Modelling and Numerical simulation of Nano-enhanced PV-PCM System for Heat Transfer Augmentation from the Panel

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Abstract. Phase change materials (PCMs) can effectively cool photovoltaic (PV) panels by the passive cooling technique, thereby enhancing its direct energy conversion efficiency. However, generally, PCMs have low thermal conductivity, and different methods can be employed to improve the heat transfer rate. Cooling techniques based on phase change materials (PCMs) enhanced by nano-sized solid particles are very promising. In this paper, a mathematical model is developed to simulate the performance analysis of PV attached with nano-enhanced PCM (NEPCM) integrated with fins and compare the same with that of pure PCM case. The system is oriented in a horizontal position and subjected to constant solar radiation flux of 1000 W/m². The PCM selected is RT25HC, and the nanoparticle used is CuO for the numerical study. The effects of volumetric concentrations (0%, 2%, and 4%) and fin number on the performance of the system are investigated numerically. Results show that adding nanoparticles is more effective in no fin case compared to finned cases. The maximum reduction in average PV temperature of 2.02 ℃ is obtained for no fin case with the nanoparticles’ volumetric concentration of 4%. Further enhancement in liquid fraction and energy storage in NEPCM is also achieved compared to the pure PCM system.

Keywords: phase change materials, nanoparticles, liquid fraction

1. Introduction

The depletion of fossil fuels and the impact of their use on the environment has motivated the call for alternate eco-friendly renewable energy sources like solar energy. The solar energy available can be utilised for generating electricity with direct conversion devices such as PV cell. Just about 20% of incoming solar radiation is converted to electrical output, with the rest being lost as heat. Thermal energy produced in the PV cells raises the temperature of the cell and consequent reduction of its output. Radziemska [1] experimentally investigated and found a decrease of 0.4% in electrical efficiency and 0.65% in power output of PV with every 1°C increase of temperature from the reference temperature of 25°C. Skoplaki and Palyvos [2] summarised a number of connections that express cell efficiency as functions of relevant weather variables and cell working conditions. High temperature also causes irreversible mechanical damage to the PV cell [3]. So it is essential to have an adequate cooling of the PV cell to minimise the adverse effects of high temperature and maintain or control the cell's operating temperature within an acceptable range. The two most popular cooling techniques used are passive and active, of which passive techniques are preferred.
Various passing cooling techniques were employed for the cooling of solar PV panel, such as heat pipe [4–6], liquid immersion [7–9], heat sink [10–12]. Smith et al. [13] determined the influence of PCM transition temperature on PV-PCM operation. The optimal transition temperature was identified. The yearly power output was found to be increased by more than 6% in places like Mexico, South Asia, Central and South America when integrated with PCM of optimal melting temperature. In Europe, the enhancement varies from 2% to 5%. Machniewicz et al. [14] investigated the effect of the PCM’s melting temperature which is attached to the PV module’s backside, in controlling sudden temperature fluctuations of the module using four PCMs. The maximum relative increase in efficiency was found to be 10% for RT20HC. Hasan et al. [15] studied the PV-PCM system under the hot climate of the UAE (United Arab Emirates). PCM with a melting range of 38°C - 43°C was integrated with PV to study the year-round performance of the system. An average peak time-temperature reduction of 10.5°C was achieved in April and a 5.9% increase in PV power output yearly. Singh et al. [16] investigated PCM heat sink, and finned PCM (FPCM) heat sink numerically for PV panel cooling and observed that the PCM incorporated with heat sink could reduce the maximum temperature by 13°C whereas FPCM can enhance cooling by 19°C.

Using two PCMs and internal fin arrangements, Huang et al. [17] provided an experimental assessment of controlling the temperature of the PV system. Huang et al. [18] studied the influence of crystalline segregation and convection current on the heat transfer efficiency within a finned PV-PCM system by varying fin spacing experimentally. Results showed that finned PV-PCM could maintain the temperature rise effectively (below 35°C) compared to PV-PCM without fins. Hassan et al. [19] compared the temperature and electrical efficiency of paraffin wax based PV-PCM system with PV panels without PCM. A decrease in temperature of 12°C and the related gain in voltage had been observed in this study. Introducing fins often increases the efficiency of the PV-PCM system. Huang et al. [20] obtained a maximum temperature reduction of 31°C using RT25 as a PCM. The surface area available for heat transfer from PV to PCM increases PCM storage ability and reduces PV temperature when the fins were added. The presence of fins also helps to achieve a sustained duration of temperature control during peak hours and keep the PV temperature uniform. Indartono et al. [21] achieved optimum efficiency enhancement by 21% using yellow petroleum jelly as PCM along with fins. The overall change in efficiency was between 5-12%.

Since PCMs thermal conductivity is very low, various methods are used to improve it, such as using finned PCMs, composite PCMs, metal foams, multiple PCMs and nano-enhanced PCM (NEPCM) [22–25]. In this paper, a two-dimensional numerical model is developed to investigate the effect of volume concentration of CuO nanoparticles on the performance of finned NEPCM attached to PV panel. The panel is oriented in a horizontal position and subjected to constant solar radiation flux. Volume concentration of nanoparticles considered for the study are, 0% (pure PCM), 2%, and 4%. The fin number of the system is varied from 0 (no fin) to 3. The system’s thermal characteristics, including the contours of temperature, the average temperature of the PV, the liquid fraction of NEPCM, and thermal energy stored in NEPCM, are studied through the simulation of the model.

2. Methodology

2.1. Physical System

The physical configuration of the PV-NEPCM system with boundary conditions is shown in Figure 1. PV panel consists of five layers, and the properties, as well as thicknesses of the same, are given in Table 1. Paraffin PCM RT25HC enhanced with CuO nanoparticles in 2 mm thickness aluminium container is attached to the bottom of PV panel in NEPCM system. The properties of PCM (Rubitherm GmbH-Germany (RT25HC)) and CuO are given in Table 2. The height of NEPCM is taken as 20 mm. Internal fin(s) with thickness 2 mm and length 20 mm is attached to the NEPCM container such that fin divides NEPCM into equal parts. Fin number (n) is varied from 0 to 3. Furthermore, the thermal performance
of PV-NEPCM is studied by varying the volume fraction of CuO nanoparticles to 2 and 4. The assumptions used for the numerical study are:

- The incident radiation on the PV panel is uniform for all the cases.
- The temperature field of the PV-NEPCM system is two dimensional (x-y plane).
- The melted PCM in the liquid phase is believed to satisfy Newtonian, unsteady, two-dimensional, incompressible and laminar flow.
- Contact resistances between layers are considered negligible.
- Different layers of a PV panel's materials are treated as isotropic and homogeneous.
- The effects of dust and rain are not taken into account.
- The PV cell's resistive losses are not considered.

![Schematic diagram of physical configuration of PV-NEPCM system](image)

**Figure 1.** Schematic diagram of physical configuration of PV-NEPCM system

| Material  | Density ($kg/m^3$) | Specific heat ($J/kg K$) | Thermal Conductivity ($W/m K$) | Thickness (mm) |
|-----------|--------------------|--------------------------|-------------------------------|----------------|
| Glass     | 3000               | 500                      | 1.8                           | 3              |
| EVA       | 960                | 2090                     | 0.35                          | 0.5            |
| Silicon   | 2330               | 677                      | 148                           | 0.3            |
| Tedler    | 1200               | 1250                     | 0.2                           | 0.1            |
| Aluminium | 2675               | 903                      | 211                           | 2              |
| Glass     | 3000               | 500                      | 1.8                           | 3              |

**Table 1.** Properties and thicknesses of different layers of PV panel

2.2. Mathematical Modelling

The portion of the incident solar radiation ($I$) that is transmitted through the glass cover and absorbed by the solar cell can be written as

$$Q_s = (\tau\alpha)_{e} I_T$$  \hspace{1cm} (1)
A small fraction of the absorbed radiation is converted into electricity, and the remaining goes as waste heat which leads to an increase in the temperature of the PV panel and can be expressed as

\[ \dot{S} = (\tau \alpha) \varepsilon I_T - \eta_{PV} I_T \]  

(2)

where \(\eta_{PV}\) is the electrical efficiency of the PV, evaluated according to temperature [2]

\[ \eta_{PV} = 20[1 - \beta_c(T_{PV} - 25^\circ C) + \gamma_c ln(I_T/1000)] \]  

(3)

The boundary conditions at the top and bottom surfaces of the PV-NEPCM system are

\[ -k_g \frac{\partial T}{\partial y} = h_t(T_a - T_g) + \dot{Q}_s \]  

(4)

\[ -k_{al} \frac{\partial T}{\partial y} = h_b(T_{al} - T_a) \]  

(5)

Boundary condition for sidewalls

\[ k \left( \frac{\partial T}{\partial x} \right) = 0 \]  

(6)

Boundary condition at the interfaces with reference to different layers is

\[ k_a \left( \frac{\partial T_a}{\partial y} \right) = k_b \left( \frac{\partial T_b}{\partial y} \right) \]  

(7)

where \(a\) and \(b\) indicate the different materials on either side of the interface.

| Properties                        | RT25HC | CuO    |
|-----------------------------------|--------|--------|
| Density (kg/m³)                  | Solid  | 785    | 6510   |
|                                  | Liquid | 749    | -      |
| Specific Heat Capacity (J/kg.K)  | Solid  | 1800   | 540    |
|                                  | Liquid | 2400   | -      |
| Thermal Conductivity (W/m.K)     | Solid  | 0.19   | 18     |
|                                  | Liquid | 0.18   | -      |
| Melting Temperature (°C)         |        | 26.6   | -      |
| Latent Heat of Fusion (J/kg)     |        | 232000 | -      |
| Dynamic Viscosity (Pa.s)         |        | 0.001798 | -      |
| Thermal expansion coefficient (K⁻¹) | 0.001 | 0.85× 10⁻⁵ |

Governing differential equation for temperature distribution of the PV and aluminium layer and PCM is

\[ \rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) + \rho c_p \bar{u} \cdot \nabla T = 0 \]  

(8)
The advection term is zero in the first two domains, but the velocity field in the PCM domain is determined by solving the equation of motion. Enthalpy-porosity technique along with Boussinesq approximation is used to model the PCM \[28\][29], which predicts both the melt front’s location and morphology at different instants with modest computational requirements. The properties of the PCM are temperature dependent and can be modelled using functions like \(B(T)\), \(D(T)\) and \(A(T)\) which are defined below.

The function \(B(T)\) can be expressed as [30]

\[
B(T) = \begin{cases} 
0 & \text{if } T < (T_m - \Delta T/2) \\
\frac{(T - T_m + \Delta T/2)}{(\Delta T)} & \text{if } (T_m - \Delta T/2) \leq T \leq (T_m + \Delta T/2) \\
1 & \text{if } T > (T_m + \Delta T/2) 
\end{cases}
\]  

(9)

\(B(T)\) is 0 and 1 in the solid and liquid phases, respectively and linearly varies from 0 to 1 in the transition region. Thermo-physical properties of PCM are modelled as [30][27][31]

\[
\rho_{pcm}(T) = \rho_s + (\rho_l - \rho_s)B(T) 
\]  

(10)

\[
k_{pcm}(T) = k_s + (k_l - k_s)B(T) 
\]  

(11)

The modified specific heat accounts for the latent heat of fusion for the PCM when it melts and it is modelled using [31]

\[
c_{p,pcm}(T) = c_{p_s} + (c_{p_l} - c_{p_s})B(T) + L_hD(T) 
\]  

(12)

Modified heat capacity is defined as the common heat capacity of the PCM. \(D(T)\) is used to create modified heat capacity, and its primary role is to distribute latent heat in the transition region. \(D(T)\) can be expressed as [32]

\[
D(T) = e^{-\frac{(T-T_m)^2}{(\Delta T/2)^2}}/\pi (\Delta T/4)^2
\]  

(13)

This function has a value of 0 at every region except over the interval \((T_m - \Delta T/2)\) and \((T_m + \Delta T/2)\), and its integral over the range of transition temperature is equal to 1 to satisfy the energy balance in the transition region. The continuity and momentum conservation equations are applied to the PCM domain, which is treated as a fluid.

Continuity:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 
\]  

(14)

\(x\)-momentum:

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + F_x 
\]  

(15)

\(y\)-momentum:

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + F_y + \rho g \beta (T - T_m) 
\]  

(16)
The additional volumetric forces $F_x$ and $F_y$ when the flow is laminar is

$$F_x = -A(T).u \quad \text{and} \quad F_y = -A(T).v$$  \hspace{1cm} (17)$$

When the PCM is in the solid state, these additional volumetric force is used to overpower all other source terms in the Navier-Stokes equation. When applied to solid PCM, it is primarily used to change both the overall viscosity and the Navier-Stokes equation. In the solid phase, this resulted in quick solver convergence to PCM velocities equal to zero. $A(T)$ is a porosity operator and is derived from the Carman-Kozeny equation for a porous media flow and was introduced by Brent et al. [28]. Overall viscosity modification of PCM and handling momentum equation for solid PCM was done by using $A(T)$ [32] which is

$$A(T) = \frac{C_m(1-B(T))^2}{B(T)^5+\varepsilon}$$ \hspace{1cm} (18)$$

The value of $A(T)$ is zero in liquid PCM. $C_m$ is a constant that represents a mushy medium, and it depends on the type of the PCM and its value varies from $10^3$ to $10^7$. $\varepsilon$ is a very small number to avoid division by zero. $A(T)$ is also be used to define the viscosity of PCM as

$$\mu(T) = \mu(1+A(T))$$ \hspace{1cm} (19)$$

Thermo-physical properties of NEPCM such as density, specific heat capacity, thermal expansion coefficient, and dynamic viscosity are estimated by [33][34]

$$\rho_{nepcm} = \varphi_{np}\rho_{np} + (1 - \varphi)\rho_{pcm}$$ \hspace{1cm} (20)$$

$$(\rho\beta)_{nepcm} = \varphi(\rho\beta)_{np} + (1 - \varphi)(\rho\beta)_{pcm}$$ \hspace{1cm} (21)$$

$$(\rho L)_{nepcm} = (1 - \varphi)(\rho L)_{pcm}$$ \hspace{1cm} (22)$$

$$(\rho c_p)_{nepcm} = \varphi(\rho c_p)_{np} + (1 - \varphi)(\rho c_p)_{pcm}$$ \hspace{1cm} (23)$$

$$\mu_{nepcm} = 0.9197\mu_{pcm} e^{22.8539\varphi}$$ \hspace{1cm} (24)$$

The thermal conductivity of NEPCM is obtained by [35]

$$k_{nepcm} = \frac{k_{np}+2k_{pcm}-2(k_{pcm}-k_{np})\varphi}{k_{np}+2k_{pcm}+2(k_{pcm}-k_{np})\varphi}k_{pcm} + B(T)\gamma \varphi_{np}\rho_{pcm}c_{p,pcm}\frac{kT}{\sqrt{\rho_{np}d_{np}^3}}f(T,\varphi)$$ \hspace{1cm} (25)$$

$$\gamma = 9.881(100\varphi)^{-0.9446}$$ \hspace{1cm} (26)$$

$$f(T,\varphi_{np}) = (28.217 \times 10^{-3}\varphi + 3.917 \times 10^{-3})\frac{T}{T_{ref, np}} + (-30.669 \times 10^{-3}\varphi - 3.91123 \times 10^{-3})$$ \hspace{1cm} (27)$$

where $\varphi_{np}$ is the volume fraction of nanoparticles. $b$, $\kappa$ and $d_{np}$ are constant for Brownian motion, Boltzmann constant and diameter of the nanoparticles, respectively. $T_{ref, np}$ is the reference temperature. $c_{p,pcm}$ in Eqn. (25) is the average specific heat of PCM.
3. Numerical Simulation Procedure
To simulate the model numerically, COMSOL Multiphysics 5.5 software is used for simultaneous equations explained in the previous section along with the boundary conditions based on the finite element method. PV-NEPCM geometry is created, and associated thermal properties are appropriately defined. In order to perform the thermal-fluid simulations, the heat transfer in solid (for PV, aluminium and solid-state PCM) is coupled with heat transfer in fluids (liquid PCM) by invoking laminar flow in fluids. This enables the numerical simulation of conduction in solid domains and conduction as well as natural convection within PCM. Through the Boussinesq approximation, volumetric force is added to allow buoyancy-driven flow. Suitable equations are used to quantify the thermo-physical properties of NEPCM. Time-dependent study is selected.

The time-stepping method chosen is backward Euler. The maximum and minimum order of backward differentiation are 5 and 1, respectively. The simulations are performed on an Intel(R) Xenon(R) CPU @ 2.4GHz, 2401MHz, 6 Cores computer with 16.00 GB of RAM. The initial temperature of the entire system is set to 20°C, and side walls are insulated. The top and bottom surfaces are subjected convective atmosphere with heat transfer coefficients $h_t = 10 \, W/m^2 \cdot K$ and $h_b = 5 \, W/m^2 \cdot K$ respectively. The front surface of the PV panel is believed to be exposed to constant solar radiation of 1000 $W/m^2$.

4. Grid Independence study and Validation of the model
For the 2-D model, simple triangular elements are used to create the entire mesh. A Grid independence study is carried out to determine the optimum element size based on accurate results and overall simulation time. Comparing the transient average PV temperatures of three fins PV-NEPCM case with four mesh combinations as in Figure 2, element size $(4.76 \times 0.0161)$ mm gives accurate, independent values with optimum simulation time. The final mesh consists of 52072 domain elements and 4627 boundary elements.

![Figure 2. Grid independence study with different mesh combinations.](image)

In Figure 3(i), predicted average temperature on the system's front surface with time by numerical simulation is compared with experimental results from Haung et al. [35]. The NEPCM system is numerically validated by tracing the liquid fraction of a heated nano-enhanced square PCM cavity of size 25.4 mm [36]. The comparison shows that the current simulation predictions and numerical data are well aligned (Figure 3(ii)).
5. Results and Discussion

The thermal performance of PV-NEPCM placed in the horizontal position is analysed with and without fins. The transient variation of the average temperature of PV, liquid fraction and thermal energy stored in NEPCM have been simulated and compared for 0, 2, and 4 % of volume fractions of nanoparticles by changing the fin number (n) from 0 to 3.

5.1. Temperature contours in PV-NEPCM system

Figure 4 shows the spatial distribution of the temperature for a horizontal system without any fins. In this system, conduction is the main heat transfer mode to drive the melting process, which causes thermal stratification. As a result, the solid-liquid interface of the PCM moves uniformly downwards. The range of motion is restricted as a result of resistance imposed by viscous force. After 90 minutes, about half of the PCM is melted. The main obstacle to the heat transfer rate inside the PCM is its low thermal conductivity which can be improved to an extent by adding nanoparticles. When CuO nanoparticles are added to the PCM, the melting rate improves considerably because of higher thermal conductivity and reduced latent heat.

Spatial distribution of temperature for horizontal finned PV-NEPCM system with the varied inclusion of nanoparticles and fins are shown in Figure 5-7. PCM melting at the early stage is driven by conduction, and due to the presence of fins, the heat transfer rate increases as more surface area is available for heat transfer inside NEPCM. However, for finned configurations, the liquid PCM circulations can be seen through the regions near to fins after 30 and 60 minutes, indicating that natural convection heat transfer is also present. The addition of nanoparticles leads to improved heat transfer rate and, as a result, a faster rate of phase front progression inside PCM. The difference in contour patterns for different vol.% of nanoparticles is evident at t = 90 min and t = 120 min.

5.2. Average PV temperature with NEPCM

The NEPCM is attached to the PV panel in order to regulate its surface temperature. Figure 8 shows the comparison of transient variation of the average temperature of PV panel for volume concentrations of...
2% and 4% with that of simple (0% volume concentration) PV-PCM. For horizontal system, the melting process of NEPCM and PV-PCM is mainly driven by conduction. As a result, the average PV temperature increases quickly with time, without any temperature stabilization. The rate of increase in the average temperature of the PV panel is low in horizontal NEPCM compared to horizontal PV-PCM due to the enhanced rate of heat transfer for the NEPCM system.

With the inclusion of fin(s) in the system, average PV temperature experiences a low rise because of the improved rate of heat transfer in NEPCM and PV-PCM systems and improved heat rejection rate to the external convective environment. The presence of fins also leads to the establishment of natural convection currents inside NEPCM and PV-PCM systems. As a result, there is a significant decrease in average PV temperatures for finned cases compared with no fin case. As fin number (n) is increased beyond 2, the drop in temperature is reduced. This is due to increased resistance to fluid motion and consequently to convection currents also. An increase in fin number also leads to a decrease in thermal regulation time. Apart from that there is a decrease in the mass of NEPCM in the system due to higher space occupied by the fins.

\[ t = 30 \text{ min} \quad t = 60 \text{ min} \quad t = 90 \text{ min} \quad t = 120 \text{ min} \]

![Temperature contours of PV-NEPCM for no fin case at different vol. % of nanoparticles](image)

**Figure 4.** Temperature contours of PV-NEPCM for no fin case at different vol. % of nanoparticles

Heat transfer from PV to NEPCM (\( \varphi = 2\% \) and \( \varphi = 4\% \)) is higher than that of PV to PCM (\( \varphi = 0\% \)) which leads to a lower average PV temperature in NEPCM systems. The heat transfer rate inside NEPCM also increases with an increase in the volumetric concentration of nanoparticles. The comparisons of the maximum reduction in average PV temperature for all cases are shown in Figure 9. The maximum reduction in temperature for the no-fin case is found to be 1.6°C and 2.02°C for vol.% 2 and 4, respectively. For finned NEPCM cases, as the fin number increases, the maximum percentage temperature reduction is gradually reduced compared to corresponding finned PCM cases. This is due to enhanced viscosity with the inclusion of nanoparticles and also enhanced viscous resistance for systems with higher number of fins. These results imply that adding nanoparticles to PCM to augment PV-PCM's thermal performance is more effective in no fin case compared to finned cases.
Figure 5. Temperature contours of PV-NEPCM with one fin case at different vol.% of nanoparticles

Figure 6. Temperature contours of PV-NEPCM with two fin case at different vol.% of nanoparticles
Figure 7. Temperature contours of PV-NEPCM with three fin case at different vol.% of nanoparticles

5.3. Liquid Fraction and Thermal Energy Stored in NEPCM
The instantaneous liquid fraction curves are plotted in Figure 10 to assess the effect of nanoparticles as well as the influence of fins on the melting rate. Comparison of the curves indicates that the melting rate improves significantly with the addition of nanoparticles and fins. The enhancement caused by the NEPCM is very advantageous over conventional PCM cases due to their higher heat transfer rates involved in NEPCM by virtue of higher thermal conductivity and lower latent heat. The enhancement of thermal conductivity and reduced latent heat outweighs the increase in the dynamic viscosity that restricts the flow of melted NEPCM. The melting rate is found to be low for no fin case. An increase in vol.% of nanoparticles positively impacts the melting rate for both finned and no fin cases. However, a close examination of Figure 10 shows that the enhancement in liquid fraction brought by nanoparticles is greater for NEPCM without fins. The influence of nanoparticles on the melting rate decreases with an increase in fin number, which can be better understood from Figure 11. At \( t = 120 \text{ min} \), for no fin case \( (n = 0) \), the percentage increase in liquid fraction for vol.% 2 and 4 are 4.16 and 6.54, respectively. For \( n = 3 \), the corresponding percentage increase in the liquid fraction is only 1.69 and 3.16 for vol.% 2 and 4. There is a slight improvement in the liquid fraction with fin number because of larger surface area available for heat transfer and weak natural convection developing inside NEPCM.
Figure 8. Average PV temperature as a function of time for $\varphi = 2\%$ and $\varphi = 4\%$.

Figure 9. Comparison of the maximum reduction in PV panel temperature for systems with various fin number
The thermal energy stored in NEPCM at any instant is the sum of sensible heat in solid PCM, latent heat during phase transition and sensible heat of PCM in the liquid state. The fins’ presence accelerates the heat transfer inside PCM and melts the PCM faster than the unfinned case. There is no appreciable change in energy storage when the fin number is greater than two; though the temperature of NEPCM is increasing with fin number, its mass is getting reduced. It can be seen from Figure 12 that for pure PCM thermal energy stored after \( t = 120 \text{ min} \) is maximum (492.5 kJ) for fin number \( n=3 \) and minimum for no fin case (410.6 kJ). Figure 13 shows the comparison of percentage increase in thermal energy storage in NEPCMs for different fin number. The maximum percentage increase is for no fin case \( (n = 0) \). With the increase in fin number, the percentage increase in thermal energy stored inside NEPCMs decreases. From \( n = 2 \) onwards, thermal energy stored is less for vol.% 4 as compared to vol.% 2. This is mainly due to reduced latent heat of NEPCM at higher vol.% of nanoparticles.
6. Conclusions
In this paper, the impact of volumetric concentration of nanoparticles on the thermal behaviour of a PCM attached to the horizontal PV panel has been numerically investigated for configurations with different fin number. The studied PV-NEPCM is modelled as a 2D thermal system and heat transfer modes by conduction and natural convection in the PCM. Change in thermo-physical properties of PCM on account of adding nanoparticles has been considered. The following conclusions can be drawn from this study.

- The improvements brought by nanoparticles is more profound for the PV-PCM system without fins. Maximum temperature reductions of 2.02°C and 1.6°C are obtained for unfinned PV-NEPCM with vol.% 4 and 2, respectively.
- Reduction in temperature is found to be decreasing with increasing fin number.
Both inclusions of nanoparticles and fins improve the liquid fraction of PCM. The highest improvement in the liquid fraction is obtained for no fin system with volumetric concentration ($\varphi$) of 4%.

Thermal energy stored in PCM is found to be increased with nanoparticles. But for fin number greater than 1, the energy storage capacity decreases when volumetric concentration increased from 2 to 4%.

**Nomenclature**

- $A$: upper surface of the PV panel ($m^2$)
- $C_p$: heat capacity ($J/kg.K$)
- $h$: heat transfer coefficient ($W/m^2.K$)
- $g$: acceleration due to gravity ($m/s^2$)
- $P$: pressure ($Pa$)
- $T_m$: melting Temperature ($^\circ C$)
- $K$: thermal conductivity ($W/m.K$)
- $u$: $x$-component velocity (m/s)
- $v$: $y$-component velocity (m/s)
- $L_h$: latent heat ($J/kg$)
- $G$: heat generation ($W/m^3$)
- $\Delta T$: phase transition temperature ($^\circ C$)
- $T_a$: external ambient temperature ($^\circ C$)
- $B$: liquid fraction
- $t$: time (min)

**Greek Symbols**

- $(\tau \alpha)_e$: absorptivity -transmissivity product for glass cover of the PV
- $\beta$: Temperature expansion coefficient ($K^{-1}$)
- $\rho$: density ($kg/m^3$)
- $\mu$: dynamic viscosity ($kg/m.s$)
- $\gamma_c$: solar irradiance coefficient
- $\nu$: kinematic viscosity ($m^2/s$)
- $\varphi$: volumetric fraction of nanoparticle

**Subscripts**

- $a$: external ambient
- $g$: Glass
- $pcm$: PCM
- $x$: along x
- $y$: along y
- $si$: Silicon
- $al$: Aluminium
- $t$: top
- $b$: bottom
References

[1] Radziemska E and Klugmann E 2002 Thermally affected parameters of the current-voltage characteristics of silicon photocell Energy Convers. Manag. 43 1889–900
[2] Skoplaki E and Palyvos J A 2009 On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations Sol. Energy 83 614–24
[3] Chow T T 2010 A review on photovoltaic/thermal hybrid solar technology Appl. Energy 87 365–79
[4] Mardiana-Idayu A and Riffat S B 2011 An experimental study on the performance of enthalpy recovery system for building applications Energy Build. 43 2533–8
[5] Anderson W G, Dussinger P M, Sarraf D B and Tamanna S 2008 Heat pipe cooling of concentrating photovoltaic cells Conf. Rec. IEEE Photovolt. Spec. Conf.
[6] Akbarzadeh A and Wadow ski T 1996 Heat pipe-based cooling systems for photovoltaic cells under concentrated solar radiation Appl. Therm. Eng. 16 81–7
[7] Wang Y, Fang Z, Zhu L, Huang Q, Zhang Y and Zhang Z 2009 The performance of silicon solar cells operated in liquids Appl. Energy 86 1037–42
[8] Tina G M, Rosa-Clot M, Rosa-Clot P and Scandura P F 2012 Optical and thermal behavior of submerged photovoltaic solar panel: SP2 Energy 39 17–26
[9] Abrahamyan Y ., Serago V ., Aroutiounian V ., Anisimova I ., Stafeev V ., Karamian G ., Martoyan G . and Mouradyan A . 2002 The efficiency of solar cells immersed in liquid dielectrics Sol. Energy Mater. Sol. Cells 73 367–75
[10] Araki K, Uozumi H and Yamaguchi M 2002 A simple passive cooling structure and its heat analysis for 500 X concentrator PV module Conf. Rec. IEEE Photovolt. Spec. Conf. 1568–71
[11] Natarajan S K, Mallick T K, Katz M and Weingaertner S 2011 Numerical investigations of solar cell temperature for photovoltaic concentrator system with and without passive cooling arrangements Int. J. Therm. Sci. 50 2514–21
[12] Solanki C S, Sangani C S, Gunashekar D and Antony G 2008 Enhanced heat dissipation of V-trough PV modules for better performance Sol. Energy Mater. Sol. Cells 92 1634–8
[13] Smith C J, Forster P M and Crook R 2014 Global analysis of photovoltaic energy output enhanced by phase change material cooling Appl. Energy 126 21–8
[14] Machniewicz A, Knera D and Heim D 2015 Effect of transition temperature on efficiency of PV/PCM panels Energy Procedia 78 1684–9
[15] Hasan A, Sarwar J, Alnoman H and Abdelbaqi S 2017 Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate Sol. Energy 146 417–29
[16] Singh P, Khanna S, Newar S, Sharma V, Reddy K S, Mallick T K, Becerra V, Radulovic J, Hutchinson D and Khusainov R 2020 Solar photovoltaic panels with finned phase change material heat sinks Energies 13 1–16
[17] Huang M J, Eames P C and Norton B 2006 Phase change materials for limiting temperature rise in building integrated photovoltaics Sol. Energy 80 1121–30
[18] Huang M J, Eames P C, Norton B and Hewitt N J 2011 Natural convection in an internally finned phase change material heat sink for the thermal management of photovoltaics Sol. Energy Mater. Sol. Cells 95 1598–603
[19] Hassan A, Nouman H, Assi A and Norton B 2014 Temperature regulation and thermal energy storage potential of phase change materials layer contained at the back of a building integrated photovoltaic panel 30th Int. PLEA Conf. Sustain. Habitat Dev. Soc. Choos. W. Forw. - Proc. 2 139–45
[20] Huang M J, Eames P C and Norton B 2006 Comparison of a small-scale 3D PCM thermal control model with a validated 2D PCM thermal control model Sol. Energy Mater. Sol. Cells 90 1961–72
[21] Atkin P and Farid M M 2015 Improving the efficiency of photovoltaic cells using PCM infused graphite and aluminium fins Sol. Energy 114 217–28
[22] Maiti S, Banerjee S, Vyas K, Patel P and Ghosh P K 2011 Self regulation of photovoltaic module temperature in V-trough using a metal-wax composite phase change matrix Sol. Energy 85 1805–16

[23] Luo Z, Huang Z, Xie N, Gao X, Xu T, Fang Y and Zhang Z 2017 Numerical and experimental study on temperature control of solar panels with form-stable paraffin/expanded graphite composite PCM Energy Convers. Manag. 149 416–23

[24] Klemm T, Hassabou A, Abdallah A and Andersen O 2017 Thermal energy storage with phase change materials to increase the efficiency of solar photovoltaic modules Energy Procedia 135 193–202

[25] Sharma S, Micheli L, Chang W, Tahir A A, Reddy K S and Mallick T K 2017 Nano-enhanced Phase Change Material for thermal management of BICPV Appl. Energy 208 719–33

[26] Khanna S, Reddy K S and Mallick T K 2017 Performance analysis of tilted photovoltaic system integrated with phase change material under varying operating conditions Energy 133 887–99

[27] Biwole P H, Groulx D, Souayfane F and Chiu T 2018 Influence of fin size and distribution on solid-liquid phase change in a rectangular enclosure Int. J. Therm. Sci. 124 433–46

[28] Brent A D, Voller V R and Reid K J 1988 Enthalpy-porosity technique for modeling convection-diffusion phase change: Application to the melting of a pure metal Numer. Heat Transf. 13 297–318

[29] C. V V R & P 1978 A Fixed grid numerical modelling methodology for convection diffusion mushy region phase change problems Int. Journa. Heat Mass Transf. 30 1709–19

[30] Groulx D, Biwole P H and Bhouri M 2020 Phase change heat transfer in a rectangular enclosure as a function of inclination and fin placement Int. J. Therm. Sci. 151 106260

[31] Biwole P H, Eclache P and Kuznik F 2013 Phase-change materials to improve solar panel’s performance Energy Build. 62 59–67

[32] Vajjha R S, Das D K and Namburu P K 2010 Numerical study of fluid dynamic and heat transfer performance of Al2O3 and CuO nanofluids in the flat tubes of a radiator Int. J. Heat Fluid Flow 31 613–21

[33] Arasu A valan, Sasmito A P and Mujumdar A S 2013 Numerical performance study of paraffin wax dispersed with alumina in a concentric pipe latent heat storage system Therm. Sci. 17 419–30

[34] Vajjha R S and Das D K 2009 Experimental determination of thermal conductivity of three nanofluids and development of new correlations Int. J. Heat Mass Transf. 52 4675–82

[35] Huang M J, Eames P C, Norton B and Hewitt N J 2011 Natural convection in an internally finned phase change material heat sink for the thermal management of photovoltaics Sol. Energy Mater. Sol. Cells 95 1598–603

[36] Arıcı M, Tüüncü E, Yıldız Ç and Li D 2020 Enhancement of PCM melting rate via internal fin and nanoparticles Int. J. Heat Mass Transf. 156