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Performance Optimization of a Simulation Study on Phase Change Material for Photovoltaic Thermal

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ABSTRACT

The integration of Phase Change Material (PCM) with the Solar Photovoltaic Thermal (PVT) serves as heat storage to enhance the system's performance. Temperature rises have an undesirable effect on efficiency results in a diminishment in the amount of energy produced by the solar panel. Parametric analysis and temperature investigation are involved in improving the performance of the system. The variation of performance will assist in developing an optimized PVT-PCM system. The model is validated by comparison from published journals on the studies related to phase change material implemented in solar PVT. For the variation of mass flow rate, the overall efficiencies achieved by 10 kg/h, 30 kg/h, 50 kg/h and 70 kg/h are 90.82%, 90.54%, 90.48% and 90.46%, respectively. In addition, solar irradiance of 200 W/m^2, 450 W/m^2 and 800 W/m^2 produced 91.17%, 90.82% and 90.33% of overall efficiencies. Increased in flow rate requires stronger pumps which increase the total cost of the system. Therefore, identifying the optimal flow rate might help to achieve an appropriate thermal efficiency while sustaining in low costs. Finally, this paper presented a numerical investigation of PCM acts as promising elements incorporated in the PVT system that has the capability to reduce the temperature of the PVT-PCM system.

1. Introduction

International energy demand is rising rapidly, leading opportunities to examine into the availability of alternative energy sources as a solution. Energy from non-renewable resources such as natural gas, fossil fuels, petroleum, coal, or nuclear sources is referred to as conventional energy. Renewable energy, on the other hand, is a type of energy that is derived from naturally renewing and never diminishing energy resources. By 2050, renewable energy is expected to account for roughly 67% of the world's energy consumption. The road plan predicts that by the year 2020, renewable energy sources will account for 58% of electric power generation, 29% of heating, and 13% of transportation [1].

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Solar energy is accomplished using a range of devices that use a variety of light energy conversion techniques to be able to produce useful energy harvesting from solar energy conversion [2]. The conversion system in solar are absolutely critical for solar energy's powerful commercialisation. Numerous conversion processes are used to transform solar energy into usable energy such as photoelectric (solar photovoltaic system), photoelectric-thermal (solar photovoltaic thermal system), and photothermal (solar collectors) [3]. The performance of these systems is mostly determined by the properties of the working fluid and cooling medium used in energy conversion or conveyance [4,5].

In research from Abdul-Ganiyu *et al.,* [6] the development in solar technologies introduces progressive development throughout the years. Integration between the conventional PV system into thermal system helps in the efficiencies and increases the performance of the PVT system. Since the operations will not be focused on one process making solar PVT, the performance of solar PVT produces higher than solar PV system. Solar PVT system able to heat the output water as solar heaters and generate energy from the solar modules. The advancements in solar thermal technology, particularly the PVT system have been introduced comprehensively by Fu *et al.,* [7]. The present PVT system is primarily composed of two types: PVT air collector systems and PVT water collector systems. In addition, Phase change materials (PCM) are compounds that possess the ability in thermal energy storage which allowing for temperature stability. Hence, in this research reviews the evidence for the development of Solar PVT integrated with Phase Change Material (PCM).

Throughout decades, numerous developments have been made in solar PVT to improve their output production and efficiencies. In this research, Phase Change Material (PCM) is chosen as the passive cooling medium to increase the performance of the solar PVT. PCM has a high energy density, a nearly constant temperature, and absorb and release thermal energy throughout the melting and freezing process. As a result, PCM is well suited for solar cell heat collection. There are 3 categories of PCM in solar PVT application include organic (paraffins, fatty acids and polyethylene glycol (PEG)), inorganic (salt hydrates) and composite materials (combination of organic and inorganic) [8].

Studies of Thakur *et al.,* [9] show the PCM releases and absorbs sufficiently as a result of the phase transition. The phase transition occurs when a solid change to a liquid and vice versa, resulting in the generation of usable heat. It is possible to use PCM to store surplus thermal energy generated during peak hours and release this stored energy when the energy is required in the future.

Analyses correlation by Badiei *et al.,* [10] and Lin *et al.,* [11] the performance of a fins-incorporated PCM-based Flat Plate Collector (FPC) was examined using a CFD model and experimental simultaneously. During the study, distinct PCM materials with differing melting temperatures are utilized. The results indicate that the FPC with PCM and fin produces cooler output temperatures in the morning. The effects of the research by Thakur *et al.,* [9] on Solar PVT performance are similar to those of by Lin *et al.,* [11].

Several examples of Phase Change Material (PCM) are paraffin wax, lauric acid, sodium sulfate, benzoic acid, bees wax and glycolic acid. Preet *et al.,* [12] conducted three different systems were used: a convectional photovoltaic (PV) system, a photovoltaic thermal (PVT) system, and a photovoltaic thermal system with phase change material (PVT-PCM). PVT and PVT-PCM have a lower temperature than convectional PV panels, with a maximum temperature reduction of 47% for PVT and 53% for PVT-PCM at a mass flow rate of 0.031 kg/s of water. This view is supported by Khan *et al.,* [13] investigated the effectiveness of solar PVT by using paraffin wax and nanoparticles into the design. They determined that increasing the surface area between the PCM and the absorber plate increases to study the output temperatures. Improved results may be achieved with PCM compared to standard absorber plate with the help of new technological developments in combination of PCM with solar PVT. Recent study by Abdullah *et al.,* [14] have improved on the combination of paraffin wax and nanoparticles. Total daily production ranges between 2500 and 5550 mL/m^2 when PCM is combined with CuO nanoparticles. As a result, production increased by 122%. Therefore, PCMs have been recognised for usage in the given application for a various of purposes, including rapid cooling, low thermal conductivity, phase separation, and reasonable cost.

Studies on the efficiencies of PCM integration in solar PVT shown in Table 1. Several researchers include nanofluid in their studies but nanofluid is costly. The combination with PCM such as paraffin wax leads to unreasonable price of solar PVT. In this study, nanofluid is neglected to improve the cost of the solar PVT. Most of the researchers use paraffin wax but with different thermophysical properties. From Table 1, Mousavi *et al.,* [15] shows highest overall efficiencies from various PCM (Paraffin C15, C18 and C22) with 94%, 94.7% and 95.9% respectively. On the other hand, Wahab *et al.,* [16] and Hassan *et al.,* [17], shows the lowest overall efficiency among the other researchers. Both of the researchers use the same type of paraffin wax which is RT-35HC, but the results turned out to be different due to the experimental setup and presents of nanofluid. Even though Wahab *et al.,* [16] and Hassan *et al.,* [17] used distilled water-graphene and Sodium Dodecyl BenzeneSulphonate (SDBS)-Graphene as active cooling medium respectively, the results of the overall efficiencies show between 14.80% to 31.2%. Overall, thermal efficiency, electrical efficiency and overall efficiency from other researchers are exhibited in Table 1.

A significant aspect in the performance of solar PVT is temperature changes. When the PVT temperature rises, the output current climbs exponentially while the voltage output decreases linearly. As a consequence, this may significantly reduce solar panel power production. In addition, temperature rises have an undesirable effect on the efficiency of solar panels. When the efficiency of a solar panel decreases, the solar panel energy production reduces. Hence, temperature is an important aspect that needs to be analysed to monitor the performance of the PVT. Consequently, the performance of PVT integrated with PCM are evaluated utilizing parametric analysis.

Table 1
Efficiencies of PCM used recently for PVT systems

Author	Nature of Study	Phase Change Material	Thermal Efficiency	Electrical Efficiency	Overall Efficiency
Fu *et al.,* [7]	Experiment	Microencapsulated Phase Change Material (MPCM)	58.3%	12.21%	70.51%
Abdullah *et al.,* [14]	Experiment	Paraffin wax	34%	-	34%
Mousavi *et al.,* [15]	Simulation	Paraffin C15 Paraffin C18 Paraffin C22	Paraffin C15: 81.8% Paraffin C18: 81.7% Paraffin C22: 83.5%	Paraffin C15: 12.2% Paraffin C18: 13% Paraffin C22: 12.4%	Paraffin C15: 94% Paraffin C18: 94.7% Paraffin C22: 95.9%
Wahab *et al.,* [16]	Experiment	Paraffin wax (RT-35HC)	1.78%	13.02%	14.80%
Hassan *et al.,* [17]	Experiment	Paraffin wax (RT-35HC)	20.8%	10.4%	31.2%
Shalaby *et al.,* [18]	Experiment	Paraffin wax and steric acid	35%	-	-
Al-Musawi *et al.,* [19]	Simulation	Paraffin wax	55%	14.2%	69.2%
Al-Waeli *et al.,* [20]	Experiment	Paraffin Wax	72%	13.7%	85.7%
Kazemian *et al.,* [21]	Simulation	PCM (not mentioned the type)	58%	14%	72%

Naghdbishi *et al.,* [22]	Experiment	Water/glycol-based and Organic paraffin wax	23.58%	4.21%	27.79%
Salari *et al.,* [23]	Simulation	PCM (type not mentioned)	MgO-water: 46.176% MWCNT-water: 47.168% MgO – MWCNT: 46.759%	MgO-water: 13.892% MWCNT-water: 13.912% MgO – MWCNT: 13.902%	MgO-water: 60.068% MWCNT-water: 61.080% MgO – MWCNT: 60.661%
Sopian *et al.,* [24]	Experiment	Paraffin Wax	72%	13.7%	85.7%
Carmona *et al.,* [25]	Experiment	Organic Paraffin wax (RT-35)	17.22%	14.14%	31.35%

2. Methodology

2.1 Overview of Solar PVT-PCM Model

This research presents proposed solar photovoltaic thermal integrated with phase change material (PVT-PCM). The proposed 3-dimensional model of PVT-PCM is developed using AutoCAD software to illustrate the components in simulation process. The components of PVT-PCM consists of 2 ethylene vinyl acetate (EVA), photovoltaic (PV) panel, tedlar polyvinyl fluoride (Tedlar), copper absorber plate, copper tube collector and phase change material (PCM). The copper absorber plate is positioned above PCM layer and the copper tube collector is partially immersed in the PCM layer. Subsequently, the model of the proposed PVT-PCM is represented as in Figure 1.

The chosen working fluid in this research is water. The flow of the fluid is anticipated in a uniform, laminar, fully developed and incompressible flow regime with no turbulence. A parallel array of tubes constitutes the real collector, however for the purposes of 3D simulations, only one tube collector is considered in order to decrease the computational cost [26,27]. Anti-reflection coatings (ARC) have a thickness of 0.0001 mm, which is neglected in the simulation [28]. Figure 2 illustrates the cross section implemented in the simulation process.

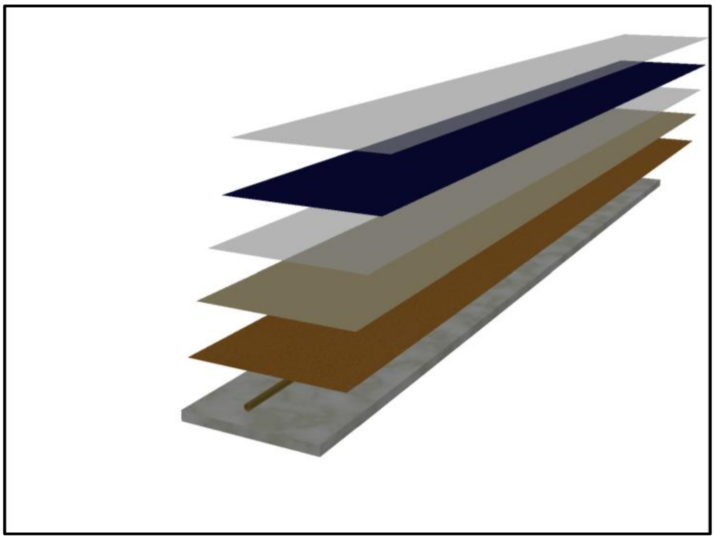


Fig. 1. Overview of solar PVT-PCM in 3D model

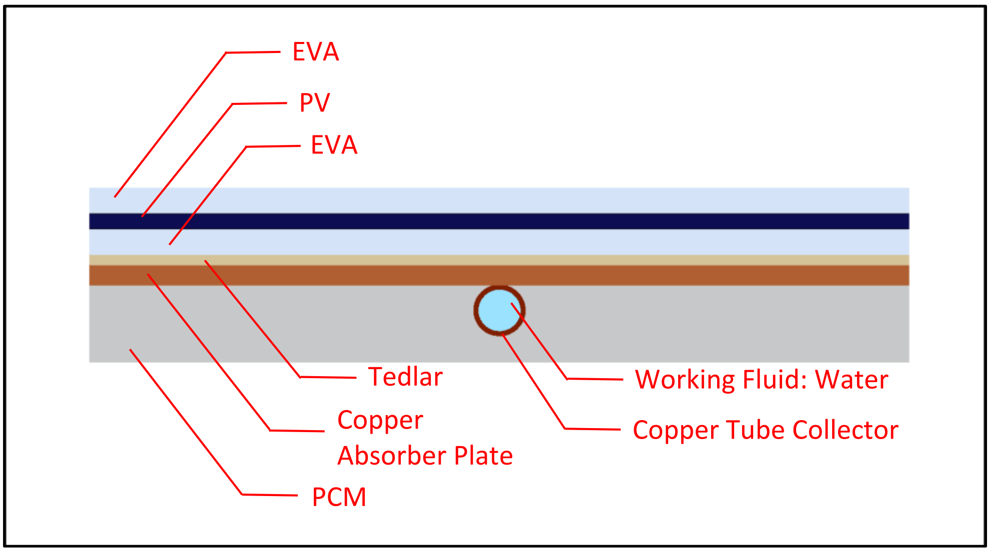


Fig. 2. Cross section of PVT-PCM model

2.2 Study Area

The simulation works is conducted under Malaysia climate condition at coordinate 2.3138° N and 102.3211° E. According to Malaysian Meteorological Department [29] the average monthly temperature in the lowland areas ranges from 25.9˚C to 29.0˚C. The average monthly sunshine hours range between 150hours and 210hours. In addition, the average number of rainy days per month varies throughout the year, ranging from 14 days (lowest) to 20 days (peak). The lowest days usually in July while the peak seasons in October, November, and April. However, the other months are moderately in between the days.

In Malaysia, the average direct solar irradiance in a year which is quite substantial for residentials and industrials. According to Shavalipour *et al.,* [30] solar irradiance received by major part in Peninsular Malaysia recorded an average of approximately 450 W/m^2 except for the east coast in the rainy season. Furthermore, Hossain *et al.,* [31] critically examined that the maximum output from a PVT or PVT-PCM panel under average Malaysian weather conditions is approximately 1000 W/m^2.

2.3 Fluid Flow Characteristics and Simulation Assumptions

In this proposed PVT-PCM, water is chosen as the working fluid acts as laminar fluid flow. Since the flow is laminar, the Reynolds number shows lower than 2300. The flow of the fluid is anticipated in a uniform, laminar, fully developed and incompressible flow regime with no turbulence [21]. In addition, the simulation undergoes transient flow analysis. The following assumptions are also imposed with the purpose of reducing the numerical simulation's complexity:

i. Thermophysical properties of solid parts (PV, EVA, Tedlar, Copper Absorber Plate, Copper Tube Collector are considered constant and do not change with temperature [21].
ii. The contact resistance between each component in the PVT-PCM is neglected [27].
iii. Thermophysical of PCM such as enthalpy of fusion, melting point, specific heat capacity and thermal conductivity are considered constant [32].
iv. PV panel are considered clean without any debris [12].
v. Solar irradiance is considered to be uniform and creates incidently in the upmost surface of the PVT-PCM which is EVA layer [15,21].

vi. PCM is considered to have a 3-dimensional liquid phase that is incompressible, unsteady flow, and Newtonian [33].
vii. It is considered that the EVA layer is completely transmissive [31,34].

2.4 Thermophysical Properties of Phase Change Material (PCM)

Phase Change Material (PCM) manufactured by Rubitherm Technologies GmbH, Berlin, Germany (Model No: RT44HC) were employed in this simulation investigation. RT represents Rubitherm from the company's name while HC represent a greater latent heat capacity by 25–30% and melts over a narrower temperature range as compared to traditional RT PCM.

In the melting process, the heat transmission from the PV layer passed down to the PCM layer occurs by conduction and natural convection. In the presence of solar irradiance, solid PCM begins to melt as a result of the heat gained from the thermal collector. However, when there is low presence of solar irradiance, the thermal collector will not be able to harvest solar energy. Therefore, the heat collected from the PCM previously will generate the energy for the PVT system. The PCM will start losses its heat and becomes solidified again slowly. Table 2 represents the thermophysical properties of RT44HC.

Table 2
Thermophysical Properties of RT44HC

Parameters	Symbol	RT-44 HC
Density at 25˚C (kg/m^3)	ρ	800
Melting Point (˚C)	T_{MP}	43
Specific Heat Capacity (J/kg.K)	C	2000
Thermal Conductivity (W/m.K)	λ	0.2
Enthalpy of Fusion (kJ/kg)	H	250
Solidus Temperature (˚C)	T_{solid}	25
Liquidus Temperature (˚C)	T_{liquid}	80
Volume Expansion (%)	V	12.5

2.5 Model Geometry and Components

In this study, the geometry is a development of the 3-dimensional model of solar photovoltaic thermal (PVT) integrated with phase change material (PCM) using Design Modeler or Space Claim. In this research, the interface of the Ansys geometry part is chosen Design Modeler. Material of fluid or solid was assigned at this stage. The dimension of the PVT-PCM implemented from the real size of model to reduce errors. The geometry consists of 8 parts and 8 bodies. PCM and Water are the elements assigned as fluid while other components are assigned as solid. Table 3 highlights the dimension of the components in Solar PVT-PCM system.

Table 3
Dimensions of the components of the solar PVT-PCM

Components	Dimensions (mm)		
	L	W	H
Ethylene Vinyl Acetate (EVA)	1640	200	0.5
Photovoltaic Panel (PV)	1640	200	0.3
Tedlar	1640	200	0.1
Copper Absorber Plate	1640	200	0.4
Phase Change Material (PCM)	1640	200	15
Copper Tube Collector	10 (diameter)		

Table 4 shows the thermophysical properties in each component. Tedlar polyvinyl fluoride (Tedlar) is a strong, flexible and fatigue-resistant layer while Ethylene Vinyl Acetate (EVA) is copolymer of ethylene and vinyl acetate monomers that acts a sealing layer for PVT. Subsequently, thermophysical properties of PCM as shown previously in Table 2. In Ansys Fluent setup, the thermophysical properties are fulfilled in material section.

Table 4
Thermophysical Properties of the components in PVT-PCM

Components	Density (kg/m^3)	Specific Heat Capacity (J/kg.K)	Thermal Conductivity (W/m.K)
Ethylene Vinyl Acetate (EVA)	960	2090	0.35
Photovoltaic Panel	2330	700	148
Tedlar	1200	1250	0.2
Copper Absorber Plate	8960	385	401
Copper Tube Collector	8960	385	401
Water	998.2	4182	0.6

Operating condition provides in Table 5 are considered as boundary condition in Ansys Fluent setup.

Table 5
Operating Condition

Parameters	Value
Inlet temperature of coolant flow (˚C)	30
Ambient Temperature (˚C)	30
Wind Speed (m/s)	1
Solar Irradiance (W/m^2)	450
Mass flow rate of coolant flow (kg/h)	10

2.6 Governing Equation

Beforehand proceeding with the setup setting, there are 2 types of solvers involved in Ansys Fluent. There are Pressure-Based and Density-Based. Density-Based Coupled Solver solves for continuity, momentum and energy equations. An equation of state is used to construct Pressure-Based Solver.

On the other hand, the pressure-based solvers take momentum and pressure (or pressure correction) as the primary variables. Pressure-velocity coupling algorithms are derived by reformatting the continuity equation. The pressure-based solver is applicable for a wide range of flow regimes from low speed incompressible flow to high-speed compressible flow.

2.6.1 Working fluid

The following equations express the mass and momentum conservation laws for the fluid domain:

$$\frac{\delta \rho_f}{\delta t} + \nabla \cdot \left(\rho_f \overrightarrow{V_f}\right) = 0 \tag{1}$$

$$\rho_f \left[\frac{\delta \overrightarrow{V_f}}{\delta t} + \left(\overrightarrow{V_f} \cdot \nabla\right)\overrightarrow{V_f}\right] = -\nabla P + \nabla \cdot \left(\mu_f \nabla \overrightarrow{V_f}\right) \tag{2}$$

where $\vec{V}$, P and μ are fluid velocity, pressure and viscosity and subscript f represents working fluid. Heat transmission occurs by a combination of conduction and convection heat transfer in the collector's fluid field. Ansys Fluent solves in the form of the energy equation from Ansys Fluent model selection. As a result, the following is the energy equation:

$$\rho C_p \frac{\delta T_f}{\delta t} + \rho_f C_{pf} \overrightarrow{V_f} \cdot \nabla T_f = \nabla \cdot \left(k_f \nabla T_f \right) \quad (3)$$

2.6.2 Solid components

Due to the fact that conduction is the only mode of heat transport in the solid components of the system (i.e., the PV layers, absorber plate, and collector). The subscript s represents solid components. The following energy equation is used to describe the system's solid components:

$$\rho C_{p,s} \frac{\delta T_s}{\delta t}_f = \nabla \cdot \left(k_s \nabla T_s \right) \quad (4)$$

2.6.3 Phase Change Material (PCM)

An enthalpy-porosity approach is utilised to model the melting process in PCM. Indeed, each cell in the solution region utilises a liquid fraction (the fraction of cell volume when it is in liquid form). In Ansys Fluent model selection, solidification and melting are chosen. The following mass and momentum equation used in enthalpy-porosity approach:

$$\frac{\delta \rho}{\delta t} + \nabla \cdot \left(\rho \cdot \vec{V} \right) = 0 \quad (5)$$

$$\rho \left[\frac{\delta \vec{V}}{\delta t} + \left(\vec{V} \cdot \nabla \right) \vec{V} \right] = - \nabla P + \nabla \cdot \left(\mu \nabla \vec{V} \right) + S \quad (6)$$

$$S = \frac{(1-\beta)^2}{(\beta^3 + \phi)} A \left(\vec{V} - \vec{V}_P \right) \quad (7)$$

where β refers to liquid volume fraction, A refers to liquid fraction constant zone which equal to 10^5, $\vec{V}_P$ refers to solid velocity due to the pulling velocity of solidified material out of the field, ϕ refers to slight number to prevent zero division and equal to 0.001. As a result, the following is the energy equation:

$$\frac{\delta}{\delta t} (\rho H) + \nabla \cdot \left(\rho \vec{V} H \right) = \nabla \cdot (k \nabla T) + S \quad (8)$$

where H, ρ, $\vec{V}$ and S are enthalpy of material, density, fluid velocity and source term, respectively. Combination of sensible and latent heat in enthalpy of material can be computed as:

$$H = h + \Delta H \quad (9)$$

where h and ΔH are enthalpy of material of sensible enthalpy and latent enthalpy, respectively. Sensible enthalpy can be computed as:

$$h = h_{ref} + \int_{T_{ref}}^{T} C_P \, dT \tag{10}$$

where h_{ref} refers to enthalpy reference and T_{ref} refers to reference temperature. On the other side, the latent heat can be computed as:

$$\Delta H = \beta L \tag{11}$$

where L refers to latent heat. The latent heat of materials is various from solid (0) to liquid (L). The liquid fraction, β of latent heat are as follows:

$$\beta = \begin{cases} 0 & if \quad T \leq T_{solidus} \\ \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & if \quad T_{solidus < T < T_{liquidus}} \\ 1 & else \quad T \geq T_{liquidus} \end{cases} \tag{12}$$

Heat absorption by PCM, E_{PCM} are defined as:

$$E_{PCM} = m_{PCM} \cdot C_{PCM} \cdot \Delta T \tag{13}$$

where m_{PCM}, C_{PCM} and ΔT are mass of PCM, specific heat capacity of PCM and temperature change of the working fluid.

2.6.4 Thermodynamics analysis

In the performance of solar PVT-PCM, the analysis involved is thermodynamic analysis. There are two type of thermodynamics analysis which are energy analysis (first law of thermodynamic) and exergy analysis (second law of thermodynamics). In this research, the performance is evaluated using the energy analysis (first law of thermodynamic).

Energy from the sunlight is absorbed by the PV cells in the panel. Solar radiation in Ansys Fluent setup is liable to boundary condition. The incident solar radiation of the system, E_{sun} can be expressed as:

$$E_{sun} = \tau_g \cdot \alpha_{cell} \cdot A_{PV} \cdot G \tag{14}$$

where $\tau_g, \alpha_{cell}, A_{PV}$ and G are transmissivity of the glass cover, absorptivity of the PV cells, solar PV panel area and rate of total solar irradiation, respectively. The energy relating to mass flow is calculated as:

$$E_{mass,out} - E_{mass,in} = E_{th} = m_f \cdot C_{p,f} \cdot \left(T_{f,out} - T_{f,in}\right) \tag{15}$$

where m_f refers to mass flow rate, $C_{p,f}$ refers to specific heat capacity, $T_{f,in}$ refers to temperature of inlet working fluid and $T_{f,out}$ refers to temperature of outlet working fluid.

The thermal efficiency of the PVT system is expressed by:

$$\eta_{th} = \frac{E_{th}}{E_{sun}} = \frac{m_f \cdot C_{p,f} \cdot (T_{f,out} - T_{f,in})}{\tau_g \cdot \alpha_{cell} \cdot A_{PV} \cdot G} \tag{16}$$

Due to the present of PCM in the system, the thermal efficiency of the PVT-PCM system is calculated as:

$$\eta_{th} = \frac{m_f \cdot C_{p,f} \cdot (T_{f,out} - T_{f,in}) + E_{PCM}}{\tau_g \cdot \alpha_{cell} \cdot A_{PV} \cdot G} \tag{17}$$

where E_{PCM} is the thermal power absorbed by PCM. The thermal power absorbed by PCM is expressed as follow:

$$E_{PCM} = \begin{cases} \frac{m_{PCm} \cdot C_{P,PCM} \cdot (T_{PCM,t} - T_{PCM,t_0})}{t - t_0} & t < t_1 \\ \frac{m_{PCM} \cdot C_{P,PCM} \cdot (T_{PCM,t_1} - T_{PCM,t_0})}{t_1 - t_0} + \frac{m_{PCM} \cdot h}{t - t_1} & t_1 \leq t \leq t_2 \\ \frac{m_{PCM} \cdot C_{P,PCM} \cdot (T_{PCM,t_1} - T_{PCM,t_0})}{t_1 - t_0} + \frac{m_{PCM} \cdot h}{t_2 - t_1} + & t > t_2 \\ \frac{m_{PCM} \cdot C_{P,PCM} \cdot (T_{PCM,t} - T_{PCM,melting})}{t - t_2} & \end{cases} \tag{18}$$

The electrical efficiency of the system is expressed by:

$$\eta_{el} = \frac{E_{el}}{E_{sun}} = \eta_r \cdot [1 - 0.0045 \cdot (T_{cell} - 298.15)] \tag{19}$$

where $\eta_r$and T_{cell}refers to PV module efficiency at standard test condition and PV cells operating temperature.

Hence, overall efficiency of the system, η_{ov} are calculated as:

$$\eta_{ov} = \eta_{th} + \eta_{el} \tag{20}$$

3. Grid Independence Study and Model Validation

3.1 Grid Independent Study

The precision of the simulation is improved by increasing the computational grid resolution, but the computational cost is also increased. Grid independence test is necessary to determine the ideal arrangement in terms of the number of computational cells. There are 3 grids utilized consists of coarse, medium, fine used in the grid independence study. The average difference in outlet temperature is between 0.01% – 0.03% which are relatively small. On the other hand, the average difference in surface temperature is 0.31% - 0.13%. Since both of the results produces small changes in the results, the simulation meshing type can be put a stop at medium meshing to reduce the computational cost and save more time as supported by Khanna *et al.,* [27].

3.2 Model Validation

The validation studies have been investigated and compared from research by Kazemian *et al.,* [21] as a major reference for validation and compared with the present study. Kazemian *et al.,* [21] stated the inlet temperature of coolant flow of 30 ˚C, mass flow rate of the coolant flow is 30 kg/h, ambient temperature of 30 ˚C, solar radiation of 800 W/m^2 and wind speed of 1 m/s. In addition, the thermophysical properties of the Phase Change Material (PCM) such as melting point of the PCM is 55 ˚C is chosen similar to Kazemian *et al.,* [21]. Furthermore, further thermophysical properties of

PCM such as density equals to 800 kg/m^3, enthalpy of fusion equals to 170 kJ/kg, the thermal conductivity is 0.25 W/m.K and heat capacity is 2300 J/kg.K.

The results of the PVT-PCM are investigated on several parts such as surface and outlet temperature to study on the performance. The uppermost layer of the PVT-PCM is considered as surface layer. At the final step in the simulation, the highest temperature produced at the surface of the present study are 57.39 ˚C while the Kazemian *et al.,* [21] shows 55.54 ˚C. The average percentage difference of surface temperature between present study and the study by Kazemian *et al.,* [21] shows 4.70%. The value of the coefficient of determination (R-squared) is 2.40 corresponds to high reliability of this research.

At the end of the simulation, the greatest temperature created at the outlet temperature of the present study is 33.34 ˚C, while the highest temperature produced by Kazemian *et al.,* [21] study is 33 ˚C. The average percentage difference of outlet temperature between the both studies show 0.66%. The value of the coefficient of determination (R-squared) is 0.52 indicates reasonable accuracy and reliability of this research.

4. Results and Discussion

In this present study, the simulation model of PVT-PCM is developed under constant solar irradiance which is 450 W/m^2. The initial temperature of the working fluid started with 30 ˚C. The selected PCM used is RT44HC as the thermophysical properties are presented in Table 3. Parametric analyses are developed to determine the influence of various parameters on the performance of the PVT -PCM. Parameters included in this study are variation of mass flow rate, various solar irradiance on PVT-PCM system will be investigated and the comparative analysis between PVT and PVT-PCM.

4.1 Performance of PVT-PCM on Various Mass Flow Rate at Constant Solar Irradiance

In this parametric analysis, the effect of various mass flow rate on the surface and outlet temperature are exhibited in this section. Four different mass flow rate of 10 kg/h, 30 kg/h, 50 kg/h and 70 kg/h are selected for these numerical analyses.

Figure 3 shows the surface temperature of the PVT-PCM on various mass flow rate. Despite the results of the surface temperature under mass flow rate 10 kg/h operation shows the highest temperature. On the other hand, mass flow rate of 70 kg/h shows the lowest temperature while other mass flow rate differences are not significant.

The results of variation of outlet temperature by applying using various mass flow rate are shown in Figure 4. The mass flow rate of 10 kg/h shows the significant temperature at the outlet as compared to 30 kg/h, 50 kg/h and 70 kg/h. As the mass flow rate increases from 10 kg/h to 70 kg/h, the average outlet temperature of the PVT-PCM decreases from 41.32˚C to 31.93˚C. Additionally, increasing in the mass flow rate reduces the temperature of the outlet since the system requires higher outlet temperature to increase the electrical efficiency of the PVT-PCM. However, higher mass flow rate will reduce the thermal efficiencies.

Increasing in mass flow rate leads in a higher Reynolds number. Subsequently, the flow turbulence and heat transfer coefficient will be escalated. It could be argued that the increased in flow rate requires stronger pumps which increase the total cost of the system. Therefore, identifying the optimal flow rate might help to achieve an appropriate thermal efficiency while sustain in low costs.

Referring to Table 6 are the performance of PVT-PCM on variation of mass flow rate. Based on the simulation output, by increasing the mass flow rate of the working fluid from 10 kg/h to 70 kg/h, the thermal efficiencies decrease while the electrical efficiencies increase. By increasing of mass flow rate from 10 kg/h to 70 kg/h, the thermal efficiency of PVT-PCM system decreases from 73.08% to 72.18% and electrical efficiency increases from 17.74% to 18.27%. Therefore, the overall efficiencies decrease as the mass flow rate increases from 10kg/h to 70 kg/h by 90.82% to 90.46%, respectively. As a consequence of the reduction in average surface and outlet temperature by increasing the mass flow rate of the working fluid.

Table 6
Performance of PVT-PCM on Various Mass Flow Rate

Mass Flow Rate (kg/h)	Thermal Efficiency (%)	Electrical Efficiency (%)	Overall Efficiency (%)
10	73.08	17.74	90.82
30	72.43	18.11	90.54
50	72.26	18.22	90.48
70	72.18	18.27	90.46

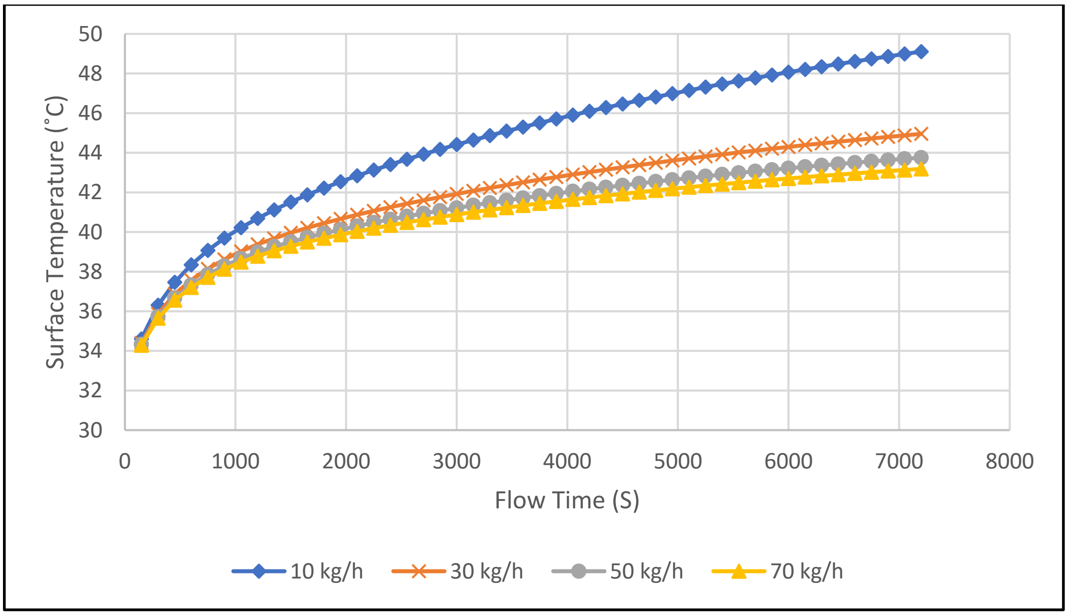


Fig. 3. Surface Temperature of PVT-PCM on Various Mass Flow Rate at Constant Solar Irradiance 450 W/m^2

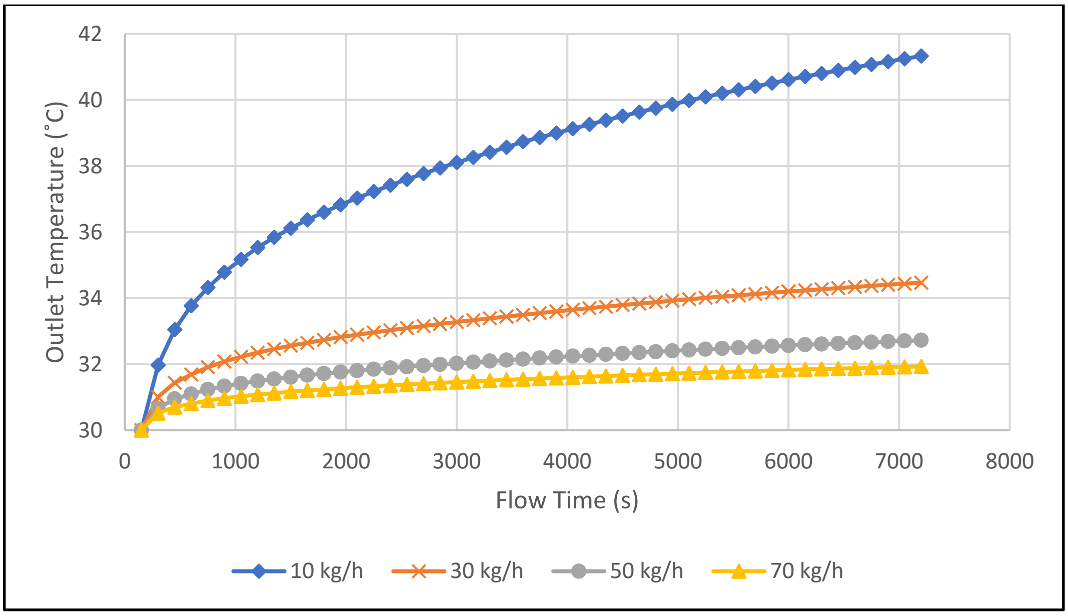


Fig. 4. Outlet Temperature of PVT-PCM on Various Mass Flow Rate at Constant Solar Irradiance 450 W/m^2

4.2 Performance of PVT-PCM on Various Mass Solar Irradiance at Constant Mass Flow Rate

In this section, the outlet temperature on various solar irradiance at constant mass flow rate of 10kg/h as shown in Figure 5. The variation of solar irradiance starts from the lowest irradiance until the highest irradiance. The lowest irradiance indicated by 200W/m^2, middle irradiance by 450 W/m^2 and the highest irradiance by 800 W/m^2. The highest temperature of the outlet shows 50.13˚C by 800 W/m^2 irradiance. Referring to the Figure 5, the outlet temperature increases as the solar irradiance increases. In this study the solar irradiance used was 450 W/m^2 shows results by 41.32˚C while the lowest irradiance of 200 W/m^2 shows with 35.03˚C. The percentage difference between 800 W/m^2 and 450 W/m^2 was 19.26%. On the other hand, the difference between 450 W/m^2 and 200 W/m^2 are 16.48%, both differences show almost similar difference. This shows a uniform change in the outlet temperature proportional to the flow time.

Thus, this shows the increment of solar irradiance will be affected with the increasing of outlet temperature. The solar irradiance will absorbed by the EVA panel of the system and transferred into the PCM layer. Next, the heat absorbed by the PCM and being transferred to the copper tube collector which containing the working fluid.

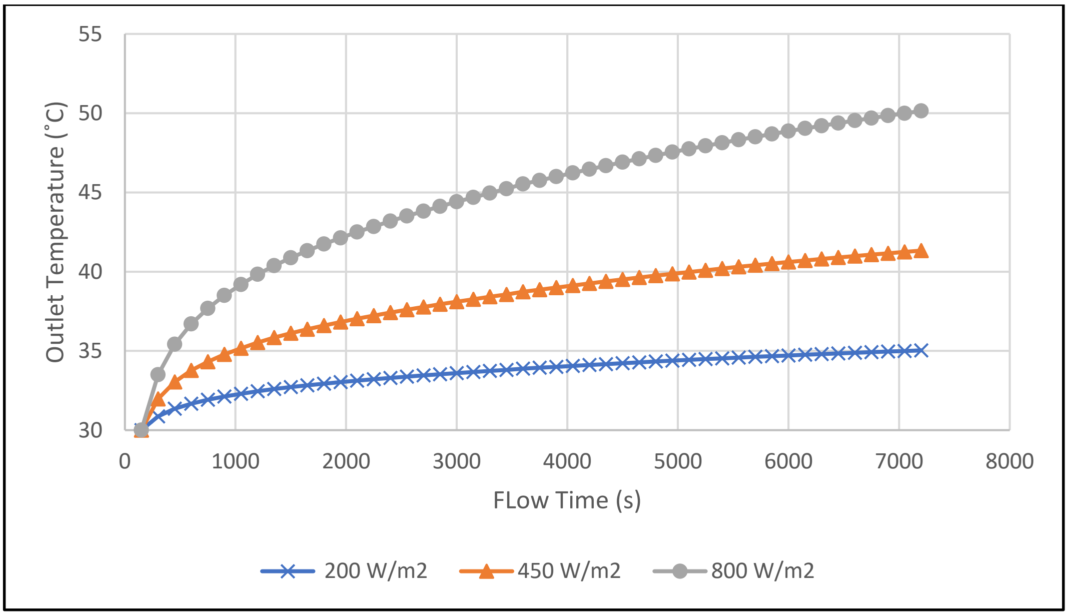


Fig. 5. Outlet Temperature on Various Solar Irradiance at Constant Mass Flow Rate 10kg/h

Referring to the Figure 6, the results of surface temperature on the variation of solar irradiance at constant mass flow rate of 10 kg/h. Based on the simulation, by increasing the solar irradiance from 200 W/m^2 to 800 W/m^2, the average surface temperatures increase from 38.49˚C to 63.96˚C. At the medium level of 450 W/m^2 solar irradiance, the surface temperature shows 49.10˚C. The percentage difference between low-medium and medium-high irradiance are 24.23% and 26.28%, respectively. At initial flow time 150s, the temperature started to rises slowly because PCM still in sold state. It can be seen that the temperature rises as the flow time pass until 7200s and the PCM encounter melting process.

Performance of thermal efficiency and electrical efficiency by the variation of solar irradiance as illustrated in Table 7. By increasing of solar irradiance from 200 W/m^2 to 800 W/m^2, the thermal efficiency of PVT-PCM system increases from 72.48 % to 73.91%. On the other hand, the electrical efficiency decreases from 18.69% to 16.41%. Furthermore, the average percentage difference between the highest and lowest irradiance at thermal efficiency and electrical efficiency are 1.96% and 12.99%, respectively. Therefore, Table 7 shows the results of overall efficiencies by 200 W/m^2, 450 W/m^2 and 800 W/m^2 are 91.17%, 90.82% and 90.33%, respectively. As the solar irradiance increases, the thermal efficiency of the PVT-PCM increases due to heat transfer occurrence in the PVT-PCM. Howver, it can be seen that by increasing the solar irradiance, the overall performance will drop accordingly. As results, heat can severely reduce the power production in solar PVT.

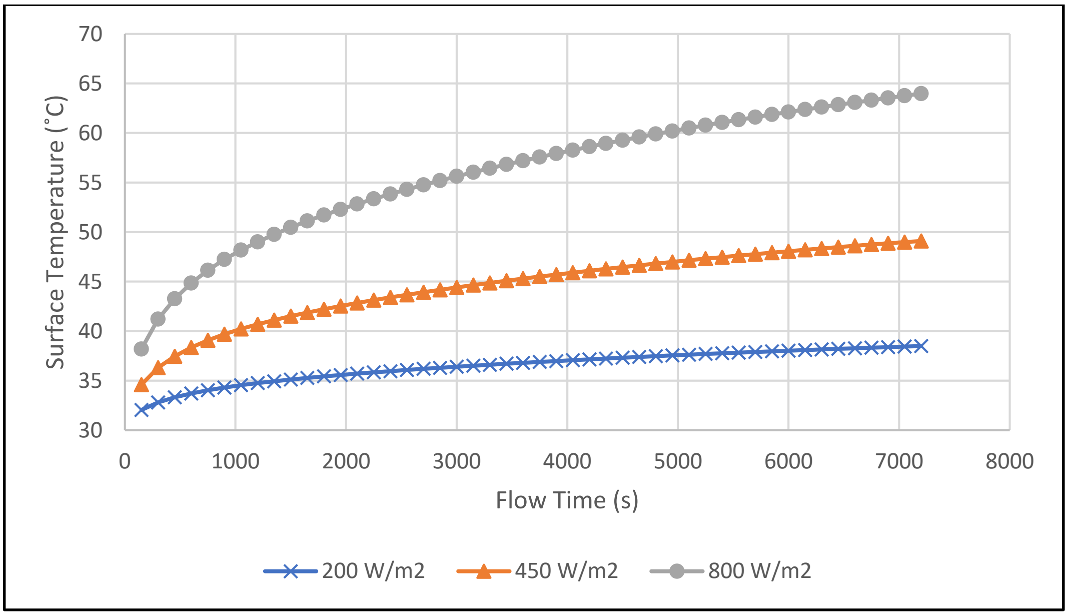
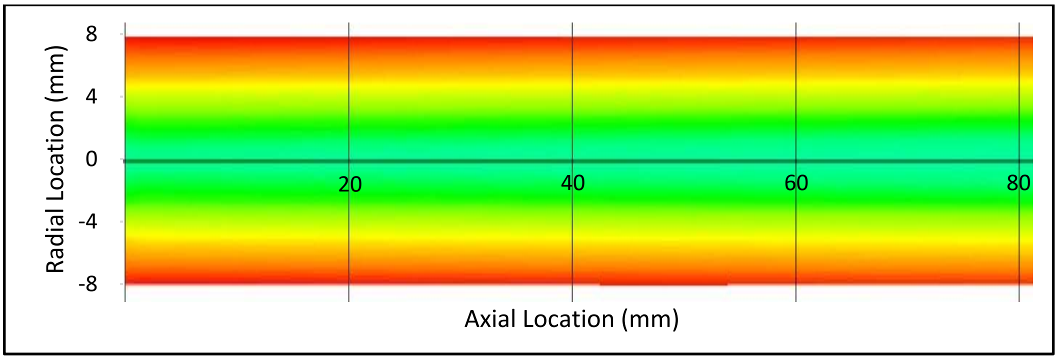


Fig. 6. Surface Temperature on Various Solar Irradiance at Constant Mass Flow Rate 10kg/h

Table 7
Performance of PVT-PCM on Various Solar Irradiance

Irradiance (W/m^2)	Thermal Efficiency (%)	Electrical Efficiency (%)	Overall Efficiency (%)
200	72.48	18.69	91.17
450	73.08	17.74	90.82
800	73.92	16.41	90.33

The axial flow assembles from the inlet to the outlet of the working fluid in the copper tube. The axial temperature examined from the outlet point denoted as 0mm through 80mm inwards. Figure 7 shows the axial temperature distribution at the outlet of the working fluid and axial temperature profile for 200 W/m^2, 450 W/m^2, 800 W/m^2.



(a)

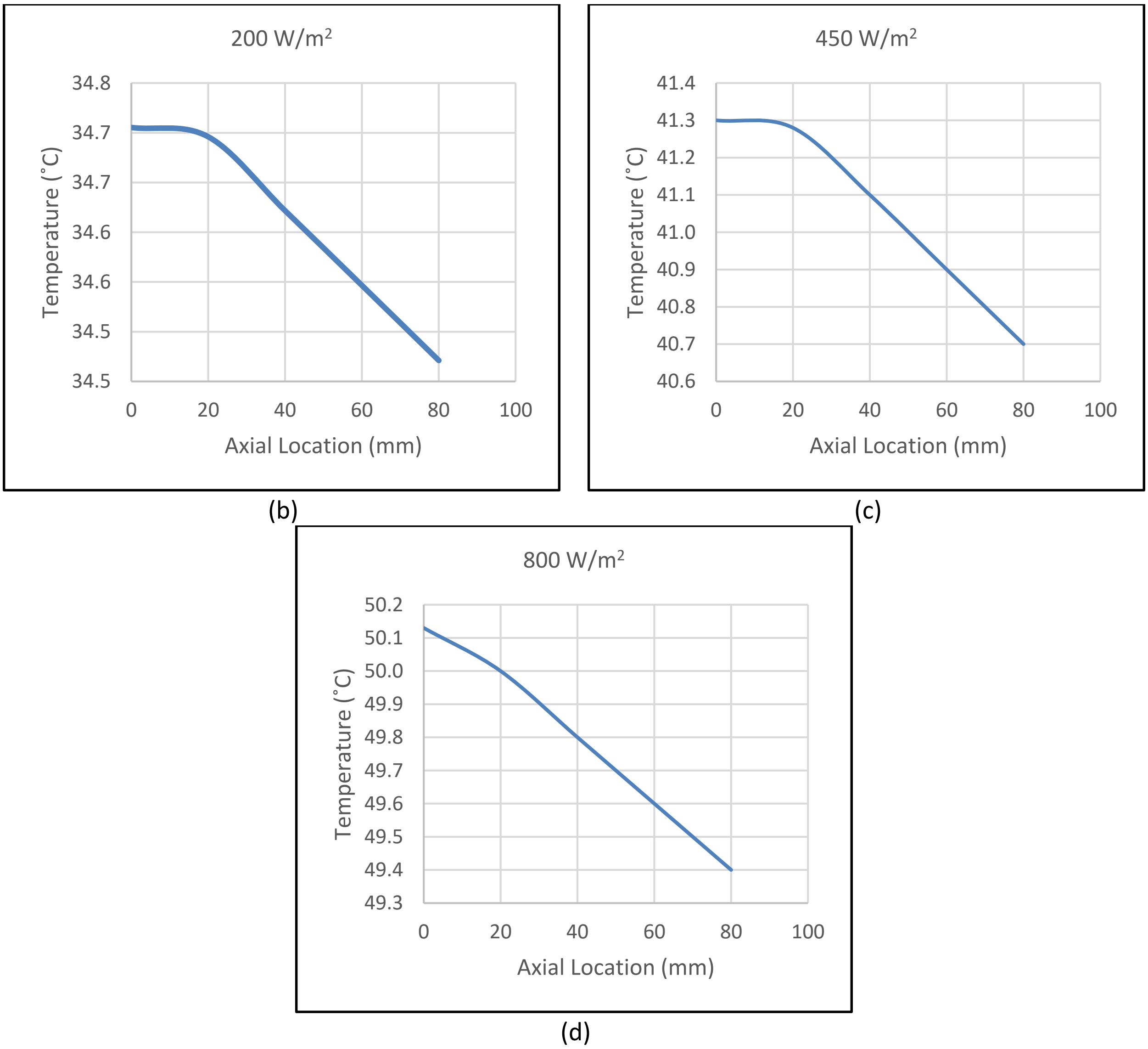


Fig. 7. (a) Axial Temperature Distribution (b) Axial Temperature Profile at 200 W/m^2 (c) Axial Temperature Profile at 450 W/m^2 (d) Axial Temperature Profile at 800 W/m^2

4.3 Comparison Between PVT and PVT-PCM

In the comparison of PVT and PVT-PCM, the geometry by PVT is designed with the absence of Phase Change Material (PCM). The surface and outlet temperature of the PVT-PCM are examined using the similar boundary condition and operating condition. Both systems undergo 7200s simulation transiently, at constant solar irradiance of 450 W/m^2, mass flow rate of coolant flow at 10 kg/h and initial temperature of coolant flow at 30˚C.

Figure 8 compares the temperature at the outlet between PVT and PVT-PCM. The outlet temperature from the PVT system rises rapidly at initial stage and started to be constant at 2000s. The final temperature of the outlet by PVT and PVT-PCM shows 44.76˚C and 41.32˚C, respectively. The outlet temperature of the PVT is 7.98% higher than PVT-PCM system. These findings provide additional evidence when the outlet temperature from the PVT-PCM system is lower than PVT system due heat absorption by the PCM and the excessive heat is reduced when transferred to the working fluid. Khodadadi and Sheikholeslami [35] support the idea of the outlet temperature of the PVT-PCM system are lower than PVT system.

Figure 9 provides the surface temperature between PVT and PVT-PCM. The final simulation output of surface temperature by PVT and PVT-PCM exhibits 54.12˚C and 49.10˚C, respectively. The percentage difference of PVT system is 9.72% higher than PVT-PCM system. Interestingly, this correlation is related to the temperature of PVT and the performance of both systems. These are remarkable results since lower temperature of surface temperature will produce higher efficiency of the PVT-PCM system. This study has been demonstrated by Navazani *et al.,* [36] and Abdullah *et al.,* [37] stated that the lower temperature, the higher the efficiency of the system.

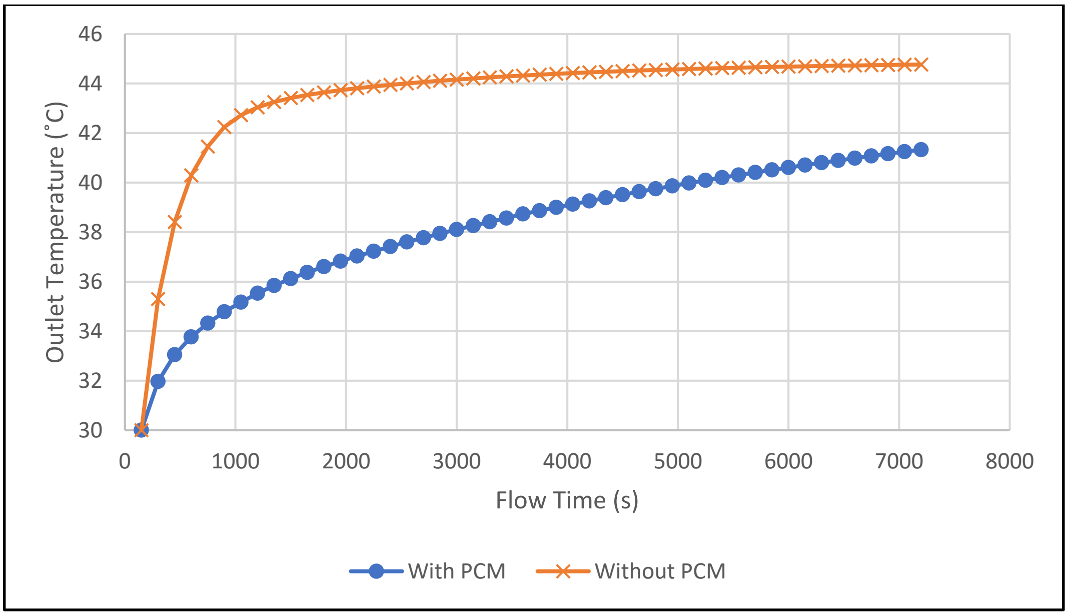


Fig. 8. Comparison of Outlet Temperature between PVT and PVT-PCM

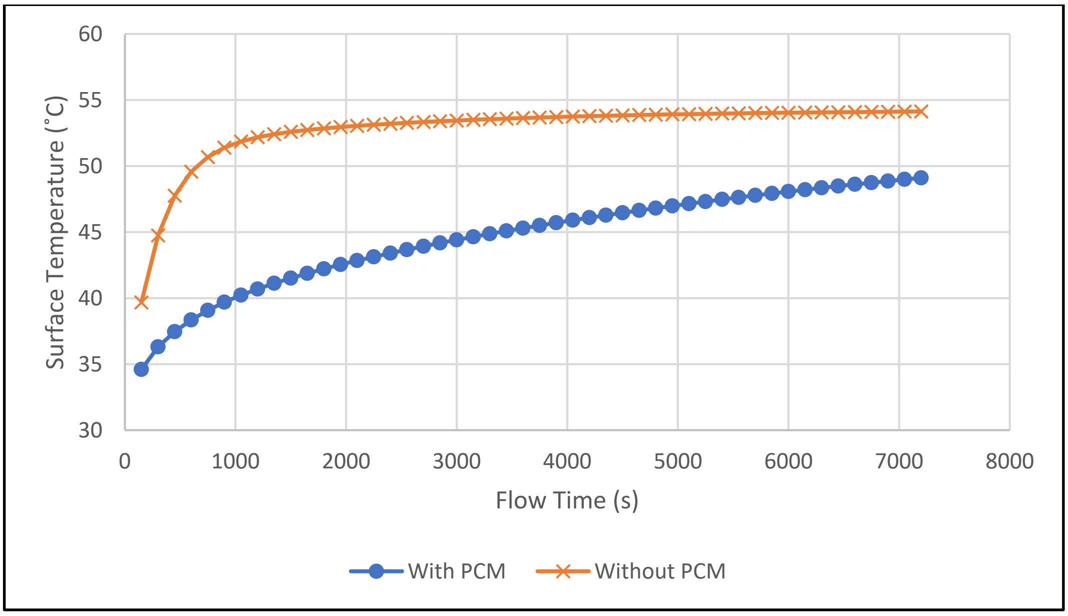


Fig. 9. Comparison of Surface Temperature between PVT and PVT-PCM

5. Conclusion

Finally, this paper presented numerical investigation of PCM acts as promising elements incorporated in the PVT system that have the capability to reduce the temperature of the PVT-PCM system. The optimum parameters in the thermal efficiencies when the mass flow rate is lower to allowed better heat transfer process from the surface to the PCM [38]. In contrast, reduction in the mass flow rate, the electrical efficiencies will be reduced.

Solar irradiances are other parameters considered in this study. The increasing of solar irradiance leads to thermal efficiency growth. Alternately, higher solar irradiance leads to reduction in electrical efficiencies due to the undesirable temperature of the PVT-PCM system and reduce the power production [39-41]. In accordance with the variation of parameters supplementary will influence of the performance of PVT-PCM [42]. Conclusively, Phase Change Materials (PCMs) are a potential technology for thermal energy storage to store and release a considerable quantity of latent [43].

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