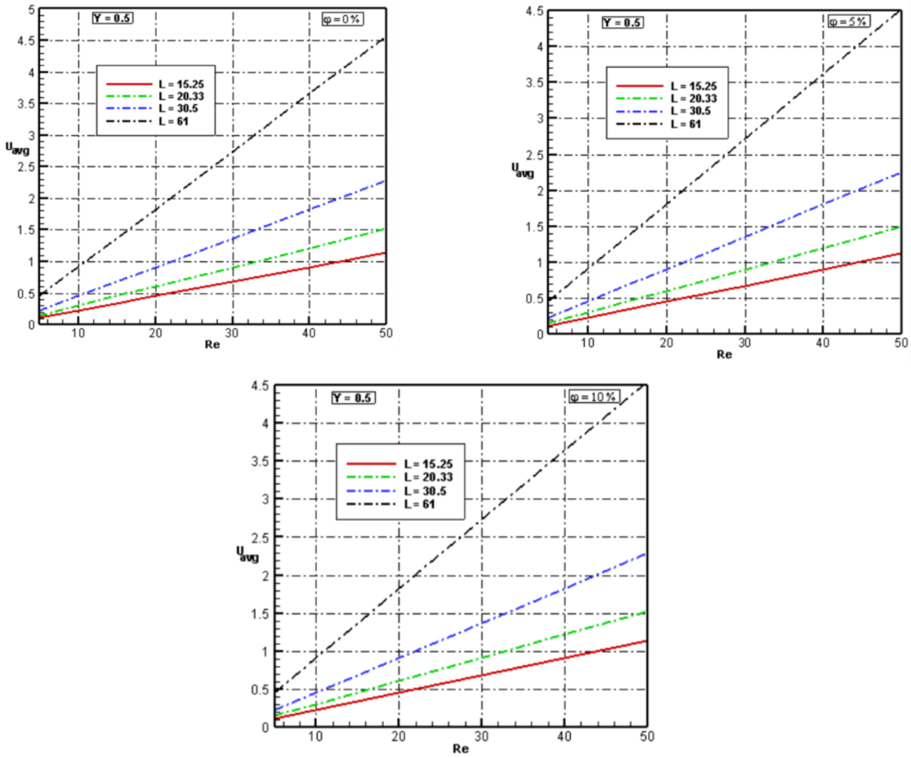

Figure 9: Average velocity vs Re

Whatever the value of the aspect ratio A, the flow is more intense on the lower wall of the sensor.For A = 15.25 and A = 20.33, the intensity is significant in the middle of this wall, this intensity shifts to the left for other values of A.Whatever the value of A and φ, the evolution of the average speed as a function of Re is linear

$$U_{avr} = a\,\mathrm{Re} + b$$

A		15.25	20.33	30.50	61.00
φ=0.00	a	0.0227	0.0206	0.0455	0.0914
	b	0.0002	0.0927	0.0001	0.0004
φ=0.05	a	0.0225	0.0300	0.0451	0.0905
	b	0.0002	0.0002	0.0001	0.0004
φ=0.10	a	0.0228	0.0304	0.0457	0.0910
	b	0.0002	0.0002	0.0001	0.004

3.2. Temperature evolution

The curve in figure 10 presents the evolution of the temperature along the vertical passing through the tube for Re = 5 and for different values of φ and A. The temperature increases as it approaches the sensor of the wall until reaching a maximum value. This maximum value decreases as Aincreases.The curve in figure 11 presents the evolution of the temperature along the horizontal passing through the tube for Re = 5, A = 15. 25 and for different values of φ. The temperature increases when we approach the lower wall of the sensor until the maximum value.

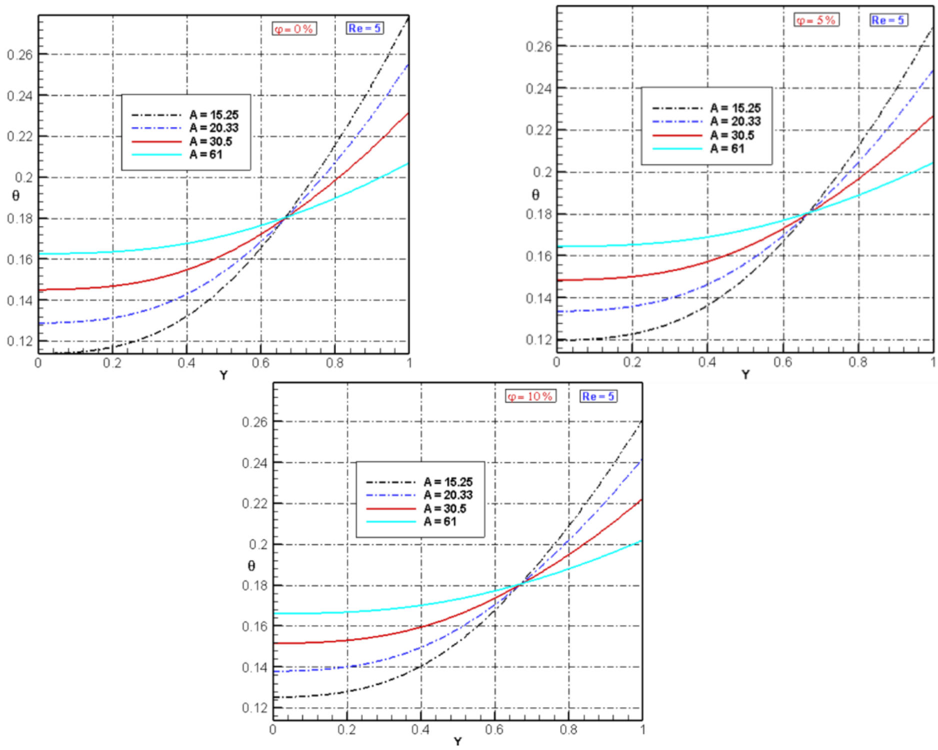

Figure 10: Temperature evolution vs Y

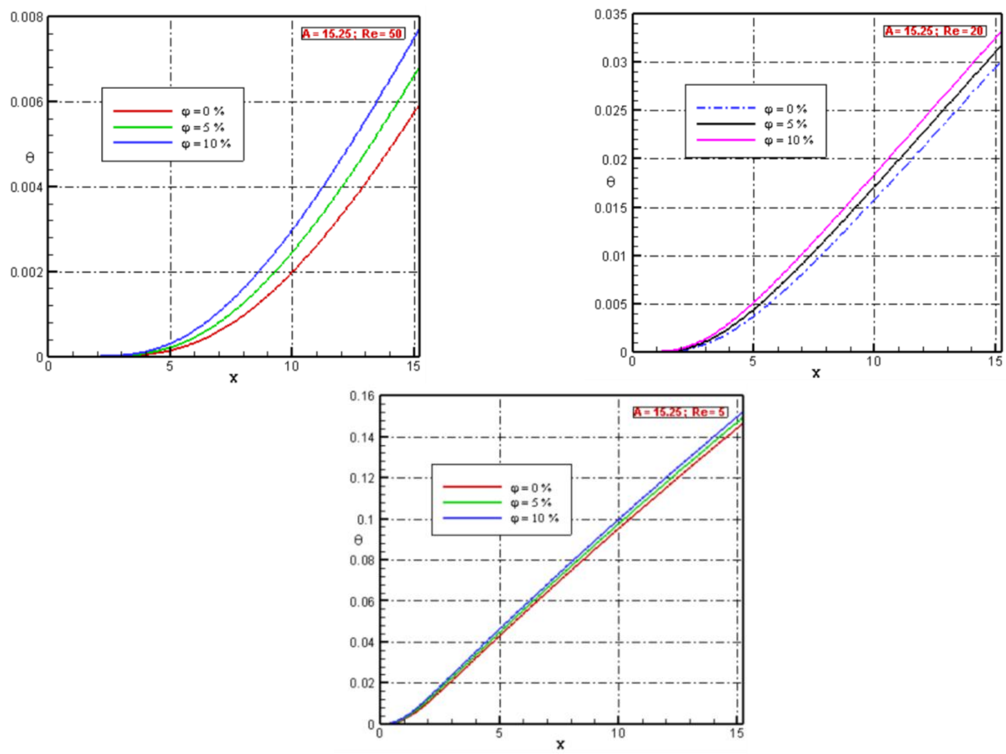

Figure 11: Temperature evolution vs X

3.3. Average Nusselt number

Figure 12 presents the evolution of the average Nusselt number as a function of the Reynolds number for different values of the aspect ratio (15.25 ≤ A ≤ 61) and for the base fluid (φ = 0) and two values of the volume concentration.For a given volume fraction, the Nusselt number increases with increasing form factor and decreases with increasing Nusselt. The cooling is carried out for a low inlet velocity.

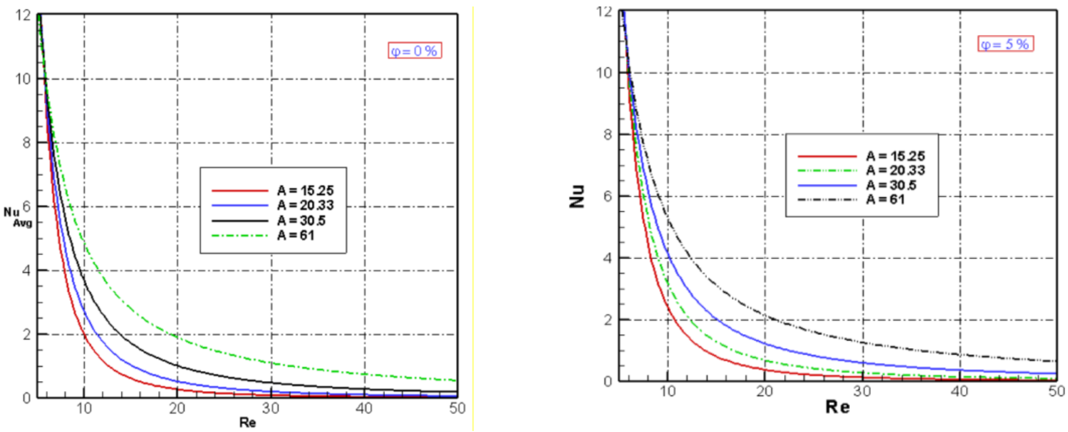

Figure 12 : Average Nusseltvs Re

3.4. Cell efficiency

Figure 13 shows the evolution of the efficiency of the solar cell as a function of Re for three values of volume fractions (ϕ=0; ϕ=0.05 and ϕ=0.10). Whatever the value of A, the efficiency (□) decreases with increasing Re, the optimal configuration middle of this wall, this intensity shifts to the left for other values of A.

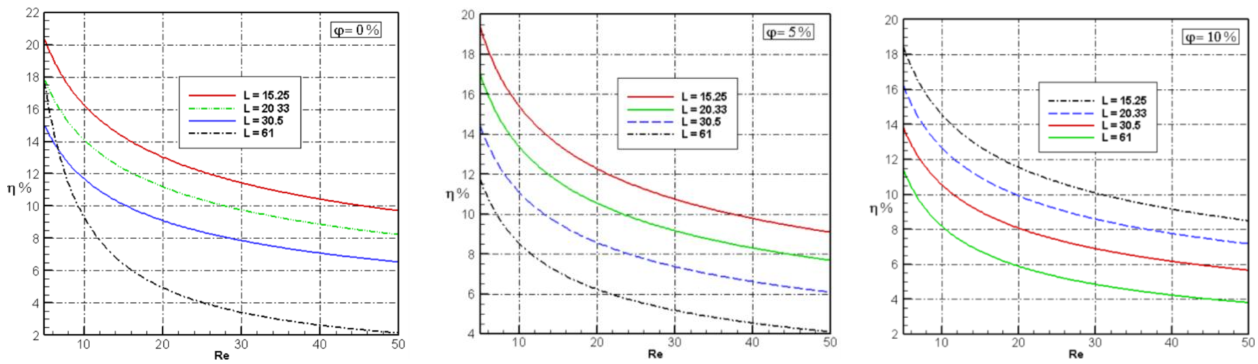

Figure 13: Cell efficiency evolution

4. Conclusion

Solar photovoltaic (PV) panels in extreme weather conditions significantly reduce their operating efficiency. It is planned to cool the solar panels using a nanofluid as a coolant. The main findings of this study are:• The addition of nanoparticles increases the rate of heat exchange between the panel and the nanofluid compared to the base fluid

- Low flow increases the exchange, which allows efficient cooling.
- Longer tubes improve solar panel efficiency. In our simulation, we studied the influence of parameters such as Reynolds number and volume fraction.

After receiving the results, the following points are noted:An increase in Reynolds number leads to an increase in average Nusselt number (Nu_m), local Nusselt number (Nu_L), temperature and velocity.

The temperature profile suggests that increasing Reynolds number promotes convection and, therefore, efficient cooling.

The volume fraction influences the profiles of average Nusselt number (Nu_m), local Nusselt number (Nu_L), temperature and velocity.In our simulation, we studied the influence of parameters such as Reynolds number and volume fraction. After receiving the results, the following points were observed:

- An increase in the Reynolds number leads to an increase in the mean Nusselt number (Nu_m), the local Nusselt number (Nu_L), the temperature and the velocity.
- The temperature profile suggests that increasing the Reynolds number promotes convection and therefore efficient cooling.
- Volume fraction affects the average Nusselt number, local Nusselt number, temperature and velocity profiles

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