Temperature Regulation of Photovoltaic Cells using Phase Change Material Heat Sinks Integrated with Metal Foam

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Abstract. This article investigates the cooling performance of Phase Change Material “PCM”-heat sinks integrated with porous metal that are attached to PV cells. Numerical simulations were carried out for a 2-dimensional configuration of a PCM-based heat sink subjected to uniform heat flux of 900W/m² on the upper side and heat convection takes place at all other sides with a uniform convective heat transfer coefficient of 10 W/m²°C. Two different PCMs were considered (n-Eicosane and RT44HC) and three values of metal foam porosity “ε” were chosen as well (ε = 1.00, 0.97 and 0.90, where ε = 1.00 refers to no-metal foam case). Results showed that addition of metal foam enhances the cooling performance of PCM-based heat sinks. In the n-Eicosane based heat sinks, the PV-surface temperature was reduced by 6.31 °C and 7.00 °C for the 97% and 90% porosities respectively when compared to the no-metal foam case (100% porosity). On the other hand, in the RT44HC based heat sinks the PV-surface temperature was reduced by 5.50 °C and 6.15 °C for the 97% and 90% porosities respectively when compared to the no-metal foam case (100% porosity).

1. Introduction
Photovoltaic cells are widely used to generate electricity since the middle of last century and they are considered very good alternative for power generated from fossil fuel. As the irradiance hits the PV surface; part of it is reflected and the other is absorbed by the cell converting fraction of it to electricity and the rest heats up the PV cell, both energy produced and temperature rise is directly proportional to incident radiation. The PV efficiency, however, is lowered by the temperature rise and reducing the PV surface temperature significantly increases the PV efficiency [1,2, 3].

The traditional cooling methods include: passive and active cooling. Passive cooling usually relies on natural convection heat transfer due to the circulation of air in the open space behind the PV panel, whereas active cooling requires the circulation of cooling fluid “mainly water” where a pump is usually used to circulate the cooling liquid [4,5,6,7].

In recent years, Phase Change Materials “PCM” were adopted by many researchers for PV cooling and they successfully reduced the PV surface temperature due to their nearly isothermal melting and their high latent heat of fusion as well. In fact, there are many types of PCMs with varying values of average melting temperature and latent heat of fusion. Tao, Ma [8] numerically investigated the effect of PCM thickness on the performance of PV modules, results showed that a PV module surface temperature decrease of about 24.9 °C was possible accompanied with a 11.02 % increase in power output. In another study Tao, Ma [9] used ANSYS Fluent software to simulate a rectangular cavity fitted with internal fins and filled with PCM, three types of PCMs were used and three values of cavity...
depths were chosen as well. In one module, the surface temperature was regulated below 45 °C for about 318 minutes with 6.35% power output increase. Atkin, et. al., [10] experimentally investigated and numerically modeled four different types of PV modules under different types of cooling techniques: reference solar panel, solar panel integrated with PCM, solar panel with fins and a solar panel with the external fins PCM container. They report an overall efficiency increase by 12.97% upon combining the PCM container with external fins. Waqas [11] experimentally tested a PCM cooled PV module equipped with movable shutters attached to the back of the PVs, where the PCM was placed inside movable shutters. Shutters are closed during sunshine to allow absorbing heat from PV panel. The absorbed heat is discharged by rotating the PCM filled shutters to ambient during non-sunshine hours and during the night period, the shutter opens to increase cooling rates of the PCM to improve the solidification. The results showed that the operating temperature was reduced by almost 25.9 °C with 9% efficiency increase in summer time with PCM melting point 35 °C, and increased by 2.2% in winter time with PCM melting point 30 °C. The main disadvantage of PCM is its low thermal conductivity, which mostly fall in the range of 0.2 W/(m⋅K) to 0.7 W/(m⋅K); therefore, effective heat transfer enhancement technologies are needed. According to [12], two main approaches are typically used to improve the heat transfer rate of PCM-Based storage systems and heat sinks; the first technique is mainly concerned with increasing the heat transfer surface area by: using fins with various sizes, shapes and spacing, considering multiple PCMs, employing metal matrix like metal pipes and lessing rings and increasing the fill volume ratio of the PCM. The second approach considers enhancing the thermophysical properties of the PCM based system and this can be achieved mainly by dispersing nano-particles/nano-tubes with high thermal conductivity into the PCM. In this work, a two-dimensional model of a PCM based heat sink filled with metal foam is simulated using Ansys Fluent software. The performance PCM Based heat sink is investigated for three different values of metal foam porosity and for two types of PCMs while holding the convective heat transfer coefficients between the heat sink enclosure and the surroundings constant, which is to the best of our knowledge, has not been addressed in the same manner before.

![Figure 1. PCM-based heat sink configuration](image)

2. Problem description and mathematical modeling
A typical two-dimension heat sink model is shown in Figure 1, a solid enclosure of width (W = 51 mm), height (B = 31 mm) and uniform thickness (C = 0.5 mm) surrounds a Cavity (50 mm × 30 mm) that is filled with PCM and metal foam composite. The top solid boundary is subjected to a uniform heat flux (\( q'' = 900 \text{ W/m}^2 \)), while heat transfer by convection with the surroundings takes place at all other boundaries with a convective heat transfer coefficient (h) of 10 W/m².K. Two types of PCMs
were chosen for this study: n-Eicosane and RT44HC with three values of metal foam porosity; $\varepsilon = 1.00, 0.97$ and $0.90$, where $\varepsilon = 1.00$ refers to no-metal foam case. Because of its low density and high thermal conductivity Aluminum was selected for the metal enclosure and the metal foam as well. Thermophysical properties of n-Eicosane, RT44HC, and Aluminum are listed in Table 1, while the specifications of different types of Aluminum foam used in this study are listed in Table 2.

**Table 1. Thermophysical properties of n-Eicosane, RT44HC, and Aluminium**

| Property           | Unit   | n-Eicosane | RT44HC | Aluminium |
|--------------------|--------|------------|--------|-----------|
| Density, $\rho$    | kg/m$^3$| 770        | 800    | 2719      |
| Heat capacity, $c_p$| J/kg-K | 2460       | 2000   | 871       |
| Latent heat, $L_f$ | kJ/kg  | 247.60     | 250    | -         |
| Thermal conductivity| W/m-K | 0.1505     | 0.20   | 202.4     |
| Dynamic viscosity  | Pa s   | 0.00385    | 0.008  | -         |
| Melting temperature, $T_i$ | °C | 35 | 41 | - |
| Solidus temperature, $T_s$ | °C | 37 | 44 | - |
| Volume expansion coefficient, $\beta$ | K$^{-1}$ | 0.0009 | 0.00259 | - |

**Table 2. Characteristics of metal foam [14]**

| Porosity | PPI | Fiber Dia (m) | Pore Dia (m) | Inertia coefficient | Permeability m$^2$ |
|----------|-----|---------------|--------------|---------------------|-------------------|
| 0.9726   | 5   | 0.00050       | 0.00402      | 0.097               | 2.7×10$^{-7}$     |
| 0.9005   | 20  | 0.00035       | 0.00258      | 0.088               | 0.9×10$^{-7}$     |

2.1. Assumptions and governing equations

The following assumptions were considered in our simulation model:

- The PCM is homogeneous and isotropic.
- The PCM in the liquid phase is considered incompressible and Newtonian, however, the Boussinesq approximation was employed to resolve the density-based buoyancy effects.
- The metal foam used is assumed to be rigid, homogeneous, and isotropic with open-cell configuration.
- The thermophysical properties are considered constant and temperature independent except for the PCM density.
- The effect of radiation heat transfer is negligible as well the viscous dissipation.

Based on the above assumption, the governing equations can be expressed as:

The continuity equation

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

The momentum equation in x and y directions are expressed by equation 2 and 3 respectively

$$\frac{\rho}{\varepsilon} \frac{\partial v}{\partial t} + \frac{\rho}{\varepsilon} \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial p}{\partial x} + \frac{\mu}{\varepsilon} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \left( \frac{\mu}{K} u + \frac{\rho}{\varepsilon} \frac{C_f |\vec{V}|}{\sqrt{K}} u \right) - S_x \quad (2)$$

$$\frac{\rho}{\varepsilon} \frac{\partial u}{\partial t} + \frac{\rho}{\varepsilon} \left( u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = - \frac{\partial p}{\partial y} + \frac{\mu}{\varepsilon} \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \varepsilon \rho \beta g (T - T_{ref}) - \left( \frac{\mu}{K} v + \frac{\rho}{\varepsilon} \frac{C_f |\vec{V}|}{\sqrt{K}} v \right) - S_y \quad (3)$$

3
Where \( \varepsilon, C_f \) and \( K \) are porosity, inertial coefficient and permeability of the porous medium, respectively. The Darcy’s momentum sink source terms \( S_x \) and \( S_y \) are defined as

\[
S_x = \frac{(1 - \alpha)}{\alpha^3 + \sigma} A_{mush} u
\]

\[
S_y = \frac{(1 - \alpha)}{\alpha^3 + \sigma} A_{mush} v
\]

\( \alpha \): the liquid fraction, \( \sigma \): a small scaler value to avoid division by zero, a preset value of to 0.001 was chosen for \( \sigma \), \( A_{mush} \) is the mushy zone constant, it is a measure of the damping amplitude and it predicts the PCM behavior during phase change. The value of the mush zone constant was set to 10\(^5\) but it can vary between 10\(^4\) - 10\(^7\) and the liquid fraction \( \alpha \) is calculated according to

\[
\alpha = \begin{cases} 
0 & \text{for } T < T_s \\
\frac{T - T_s}{T_l - T_s} & T_s < T < T_l \\
1 & \text{for } T > T_l
\end{cases}
\]

The energy equation for the PCM/metal foam composite will be

\[
(\varepsilon \rho C_p + (1 - \varepsilon) \rho_m C_{pm}) \frac{\partial T}{\partial t} + \varepsilon \rho L_f \frac{\partial \alpha}{\partial t} + \frac{\partial (\rho u H)}{\partial x} + \frac{\partial (\rho v H)}{\partial y} = k_{eff} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\]

where \( \rho \) and \( C_p \) are the density, specific heat of the PCM while \( \rho_m \) and \( C_{pm} \) are the density, specific heat of the metal foam, and \( k_{eff} \) is the effective thermal conductivity of the PCM/metal foam arrangement, although the literature contains numerus formulas for the effective thermal conductivity, Fluent software uses the following simple relation

\[
k_{eff} = \varepsilon k_{PCM} + (1 - \varepsilon) k_m
\]

\( H \) in equation (7) is defined as

\[
H = h^* + \Delta H^*
\]

Where \( h^* \) is the sensible enthalpy and \( \Delta H \) is the latent heat, they are calculated according to

\[
h^* = h^*_{ref} + \int_{T_{ref}}^T c_{p,eff} dT
\]

\[
\Delta H = \alpha L_f
\]

\( C_{p,eff} \) is the effective specific heat of the PCM/metal foam composite

\[
\rho_{eff} c_{p,eff} = \varepsilon \rho_{PCM} c_{p,PCM} + (1 - \varepsilon) \rho_m c_{p,m}
\]

Where \( \rho_{eff} \) is the effective density of the PCM/metal foam composite, which is written as

\[
\rho_{eff} = \varepsilon \rho_{PCM} + (1 - \varepsilon) \rho_m
\]

The specific heat of PCM is given by Eq.

\[
C_p = \begin{cases} 
C_{ps} & \text{for } T \leq T_s \\
C_{ps} (1 - \alpha) + C_{ps} (\alpha) + \frac{\Delta H}{T_l - T_s} & T_s < T < T_l \\
C_{pl} & \text{for } T \geq T_l
\end{cases}
\]

Here, \( C_{ps} \), \( C_{pl} \), \( T_s \), \( T_l \), and \( \Delta H \) are the specific heat of solid, specific heat of liquid, solidus temperature, liquidus temperature, and latent heat of the PCM, respectively.
2.2. Initial and boundary conditions

The initial conditions considered in the present study are: At \( t = 0 \), \( T_a = 298 \text{ K} \), and \( u = v = 0 \).

The following boundary conditions are applied to obtain the solution:

- No-slip condition is considered at the walls: \( u = v = 0 \)
- Conduction–convection boundary conditions at the left, lower and right sides of the container:

\[
-k \frac{\partial T}{\partial n} = h (T - T_\infty) \tag{15}
\]

- Continuous heat flux is employed between the wall and PCM-foam composite interfaces, as:

\[
-k \frac{\partial T}{\partial n}_{\text{PCM}} = -k \frac{\partial T}{\partial n}_{\text{Al}} \tag{16}
\]

Ansys Fluent 15.0 commercial software was used to model and solve the physical problem described above. The software employs the enthalpy porosity method to solve the PCM melting, in which, the melt fraction \( \alpha \) and cell volume fraction in the liquid phase is computed at each iteration by performing enthalpy balance. Moreover, the melt region of the PCM, which is represented by the mushy zone, is considered as a porous medium with melt fraction varying form 0.0 for a total solid phase to 1.0 for a total liquid phase. Initially, the system was in thermal equilibrium with surroundings at 305 K, however, during the simulation a constant heat flux of 900 W/m\(^2\) was applied at the top surface of the metal enclosure and the convective heat transfer boundary condition was imposed on all the other container sides. A quadrilateral mesh of about 2598 elements was suitable of all cases with time step of 0.1 seconds, melt fraction and average PCM temperature as well as the temperature at interface of the PV-surface and PCM were evaluated every 60 seconds (600-time steps).

2.3. Model Validation

The work of Sunuku et al. [13] was used to validate the proposed numerical technique, in which a simulation was carried out for 2-dimensional heat sink (30 cm × 50 cm) that was bounded by a 2-mm thickness Aluminum enclosure. Moreover, the cavity was equally subdivided by two 2.0 mm vertical thickness slabs and filled with RT44HC. A constant heat flux was applied on the lower side of the heat sink. The average melt fraction variation versus time during melting were compared for three different values of heat flux and figure shows that satisfactory agreement between the two studies is present.

![Figure 2. Progress of melt fraction with time, present work, vs Sunuku [13]](image)

3. Data and results
The proposed heat sink was investigated for two different types of PCM, \( n \)-Eicosane and RT44HC for a heat flux value of 900 W/m\(^2\) and three values of porosity; \( \varepsilon = 1.00, 0.97 \) and 0.90, where \( \varepsilon = 1.00 \) refers to no-metal foam case. In addition, convective heat transfer is present between the container sides and the surroundings with a convection heat transfer coefficient of 10 W/m\(^2\).K.

Initially, heat is transferred from the hot surface to the adjacent PCM causing its temperature to rise and once the melting temperature is reached it starts melting. During the early stage of melting conduction dominate the heat transfer. Now, two distinctive regions of PCM exist: molten PCM in liquid phase and Non-melted PCM in solid phase. The solid region receives heat from the molten liquid by convection and heat transferred within the solid matrix by conduction. As melting continues, the molten region gets bigger and the hot fluid ascends to the top side of the molten region and the cold fluid descends downward due to buoyancy effects induced by density gradients that are caused by temperature difference. As a result, convection currents and vortices are formed and due to circulation, mixing is enhanced as well as heat transfer within the molten PCM.

The Melting process of PCM is nearly isothermal and the PCM temperature rise is bounded by its solidus and liquidus temperatures during the melting process. However, the PV surface temperature will always be greater than that of the average PCM temperature but at the interface thermal equilibrium always exists. For a fixed heat flux, the temperature rise of PV surface is inversely proportional to the cooling rate out of the heat sink which is significantly dependent on the thermal conductivity of the PCM.

The variation of melt fraction with time for the \( n \)-Eicosane is shown in figure (3). Melting starts sooner in the no-metal foam case (\( \varepsilon = 1.00 \)) this due to the fact that metal foam composite improves heat transfer propagation through the PCM to the sides of heat sink, and overall thermal conductivity of the heat sink is enhanced. However, as simulation continues, the improved thermal conductivity results in a better propagation of heat transfer in all directions toward the cold walls and the melting process is accelerated accordingly. Both, the time needed for melting and PV-surface temperate are inversely proportional to porosity. In PCM-Based heat sink, \( n \)-Eicosane case; the time required for melting was (124, 119 and 114) minutes for (\( \varepsilon = 1.00, 0.97 \) and 0.90) cases respectively, whereas in the RT44HC case, the melting time was (121, 120, and 115) minutes for (\( \varepsilon = 1.00, 0.97 \) and 0.90) cases respectively.

Figure (4) shows the time evolution for the average PCM temperature inside the heat sink. Initially, the whole arrangement was at a lower temperature than the PCM melting temperature, as simulation starts and power source is turned on, temperature rises rapidly and as the melting temperature is reached the slope of the curve becomes less steeper. The temperature in the no-metal foam case (\( \varepsilon=1.00 \)) is higher than those in the metal foam cases (\( \varepsilon=0.97, \varepsilon=0.90 \)), this is due to the poor heat
propagation within the PCM resulted from low thermal conductivity and this in turn heats up the molten PCM in the vicinity of the PV-surface. On contrast, the metal foam insertion allows for better heat transfer from the interfacial region towards the cold walls and better cooling is achieved. The same argument can be made to the slope variation where absence of metal foam constitutes large temperature gradients within the PCM.

Figure 4. The time evolution the average PCM temperature inside the heat sink.

The time evolution for the temperature at interfacial region “PV-surface and PCM” is plotted in figure (5). The Interfacial temperature profile exhibits similar behavior as that of the average PCM temperature and the same argument can be made as well.

Figure 5. The time evolution of temperature at interfacial region “PV-surface and PCM”.

In the n-Eicosane heat sink the metal foam insertion resulted in PV-surface temperature reduction by (6.31 and 7.00) °C for the (ε = 0.97 and 0.90) cases respectively when compared with surface temperature of (ε = 1.00) case. Similarly, in the RT44HC heat sink the metal foam insertion resulted in PV-surface temperature reduction by (5.50 and 6.15) °C for the (ε = 0.97 and 0.90) cases respectively when compared with surface temperature of (ε = 1.00) case.

In the n-Eicosane heat sink the average difference between the interfacial temperature and average PCM temperature was (6.29, 1.21 and 0.42) °C for (ε = 1.00, 0.97 and 0.90) cases respectively. Similarly, in the RT44HC heat sink the average difference between the interfacial temperature and average PCM temperature was (5.83, 1.22 and 0.42) °C for (ε = 1.00, 0.97 and 0.90) cases respectively.
Figure (6) shows contour plots of the temperature distribution within the n-Eicosane based heat sink vs time, and Figure (7) shows the corresponding melt fraction contour plots. In the no-metal foam case, heat flows from the hot surfaces “PV-surface and enclosure sides” to the PCM, and consequently melting starts from the outer region of the PCM towards the center. In fact, due to the high thermal conductivity of Aluminum, significant amount of the heat transferred to the PCM is contributed to the enclosure Aluminum boundaries. Meanwhile, part of the heat flow within the metal enclosure is rejected by convection at the outer boundaries of the heat sink. As time evolves, more heat is transferred from the PV-surface into the PCM and the outer region of the PCM is completely melted and its temperature rises, however, the center of the PCM receives heat at a lower rate and consequently temperature slightly increases and the molten region propagates slowly.

In the metal foam cases, the thermal conductivity of the heat sink is remarkably enhanced and heat flows through the PCM towards the enclosure boundaries causing a more uniform temperature distribution within the PCM and the container boundaries as well. It also can be observed from figure (6) that the PV-surface temperature as well as the enclosure boundaries temperature are less than those of no-metal foam case; the metal foam improves heat transfer within the PCM and effectively directs the heat flow towards the enclosure boundaries and consequently enhances heat rejection for better cooling.

**Figure 6.** The temperature distribution within the n-Eicosane based heat sink vs time, at 30, 60, 90, 110 and 120 minutes from top row to bottom.
Figure 7. The melt fraction distribution within the n-Eicosane based heat sink vs time, at 30, 60, 90, 110 and 120 minutes from top row to bottom.

4. Conclusions
The PCM-based heat sink integrated with metal foam was successfully simulated and the primary results showed that significant improvement the heat transfer rate across the heat sink towards the colder boundaries due to the enhanced thermal conductivity of the PCM.

The improvement of the PCM thermal conductivity resulted in a more uniform temperature distribution within the PCM, enhanced the heat transfer rate from the heat sink and resulted in less PV-surface temperature rise than that in the no-metal foam case as long as the melting process takes place. However, it also reduced the melting time.

For the heat sink filled with n-Eicosane, the addition of Aluminum foam with porosity of (0.97 and 0.90) reduced the PV-surface temperature on average by (6.31 and 7.00) °C respectively when compared to the no-metal foam case.

For the heat sink filled RT44HC, the addition of Aluminum foam with porosity of (0.97 and 0.90) reduced the base temperature on average by (5.50 and 6.15) °C respectively when compared to the no-metal foam case.

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