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Research Article

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Energy Storage: CFD Modeling of Thermal Energy Storage for a Phase Change Materials (PCM) added to a PV/T using nanofluid as a coolant

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Abstract PV/T systems are a promising way to reduce solar cell temperature and take advantage of the dissipated heat in other applications. The optimum utilization of the absorbed heat needs to store it in a material that can then be recovered from it. The most critical materials suitable for these applications are phase change materials (PCM). PCM is characterized by its high latent heat potential when changing the phase from solid to liquid in the fusion phase. The main disadvantage of these materials is the low thermal conductivity. The idea of adding nanomaterials to the PCM to enhance its thermal conductivity proved its suitability.

This paper presents an assessment of the modeling of the PV/T system by adding PCM to the solar collector using computational fluid dynamics (CFD). The heat storage process was studied in PCM with the addition of nano-SiC and its transfer by a nanofluid (water + nano-SiC). The effect of nanoparticle dispersion rate (φ = 0, 10 and 20%) and the temperature difference between the hot and cold wall on PCM hardening was also studied. The results show that suspended nanoparticles cause a significant increase in the rate of heat transfer and also increase the amount of heat absorbed by the nanofluid.

Keywords Phase change material (PCM), thermal energy storage, CFD, nanofluid, PV/T

Introduction

Due to the substantial environmental risks to the world due to the excessive use of fossil fuels from coal, oil and natural gas to meet the need of energy, the world may now turn to renewable energies [1, 2]. Solar energy can be considered the cleanest of the available powers and is free and open most of the year and in considerable quantities in some areas [3]. Solar energy can be used to generate heat and electricity [4-6]. Also, it can be used directly to generate electricity through solar cell. Solar cells that convert solar radiation into electricity have become popular and successful, and their prices have become acceptable, increasing their popularity [7]. The photovoltaic uses have many applications, which it prove its benefit in reducing air pollution, noise, and enhancing air quality [8-10].

The photovoltaic cell (PV) performanceis affected by many climatic parameters such as solar radiation intensity [11], humidity [12], wind [13], dust [14], and temperature [15]. The efficiency of PV modules and the generated power are decreased with increasing the temperature [16]. The researchers suggested cooling the solar cell board using different fluids such as air or water [17-18]. However, it has been shown that it is better to use a nanofluid that has a higher thermal conductivity than water and a relatively similar thermal capacity, which makes PV/T systems have higher electrical efficiency than PV, as well as high thermal efficiency [19]. Despite this, Ref. [20] proved that using PCM in the solar collector to store heat with the use of nanofluid for cooling PCM gives a much higher thermal and electrical capacity than any proposed PV/T system to date.

Many researchers have published studies on thermophysical properties of different types of PCM as well as their specification changes when adding nanomaterials [21-24]. They have also identified many various applications that can be used [25-27]. The enhancement of heat transfer mechanism and thermal storage using advanced materials have been studied theoretically, experimentally, and numerically.

The use of CFD gives an adequate assessment and a useful way to save time and money by providing the best solution to achieve the best possible efficiency of these systems [28]. Many researchers have studied and reviewed extensively the previous studies that focus on enhancing thermal storage using nanomaterials added to PCM [29, 30]. Also, many of them have studied the use of CFD as a useful tool to increase engineering development and to evaluate the various thermal energy storage technologies [31].

Ref. [32] studied the transient behavior of a phase change material at elevated temperatures stored in a heat exchanger type shell and tube. The study found that some of the PCM near the tube outlet remained in solid state because the temperature of the nanotubes at the outlet is close to PCM temperature and there is little difference between them, which reduces the rate of heat transfer. The researchers also suggested that the addition of a few ring fins would maintain a relatively high-temperature difference between the cooling fluid and the PCM used to cause complete fusion everywhere within the heat exchanger.

Ref. [33] Review of the extensive thermal energy storage systems used by PCM, and published studies on heat transfer in such applications. R. [34] analyzed numerically a system used PCM with tight insulation. Reference [35] practically verified the hardening and melting of PCM in heat exchanger type shell and tube. In this study, the use of the heat transfer fluid (HTV) flowing in the inner tube and the paraffin wax outside are stored. The results showed that conduction and convection are the dominant forms of solubility and hardening.

Ref. [36] numerically and experimentally studied the effect of the temperature of the nanofluid inside the heat exchanger type of shell and tube on the phase change process. The researchers found that the melting front appeared at locations close to the tube that advanced in different rates towards the outside of the shell, as repeated it in several times. The researchers found that this condition occurred when the temperature of the nanoparticle interring the heat exchanger increased to 80°C, reducing the PCM melting time by 37%.

This study uses the CFD facilities to verify the efficiency of the PV/T system by adding nanomaterials to the PCM and cooled with nanofluid. The theoretical results will also be compared to another practical process that was carried out in the atmosphere of Malaysia.

Problem Statement and Boundary Conditions

A tank is included in a PV/T system. The container contains a paraffin wax as the used phase change material (PCM) mixed with nano-SiC to enhance the heat transferred from the PV panel. The PCM has a high thermal storage ability that makes it draws all the thermal energy collected by the PV module. The increasing of the temperature difference between the PCM and PV module enhances the heat transfer operation resulting in a reduction in the module temperature.

Photovoltaic panels begin to produce electricity as soon as they are exposed to sunlight and at the same time absorb a large part of this radiation as heat. Consuming and storing this heat in the cell causes an increase in temperature, which affects the generated power. In this research, the heat absorbed by the cell will move to the paraffin wax in the reservoir below and because it has a high thermal capacity will absorb most of the heat received by the cell. The high temperature of the wax will cause it to reach the melting point, and then the thermal storage increases more during the stage of the phase change. As the heat continues to flow after full wax fusion, the temperature of the paraffin wax begins to rise, and at this stage, the stored heat is a significant temperature. During this time, the nanofluid with a high thermal conductivity circulates in the wax-absorbing tubes, and it is being heated by direct contact with the wax. The fluid takes part of the heat and moves to an external heat exchanger to get rid of the heat and return to complete a coin in reducing the temperature of the wax.

The system used is a closed circuit, as the cooling fluid enters the system and absorbs as much heat as possible and then releases it to the outer heat exchanger to return to a colder temperature. This cycle works to cool the PV panel and reduce its temperature, which increases the productive power. The experimental setup was established in the green innovation and technology parks' outdoors laboratory, which is a part of the UKM (National University of Malaysia). Fig. 1 represents a top view photo of the PCM collector.

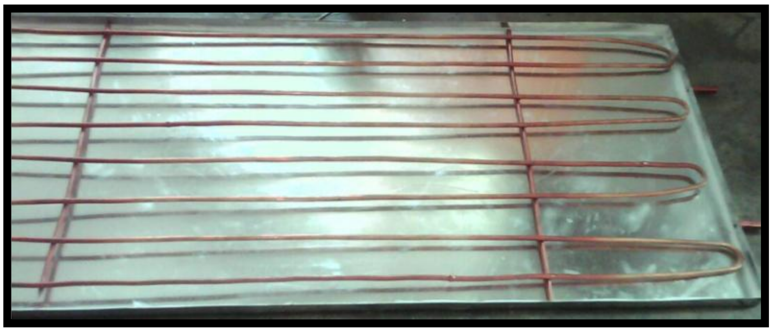

Figure 1: Top view photo of the PCM tank

The PV/T system composes of a supporting pole which is used to carry the PV panels, a cabinet which contains a heat exchanger, water pumps, nanofluid container, laptop, and data acquisition system. Behind the enclosure, a water tank was installed to hold the produced thermal output. The PCM vessel was isolated from its back and sides with glass wool with a 2 cm thickness to prevent heat leakage to the ambient. This insulation will make all the heat drawn from the PV panel aggregate in the reservoir and then pull out via water and nanofluid.

Figure 2: View of the experimental rig

The new PV/T design was operated, and its practical results outcomes are compared with the mathematical formulation to validate the CFD results. Table 1 lists the used nano-SiC and paraffin wax properties.

Table 1: The used SiC nanoparticles and paraffin wax properties

Properties	Nano-SiC	Paraffin wax
Melting point K	2730	50
ρ Kg/m^3	8960	930/830
μ Pa s	-	0.0071
cP kJ/kg K	0.383	2.1

Mathematical Formulation

Studying and evaluating complex fluid flow and heat transfer using computational fluid dynamics in the present state of the thermoelectric collector is considered a reliable procedure. CFD is a technique that simulates the behavior of the systems through which fluids flow through, and they are transported to heat, and the accompanying physical processes, such as phase change, as in our current study. We have used the CFD method in the present study to investigate the best designs that can be used with the best rate of nanomaterial movement as coolants to work in a bit collector containing a quantity of PCM mixed with nanoparticles. The benefit of such a simulation of flow is to find the best solution to problems related to the use of arithmetic scale.

Numerical simulations used the computational domain that was formatted with network-based control sizes using ANSYS software program. Numerical simulations were performed using Fluent-programs based on constant state pressure. The steady incompressible flow was used to solve the partial differential equations for mass and momentum. The continuity, momentum, and energy equations were set to a complete CFD analysis for the PV/T collector. The studied case is defined in the tripartite arithmetic field of continuity, time-averaged incompressible Navier-Stokes equations and energy equation. In the Cartesian tensor system, these equations could be written as Ref. [37].

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad (1)$$

Momentum equation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}(-\rho\overline{u_i' u_j'}) \qquad (2)$$

The thermal energy equation:

$$\partial h/\partial t + \partial H/\partial t + \nabla\cdot(\vec{V}h) = \nabla\cdot(k_{eff}/(\rho cp)_{nf}\nabla h) \qquad (3)$$

The enthalpy of the material is computed as the sum of the sensible enthalpy, h , and the latent heat, ΔH:

$$H = h + \Delta H \qquad (4)$$

where

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p dT \qquad (5)$$

The latent heat content can be written in terms of the latent heat of the material, L:

$$\Delta H = \lambda L \qquad (6)$$

where ΔH may vary from zero (solid) to L (liquid).Therefore, the liquid fraction, λ can be defined as:

$$\lambda \begin{cases} \frac{\Delta H}{L} = 0 & \text{if } T < T_m \\ \frac{\Delta H}{L} = 1 & \text{if } T > T_m \end{cases} \qquad (7)$$

The density of the nanofluid is given by

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_s \qquad (8)$$

The heat capacities of the nanofluid and part of the Boussinesq term are:

$$(\rho c_p)_{nf} = (1-\phi)(\rho c_p)_f + \phi(\rho c_p)_s$$

$$(\rho\beta)_{nf} = (1-\phi)(\rho\beta)_f + \phi(\rho\beta)_s \qquad (9)$$

In above equations, ϕ is the volume fraction of the solid particles and subscripts f, nf, and s stand for base fluid, nanofluid, and solid particle, respectively. The effective dynamic viscosity of the nanofluid containing a dilute suspension of small rigid spherical particles given by Brinkman [38] is:

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \qquad (10)$$

The thermal conductivity of the stagnant (subscript 0) nanofluid is given by

$$\frac{k_{nf0}}{k_f} = \frac{k_s + 2k_f - 2\phi(k_f - k_s)}{k_s + k_f + \phi(k_f - k_s)} \qquad (11)$$

The effective thermal conductivity of the nanofluid is

$$k_{eff} = k_{nf0} + k_d \tag{12}$$

The thermal conductivity enhancement term due to thermal dispersion is given by:

$$k_d = C(\rho c_p)_{nf} \left|\vec{V}\right| \phi d_p \tag{13}$$

The empirically determined constant C is evaluated following the work of Wakao and Kaguei [39]. Also the latent heat evaluated using [40] is:

$$(\rho L)_{nf} = (1-\phi)(\rho L)_f \tag{14}$$

In (2), $\vec{S}$ is the Darcy's law damping terms (as source term) that are added to the momentum equation due to phase change effect on convection. It is defined as:

$$\vec{S} = \frac{(1-\lambda)^2}{\lambda^3} A_{mush} \vec{V} \tag{15}$$

The coefficient A_{mush} is a mushy zone constant. This constant is a large number, usually 10^4–10^7. In the current study, A_{mush} is assumed constant and is set to 10^6.

Mesh Selection

In selecting a mesh, the following parameters are taken into consideration: computer resources, quantity y+. Generally speaking, the network is refined towards the walls so that it complies with the requirements of wall function y+<30. Under the relations between the Grasshoff and the Reynolds number, these values can be roughly determined, which amount to 8.5mm and 24.6mm for air, or 0.01mm and 0.03mm for water. Having all this in mind, the Cartesian mesh is selected with 100×50×25 cells in the x, y and z directions, respectively.

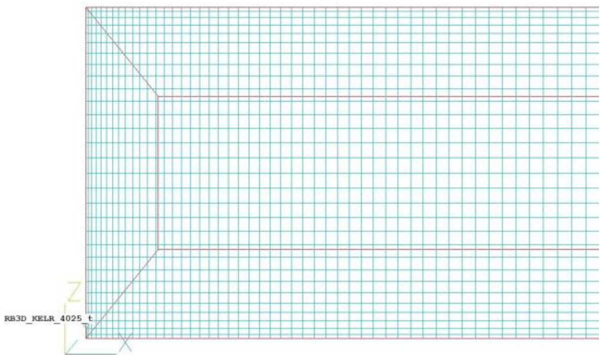

Figure 3: Generated mesh near the walls

Results of the numerical simulations

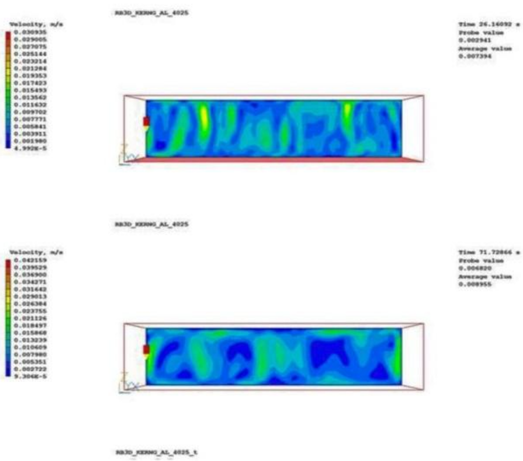

Figure 4 Heat transfer forming over the entire domain of the structures at charging period

Fig. 4 presents the typical results for the PCM tank during the charging process. The figure shows the heat is transferred from the warmer upper surface coming from the PV panel. In time the wax "warmed-up" parts specific volume raised and put pressure on the lower layers of wax, thus causing the heat movement, aided by friction on the side walls, which creates tangential stresses on the PCM. As the PCM heats, its heat waves velocity moved with a very little speed up to 0,001m/s. The more significant the temperature difference between the PV panel and the wax inside the tank, the higher the amount of heat transferred and thus increase the heat transfer rate.

Fig. 5 shows the wax's heat transfer during the discharge process. In this case, the heat moved from below to upper surface as the other surfaces are isolated. In this stage, the top layers of the wax were "cooled-down" but it can't solidificate as heat streams were coming from below where there are many parts with lower specific volume, thus causing the heat movement upward. The solidification process is supposed to start from the top, but in this case, as convective heat heats the upper layers, the lower layers of the wax will begin to solidify, and then the other neighbor layer, and so on. The top layer hardened at the end because it is the PCM's stored heat passageway that is dissipated through the PV surface at night. The speed of heat loss from the paraffin wax tank depends on the air temperature and the higher the difference, the better.

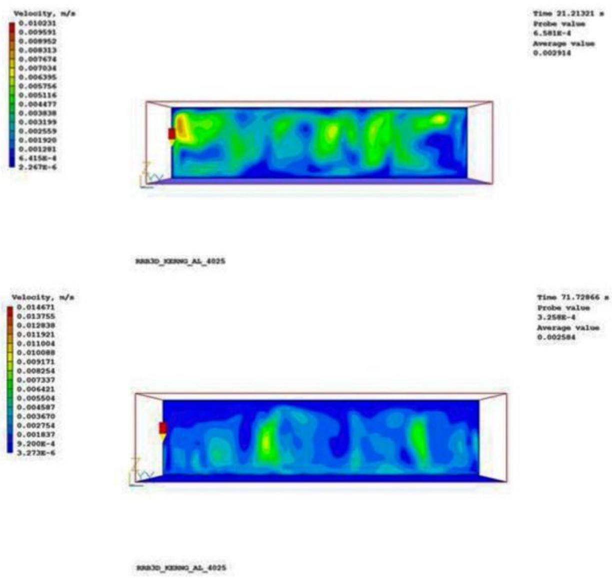

Figure 5: Heat transfer forming over the entire domain of the structures at discharging period

The System Validation

In order to verify the validity of the calculations and programming used in the research, we compared the numerical results with the results obtained and published in the Ref. [40]. Fig. 6 shows numerically the effect of four solar radiation intensities and the nanofluid pipe diameter size on the PV panel temperature. Increasing the diameter size increases the mass flow rate that could pass through; as a result, the pumping flow rate can be increased. However in the practical work, the diameter of the pipe is determined by the thickness of the tank, which is not taken into account here.

Fig. 7 represents numerically the effect of the nanofluid mass flow rate on the PVT system components temperature. PV plate temperatures, paraffin wax, and nanofluid are all reduced by increasing the mass of nanofluids flowing through the tubes.As long as nanofluid is at a temperature lower than wax, the heat will move from the wax to it, and the wax temperature will be reduced. The difference in temperature between wax and PV panel is very important for heat transfer. The higher the temperature difference, the lower the temperature of the board, which can gain more heat from the solar radiation, causing a flow of heat that can be used in other applications while simultaneously reducing the temperature of the PV panel that makes the power produced from it larger.

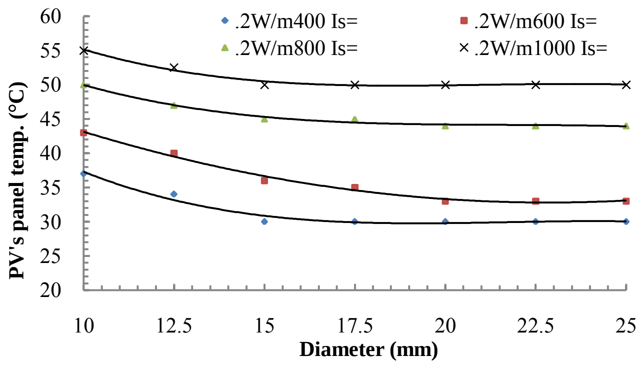

Figure 6: The effect of solar radiation and diameter size on the PV panel temperature

The higher the mass flow rate of the flowing nanofluid, the lower the system's components temperatures are. In theory, it is possible to continue increasing the mass flow rate to obtain the greatest reduction in the system temperatures, but in practice, there are limitations that cannot be exceeded in the amount of flowing nanofluid mass flow rate. The practical experiments proofed that a mass flow rate larger than 0.175 kg/s produced high vibration in the tubes and if it is allowed to proceed it may distracted the system. In general, this choice was reasonable as it is near the maximum value in the figure.

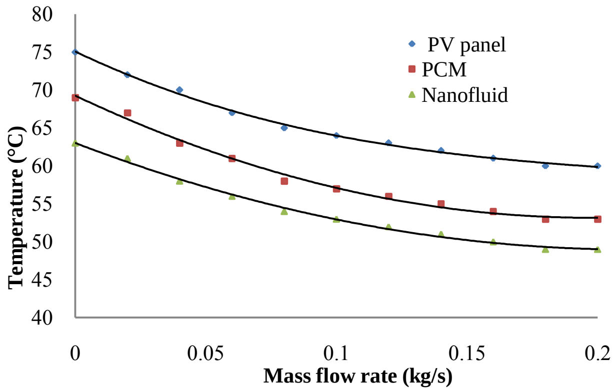

Figure 7: The effect of the nanofluid mass flow rate on the PVT system components temperature numerically presented

Fig. 8 compares between the numerical and experimental measured temperatures of the paraffin wax temperature variation with the changing of nanofluid mass flow rate. The figure shows a clear affinity between the practically measured and numerically calculated wax temperatures. This result can confirm that the steps used to create the CFD program were successful and the numerical results confirm our practical results.

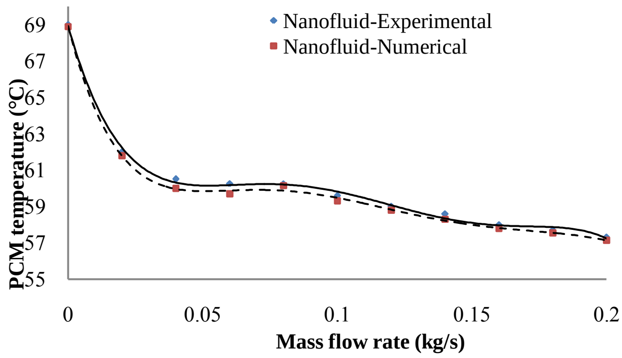

Figure 8: The effect of nanofluid mass flow rate on PCM temperature variations numerically and experimentally

Conclusions

The melting and solidification processes of the nano-enhanced phase change material (paraffin wax) in the fabricated and tested PV/T system was studied using CFD. The system uses nanofluid runs through the PCM for cooling purposes. Various nanofluids mass flow rates were considered to evaluate the optimum rate. The study results introduced the following conclusions:

• The heat transfer from the PV panel is significantly enhanced with the use of nano-PCM and nanofluid circulation compared to a single PV panel.

• The temperature difference reduced by increasing the mass flow rate, but the mass flow rate enlarging is eliminated by the system withstand for the vibration generated.

• Increasing the added nanoparticle mass fraction in the paraffin wax decreases the melting and solidification time.

• The temperature difference between the PV panel and the PCM greatly affected the heat transfer rate. Increasing the temperature difference between these components increases the heat transfer rate.

• In the used system, the heat source (sun) subjected from the upper side which makes the convection heat transfer very slow and depends on the wax's specific heat changes through the charging period.

• On the contrary, the situation is in the discharging period, as the heat moves by the convection currents upward where it is dissipated to outside the air through the PV panel.

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