PENINGKATAN EFISIENSI SEL SURYA DAN ENERGI LISTRIK PADA SISTEM FOTOVOLTAIC-TERMAL (PV/T) DENGAN MENGGUNAKAN MATERIAL PENGUBAH FASA (PCM) TERENKAPSULASI NANOFLUIDA

TUGAS AKHIR

Diajukan Sebagai Salah Satu Syarat untuk Memperoleh Gelar Sarjana Teknik
Pada Program Studi Teknik Elektro Fakultas Sains dan Teknologi

UIN SUSKA RIAU

Oleh:

SYARIFAH ADRIANA
12150522248

PROGRAM STUDI TEKNIK ELEKTRO
FAKULTAS SAINS DAN TEKNOLOGI
UNIVERSITAS ISLAM NEGERI SULTAN SYARIF KASIM RIAU
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2025

LEMBAR PERSETUJUAN

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TUGAS AKHIR

Oleh :

SYARIFAH ADRIANA
12150522248

Telah diperiksa dan disetujui sebagai laporan Tugas Akhir Program Studi Teknik Elektro di Pekanbaru, pada tanggal 02 Mei 2025

a.n Ketua Program Studi Teknik Elektro
Sekretaris Program Studi Teknik Elektro

Sutoyo, S.T., M.T
NIP. 19841202 201903 1 004

Pembimbing

Marhama Jelita, S.Pd., M.Sc.
NIK. 130517054

LEMBAR PENGESAHAN

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TUGAS AKHIR

Oleh :

SYARIFAH ADRIANA
12150522248

Telah dipertahankan di depan Sidang Dewan Penguji
sebagai salah satu syarat untuk memperoleh gelar Sarjana Teknik
Fakultas Sains dan Teknologi Universitas Islam Negeri Sultan Syarif Kasim Riau
di Pekanbaru, pada tanggal 02 Mei 2025

Pekanbaru, 02 Mei 2025

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Plh. Dekan,	**a.n Ketua Program Studi Teknik Elektro** **Sekretaris Program Studi Teknik Elektro**
Dr. H. Kunaifi, ST., PgDipEnSt., M.Sc **NIP. 19760724 200710 1 003**	**Sutoyo, S.T., M.T** **NIP. 19841202 201903 1 004**

Dewan Penguji :

Ketua	**: Ahmad Faizal, S.T., M.T.**
Sekretaris	**: Marhama Jelita, S.Pd., M.Sc**
Anggota I	**: Dr. Kunaifi, ST., PgDipEnSt., M.Sc**
Anggota II	**: Nanda Putri Miefthawati, M.Sc., B.Sc.**

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Nama	: Syarifah Adriana
NIM	: 12150522248
Tempat/Tanggal Lahir	:Pekanbaru/ 24 Februari 2003
Fakultas	: Sains dan Teknologi
Prodi	: Teknik Elektro
Judul Artikel	:

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METERAI TEMPEL
CADE7AMX311912775

Syarifah Adriana
NIM. 12150522248

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Improving Solar Cell Efficiency PV/T Using NEPCM by FEM Method

Syarifah Adriana [1], *Marhama Jelita* [2]

Department of Electrical Engineering, Faculty of Science and Technology, UIN Suska Riau, 28291, Indonesia

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CORRESPONDENCE

Phone: 0813-1973-9372
E-mail: marhama.jelita@uin-suska.ac.id

ABSTRACT

Energy generated from photovoltaic (PV) systems is often wasted, with about 80% converted to heat and only 20% converted to electricity. This indicates the need for further research to improve the energy conversion efficiency in PV systems. This study aims to analyze the cell efficiency and power generation in a photovoltaic-thermal (PVT) system with variations in nano-encapsulated phase change material (NEPCM) concentration and reservoir thickness. The developed PVT configuration includes a photovoltaic cell layer, a thermal paste layer, a reservoir wall, and a channel filled with nanofluid containing NEPCM surrounded by a protective shell. The research method involves simulation using the Finite Element Method to measure system performance regarding energy conversion efficiency, with encapsulated PCM concentration variations at 2%, 10%, and 20%. Additionally, the laminar flow velocity used is 0.5 m/s under steady-state conditions, and the thickness of the PCM material used is 1 mm and 15 mm. The results show that increasing the NEPCM concentration by 5% can improve the electrical and thermal performance of the system by more than 50%. In addition, variations in reservoir thickness also contribute to the overall efficiency. This study concludes that the proposed PVT configuration can improve energy efficiency and optimize thermal management in the system, making it an effective solution for developing renewable energy technologies. Thus, implementing NEPCM in PVT systems can significantly contribute to overall energy efficiency.

INTRODUCTION

Energy is a fundamental element for human life. Energy is vital in supporting economic growth and prosperity from daily needs to industry. As the population and economy grow, global energy demand continues to increase. According to the International Energy Agency (IEA), world energy consumption will increase by around 5% between 2020 and 2023 [1]. In Indonesia, energy demand is growing by around 6.5% per year, driven by economic growth. Data from the Ministry of Energy and Mineral Resources (ESDM) shows that Indonesia's primary energy consumption will reach 300 million tons of oil equivalent (MTOE) in 2023, up from 270 MTOE in 2020. This increase reflects the significant challenges in providing sustainable energy [2].

Regarding energy supply, Indonesia is still highly dependent on fossil fuels. Based on data from the National Energy Council (DEN), Indonesia's energy mix in 2023 will be dominated by coal (40.46%), followed by oil (30.18%) and natural gas (16.28%) [3]. New and renewable energy (EBT) only contributed 13.09%, although it experienced an increase of 0.79% from the previous year. However, this figure is still far below the target set of 17.87% [4]. High dependence on fossil fuels brings various challenges, including limited non-renewable resources, environmental pollution impacts, and risks to public health due to greenhouse gas emissions [5].

One of the leading solutions to reduce dependence on fossil fuels is to use renewable energy. Indonesia has great potential for renewable energy from various sources, including hydropower, geothermal, wind, biomass, and ocean energy. Hydropower potential, for example, is estimated to reach 94.5 GW, with utilization of around 6.1 GW until 2023. Indonesia's geothermal potential is one of the largest in the world, reaching 23.9 GW with an installed capacity of around 2.3 GW. In addition, wind energy also has great potential, especially in the southern coastal areas of Java, Nusa Tenggara, and Sulawesi [6]. However, other renewables, such as biomass and ocean energy, are still in the early stages of development. Meanwhile, solar energy, one of the largest sources, requires more attention for future growth. Renewable energy provides a long-term solution for the sustainability of energy supply. It reduces negative environmental impacts, and Indonesia has an excellent opportunity to utilize this potential in the future [7].

One of the largest sources of renewable energy in Indonesia is solar energy. Located around the equator, Indonesia receives abundant exposure to sunlight throughout the year. Indonesia's average solar radiation level ranges from 4.8 to 5.4 kWh/m² per day, depending on the region [8]. This makes Indonesia one of the countries with the world's most significant solar energy potential. Based on data from the Ministry of Energy and Mineral Resources, the potential for solar energy in Indonesia reaches

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207.8 GW, which is spread throughout the country, especially in the eastern parts such as East Nusa Tenggara, Maluku, and Papua, which have the highest levels of solar radiation. This shows excellent opportunities for further development [9].

Photovoltaic (PV) systems are a technology used to convert solar energy into electricity. PV uses the photoelectric effect, where semiconducting materials such as silicon absorb sunlight and release electrons, producing an electric current. Although this technology is widely used, the efficiency of PV panels is still an issue. Current PV efficiency averages between 15% and 20%, meaning that only a tiny portion of the solar energy received is converted into electricity, while most of the rest is lost as heat. Research [10] found that these efficiency challenges depend on environmental conditions like temperature, dust, and sunlight intensity.

One of the main problems with PV technology is its inability to convert all solar energy into electricity. Research [8] shows that PV panels cannot convert 100% of solar energy into electrical energy; about 80% is converted into thermal energy. Many studies have shown that the efficiency of PV cells decreases with increasing temperature. For example, the one conducted by [11] revealed that cell efficiency can decrease by 0.03% to 0.05% for every 1°C increase in cell temperature. At very high operating temperatures, efficiency can decrease drastically to 69% when the temperature reaches 64°C. In addition, research conducted by [12] found the same thing, namely that every 1°C increase in temperature in Photovoltaic (PV) cells can cause a decrease in PV cell efficiency of 2%. This is related to the nature of semiconductor materials, which become less effective in converting solar energy into electrical energy when exposed to high temperatures. The impact of low efficiency is very significant, especially in areas with tropical climates such as Indonesia, where environmental temperatures are often high [12].

The decrease in PV cell efficiency due to temperature increase can be overcome by adding a cooling system to the PV panel. This system is known as a photovoltaic—thermal (PV/T), which combines the functions of electricity generation and thermal management functions. Research [13] studied the temperature reduction of PV cells using PV/T technology with water as the cooling medium and found that the temperature can be reduced by 2°C, contributing to an efficiency increase of 3%. In addition, PV/T cooling systems using water in a laminar or forced convection configuration can reduce the temperature of PV cells by up to 2°C, as found in the study [14]. The forced flow of water helps remove heat from the solar cells more efficiently than natural flow. With this temperature reduction, the performance of the PV panels can be significantly improved, allowing for the optimization of solar energy use.

In the cooling system in PV/T, nanofluid can be used in addition to water fluid. Nanofluid is a fluid that is added with nanoparticles, usually measuring between 1 and 100 nanometers, which can improve the fluid's thermal properties. Research [15] found that using sand-propyleneglycol-water nanofluid with a concentration of 2% nanoparticles resulted in an increase in solar energy collection efficiency of up to 16.5% compared to using only propylene glycol and water. In addition, research [10] showed that variations in nanofluid concentration and fluid flow rate significantly affected reducing PV cell temperature. There was an increase in efficiency of 11% for every 10% increase in nanoparticle volume fraction. Thus, applying nanofluid in PV/T systems improves energy collection efficiency and helps maintain optimal PV cell temperatures, contributing to overall system performance [16].

The latest technology that can absorb heat energy is Phase Change Materials (PCM). PCM is a material that can store and release energy in the form of heat when undergoing a phase change, such as from solid to liquid or vice versa [17]. In research [18], a box system using PCM material showed that the use of Nano-Encapsulated Phase Change Materials (NEPCMs) can increase heat transfer by about 10% compared to the base fluid at a specific non-dimensional fusion temperature in the range $¼ < hf < ¾$. In addition, research [19]. Combining PCM with nanofluids can increase the heat transfer rate by up to 30% compared to a system that only uses the base fluid. These results indicate that using PCM and nanofluids together can produce higher thermal efficiency, especially in building energy storage applications.

Based on the existing problems, PV panels can only convert 20% of solar energy into electricity. In comparison, the remaining 80% is wasted as heat energy, which causes a decrease in PV cell efficiency. One solution to improve PV cell efficiency is to use a PV/T system with water-cooled fluid, which has been studied in studies [13] and [14]. In addition, PV/T cooling systems can also use nanofluids, as found in studies [14] and [15]., which show the potential for further efficiency improvements. The absorption of heat energy produced by PV can be maximized using PCM, which is studied in studies [18] and [19]. This study uses nanofluid-encapsulated PCM fluids as a cooling system in PV/T, aiming to improve PV cell efficiency and overall electrical energy production.

This study has limitations related to heat distribution in PV/T systems with PCM and nanofluids that have not been fully explored, especially the influence of design configuration, orientation, and flow velocity of nanofluids on system performance [20]. Using a combination of PCM and nanofluids in PV/T is relatively new because previously, they were generally used separately. Although this combination offers increased heat transfer and more efficient energy storage, challenges such as complex interactions between PCM and nanofluids, long-term stability, encapsulation process, and performance degradation due to material degradation need further study [21] [22].

This study aims to improve the efficiency of PV cells and electrical energy production in PV/T systems using nanofluid-encapsulated PCM. The PV/T system model comprises PV cells, thermal paste, and cooling channels containing aluminum and copper materials. Where the cooling system uses nanofluid encapsulated PCM with concentrations of 2%, 10%, and 20% and a laminar flow velocity of 0.5 m/s with a steady state. Analysis of the heat capacity and temperature of PV cells is essential to determine the temperature drop, which impacts energy conversion efficiency. The Finite Element Method (FEM) was chosen because of its ability to solve complex problems in thermal analysis with the help of COMSOL software version 5.4, which is adequate for multiphysics simulations. PV cell

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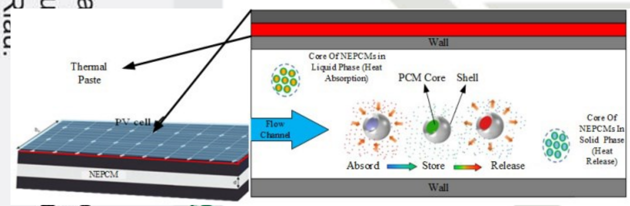
efficiency, thermal efficiency, and total efficiency of the PV/T system will be analyzed using the Second Law of Thermodynamics, which explains that energy always moves from a high to a low state, providing insight into the overall efficiency of the system [23].

PCM is a technology that increases energy conversion efficiency in PV/T systems. PCM works by absorbing and releasing heat during the phase change from solid to liquid, which helps to keep the panel temperature low. Research from Iran shows that the use of PCM in PV/T systems can increase heat transfer by up to 30%. PCM can absorb excess heat energy from PV panels and release it slowly, keeping the system efficiency high even in extreme environmental conditions [24].

Based on the problem that only 20% of solar energy is converted into electricity in the PV system, this study aims to increase efficiency by utilizing PV/T technology. In the PV/T system, fluid flow is used to help absorb heat generated by the panel, with one fluid that has proven effective being nanofluids encapsulated in PCM. This study focuses on increasing the efficiency of solar cells and electrical energy in the PV/T system through nanofluid-encapsulated PCM, which is expected to improve energy conversion into electricity and reduce wasted heat significantly [25].

Based on the previous explanation and description, this study aims to determine the increase in solar cell efficiency and electrical energy in photovoltaic-thermal (PV/T) systems using phase change materials (PCM) wrapped in nanofluids.



(a) (b)

Figure 1. Model Scheme 3D (a) dan 2D (b)

METHODS

The PV/T system model is shown in Figure 1, which consists of two representations: a 3D model (a) and a 2D model (b). Figure 1a shows the layers of the PV/T system, which include the PV cell layer, thermal paste layer, reservoir wall, and reservoir flow channel filled with NEPCM. Each layer contributes significantly to energy conversion efficiency from solar radiation to electricity and heat. Figure 1b illustrates the structure of NEPCMs, an innovation that integrates phase change materials into nanoparticles. The NEPCM core is made of a phase change material (PCM) that can transition from solid to liquid at a specific temperature. At the same time, the nanoparticle shell enhances stability and control over energy release. NEPCMs have great potential in energy storage and temperature management, making them a rapidly growing focus of research [26]. Their ability to absorb energy as temperature increases and release it as temperature decreases makes NEPCMs adequate thermal buffers essential for maintaining optimal temperatures in PV/T systems. The integration of NEPCMs is expected to improve thermal efficiency and energy management, which is the main focus of this research.

This research uses a quantitative approach to analyze the effectiveness of a PV/T system with encapsulated PCM nanofluids. It starts with a literature review to gather information on PV/T systems, followed by system modeling using COMSOL software version 5.4 and the FEM. Data is collected through simulations to obtain PV cells' efficiency, heat capacity, and temperature. The analysis compares the efficiency of the PCM system with conventional systems and validates the findings against previous studies. The research employs statistical techniques and the Second Law of Thermodynamics to evaluate overall system efficiency.

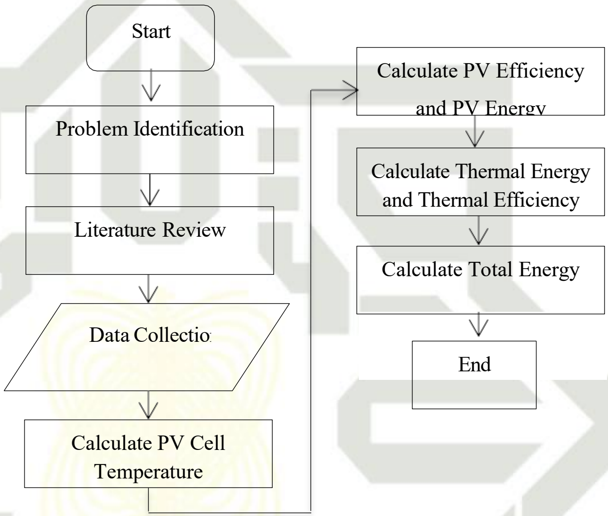


Figure 2. Overview of Flowchart Methodology

PV cells are the main components in a PV/T system that function to convert light energy into electrical energy through the photovoltaic effect. This system uses monocrystalline silicon (c-Si) panels with a design size of 30.5 cm on the side, and a thickness of 0.27 mm are used. The c-Si cell has a heat coefficient of 0.54 and a photovoltaic conversion efficiency of about 13%. This efficiency indicates how well the PV cell can convert solar radiation into electricity, which is key to improving the system's overall performance. The second layer is the Thermal Paste, which is a conductor material that efficiently distributes heat from the PV cells to other components [27]. The third layer is the Reservoir Wall, which stores the system's heat energy and helps maintain a stable temperature, which is essential for the optimal performance of the PV cells and other components. Figure 1a shows a 3D model of a PV/T system, where each layer contributes to optimizing energy conversion from solar radiation into electricity and heat. The model is simplified to focus on the relevant technical issues, enabling a more in-depth analysis of the thermal interactions in the system. Integrating these layers is expected to improve thermal efficiency and energy management in PV/T applications [28].

PV uses Standard Test Conditions (STC) to measure and compare its performance, where environmental parameters such as

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temperature, solar irradiance, and atmospheric pressure are set for consistent measurements. STC defines the relevant solar radiation domain in the analysis and incorporates this data into the simulation model. In this context, the equations used in COMSOL for laminar flow and heat transfer analysis will consider solar radiation as the primary input. Table 1 shows the nature of the incoming energy from the sun and the environmental conditions used in the study, where the heat transfer equations for the PV cell layer, thermal paste, reservoir wall, and reservoir flow channel are constructed based on the conjugate heat transfer equation. In this analysis, the PV surface is assumed to have a constant and uniform temperature, with the sky considered an ideal body for long-wave radiation, as well as the assumption that no dust is blocking the transmission of energy from the sun.

Table 1. Incoming Energy Properties of the Sun and Environmental Conditions

Distance (m)	Name	Quantity Value
G (kg/m²)	Solar Radiation	1,000 W/m²
hc (W/(m-K))	Heat Transfer	Coefficient 6.5 W/(m-K)
Tamb (K)	Ambient	Temperature 298.15 K
ε (kg/m²)	Radiative Emissivity	0.3

As shown in Figure 1, PV panels receive energy from sunlight and convert some of the radiation into electricity through the photovoltaic effect, while the remaining radiation is converted into heat. This radiation hits the entire panel surface, causing an increase in temperature that can affect system performance. To solve this problem, the thermal paste underneath the PV array aims to disperse a large amount of heat efficiently to increase electrical conversion efficiency. The heat convection that occurs at the top and bottom interface of the PV panel plays a vital role in regulating the temperature and maintaining optimal performance and can be described as:

$$q_{conc} = -h_c A(T_{pv} - T_{amb}) \quad (1)$$

On the other hand, heat loss due to convection and surface area also contribute to the heat transfer process in PV/T systems. The overall conjugate convection includes a combination of heat transfer at the top and bottom interfaces of the PV/T panel, as well as energy derived from the nanofluid flow in the reservoir. In addition, electromagnetic radiation emitted by the panel surface and the atmosphere in the form of infrared heat loss is also an essential factor in thermal energy management. This radiation can be expressed in the following equation:

$$(T_{pv}^4 - T_{amb}^4) \quad (2)$$

Table 2. Thermophysical properties of PV cells with thermal paste and aluminum

Properties	Sel PV	Thermal Paste	Aluminium
$\mu (unit)$	0.1	0.5	N/A
$\rho (kg/m^3)$	2329	2600	2700
K (W/m K)	130	1.9	160
C (J/kg K)	700	700	900

For all layers in the PV/T system, heat transfers from the nanofluid to the solid material, from the solid material to the nanofluid, or via conduction between the solid layers utilizing conjugate convection modes. The nanofluid at the inlet has a uniform temperature, and a hybrid concept is applied to enable the solar cell to convert solar radiation into electrical energy at peak conditions. Most of the solar energy received is converted into heat, which can increase the solar cell's temperature. This temperature increase can be utilized through the cooling system on the PV/T module with nanofluid to maximize the generated electrical energy. To achieve efficiency, various calculation equations are used. When the sun's heat hits the PV panel, solar energy is not utilized correctly in heat on the panel's surface—heat conduction through the PV cell, thermal paste, and reservoir wall.

The reservoir in a PV/T system serves as a container for fluid flow, with the top and bottom walls as solar collectors. Between these walls, the flow of the NEPCM nanofluid occurs according to the laws of thermodynamics, where the principles of mass and energy conservation are highly relevant. Momentum also plays an important role, especially when NEPCM particles collide, which affects the flow and heat transfer efficiency. The equations for describing phase changes, as well as calculating beta parameters and the FEM (Finite Element Method), are crucial, as the FEM allows the handling of diverse boundary conditions. The data in Table 2 helps to understand how these thermophysical properties contribute to the overall efficiency of the PV/T system, as well as the interactions between materials and fluid flow in improving system performance. In the fluid flow analysis, nanoparticles, such as aluminum oxide, are considered uniform and in thermal equilibrium with the parent fluid. The density differences are assumed linear based on the Boussinesq model, which is accurate when minor density variations do not affect convective flow.

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (4)$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{1}{\rho_{nf}}\frac{\partial P}{\partial X} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) + 39\ sin \quad (5)$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{1}{\rho_{nf}}\frac{\partial P}{\partial Y} + \frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) + \beta_{nf} g(T - T_{amb})(8) \quad (6)$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = \alpha_{nf}\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) + \frac{1}{(\rho Cp)_{nf}}\nabla . Q_r \quad (7)$$

Equations 3 to 7 are solved numerically using the FEM method through COMSOL. By solving these equations, the electrical efficiency of the PV cell is evaluated based on the following formula:

$$\eta_{pv} = \eta_{ref}\left[1 - \beta_{ref}(T_{pv} - T_{ref})\right] \quad (8)$$

The electrical energy produced by a PV/T system is measured in joules per second or Watts. To calculate this energy output, a formula considers various factors that affect the system's performance, giving an idea of the effectiveness of converting solar energy into electrical energy.

$$E_{pv} = \eta_{pv} \times A_m \times G \quad (9)$$

Electrical output is formulated as a function of PV cell efficiency, surface area, and solar irradiation. The electrical energy received by the PV module exposed to solar irradiation is defined as:

$$E_{in} = G.A_m \tag{10}$$

The thermal energy taken by using nanofluid as PV/T coolant is assessed as:

$$E_{nf} = m_{nf}\, C_p (T_{out} - T_{in}) \tag{11}$$

The percentage of thermal energy successfully converted into electrical energy can be calculated using:

$$\eta_{th} = \frac{E_{nf}}{E_{in}} \times 100\% \tag{12}$$

The total or global efficiency of the PV/T system is a combination of the electrical energy output and thermal energy compared to the electrical energy received, as follows:

$$\eta_{glob} = \frac{E_{nf} + E_{pv}}{E_{in}} \times 100\% \tag{13}$$

The thermophysical properties of the mixture include density, heat capacity, thermal volumetric expansion, thermal conductivity, and dynamic viscosity. The density of the mix can be calculated using the densities of the NEPCM particles and the base fluid, as follows:

$$\rho_b = (1 - \emptyset)\rho_f + \emptyset\rho_p \tag{14}$$

Where Ø indicates the volume fraction of NEPCM particles, and ρ refers to the density.The subscripts ρ and f represent NEPCM nanoparticles and base fluid, respectively. Since the nano-encapsulated phase change particles are synthesized with both core and shell structures, the effective density of these particles can be calculated as:

$$\rho_b = \frac{(1 + l)\rho_c\rho_s}{\rho_s + l\rho_c} \tag{15}$$

Based on the energy equation and taking into account the thermal balance between the nanoparticles and the base fluid, the following formula to calculate the specific heat capacity of the mixture:

$$Cp_b = \frac{(1 - \emptyset)\rho_f Cp_f + \emptyset\rho_p Cp_b}{\rho_p} \tag{16}$$

The total specific heat capacity of the encapsulated nanoparticles, which consists of the core and shell without any phase change, can be calculated as:

$$\rho_b = \frac{(1 + l)\rho_c\rho_s}{\rho_s + l\rho_c} \tag{17}$$

To calculate the average heat capacity of the mixture in the system, the following equation is used:

$$Cp_b = \frac{(1 - \emptyset)\rho_f Cp_f + \emptyset\rho_p Cp_b}{\rho_p} \tag{18}$$

To calculate the heat capacity of the solid particles in the system, the following equation is used:

$$Cp_p = \frac{(C\rho_{cl} + lC\rho_s)\rho_c\rho_s}{(\rho_s + l\rho_c)\rho_p} \tag{19}$$

These equations illustrate how the heat capacity of the mixture (Cpc) is affected by the heat capacity of the fluid ($Cpcl$), the surface enthalpy hsf, and the temperature conditions in the system. These various approaches allow for a more comprehensive analysis of the heat transfer in the system, which is essential for improving thermal efficiency.

$$Cp_c = Cp_{cl} + \frac{h_{sf}}{T_{Mr}} \tag{20}$$

$$Cp_c = Cp_{cl} + \left\{\frac{\pi}{2}.\left(\frac{h_{sf}}{T_{Mr}} - Cp_{cl}\right).sin\left(\pi\frac{T - T_1}{T_{Mr}}\right)\right\} \tag{21}$$

$$Cp_c = Cp_{cl} + 2\left(\frac{h_{fs}}{T^2{}_{Mr}} - \frac{Cp_{cl}}{T_{Mr}}\right)(T - T_1) \tag{22}$$

Using sinusoidal profiles significantly improves the numerical convergence by smoothing the variation of the specific heat capacity of the NEPCM core. By considering the sensible heat and latent heat of phase change, the total specific heat capacity of the PCM core can be expressed as:

$$Cp_c = Cp_{cl} + \left\{\frac{\pi}{2}.\left(\frac{h_{sf}}{T_{Mr}} - Cp_{cl}\right).sin\left(\pi\frac{T - T_1}{T_{Mr}}\right)\right\}$$
$$\{0\ 1\ 0\ T < T_f + T_{Mr}/2 \quad T_f - T_{Mr}/2 < T < T_f + T_{Mr}/2\ T > T_f + T_{Mr}/2 \tag{23}$$

The thermal volumetric expansion of the mixture of nanoparticles and base fluid can be modeled as a combination of the thermal expansion of the fluid and nanoparticles.

$$\beta_b = (1 - \emptyset)\beta_f + \emptyset\beta_p \tag{24}$$

In this study, validation was carried out by comparing simulation results with the research of [12] using COMSOL. The FEM model was used to solve the continuity, momentum, and energy equations, assuming incompressible and laminar flow, as well as heat transfer in fluids. Irradiation was considered to be constant heat flux. Various grid sizes were tested, ranging from very coarse to extremely fine, with the N8 mesh comprising 19,200 elements selected for accurate results. The comparison of temperature distribution showed good agreement, confirming the validity of the model developed in this study.

(a) experiments conducted

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(b) Fontenault dan Gutierrez-Miravete (2012)

Figure 3. Validation of current isotherms (a) with published work (b)

The consistency between this study's simulation results and those from [12] confirms that the developed model is well-validated and reliable in representing actual system conditions. The model assumes incompressible, laminar flow (SPF) to solve equations (6)–(8) and heat transfer in fluids (ht) for equation (9), with irradiation treated as constant heat flux at the boundary.

RESULTS AND DISCUSSION

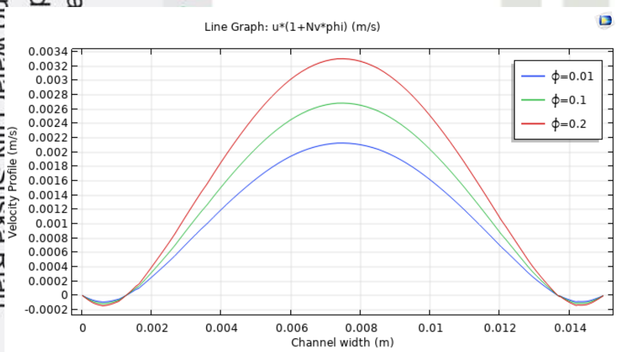


Figure 4. Velocity Profile

Figure 4 shows the velocity distribution of nanofluids in the channel for different volume fractions (ϕ = 0.01, 0.1, and 0.2), which is related to improving the efficiency of the PV/T system. In the PV/T system, nanofluids encapsulated with PCM can enhance the heat transfer from the solar panel to the thermal fluid. Increasing the volume fraction of nanofluids leads to an increase in the fluid flow velocity, which accelerates the heat transfer process. This helps to reduce the solar panel's temperature, thereby improving the electrical energy conversion efficiency. The graph results show that the maximum velocity for ϕ = 0.01 is 0.0022 m/s, increasing to 0.0027 m/s at ϕ = 0.1 and 0.0032 m/s at ϕ = 0.2, growing about 45%. This increase in velocity indicates that a higher volume fraction of nanofluids contributes to improving the thermal and electrical efficiencies of the PV/T system. Thus, using PCM-encapsulated nanofluids can significantly increase the efficiency of PV/T systems, both in heat management and in generating more optimal electrical energy [18].

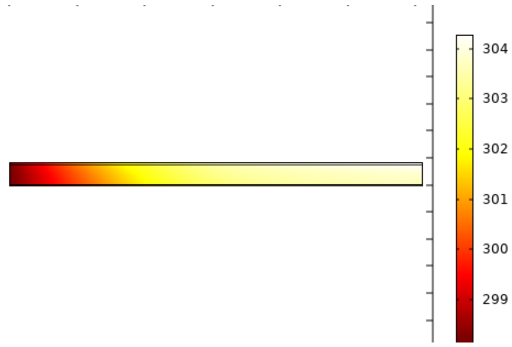
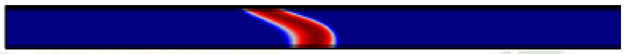
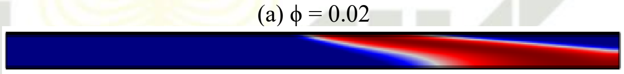


Figure 5. Temperature

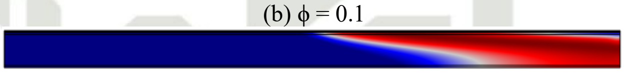
Figure 5 shows the surface temperature distribution of the material in Kelvin (K) resulting from the simulation using COMSOL Multiphysics 5.4. The parameters used are t_ch = 0.015 (channel thickness) and ϕ = 0.2 (nanoparticle volume fraction). The simulation results show a temperature gradient from 299 K on the left side to 304 K on the right side, which is displayed through a color shift from red to yellow. This distribution indicates effective heat transfer, where increasing the nanoparticle volume fraction increases the thermal conductivity while the channel thickness helps maintain the temperature gradient. In this case, the observed temperature in the system indicates that nanofluids with higher nanoparticle concentrations can improve temperature management, which in turn supports the performance of solar panels in generating electrical energy. The measured temperature in the channel indicates that using PCM and nanofluids can help reduce excess temperature in solar panels, increasing the overall efficiency of the photovoltaic-thermal system.



(a) ϕ = 0.02



(b) ϕ = 0.1



(c) ϕ= 0.2

Figure 6. Heat Capacity

Figure 6 illustrates the impact of varying the volume fraction (ϕ) of nanofluids on the heat capacity in a PV/T system using nanofluid-encapsulated PCMs. In plots (a), (b), and (c) for ϕ = 0.02, ϕ = 0.1, and ϕ = 0.2, respectively, the heat capacity shows an apparent change based on the nanofluid concentration. The red areas in the plots indicate the areas undergoing phase change, where the PCM begins to melt as the temperature increases, while the blue areas indicate the regions at lower temperatures, where the PCM is still in the solid state. At ϕ = 0.02 (plot a), the phase change is limited, with a small area affected by the temperature change. At ϕ = 0.1 (plot b), more areas undergo a phase change, indicating that with the increase in the volume fraction of nanofluids, more heat is absorbed and stored by the PCM. At ϕ = 0.2 (plot c), almost the entire channel area undergoes a phase change, indicating a larger heat capacity is absorbed and stored by the PCM in liquid form. This suggests that the higher the volume fraction of nanofluids, the larger the heat capacity that can be stored and released by the PCM, contributing to the thermal efficiency of the PV/T system.

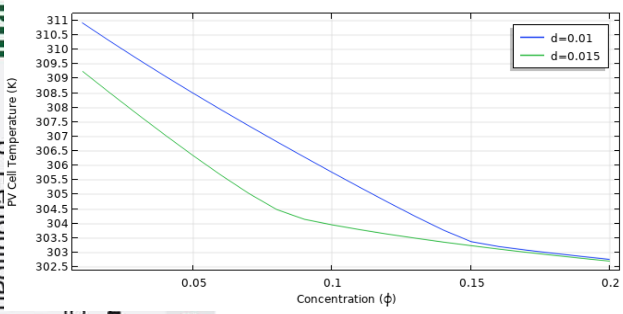


Figure 7. Average Temp of Pv Cell

Figure 7 illustrates the relationship between PCM concentration (ϕ) and the average PV cell temperature in a PV/T system that uses PCM as a coolant. The horizontal axis represents the PCM concentration from 0 to 0.2, while the vertical axis shows the PV cell temperature in Kelvin (K). The figure presents two curves corresponding to different PCM reservoir thicknesses: d = 0.01 meters (blue line) and d = 0.015 meters (green line). As the graph shows, increasing PCM concentration leads to a consistent decrease in PV cell temperature for both reservoir thicknesses. At a low PCM concentration of ϕ = 0.02, the PV cell temperature is approximately 309 K for d = 0.01 and about 307 K for d = 0.015. When the concentration increases to ϕ = 0.2, the PV cell temperature drops to around 303 K for d = 0.01 and 302.5 K for d = 0.015.

The green curve (d = 0.015) demonstrates a more significant temperature reduction at lower concentrations due to the higher heat storage capacity of the thicker reservoir. However, the temperature difference between the two curves diminishes as the concentration approaches ϕ = 0.2, suggesting that the cooling effect of PCM has reached its maximum limit. This indicates that additional PCM or increased reservoir thickness beyond a specific concentration may not provide further significant temperature reduction. Lower PV cell temperatures are directly linked to higher energy conversion efficiency, making PCM an essential component for improving PV/T system performance. Combining thicker reservoirs (d = 0.015) and higher concentrations (ϕ = 0.2) is most effective for cooling PV cells and enhancing system efficiency.

Furthermore, this behavior aligns with previous studies, such as [26], which concluded that nanofluid concentration has an optimal limit for improving PV cell efficiency. Beyond this point, further concentration increases do not significantly enhance heat transfer, leading to a plateau in system efficiency. This underscores the importance of optimizing PCM reservoir design based on cost and cooling requirements for specific applications.

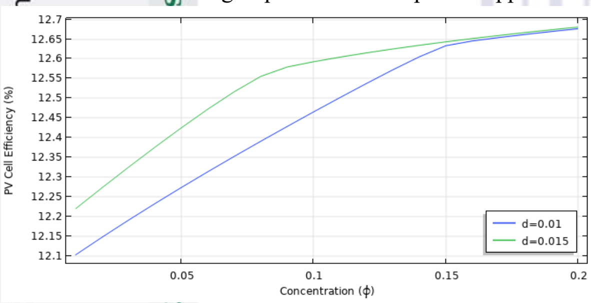


Figure 8. PV efficiency

Figure 8 illustrates the relationship between PCM concentration (ϕ) and photovoltaic (PV) cell efficiency in PV/T systems using PCM as a thermal management solution. The horizontal axis represents the PCM concentration, ranging from 0 to 0.2, while the vertical axis shows the PV cell efficiency in percentage (%). The graph contains two curves representing different PCM reservoir thicknesses: d = 0.01 meters (blue line) and d = 0.015 meters (green line). As shown in the figure, increasing PCM concentration steadily improves PV cell efficiency for both reservoir thicknesses. At low concentrations, such as ϕ = 0.01, the PV cell efficiency reaches approximately 12.15% for d = 0.01 and 12.3% for d = 0.015. As the concentration increases to ϕ = 0.2, the efficiency rises to around 12.6% for d = 0.01 and 12.65% for d = 0.015. This highlights that a thicker PCM reservoir (d = 0.015) offers more remarkable efficiency improvement, particularly at low to medium concentrations. However, as the concentration approaches higher values, the difference in efficiency between the two thicknesses diminishes. For the green curve (d = 0.015), a slight plateau effect is observed around ϕ = 0.08, suggesting that the PCM's heat absorption and release capacity is nearing its limit. The blue curve (d = 0.01) shows a similar trend, with efficiency gains flattening beyond ϕ = 0.15. This saturation effect indicates that increasing the PCM concentration beyond a certain point provides little additional benefit, aligning with previous findings [30]. The higher PV cell efficiency directly translates to improved electrical energy output. The system reduces energy loss due to temperature-induced voltage drops by effectively managing cell temperatures through PCM use.

The plateauing of PV efficiency at higher PCM concentrations results from diminishing thermal regulation returns as the PCM reservoir nears thermal saturation, limiting further heat absorption and dissipation. This highlights the trade-off between electrical and thermal efficiency, where excessive PCM acts as a thermal buffer, reducing heat dissipation rates and negatively impacting efficiency. While thicker reservoirs provide greater thermal capacity, they may also increase thermal inertia, delaying heat dissipation and reducing cooling efficiency. Therefore, optimizing PCM concentration and reservoir thickness is crucial to balance heat absorption and dissipation, achieving maximum efficiency in PV/T systems. Overall, this analysis demonstrates that while increasing PCM concentration and reservoir thickness can enhance PV cell efficiency, there are diminishing returns beyond certain thresholds. Therefore, optimizing the PCM reservoir design is critical for achieving maximum efficiency in PV/T systems. These findings are especially significant for large-scale applications, as they directly impact electrical energy output and overall system performance.

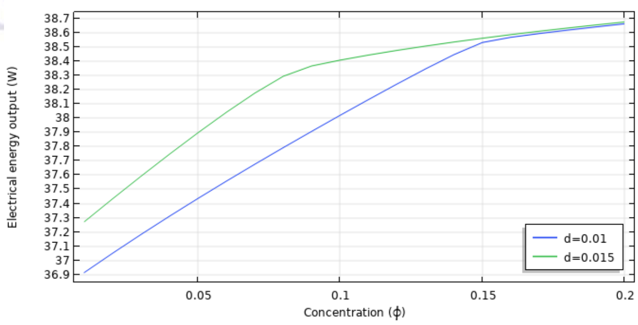


Figure 9. PV Electric Power

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The figure shows the relationship between PCM concentration (ϕ) and the electrical power output of the PV system in a PV/T system using PCM. The horizontal axis (X) shows the PCM concentration (ϕ) in the range of 0 to 0.2, while the vertical axis (Y) shows the electrical power output in Watts (W). The graph shows two curves based on the thickness of the PCM reservoir (d), namely (d = 0.01) meters (blue line) and (d = 0.015) meters (green line). Based on the graph, the electrical power output increases with the increase in PCM concentration. The larger PCM reservoir thickness (d = 0.015) produces higher electrical power than the thinner reservoir (d = 0.01). At low PCM concentration (ϕ = 0.01), the electrical power reaches about 37 W for (d = 0.01) and 37.3 W for (d = 0.015). With increasing PCM concentration up to (ϕ = 0.2), the electrical power increases to about 38.6 W for (d = 0.015) and 38.5 W for (d = 0.01).

This increase in power output indicates that PCM helps keep the PV cell temperature low, which positively impacts the energy conversion efficiency of the PV cell. With a more stable and lower temperature, the PV cell can operate more optimally, thus producing greater power. In addition, the difference in power output between the two reservoir thicknesses (d = 0.01) and (d = 0.015) is more significant at low to medium PCM concentrations but tends to shrink at high PCM concentrations (ϕ = 0.2), indicating that increasing reservoir thickness has a specific effectiveness limit. Overall, the use of PCM in the PV/T system can significantly increase PV power. With a larger reservoir thickness (d = 0.015) and optimal PCM concentration (ϕ 0.1), the system can produce more extraordinary power, indicating the potential for improving energy performance in PV/T applications. This narrative aligns to evaluate the impact of PCM on cell efficiency and electrical energy output in the PV/T system.

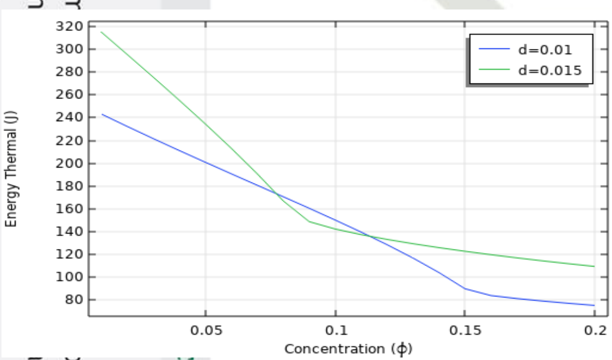

Figure 10. Thermal Energy

Figure 10 illustrates the relationship between concentration (ϕ) and thermal energy (J) for two reservoir thickness values, d = 0.01 (blue line) and d = 0.015 (green line). In general, it is observed that thermal energy tends to decrease as particle concentration in the fluid increases. This occurs due to the increasing number of particles that hinder fluid movement, thereby reducing the efficiency of thermal energy transfer within the system. The higher the concentration, the more significant the impact of this resistance on energy distribution within the fluid. The pattern of thermal energy variation can be observed at the three main concentrations used in this study: ϕ=0.02, ϕ=0.1.1ϕ=0.1, and ϕ=0.2. At ϕ=0.02, thermal energy is relatively high, where the reservoir with d = 0.015 maintains a higher thermal energy value than d = 0.01. As the concentration increases to ϕ=0.1, a bending and intersection of the lines occur, indicating that the thermal energy values for both reservoir thicknesses are nearly identical at this point. This suggests that at a specific concentration, reservoir thickness is no longer a dominant factor in determining the system's thermal energy. At ϕ=0.2, thermal energy decreases for both reservoir thicknesses, with d = 0.01 experiencing a sharper decline compared to d = 0.015, demonstrating that thinner reservoirs are more sensitive to concentration changes and experience more significant thermal energy loss.

An interesting phenomenon observed in this graph is the bending of the green line (d = 0.015) around ϕ=0.1. At this point, the two lines almost intersect, showing that the effect of reservoir thickness on thermal energy becomes insignificant. Beyond this point, the green line continues to decline but slower than the blue line. This indicates that thicker reservoirs retain more thermal energy at higher concentrations. This phenomenon is also supported by other studies, as reported in [31], which state that at specific concentrations, the effect of reservoir thickness on thermal energy diminishes because heat transfer mechanisms between particles within the fluid become a more dominant factor. As concentration increases, particle interactions become more significant, rendering differences in reservoir thickness less influential on the system's thermal energy. Thus, it can be concluded that increasing particle concentration in the fluid leads to a decrease in thermal energy, with a more significant effect on thinner reservoirs (d = 0.01). An equilibrium point exists around ϕ=0.1 where reservoir thickness is no longer necessary in determining the system's thermal energy.

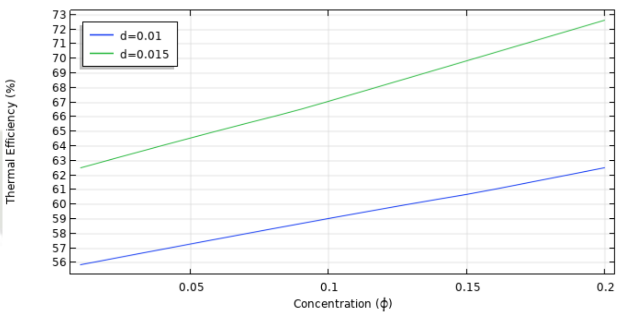

Figure 11.Thermal Efficiency

Figure 11 illustrates the relationship between PCM concentration (ϕ) and thermal efficiency (%) of a PV/T system using PCM as a heat storage medium. The horizontal axis represents the PCM concentration ranging from 0 to 0.2, while the vertical axis indicates thermal efficiency in percentage (%). The graph presents two curves corresponding to different PCM reservoir thicknesses: d = 0.01 m (blue line) and d = 0.015 m (green line). The graph analysis reveals that thermal efficiency increases with rising PCM concentration. A larger PCM reservoir thickness (d = 0.015 m) consistently results in higher thermal efficiency than a thinner reservoir (d = 0.01 m). At a low PCM concentration of ϕ=0.02, the thermal efficiency is approximately 56% for d = 0.01 m and 62% for d = 0.015 m. As the PCM concentration increases to ϕ=0.1, the thermal efficiency improves further, demonstrating the positive impact of PCM concentration on system performance. At the highest PCM concentration of ϕ=0.2, the thermal efficiency reaches 63% for d = 0.01 m and 72% for d = 0.015 m, highlighting a significant improvement in thermal performance.

The increase in thermal efficiency can be attributed to the ability of PCM to absorb and store heat during the phase change process. PCM absorbs excess heat energy generated by the PV module and gradually releases it to the cooling fluid, preventing rapid heat dissipation. A thicker PCM reservoir (d = 0.015 m) enhances heat storage capacity, leading to more efficient heat transfer to the cooling fluid. This reduces heat loss to the environment and improves the overall thermal performance of the system. Maintaining high thermal efficiency is crucial for enhancing PV/T system performance, especially in water heating and space heating applications. The graph indicates that optimizing PCM concentration and using a thicker reservoir improves system efficiency. Thus, incorporating PCM in PV/T systems enhances passive cooling and increases thermal efficiency, ultimately contributing to a more efficient and sustainable system operation.

Figure 12 illustrates the relationship between total energy efficiency and PCM concentration (ϕ) for two reservoir thicknesses: d = 0.01 meters (blue line) and d = 0.015 meters (green line). The horizontal axis represents PCM concentration, ranging from 0 to 0.2, while the vertical axis shows total energy efficiency as a percentage. Overall, higher PCM concentration for both thickness values increases total energy efficiency. Initially, at ϕ = 0.05, the efficiency for d = 0.01 is approximately 73.2%, whereas d = 0.015 achieves around 75.2%, indicating a higher baseline efficiency for the thicker PCM reservoir. As the concentration increases, the green curve (d = 0.015) shows a slight plateau around ϕ = 0.1, reaching around 75.8%, suggesting that the efficiency gains slow down at this point. In contrast, the blue curve (d = 0.01) rises more linearly, reflecting ongoing efficiency improvement. The two curves converge at a concentration of ϕ = 0.2, with d = 0.015 nearing 76.2% and d = 0.01 approaching 76%.

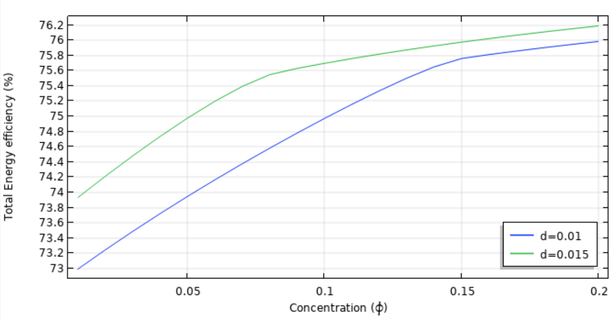

Figure 12.Total Energy Efficiency

The convergence of the curves at higher concentrations indicates that the cooling effect of PCM reaches its maximum limit. This behavior is more evident for d = 0.015 around ϕ = 0.08 and d = 0.01 around ϕ = 0.15, beyond which further PCM additions no longer yield significant efficiency improvements. This indicates that the heat storage capacity of the PCM for each thickness is fully utilized. Research has shown that increasing PCM volume fraction helps reduce PV module temperatures and enhance electrical efficiency. However, studies have also noted that additional material does not significantly improve efficiency once the PCM reaches its heat storage limit. For instance, [32] demonstrated that using paraffin-based PCM can lower panel temperatures and boost output power, but its cooling effectiveness is influenced by material type, composition, and thickness. In conclusion, optimizing PCM concentration and reservoir thickness is critical for achieving maximum energy efficiency in PV/T systems. Using thicker reservoirs (d = 0.015) helps reach peak efficiency faster and provides better thermal stability, making it an effective strategy for large-scale energy applications.

Comparative Analysis of the Efficiency and Thermal Stability of PV/T Systems Using NEPCM

Previous studies have shown that a new design of an aluminum-based thermal collector can improve heat transfer efficiency, with a reduction in the maximum temperature of the PV/T-PCM cell by up to 12.8°C, as well as an increase in the electrical efficiency of the PV/T system by 6.2% and the PV/T-PCM system by 7.2% numerically and 7.6% experimentally [23]. These results align with the current research, which explores the impact of Nano-Encapsulated Phase Change Material (NEPCM) in minimizing operational temperatures and improving the system's overall efficiency. Furthermore, a study by Khan et al. demonstrated that combining PCM with nanofluids can increase the efficiency of PVT systems by up to 25% [21]. This research supports these findings, showing an over 50% improvement in efficiency using NEPCM, indicating that the innovative combination of PCM and nanofluids offers significant efficiency benefits. On the other hand, research by Solgi et al. explained that using PCM in PV systems can drastically reduce the panel temperature, enhancing electrical output power [22].

These findings align with the results of this study, which shows that NEPCM not only functions as a heat absorber but also enhances the thermal stability of the system. Additionally, Ghalambaz et al. found that using nanoparticles in conventional PCM can increase the heat transfer rate by up to 30% [18]. However, this research indicates that NEPCM is more effective in improving overall efficiency than PCM without nanofluids. Zeng et al. also emphasized that nanofluids' design and flow configuration significantly influence thermofluidic performance [20]. This study found that variations in the reservoir thickness significantly affect efficiency, underscoring the importance of design considerations in optimizing PVT systems. Finally, the research by Yang et al. highlighted the importance of developing enhanced PCMs for energy storage applications [27].

This research focuses on NEPCM, showing thermal efficiency improvements and the potential for extending the lifespan of PVT systems. Therefore, this study provides evidence that using NEPCM in PVT systems can lead to better efficiency and thermal management while emphasizing the need for continued research in renewable energy technologies to address existing challenges. Additionally, it is essential to note that the concentration of the nanofluid cannot be raised to its maximum level, as doing so would result in the complete cessation of flow. This is due to the increased viscosity at higher concentrations, which hinders the fluid's ability to flow efficiently through the system, potentially causing blockages and reducing the overall performance of the heat transfer system.

CONCLUSIONS

This study successfully developed a PV/T system model using nanofluid-encapsulated PCM, demonstrating enhanced thermal management and energy conversion efficiency. The COMSOL

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Multiphysics simulations showed that increasing nanoparticle concentration (ϕ) reduces average PV cell temperature, improving efficiency. At a concentration of $\phi = 0.2$, the cell efficiency reaches approximately 76% for d = 0.01 and 76.2% for d = 0.015. Additionally, larger particle diameters (d = 0.015) yielded higher efficiencies than smaller ones (d = 0.01), particularly at low to medium concentrations. For instance, at $\phi = 0.1$, the total energy efficiency for d = 0.015 is 75.8%, while for d = 0.01 it is 75.2%. However, the model's limitations must be acknowledged, particularly the assumptions in the FEM model, such as steady-state conditions and uniform nanoparticle distribution and the absence of experimental validation. Future research should focus on validating the FEM model with experimental studies to enhance both electrical and thermal efficiency. Furthermore, evaluating the environmental impact of using nanofluid-encapsulated PCMs is essential to ensure sustainable and eco-friendly energy solutions.

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AUTHOR(S) BIOGRAPHY

Syarifah Adriana

Syarifah Adriana is a final-year student pursuing a Bachelor's degree in Electrical Engineering at the Faculty of Science and Technology, Sultan Syarif Kasim Riau State Islamic University. She focuses on Energy and Thermodynamics. Her research interests include renewable energy and power systems.

Marhama Jelita

Marhama Jelita was born and raised in Ranah, Riau. She is a lecturer in Electrical Engineering at the State Islamic University of Sultan Syarif Kasim Riau, focusing on Energy and Thermodynamics. She completed her Bachelor's degree at STTP University of Riau and continued her education with a master's degree at Universiti Kebangsaan Malaysia (UKM) in 2012. Her research interests include boiler operation engineering, metal forming, community health, solar energy, and aerodynamics.

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This is to inform you that your manuscript ID: 1306, "Improving Solar Cell Efficiency and Electrical Energy in Photovoltaic-Thermal (PV/T) Systems Using Phase Change Materials (PCM) Encapsulated in Nanofluids" has been **ACCEPTED** based on the recommendations provided by JURNAL NASIONAL TEKNIK ELEKTRO review committee. This manuscript is estimated to be available online in Vol. 14 No. 1 March 2025.

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