J. Appl. Comput. Mech., 11(2) (2025) 358-370
DOI: 10.22055/jacm.2024.47256.4683

ISSN: 2383-4536
jacm.scu.ac.ir

Shahid Chamran University of Ahvaz

Journal of Applied and Computational Mechanics

Research Paper

Investigating the Effect of Cu-Al_2O_3 Hybrid Nanofluids on the Electrical Performance of PV/T Systems with Backward Step Flow Channel

F.M. Allehiany[1], Gul M. Shaikh[2], Abid A. Memon[2], M. Asif Memon[2], A.M. Obalalu[3]

[1] Department of Mathematics, Faculty of Sciences, Umm Al-Qura University, Makkah, Saudi Arabia, Email: fmlehiany@uqu.edu.sa

[2] Department of Mathematics and Social Sciences, Sukkur IBA University, Sukkur, 65200, Sindh, Pakistan,
Email: g.shaikh@iba-suk.edu.pk (G.M.S.); abid.ali@iba-suk.edu.pk (A.A.M.); asif-memon@iba-suk.edu.pk (M.A.M.)

[3] Department of Mathematics and Statistics, Kwara State University, Malete, Nigeria, Email: adebowale.obalalu17@gmail.com

Received June 24 2024; Revised July 29 2024; Accepted for publication July 30 2024.
Corresponding author: M. Asif Memon (asif-memon@iba-suk.edu.pk)

Abstract. Photovoltaic thermal (PV/T) systems, which generate electrical energy by harnessing solar radiation, often face efficiency challenges due to heat buildup. To address this issue, we propose a novel solution integrating a flow channel to facilitate coolant flow, thereby reducing the cell temperature. This study aims to numerically investigate the electrical performance of two-dimensional PV/T systems with a backward step flow channel using Cu-Al_2O_3 hybrid nanofluids. Employing COMSOL 6.2 software, we vary parameters such as Reynolds number (100-400), downstream height (0.25-0.7 mm), copper volume fraction (0.01-0.2), and inlet temperature (5°C-40°C) to examine their impact on cell efficiency (%). Our findings indicate that the cell efficiency decreases along the length of the channel. Increasing the volume fraction and Reynolds number improves cell efficiency, while higher inlet temperatures and downstream heights decrease efficiency. The study identified an optimal cell efficiency of approximately 5.99% with a copper volume fraction of 0.2. Specifically, efficiency improved by up to 0.23% with increased copper volume, decreased by 4.5% at 40°C, and increased by up to 0.33% with higher Reynolds numbers. However, increasing the downstream height reduced efficiency, suggesting that the backward flow channel did not benefit the system.

Keywords: Photovoltaic, Electrical energy, Heat transport, Backward step channel, Hybrid nanofluids.

1. Introduction

Meeting the demand for electrical energy through PV/T systems is a globally adopted and viable strategy for economic growth. PV/T systems are considered highly sustainable as they meet energy requirements without causing environmental pollution [1]. By harnessing solar radiation, these systems not only reduce the cost of electricity production but also allow for enhanced production levels through the use of various materials. It is well known that elevated solar cell temperatures owing to solar radiation, can significantly decrease the performance of the solar cell. To mitigate this issue, a continuous flow channel must be integrated into the device to provide effective cooling. Additionally, selecting an appropriate coolant material, such as nanofluids, is crucial for managing the increasing temperature of the solar cell. Moreover, the heat extracted from the system can be utilized for other beneficial applications, such as maintaining a warm atmosphere in buildings and rooms [2]. This multi-functional approach not only enhances overall the effectiveness of PV/T systems but also contributes to sustainable energy solutions.

Several investigations [3-17] have looked into the use of nanofluids to improve the efficiency of PV/T systems. Studies have revealed that certain nanofluids, such as metallic oxides and hybrid mixes, can greatly increase thermal and electrical capabilities. Particularly, copper/water and alumina/water nanofluids have shown encouraging results, with efficiency gains of up to 26% and temperature lowering of up to 50%. Furthermore, developments such as trapezoidal channels and hybrid nanofluids have revolutionized the field, resulting in significant improvements in both thermal and electrical efficiency. All of these studies are explained below in detail, including their experimental and numerical findings.

An experimental study was conducted by Sardarabadi and Passandideh-Fard [3] to improve cell efficiency by transporting nanofluids composed of different metallic oxides and water. They used a minimum of 0.2 percent nanofluids. The study revealed that using metallic oxides such as Al_2O_3, ZnO, and TiO_2 decreased the cell temperature by approximately 11°C-12°C. This decrease resulted in an increase in cell efficiency for electricity production from 5.5% to 6.5%. The experiments indicated that by increasing the volume fraction within this range, the thermal efficiency of PV/T systems was further enhanced, resulting in an improvement from 0.05% to 10%. A photovoltaic system containing a glazing material on top of the panel was investigated using water and CuO/water [4]. The flow channel was chosen to be rectangular, and it was observed that the electrical efficiency declined by 6.2-6.4% when glazing was used. In contrast, for the case without glazing, the electrical efficiency decreased in the range of 7.6-8.8%. To avoid these impractical results, it was suggested to use a heat exchanger with a high rate of heat conduction. Based on a hybrid

Published online: August 06 2024

mixture of two oxides, Al_2O_3 and ZnO, with a volume fraction of 0.3-1.7%, a photovoltaic thermal system was investigated numerically to enhance the thermal performance via forced convection [5]. By using different volume fractions of the hybrid mixture, they deduced that using nanofluids as the transportation material enhances thermal production levels by 91% and electrical production by a maximum of 14%. It was also concluded that with a mass-flow rate in the range of 0.01-0.1 kg/s, the cell's temperature declines by 2%.

Another study conducted a numerical analysis of the PV/T system to enhance its thermal and electrical efficiencies. This was achieved by implementing the transportation of mono and hybrid nanofluids in water with equal volume fractions of TiO_2 and Al_2O_3 [6]. It was concluded that using hybrid fluids instead of mono nanofluids increases thermal efficiency in the range of 19-26%. Additionally, the article noted that increasing electricity production levels is cheaper with hybrid fluids than with mono fluids. The electrical and thermal efficiency was also evaluated for a PV/T system using the transport of two types of mono and hybrid mixtures: Al_2O_3/water and CuO/water [7]. By mixing the volume fraction of these nanofluids at 0.01, these mixtures were set to flow from the inlet at rates of 1-4 liters per minute. The research findings indicate that electrical efficiency is at its lowest when the mixture is introduced at a rate of 1 liter per minute, and it reaches its highest point when the mixture is introduced at a rate of 2 liters per minute. They also concluded that using nanofluids, whether mono or hybrid, increases cell efficiency by 75% more than the usage of conventional fluids. An evaluation was performed by Verma et al. [8] to assess the influence of transporting hybrid nanofluids on the heat efficiency of a PV/T system featuring a flat flow channel. The base fluid was mixed with CuO, MgO, and MWCNTs at a volume fraction of 0.2-0.25%. The nanofluids were introduced into the channel through the inlet with a controlled flow rate ranging from 0.5 liters per minute to 2 liters per minute. When solely employing MgO as the nanofluid, both the energy and exergy levels exhibited a significant enhancement of around 71% and 70%, respectively. However, in the case of CuO, the improvement percentages in energy and exergy were determined to be 70% and 69%, respectively.

A numerical investigation was conducted by Khanjari et al. [9] to improve the energy conservation ratio using mono nanofluids of Ag and Al_2O_3 with water as the base fluid. The volume fractions of both nanomaterials in water were tested in the range of 1-10%, and the whole mixture was allowed to flow within the range of 0.04-0.23 m/s. The investigation concluded that the use of nanofluids resulted in improved energy and exergy compared to conventional fluids. It was noted that the Ag/water mixture enhanced electrical efficiency by 5.15%, whereas for Al_2O_3, this enhancement was found to be 1.36%. Regarding thermal efficiency, the Ag/water mixture showed an enhancement of 1.88%, while Al_2O_3/water showed an enhancement of 0.95%. The electrical/thermal performance enhancement of a PV/T system was examined by conducting tests using Cu/water and Al_2O_3/water nanofluids separately [10]. It was found that the transportation of Cu/water nanofluids improved the thermal/electrical efficiency of PV/T systems by 1.9% and 4%, respectively. However, in the case of Al_2O_3/water, this range of efficiency improvement was found to be 2.7% and 1.2%, respectively. Another point added to the conclusion was that the overall performance of the system improves with an increased flow rate. The electrical and thermal performance of PV/T systems using aluminum oxide-water nanofluid, copper oxide-water nanofluid, and their combined mixture was analyzed in an experiment [11]. The experiment investigated a variety of volume fractions, ranging from 0.01% to 0.2%. The changes in temperature and volume concentration were examined, specifically focusing on the impact of manipulating viscosity and heat transfer rate. The study's findings indicate that incorporating nanofluids in a PV/T system led to a significant enhancement in thermal performance, with an increase of 75-80%. Additionally, cell efficiency improved by 11-15%. Notably, these improvements were achieved using a low metallic concentration of just 0.2% in the base fluids.

ZnO/water and Al_2O_3/water were used by Younis et al. [12] to study the thermal and electrical performance of photovoltaic cells with a unique volume concentration of 0.05. This study was conducted using both numerical and experimental approaches, and it was noted that using these nanofluids, only a 4.1% improvement in cell efficiency could be achieved. However, the temperature change at the solar surface was only 0.65%. The performance of solar cells was analyzed by testing both mono and hybrid nanofluids [13]. To improve the thermal and electrical performance, Mono Al_2O_3/water and hybrid Al_2O_3+Fe/water nanofluids were selected. Performance improvement of 2.17% was observed when using mono nanofluids for transportation, whereas a performance decrease of 1.79% was observed with the hybrid mixture, as compared to using only water. The study did not demonstrate that thermal performance is enhanced through the use of a hybrid mixture. However, it did show that the energy gained increased by 6.9%, compared to only 5.7% when using mono nanofluids. A study was conducted to compare aluminum oxide-water nanofluids and titanium dioxide-water nanofluids in terms of performance enhancement in photovoltaic thermal systems [14]. It was noticed that the combination of water and Al_2O_3 improved cell efficiency more than the combination of water and TiO_2. It was also found that the minimum temperature of the cell occurs when only a 0.03 kg/s mass flow is used. Another point added was that only a 0.28% increment in cell efficiency can be observed when a 3% volume concentration was used.

The application of Al_2O_3/water nanofluids was used by Aneli et al. [15] to enhance both the energy and exergy performance of a photovoltaic cell with a volume fraction of only 3%. The rate of thermal transport in the solar cell was also observed by varying the inlet temperature from 5°C to 45°C. It was found that increasing this temperature range improved thermal performance by a maximum of 2%. However, electricity production decreased slightly. A numerical study using COMSOL 6.0 was conducted by Alghamdi et al. [16] to investigate a PV/T system's efficiency improvements. Copper-alumina-water hybrid nanofluid was employed, and a trapezoidal channel was introduced for the first time. The PV/T setup included a silicon panel, absorber, and flow channel. Augmentation of the Reynolds number from 100 to 1000 reduced the cell's temperature by approximately 50%, which improved electrical efficiency by 4.4%. Additionally, optimizing the trapezoidal channel enhanced electrical performance by 1.6%. A numerical investigation was carried out by Diwania et al. [17] to improve the efficiency of a photovoltaic collector. This was achieved by exploring the use of copper/water and alumina/water combinations. The system was examined by developing and experimentally verifying a mathematical model based on the energy-balance equation. The alumina/water combination was found to be less effective in enhancing efficiency compared to the copper/water combination. Additionally, the study found that increasing the number of tubes significantly enhances efficiency, while increasing the tube diameter did not contribute to efficiency improvement.

Other studies [18-23] also demonstrate that research projects undertaken with COMSOL Multiphysics make a substantial contribution to improving PV/T system effectiveness through innovative cooling approaches. Numerical calculations and experimental studies show that nanofluids such as Cu/H_2O, SiO_2/H_2O, and TiO_2/H_2O boost thermal efficiency. Specific attempts, such as using a revolving circular cylinder and adjusting the Reynolds number and nanoparticle quantity, resulted in efficiency gains of up to 16.8%. They are also explained below in detail.

Diwania et al. [18] conducted a numerical study to improve the thermo-electrical effectiveness of a PVT system by utilizing nanofluids for cooling purposes. In this investigation, three different nanofluid combinations were used: TiO_2/H_2O, SiO_2/H_2O, and Cu/H_2O. The results indicated that the Cu/H_2O nanofluid combination was particularly effective in enhancing both the thermal/electrical efficiency of the hybrid PV/T system. The PV/T system showed improved thermal and electrical efficiency, with an enhancement of up to 2% when using a 4% volume concentration of Cu/H_2O, compared to using pure water. Using COMSOL Multiphysics 6.0, a numerical simulation for the PV/T system incorporating a recirculating circular cylinder was established by Allehiany et al. [19] to enhance its electrical performance. The Reynolds number was tested in the range of 100-1000, and silver and titanium oxide nanoparticles were chosen as the constituents in the nanofluids. It was found that using a volume fraction of ternary nanofluids in the range of 4-5% with a high-speed circular cylinder improves the electrical efficiency of the system. Akram et al. [20] computationally explored improving the electrical performance of a 2D photovoltaic thermal (PV/T) system using hybrid nanofluids containing titanium oxide and silver nanoparticles, utilizing the finite element analysis (FEA) tool COMSOL Multiphysics 6.0. By varying the Reynolds number (100-1000), cylinder rotational speed (0.01-0.2 m/s), and silver volume fraction (0.01-0.2), it was found that these adjustments reduce the cell's maximum temperature and enhance efficiency by 5.93%.

The electrical effectiveness of a PV/T system was enhanced by incorporating copper and alumina nanofluids as cooling agents and attaching a cavity as the flow channel. In another study by Memon et al. [21], a parametric analysis was conducted using COMSOL Multiphysics, with the Reynolds number having the range from 100 to 1000 and the inlet temperature varying from 5°C to 50°C. It was observed that electrical efficiency increased by 6% under the conditions of a Reynolds number of 1000, an aspect ratio of 0.5, and a volume fraction of 10%, with the inlet temperature set at 5°C. Using COMSOL Multiphysics 6.0, Khan et al. [22] investigated a PV/T system with an annular flow channel and ternary hybrid nanofluids, considering shape factor effects. The study examined Reynolds numbers ranging from 100 to 1500 under steady-state conditions, with the inlet temperature fixed at 5°C. The findings revealed that with a 10% volume fraction, electrical efficiency improved by 9.3%, and thermal efficiency reached 85%. Blade-shaped particles achieved the maximum thermal efficiency. Sharaby et al. [23] experimentally investigated the potential of a PV/T system using hybrid nanofluids composed of zinc and multi-walled carbon nanotubes. By maintaining a flow rate of 0.156 kg/m^3 and a nanofluid concentration of 0.1%, significant improvements were observed. The cell temperature decreased by 14.9°C, and the electrical efficiency increased by 16.8%. Additionally, the overall efficiency, encompassing both electrical and thermal aspects, reached 58.7%.

Research Gap and Novelty: A thorough review of the literature [1-23] reveals that the study of PV/T systems with the application of nanofluids for cooling is crucial for enhancing the system's electrical efficiency. The studies identified four key parameters that should be investigated on a trial basis: Reynolds number, nanofluid volume fraction, inlet temperature, and geometric configuration. Most simulations were conducted using COMSOL Multiphysics, and many studies were based on experimental investigations. Previous studies overlooked or did not attempt the configuration of a backward step channel attached to the PV/T system. The advantage of the backward step is the creation of a recirculation region downstream. Previous studies attempted to create a recirculation region by attaching a circular cylinder, but in the present study, the length of the downstream region is utilized to produce a recirculation region at the corner of the backward step channel. This is the novelty of the work: attaching a backward step channel to the PV/T system to improve efficiency while maintaining a simple PV panel configuration. In the present study, the photovoltaic thermal system is composed of a silicon panel, a copper absorber, and a flow channel. The flow channel attached to the panel is a backward step channel. This is a combined conduction and forced convection problem, with pure conduction analyzed in the top two layers, composed of silicon and the absorber. Nanofluids will be utilized to examine forced convection to lower the temperature of the solar cell. COMSOL Multiphysics 6.2 will be used for the complete modeling and simulation process, employing a finite element approach. A thorough investigation will be conducted to improve the channel's performance by modifying key parameters, including inlet temperature, downstream height, Reynolds number, and copper volume fraction. The simulation will be validated through a sequential approach, beginning with the examination of previous results, followed by performing a mesh independence study and validation with correlations. Our objective is to enhance the cell efficiency of solar cells for the parameters used in this simulation.

Detail about the sub-sections: To complete this study, we will follow a structured approach. After the introduction, we will detail the problem formulation, which includes the geometry structure, PV panel configuration, thermophysical properties of both the PV panel and the hybrid nanofluids, along with their empirical equations. This section will also explain the governing equations utilized to achieve the numerical solution through the Finite Element Method (FEM) and built-in code. The subsequent section will cover the mesh independence or grid independence test to ensure accuracy, including validation of the results. The results and discussion section will then present and analyze the key findings of the study. Finally, the conclusion will summarize the main points and implications of the research.

2. Problem Formulation

Figure 1 illustrates a two-dimensional perspective of a PV/T system composed of three distinct domains made of different materials. The top domain consists of silicon, commonly used in photovoltaic cells. The middle domain is an absorber made of copper. The bottom domain features a backward step flow channel, often analyzed in flow problems. The channel's construction specifies that the upstream length is 20% of the total length, while the base length is 80%. The inlet height H_1 is fixed at 0.25 mm. The lengths of the silicon cell and absorber are equal to the flow channel length, with both domains having heights of 0.05 mm. Detailed geometric construction information is provided in Table 1, and the material specifications for these domains are given in Table 2.

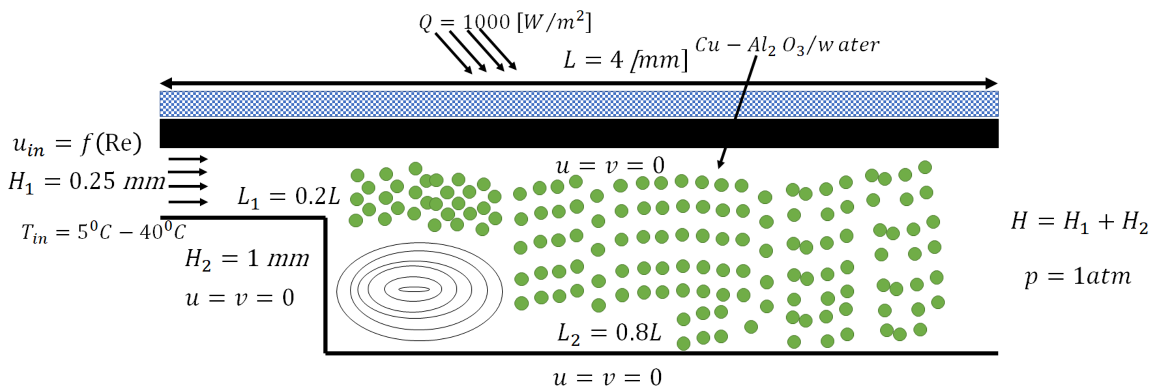


Fig. 1. Schematic presentation of the flow channel and photovoltaic cell.

Table 1. Parameters used to construct the geometry of the channel [27].

Symbols	Value	Description
H_1	0.25 [mm]	Inlet height
H_2	1 [mm]	Height of downstream
Ar	$H_2/(H_1+H_2)$	The aspect ratio of height to the downstream to the total height of the backward step channel
L	4 [mm]	The total length of the channel
L_2	$0.8\times L$	Length of the base at the downstream
L_1	$L-L_2$	Length of upstream
A	$L\times H_1+L_2\times H_2$	The total area of the channel
P	$L+L_1+L_2+2\times(H_1+H_2)$	The perimeter of the backward step channel
D_h	$4\times A/P$	Hydraulic Diameter of channel
H	H_1+H_2	Total height of the channel
H_3	0.05 [mm]	Height of the absorber
H_4	0.05 [mm]	Height of the silicon panel

Table 2. Material Properties of photovoltaic cell [22, 24].

Symbols	Value	Description
$\rho_{silicon}$	2330 [kg/m³]	Density of silicon
$C_{p_{silicon}}$	716 [J/(kg.K)]	Heat capacity of silicon
$\kappa_{silicon}$	157 [W/(m.K)]	Thermal conductivity of silicon
β	0.003 [1/K]	Temperature coefficient
α	0.9	Absorptance
η_{ref}	0.2	Reference efficiency of cell
$C_{p_{absorber}}$	386 [J/(kg.K)]	Specific heat for copper
$\rho_{absorber}$	8900 [kg/m³]	Density of copper
$\kappa_{absorber}$	398 [W/(m.k)]	Thermal conductivity of copper

Table 3. Thermophysical properties of hybrid nanofluids [25].

	Density [kg/m³]	Thermal conductivity [W/m.k]	Specific heat constant pressure [J/kg.K]
Al_2O_3	$\rho_{np1} = 3880$	$\kappa_{np1} = 40$	$(c_p)_{np1} = 765$
Cu	$\rho_{np2} = 8954$	$\kappa_{np1} = 386$	$(c_p)_{np2} = 383.1$
H_2O	$\rho_{bf} = 998$	$\kappa_{bf} = 0.597$	$(c_p)_{bf} = 4182$

Table 4. Empirical equations for determining thermophysical properties of nanoparticles, hybrid nanofluids and other parameters.

Description	Formula
Viscosity of hybrid nanofluids	$\mu_{hnf} = \mu_{bf}\dfrac{1}{(1-\phi)^{2.5}}$
Density of nanoparticles mixture	$\rho_{np} = \dfrac{\phi_1\rho_{np1} + \phi_2\rho_{np2}}{\phi_1 + \phi_2}$
Density of hybrid nanofluids	$\rho_{hnf} = \rho_{bf}(1-\phi) + \phi\rho_{np}$
Specific heat at constant pressure of nanoparticles	$(c_p)_{np} = \dfrac{\phi_1\rho_{np1}(c_p)_{np1} + \phi_2\rho_{np2}(c_p)_{np2}}{\rho_{np}(\phi_1+\phi_2)}$
Specific heat at constant pressure of hybrid nanofluids	$(c_p)_{hnf} = \dfrac{(1-\phi)\rho_{bf}(c_p)_{bf} + \phi\rho_{np}(c_p)_{np}}{(\phi_1+\phi_2)}$
Thermal conductivity of nanoparticles	$\kappa_{np} = \dfrac{\phi_1\kappa_{np1} + \phi_2\kappa_{np2}}{(\phi_1+\phi_2)}$
Thermal conductivity of hybrid nanofluids	$\kappa_{hnf} = \kappa_{bf}\left(\dfrac{\kappa_{np} + 2\kappa_{bf} + 2(\kappa_{np}-\kappa_{bf})\phi}{\kappa_{np} + 2\kappa_{bf} - 2(\kappa_{np}-\kappa_{bf})\phi}\right)$
Volume fraction of alumina (aluminum oxide)	$\phi_1 = 1\% = 0.01$
Volume fraction of copper	$\phi_2 = 2\phi_1$
Reynolds number	$\mathrm{Re} = \dfrac{\rho_{hnf}\upsilon_{in}D_h}{\mu_{hnf}} = 100-400$
Inlet velocity	υ_{in}
Inlet temperature	$T_{in} = 5^\circ C - 40^\circ C$
Reference temperature	$T_{ref} = 25^\circ C$

Applying the transport of nanofluids in the flow channel can cool down the photovoltaic cell, thereby mitigating potential performance issues caused by rising temperatures. In this study on modeling and simulation, our objective is to enhance the effectiveness of photovoltaic cells. This will be achieved through the utilization of a hybrid mixture consisting of copper and aluminum oxide, with water as the primary transport fluid. The volume fraction of copper is always half that of aluminum oxide due to the significant difference in thermal conductivity between the two materials. The analysis will focus on heat transport in the flow channel, achieved by varying the volume fraction of copper. The selected volume fractions are 0.01, 0.05, 0.1, and 0.2.

The flow channel will be supplied with a hybrid nanofluid mixture at an initial temperature range of 5°C to 40°C, starting from the higher end and progressively cooling. The nanofluid, consisting of copper and aluminum oxide with water as the base fluid, will be introduced with an initial horizontal velocity determined by the Reynolds number (Re), which will be varied within the range of 100 to 400 to investigate forced convection effects. Detailed thermophysical properties of water, copper, Al_2O_3, and their mixtures are presented in Table 3 and 4.

2.1. Governing equations

The current modeling with simulation aims to investigate the electrical efficiency of a PV/T system. The finite element software COMSOL Multiphysics 6.2 was used to generate the numerical results for this study. The flow is considered to be laminar, steady, and Newtonian. The numerical solution is obtained by solving the governing Navier-Stokes equations and the energy Eqs. (1) to (4), which are partial differential equations. As previously described, pure conduction occurs in the top two layers, composed of silicon and copper, respectively. In the flow channel, forced convection is analyzed. Solar irradiation falls on the silicon surface and is transmitted to the absorber. To mitigate the rising temperature of the solar cell, nanofluid coolant is passed through the flow channel. After obtaining reliable results, post-processing will be conducted using Eqs. (5) to (12):

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = 0 \tag{1}$$

$$u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + \frac{1}{\rho_{nf}} \frac{\partial p}{\partial x} - \mu_{hnf} \left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} \right) = 0 \tag{2}$$

$$u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + \frac{1}{\rho_{nf}} \frac{\partial p}{\partial y} - \mu_{hnf} \left(\frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} \right) = 0 \tag{3}$$

$$u_x \frac{\partial T}{\partial x} + u_y \frac{\partial T}{\partial y} - \alpha_{hnf} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) = 0 \tag{4}$$

where u_x and u_y are the horizontal component of the velocity field, respectively and T is the temperature.

2.2. Computational parameters

- Local Nusselt number:

$$Nu_x = \frac{hx}{\kappa_{nf}} \tag{5}$$

- Heat transfer coefficient:

$$h = \frac{Q}{T - T_b} \tag{6}$$

- Bulk temperature:

$$T_b = \frac{\int_0^{H_1} u_x T dx}{\int_0^{H_1} u_x dx} \tag{7}$$

- Prandtl number:

$$\Pr = \frac{\mu_{hnf} Cp_{hnf}}{\kappa_{hnf}} \tag{8}$$

- Nusselt number correlation:

$$Nu_{Correlation} = 0.021 \mathrm{Re}^{0.8} \Pr^{0.5} \tag{9}$$

- Cell efficiency:

$$\eta = \eta_{ref} [1 - \beta (T_{cell} - T_{ref})] \tag{10}$$

- Percentage change in the cell efficiency:

$$\eta_{\%} = 100 \mathrm{x} \frac{\eta - \eta_{ref}}{\eta_{ref}} \tag{11}$$

Table 5. Table of working procedure of COMSOL 6.2.

Step 1: Selecting parameters for construction of geometries, material properties of PV/T systems, and thermo-physical properties of nanofluids
Step 2: Sketching the geometry or channel using the GUI interface of COMSOL 6.2
Step 3: Applying the required boundary conditions or physics to the selected channel
Step 4: Meshing procedure for the numerical investigation, including a mesh independence study and validation
Step 5: Post-processing procedure

2.3. COMSOL working wagon wheel

The scrutiny of the numerical modeling of a PV/T system is conducted using the Multiphysics software COMSOL 6.2. We believe that such a complex phenomenon, involving pure conduction in two domains and both convection and conduction in two other domains, can only be effectively managed using this software. The functionality of COMSOL 6.2 is detailed in Table 5.

Finally, we make the following assumptions to investigate this PV/T system:

- **Steady-State Assumption:** The study focuses on a steady-state problem. Fluid materials are assumed to be incompressible and uniform.
- **Nanofluid Assumption:** Nanofluids, composed of a base fluid and nanoparticles, are assumed to be in thermal equilibrium. This means that nanofluids are considered to exhibit behavior similar to pure fluids.
- **Flow Regime:** The flow regime is assumed to be purely laminar, with the outlet considered to be fully developed.
- **PV Cell Energy Conversion:** The PV cell does not convert all heat energy into electrical energy but uses part of the energy to generate electricity and raise the cell's temperature.
- **Sunlight Orientation:** The solar cell is oriented so that sunlight falls perpendicularly on its surface.
- **Heat Loss Neglect:** Heat loss due to radiation at low temperatures is disregarded.
- **Insulated Bottom Surface:** The bottom surface of the cell is assumed to be insulated, preventing both heat entry and escape from that direction.

3. Mesh Independence Study and Validation

To warrant the validity of the numerically computed results, a grid independence study was conducted, as the numerical scheme used for this application necessitates reliable outcomes. This study involves selecting key variables and adjusting the density of the mesh or the number of elements. The process is deemed reliable when augmenting the number of elements no longer improves the results for the selected variables, indicating that the mesh has reached a sufficient level of refinement. We performed a mesh independence test for maximum velocity, temperature, and pressure at the outlet. The results, presented in Figs. 2(a) to 2(c), confirm that mesh independence is achieved when the number of irregular triangular elements exceeds 100,000.

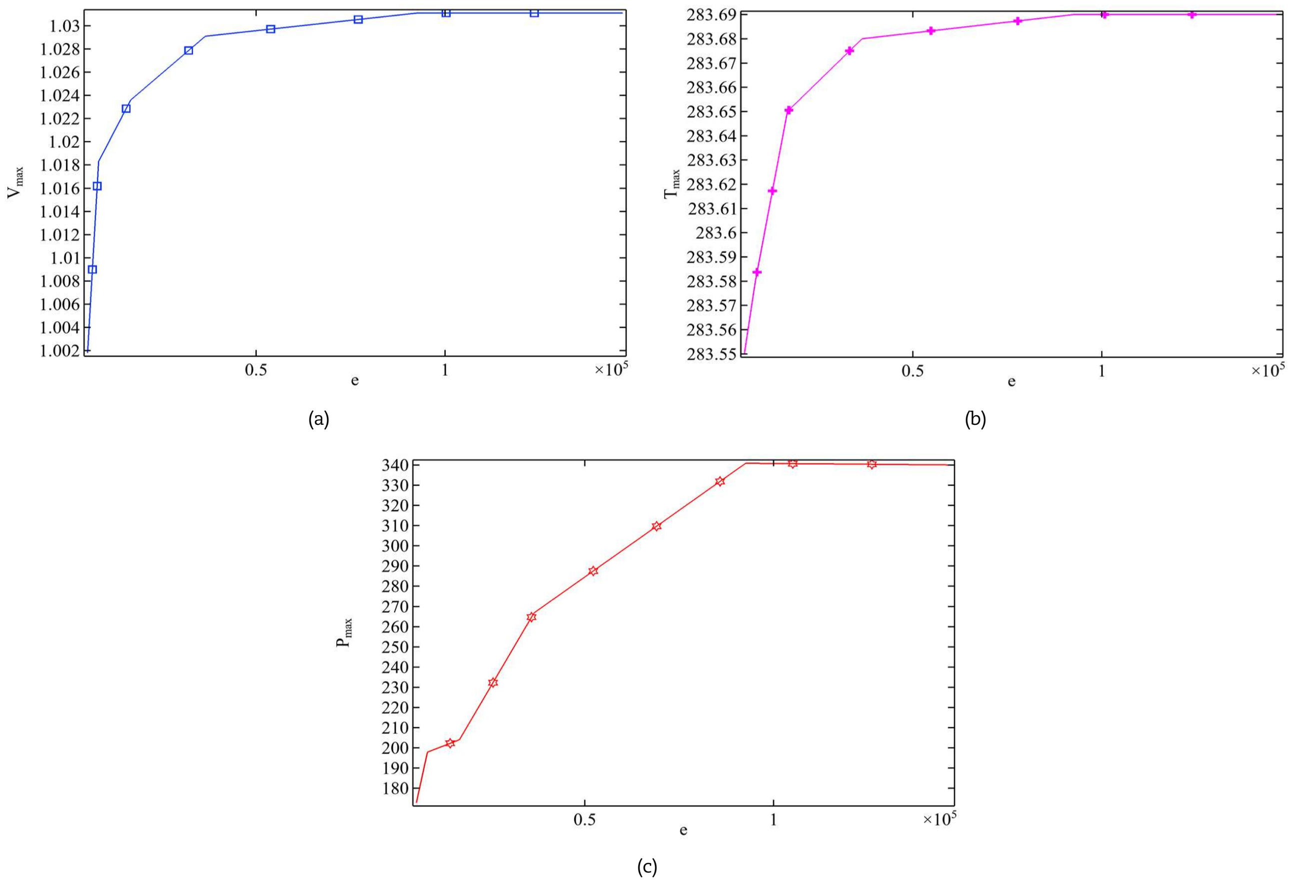
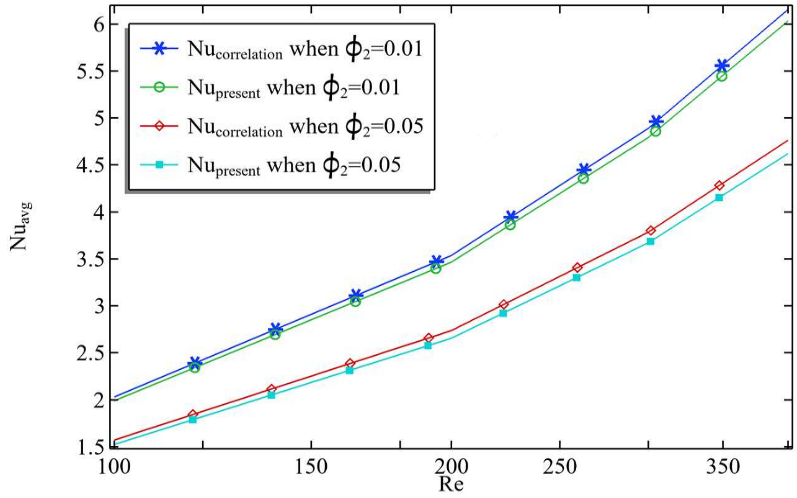
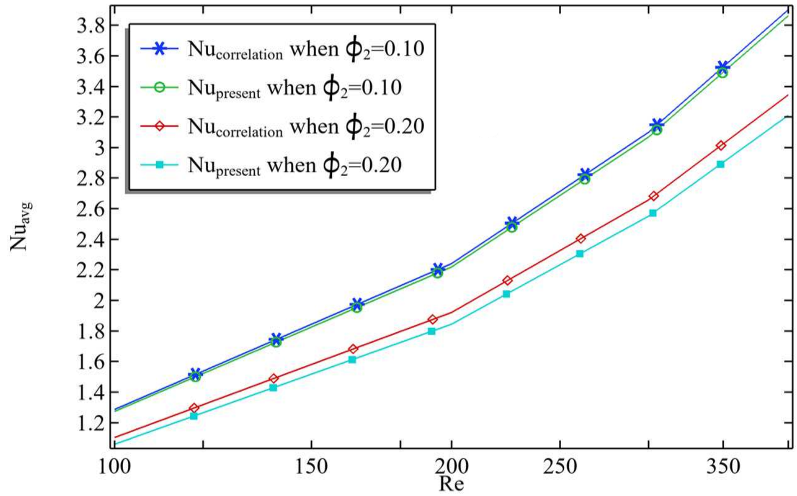


Fig. 2. Mesh independence study for maximum (a) velocity (b) temperature and (c) pressure.



(a)



(b)

Fig. 3. Comparison of the average Nusselt number at the outlet of the channel with experimental correlations, plotted against Reynolds number values for $T_{in} = 50^{\circ}C$ and $H_2 = 0.25$ [mm].

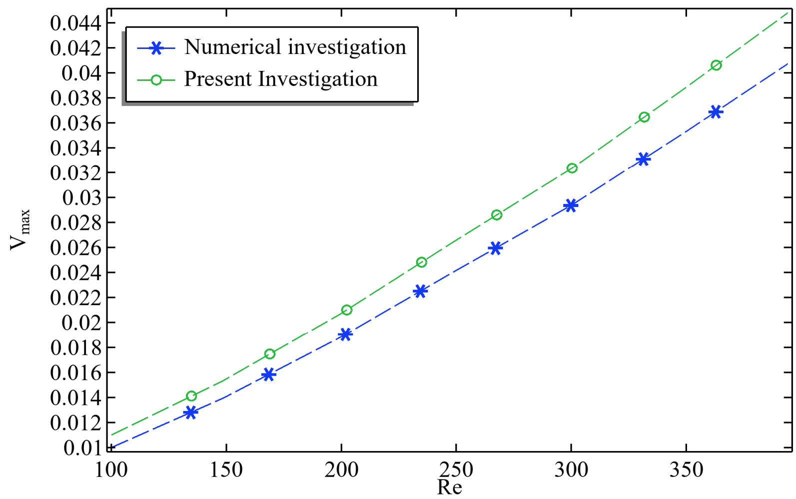


Fig. 4. Validation of the present code of finite element scheme.

Comparing with the experimental work reported in Ref. [5], Figs. 3(a) and 3(b) show the average Nusselt number at the outlet of the channel. The results indicate a rapid convection process, as evidenced by the increasing average Nusselt number with rising Reynolds number. Figure 4 presents a comparison of the velocity profile for the backward step channel, based on the study [26], which provides a slight validation of our findings.

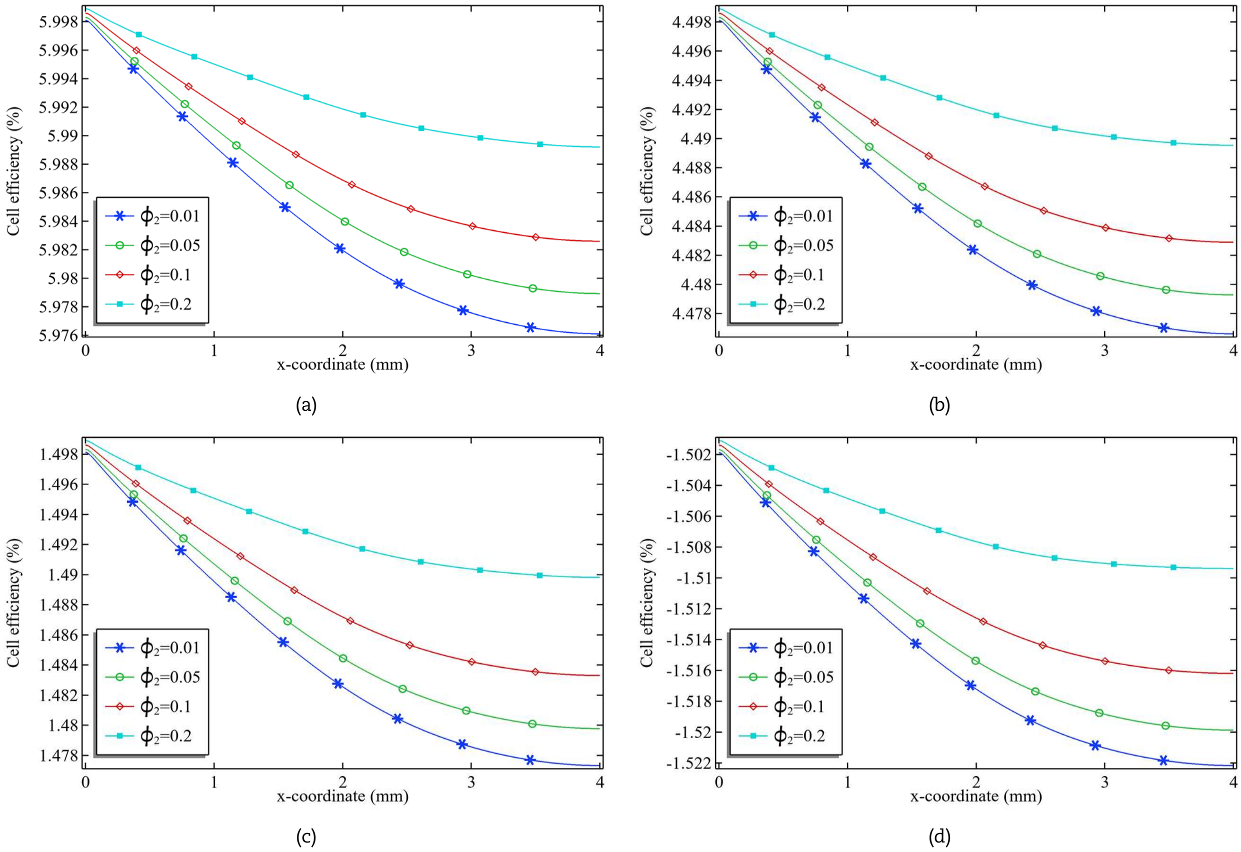


Fig. 5. Cell efficiency (%) vs the length of the cell for all volume fractions of copper at Re = 400, $H_2 = 0.25$, (a) $T_{in} = 5^{\circ}C$ (b) $T_{in} = 10^{\circ}C$ (c) $T_{in} = 20^{\circ}C$ (d) $T_{in} = 30^{\circ}C$.

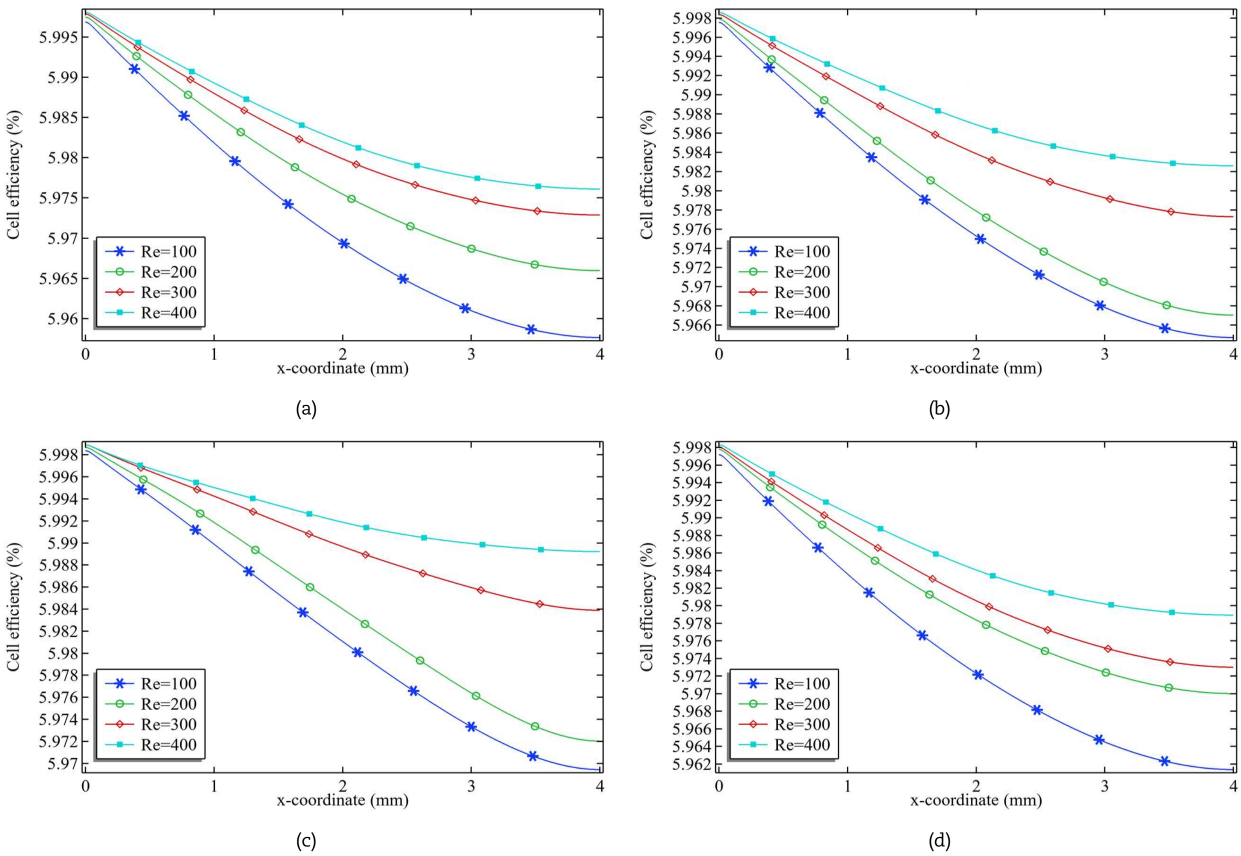


Fig. 6. Cell efficiency (%) vs the length of the cell for all Reynolds number at $T_{in} = 5^{\circ}C$, $H_2 = 0.25$, (a) $\phi_2 = 0.01$ (b) $\phi_2 = 0.05$ (c) $\phi_2 = 0.1$ (d) $\phi_2 = 0.2$.

4. Results and Discussion

The current modeling and simulation aim to numerically investigate the percentage improvement in cell efficiency relative to the reference efficiency. By varying specific parameters namely, the Reynolds number, volume fraction, inlet temperature, and downstream height in the backward step channel enhancements in cell performance will be evaluated along the entire length of the silicon cell. This approach seeks to identify improvements throughout the cell's size.

4.1. Cell efficiency against the volume fraction and inlet temperature

The study aims to augment the efficiency of PV/T system by utilizing Cu + Al_2O_3/water nanofluids as the transport medium. The primary focus is on improving cell efficiency. Figures 5(a) to 5(d) illustrate the relationship between channel length and cell efficiency (%). As depicted in Fig. 5(a), cell efficiency improves with increasing copper volume fraction, with each graph representing a specific volume fraction and inlet temperature. Although efficiency generally decreases along the channel, it improves at both the inlet and outlet ends, where higher copper volume fractions are associated with increased efficiency. The maximum cell efficiency observed is approximately 6% along the length of the photovoltaic cell. A significant improvement of 0.23% in cell efficiency is noted when the copper volume fraction is increased from 0.01 to 0.2, particularly at the end of the measurement.

Figures 5(b) to 5(d) explore the impact of varying the inlet temperature of the hybrid mixture. A reduction in inlet temperature correlates with a decrease in cell efficiency percentage. Specifically, the maximum efficiency drops by about 25% when the temperature increases from 5°C to 10°C, and by 66% when the temperature rises from 10°C to 20°C. Figure 5(d) reveals a negative efficiency change, indicating a decrease compared to the reference cell efficiency. The significant reduction in cell temperature and the effective use of nanofluids as a coolant enhance cell efficiency. Conversely, higher inlet temperatures are detrimental to improving cell efficiency.

4.2. Cell efficiency against the Reynolds number

Increasing the inlet velocity in a domain is known to reduce the surrounding temperature, independent of the channel structure. The current numerical investigation analyzed the effect of Reynolds number on cell efficiency while maintaining constant temperature and downstream height (see Figs. 6(a) to 6(d)). As depicted in Fig. 6(a), cell efficiency improves along the length of the cell with an increase in Reynolds number from 100 to 400. Although overall efficiency decreases along the cell length, it exhibits a gradual improvement at the cell's end with higher Reynolds numbers. Specifically, increasing the Reynolds number from 100 to 400 results in a roughly 0.33% improvement in efficiency. However, this enhancement is depending on the copper volume fraction and inlet temperature, as shown in Fig. 6(d), where the improvement at the end of the cell length is approximately 0.25%.

With a reference efficiency of 0.2 and a baseline temperature of 25°C, the cell efficiency near this inlet temperature is expected to be negative, according to the efficiency formula (12). The effect of increasing Reynolds number at an inlet temperature of 40°C was also evaluated (see Figs. 7(a) to 7(d)). The results clearly indicate that boosting the Reynolds number leads to a decrease in cell efficiency towards the end of the cell length. Nonetheless, a slight enhancement in cell efficiency is observed at the end of the cell length with a higher volume fraction of copper. The trend of improved efficiency along the channel length is illustrated in Fig. 7(c). At elevated inlet temperatures, the pattern of cell efficiency variation with Reynolds number reveals distinct differences.

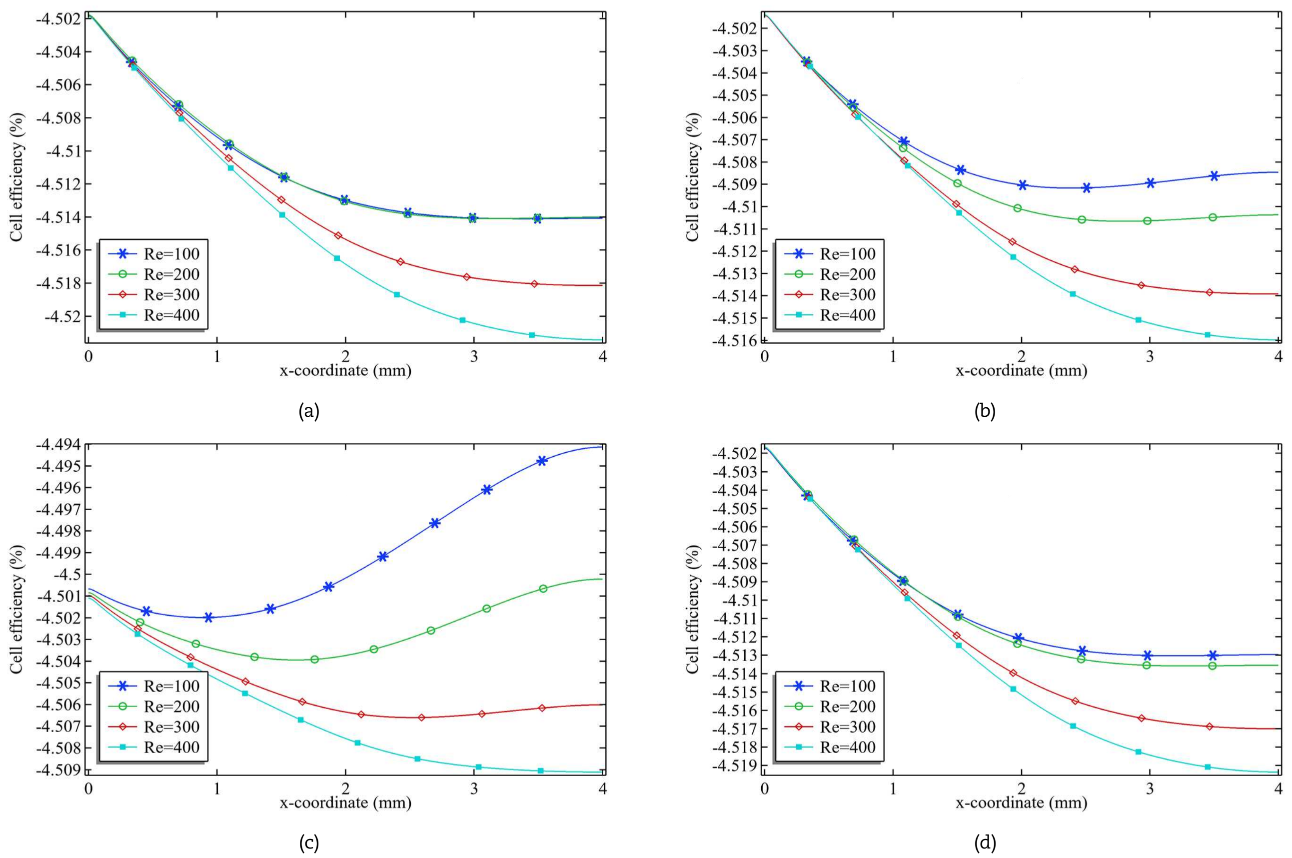


Fig. 7. Cell efficiency (%) vs the length of the cell for all Reynolds number at $T_{in} = 40^{\circ}C$, $H_2 = 0.25$, (a) $\phi_2 = 0.01$ (b) $\phi_2 = 0.05$ (c) $\phi_2 = 0.1$ (d) $\phi_2 = 0.2$.

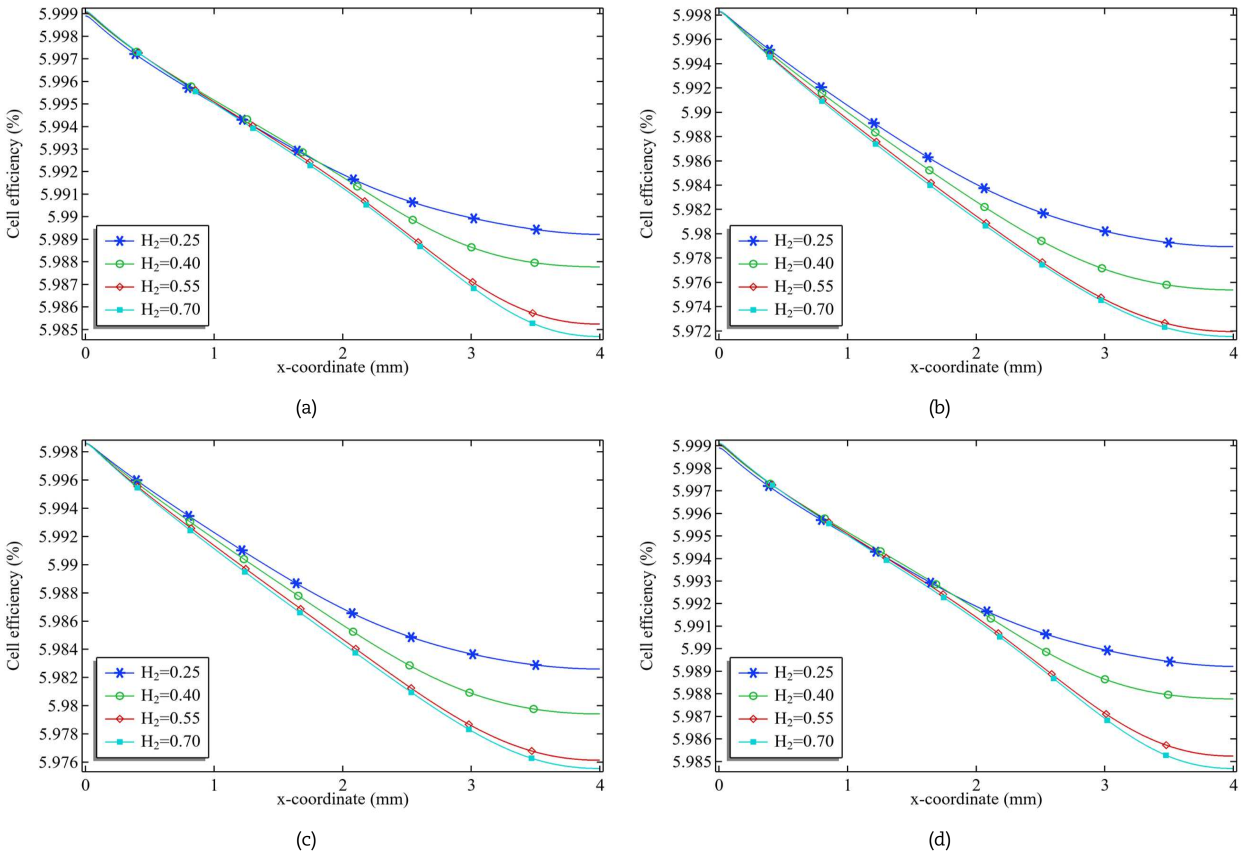


Fig. 8. Cell efficiency (%) vs the length of the cell for all H_2 at $T_{in} = 5^{\circ}C,\ Re = 400$ (a) $\phi_2 = 0.01$ (b) $\phi_2 = 0.05$ (c) $\phi_2 = 0.1$ (d) $\phi_2 = 0.2$.

4.3. Cell efficiency vs the increasing height of downstream

The study aims to boost the effectiveness of a photovoltaic cell by incorporating a flow channel with a backward step at the bottom. The objective is to numerically improve the cell's performance. Hybrid nanofluids are employed for transport, with variations in Reynolds number, inlet temperature, and downstream height. Figures 8(a) to 8(d) illustrates the analysis of cell efficiency as the downstream height (H_2) is increased from 0.25 to 0.7 mm, while keeping the Reynolds number and copper volume fraction constant. As shown in Fig. 8(a), cell efficiency decreases along the channel length. Increasing the downstream height results in a reduction of maximum cell efficiency at the channel's end. This reduction, attributable to the increase in downstream height from 0.25 mm to 0.7 mm, is minimal, amounting to only 0.006%. The final cell efficiency value shows only a negligible difference compared to the initial value.

Finally, Table 6 presents the average percentage change values for a volume fraction of copper set at 0.2. According to Table 6, it is evident that increasing the downstream height and inlet temperature leads to a decrease in cell efficiency (%) along the length of the cell. Conversely, the average cell efficiency consistently increases with higher Reynolds numbers and volume fractions, as discussed earlier.

Figures 7 (a) to 7(d) and Table 4 show a decrease in cell efficiency, indicated by negative values for the percentage change. The PV/T system's cell efficiency cannot be negative in actuality. However, here we are calculating the percentage change in cell efficiency relative to the reference efficiency, as given in Eq. (11). According to Eq. (11), the percentage can become negative only when the cell efficiency is lower than the reference efficiency. Examining Eq. (10), we calculate the cell efficiency (η). It is clear that when the cell temperature (T_{cell}) is lower than the reference temperature (T_{ref}), the cell efficiency will increase. Conversely, when the cell temperature exceeds the reference temperature, the cell efficiency will decrease. An increase in cell temperature is only possible when the inlet temperature is increased. Clearly, at temperatures of 30°C and 40°C, the increase in temperature surpasses the reference temperature, resulting in cell efficiency being lower than the reference efficiency. This is the reason we observe negative values for the percentage change in cell efficiency relative to the reference efficiency.

5. Conclusions

This article aimed to improve the electrical efficiency of a thermal photovoltaic system by developing advanced modeling and simulation techniques. The system comprised a silicon panel, an absorber and a flow channel. A backward step channel was employed as the flow channel, and a hybrid mixture of Cu-Al_2O_3 with water was selected as the base fluid to flow through it. In this study, nanofluids were utilized as a coolant to counteract the cell's rising temperature. The finite element package COMSOL Multiphysics 6.2 was utilized for the modeling with simulation of this application. The governing partial differential equations and the two-dimensional energy equation were considered to acquire the numerical solution for the present geometry. This study addressed a combined convection and conduction problem, where conduction occurs only in the top two layers of the solar cell. To enhance the cell efficiency and analyze the patterns, a parametric study was conducted varying the volume fraction (0.01 - 0.2), Reynolds number (100 - 400), inlet temperature (5°C - 40°C) of the mixture, and the downstream height (0.25 mm - 0.7 mm) of the backward step channel. We have successfully highlighted the following points:

Table 6. The average percentage of the cell efficiency.

T_{in}	ϕ	Re	$H_2 = 0.25$ mm	$H_2 = 0.4$ mm	$H_2 = 0.55$ mm	$H_2 = 0.7$ mm
5	0.2	100	5.9818	5.9813	5.9812	5.9841
5	0.2	200	5.9842	5.9884	5.9894	5.9886
5	0.2	300	5.9901	5.9917	5.9909	5.9901
5	0.2	400	5.9926	5.9921	5.9913	5.9911
10	0.2	100	4.4804	4.4845	4.4837	4.4833
10	0.2	200	4.4871	4.4893	4.4896	4.4888
10	0.2	300	4.4911	4.4917	4.4909	4.4901
10	0.2	400	4.4927	4.4921	4.4913	4.4911
20	0.2	100	1.487	1.4852	1.486	1.4851
20	0.2	200	1.4898	1.4906	1.4898	1.489
20	0.2	300	1.4924	1.4918	1.4908	1.49
20	0.2	400	1.4928	1.492	1.4912	1.491
30	0.2	100	-1.5052	-1.5066	-1.5102	-1.5116
30	0.2	200	-1.5051	-1.5084	-1.5098	-1.5108
30	0.2	300	-1.5066	-1.5082	-1.5092	-1.51
30	0.2	400	-1.5069	-1.508	-1.5089	-1.509
40	0.2	100	-4.4991	-4.5061	-4.508	-4.5099
40	0.2	200	-4.5025	-4.5071	-4.5096	-4.5106
40	0.2	300	-4.5053	-4.5082	-4.5093	-4.5101
40	0.2	400	-4.5068	-4.5081	-4.5089	-4.5091

- The study observed that cell efficiency decreases along the channel's length. However, an increase in the volume fraction of copper results in improved cell efficiency at the end of the channel, with a maximum enhancement of 0.23%.
- The efficiency of photovoltaic cells diminishes as the temperature of the solar cell increases. Specifically, an increase in the inlet temperature of the hybrid mixture leads to a decline in cell efficiency. At 40°C, our research indicates a 4.5% decrease in photovoltaic cell efficiency.
- The relationship between the Reynolds number and cell efficiency was also examined. When the cell efficiency is positive or the temperature is below 40°C (refer to Table 4 for details), an increase in the Reynolds number enhances cell efficiency. A moderate volume fraction of copper results in a 0.33% increase in cell efficiency at the end of the cell length, while other values exhibit a maximum increase of 0.25%.
- A decrease in cell efficiency at the end of the length was noted when the downstream height was increased. This indicates that connecting the backward flow channel to the photovoltaic cell does not contribute to an improvement in electrical efficiency.

Author Contributions

G.M. Shaikh and A.A. Memon planned the scheme, initiated the project, and did writing and editing of the manuscript; M.A. Memon worked through software and did the formal analysis; F.M. Allehiany and A.M. Obalalu developed the mathematical modeling and examined the theory validation. F.M. Allehiany also provided critical feedback and assisted in revising the manuscript's updated version. All authors reviewed the results and approved the final version of the manuscript.

Acknowledgments

The authors extend their profound gratitude to Sukkur IBA University for fostering an exceptionally conducive environment that supports and encourages research publications.

Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

Funding

The authors received no financial support for the research, authorship, and publication of this article.

Data Availability Statements

No data were utilized to perform this research.

Nomenclature

α	Absorbance	η_{ref}	Reference efficiency of cell
Ar	Aspect ratio between the downstream and the total height of the channel	$(c_p)_{bf}$	Specific heat of water
		$(c_p)_{np}$	Specific heat at a constant pressure of nanoparticles
T_b	Bulk temperature	$(c_p)_{hnf}$	Specific heat at a constant pressure of hybrid nanofluids
ρ_{bf}	Density of water	$(c_p)_{np1}$	Specific heat of alumina

ρ_{hnf}	Density of hybrid nanofluids	$(c_p)_{np2}$	Specific heat of copper
ρ_{np}	Density of nanoparticles mixture	A	Total area of the channel
ρ_{np1}	Density of aluminum oxide	κ_{bf}	Thermal conductivity of water
ρ_{np2}	Density of copper nanoparticles	$\kappa_{silicon}$	Thermal conductivity of silicon
$\rho_{silicon}$	Density of Silicon panel	β	Temperature coefficient
$\rho_{absorber}$	Density of absorber	α_{hnf}	Thermal diffusivity
D_h	Hydraulic diameter of the channel	$\kappa_{absorber}$	Thermal conductivity of copper
H	Height of the channel	κ_{np1}	Thermal conductivity of alumina
H_2	Height of downstream	κ_{np2}	Thermal conductivity of copper
H_3	Height of the absorber	κ_{np}	Thermal conductivity of nanoparticles
H_4	Height of the silicon panel	κ_{hnf}	Thermal conductivity of hybrid nanofluids
$Cp_{silicon}$	Heat capacity of silicon	u_y	Vertical component of velocity
$Cp_{absorber}$	Heat capacity of absorber	μ_{bf}	Viscosity of base fluid
u_x	Horizontal component of velocity	μ_{hnf}	Viscosity of hybrid nanofluids
v_{in}	Inlet velocity	ϕ	Volume fraction of hybrid nanofluids
T_{in}	Inlet temperature	ϕ_1	Volume fraction of alumina
L	Length of the channel	ϕ_2	Volume fraction of copper
L_2	Length of the base of downstream	**Abbreviations**	
L_1	Length of upstream	*bf*	Base fluid
P	Perimeter of the backward step channel	*hnf*	Hybrid nanofluids
Re	Reynolds number	*np*	Nanoparticles
T_{ref}	Reference temperature		

References

[1] Pearce, J.M., Photovoltaics—a path to sustainable futures, *Futures,* 34(7), 2002, 663-674.
[2] Chow, T.T., A review on photovoltaic/thermal hybrid solar technology, *Applied Energy,* 87(2), 2010, 365-379.
[3] Sardarabadi, M., Passandideh-Fard, M., Experimental and numerical study of metal-oxides/water nanofluids as coolant in photovoltaic thermal systems (PVT), *Solar Energy Materials and Solar Cells,* 157, 2016, 533-542.
[4] Michael, J.J., Iniyan, S., Performance analysis of a copper sheet laminated photovoltaic thermal collector using copper oxide–water nanofluid, *Solar Energy,* 119, 2015, 439-451.
[5] Wole-Osho, I., Adun, H., Adedeji, M., Okonkwo, E.C., Kavaz, D., Dagbasi, M., Effect of hybrid nanofluids mixture ratio on the performance of a photovoltaic thermal collector, *International Journal of Energy Research,* 44(11), 2020, 9064-9081.
[6] Farajzadeh, E., Movahed, S., Hosseini, R., Experimental and numerical investigations on the effect of Al_2O_3/TiO_2-H2O nanofluids on thermal efficiency of the flat plate solar collector, *Renewable Energy,* 118, 2018, 122-130.
[7] Hajabdollahi, Z.O., Mirzaei, M., Kim, K.C., Effects of a mixture of Cuo and Al_2O_3 nanoparticles on the thermal efficiency of a flat plate solar collector at different mass flow rates, *Heat Transfer Research,* 50(10), 2019, 945-965.
[8] Verma, S.K., Tiwari, A.K., Tiwari, S., Chauhan, D.S., Performance analysis of hybrid nanofluids in flat plate solar collector as an advanced working fluid, *Solar Energy,* 167, 2018, 231-241.
[9] Khanjari, Y., Pourfayaz, F., Kasaeian, A.B., Numerical investigation on using of nanofluid in a water-cooled photovoltaic thermal system, *Energy Conversion and Management,* 122, 2016, 263-278.
[10] Hissouf, M., Najim, M., Charef, A., Numerical study of a covered Photovoltaic-Thermal Collector (PVT) enhancement using nanofluids, *Solar Energy,* 199, 2020, 115-127.
[11] Gangadevi, R., Vinayagam, B.K., Experimental determination of thermal conductivity and viscosity of different nanofluids and its effect on a hybrid solar collector, *Journal of Thermal Analysis and Calorimetry,* 136(1), 2019 199-209.
[12] Younis, A., Elsarrag, E., Alhorr, Y., Onsa, M., The influence of Al_2O_3-ZnO-H_2O nanofluid on the thermodynamic performance of photovoltaic-thermal hybrid solar collector system, *Innovative Energy and Research,* 7(187), 2018, 2576-1463.
[13] Okonkwo, E.C., Wole-Osho, I., Kavaz, D., Abid, M., Al-Ansari, T., Thermodynamic evaluation and optimization of a flat plate collector operating with alumina and iron mono and hybrid nanofluids, *Sustainable Energy Technologies and Assessments,* 37, 2020, 100636.
[14] Jia, Y., Ran, F., Zhu, C., Fang, G., Numerical analysis of photovoltaic-thermal collector using nanofluid as a coolant, *Solar Energy,* 196, 2020, 625-636.
[15] Aneli, S., Gagliano, A., Tina, G.M., Hajji, B., Analysis of the energy produced and energy quality of nanofluid impact on photovoltaic-thermal systems, *Proc. of the ICEERE 2nd International Conference on Electronic Engineering and Renewable Energy Systems,* Saidia, Morocco, 2020.
[16] Alghamdi, M., Memon, A.A., Muhammad, T., Ali, M.R., A numerical investigation of a photovoltaic thermal system contained a trapezoidal channel with transport of silver and titanium oxide using the water as base fluids, *Case Studies in Thermal Engineering,* 47, 2023, 103056.
[17] Diwania, S., Siddiqui, A.S., Agrawal, S., Kumar, R., Modeling and assessment of the thermo-electrical performance of a photovoltaic-thermal (PVT) system using different nanofluids, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 43, 2021, 1-18.
[18] Diwania, S., Kumar, R., Kumar, M., Gupta, V., Alsenani, T.R., Performance enrichment of hybrid photovoltaic thermal collector with different nano-fluids, *Energy & Environment*, 34(6), 2023, 1747-1769.
[19] Allehiany, F.M., Memon, A.A., Memon, M.A., Fenta, A., Maximizing electrical output and reducing heat-related losses in photovoltaic thermal systems with a thorough examination of flow channel integration and nanofluid cooling, *Scientific Reports*, 13(1), 2023, 16961.
[20] Akram, M., Memon, A.A., Memon, M.A., Obalalu, A.M., Khan, U., Investigation of a two-dimensional photovoltaic thermal system using hybrid nanofluids and a rotating cylinder, *Nanoscale Advances,* 5(20), 2023, 5529-5542.
[21] Memon, A.A., Memon, M.A., Haque, M.M., Numerical investigation of electrical efficiency with the application of hybrid nanofluids for photovoltaic thermal systems contained in a cavity channel, *Journal of Mathematics,* 2023, https://doi.org/10.1155/2023/5465847.
[22] Khan, M.S., Wang, J., Memon, A.A., Muhammad, T., Investigating the Enhanced Cooling Performance of Ternary Hybrid Nanofluids in a Three-Dimensional Annulus-Type Photovoltaic Thermal System for Sustainable Energy Efficiency, *Case Studies in Thermal Engineering,* 2024, https://doi.org/10.1016/j.csite.2024.104700.

[23] Sharaby, M.R., Younes, M.M., Abou-Taleb, F.S., Baz, F.B., The influence of using MWCNT/ZnO-Water hybrid nanofluid on the thermal and electrical performance of a Photovoltaic/Thermal system, *Applied Thermal Engineering,* 248, 2024, https://doi.org/10.1016/j.applthermaleng.2024.123332.
[24] Karaaslan, I., Menlik, T., Numerical study of a photovoltaic thermal (PV/T) system using mono and hybrid nanofluid, *Solar Energy,* 224, 2021, 1260-1270.
[25] Elhag, S.H., Memon, A.A., Memon, M.A., Bhatti, K., Jacob, K., Alzahrani, S., Seidu, J., Analysis of Forced Convection with Hybrid Cu-Al2O3 Nanofluids Injected in a Three-Dimensional Rectangular Channel Containing Three Perpendicular Rotating Blocks with Turbulent Modeling, *Journal of Nanomaterials,* 2022, https://doi.org/10.1155/2022/2446972.
[26] Memon, A.A., Shaikh, H.U., Soomro, M.A., Shaikh, A.G., Shaikh, A.H., Modeling and simulation of newtonian fluid flow through two-dimensional backward-facing step channel with finite element's technique, *Indian Journal of Science and Technology,* 12(32), 2019, 1-6.
[27] Memon, A.A., Khan, W.A., Muhammad, T., Numerical investigation of photovoltaic thermal energy efficiency improvement using the backward step containing Cu-Al_2O_3 hybrid nanofluid, *Alexandria Engineering Journal*, 75, 2023, 391-406.

ORCID iD

F.M. Allehiany https://orcid.org/0000-0001-6604-9606
Gul M. Shaikh https://orcid.org/0009-0008-2623-5146
Abid A. Memon https://orcid.org/0000-0002-3114-8062
M. Asif Memon https://orcid.org/0000-0002-2608-6557
A.M. Obalalu https://orcid.org/0000-0003-0638-5928

How to cite this article: Allehiany F.M., Shaikh G.M., Memon A.A., Memon M.A., Obalalu A.M. Investigating the Effect of Cu-Al_2O_3 Hybrid Nanofluids on the Electrical Performance of PV/T Systems with Backward Step Flow Channel, *J. Appl. Comput. Mech.*, 11(2), 2025, 358-370. https://doi.org/10.22055/jacm.2024.47256.4683