Performance analysis of tilted photovoltaic system integrated with phase change material under varying operating conditions

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In photovoltaic (PV) cells, a large fraction of solar radiation gets converted into heat which raises its temperature and decreases its efficiency. The heat can be extracted by attaching a box containing phase change material (PCM) behind the PV panel. Due to large latent heat of PCM, it can absorb heat without rise in temperature. It will lower down the PV temperature and will increase its efficiency. The available numerical studies analysed the vertical PV-PCM systems. However, PV panels are generally tilted according to latitude of the place. Thus, in the current work, performance analysis of the tilted PV-PCM is carried out. The effects of tilt-angle, wind-direction, wind-velocity, ambient-temperature and melting-temperature of PCM on the rate of heat extraction by PCM, melting process of PCM and temperature of PV-PCM system are also studied. The results show that as tilt-angle increases from 0° to 90°, the PV temperature (in PV-PCM system) decreases from 43.4°C to 34.5°C which leads to increase in PV efficiency from 18.1% to 19%. The comparison of PV-PCM with only-PV is also carried out and it is found that PV temperature can be reduced by 19°C by using PCM and efficiency can be improved from 17.1% to 19%.

1. Introduction

Electricity generation using photovoltaic (PV) cells is one of the economically feasible renewable technologies. However, the PV cells convert only a fraction of the incident solar radiation into electricity. A major fraction gets converted into heat and raises the temperature of the cell. The temperature rise reduces the solar to electricity conversion efficiency of the cell [1]. The use of phase change material (PCM) for the thermal management of the PV cells by extracting the heat has been reported by some studies.

The studies presented the one-dimensional (1-d) numerical models for the PV-PCM system are as follows: Brano and his co-workers [2-3] have presented a finite difference method for the thermal modelling of the PV-PCM system. Mahamudul et al. [4] have analysed the PV-PCM system for Malaysian whether. Smith et al. [5] have computed the power output from the PV-PCM system for countries all over the globe. Atkin and Farid [6] have analysed the thermal management of the PV using PCM infused graphite integrated with finned heat sink. Kibria et al. [7] have compared the performance of the PV-PCM using three different PCMs. Park et al. [8] have analysed the effect of the thickness of PCM layer behind the PV panel on the performance of the system. Aelenei et al. [9] have studied the building integrated PV-PCM system.

All the above numerical studies consider only the conductive energy flow inside the PCM. However, the convective energy flow inside the melted PCM has significant effect on the thermal performance of the PV-PCM system [10]. The following studies have considered it and presented the two-dimensional (2-d) thermal models. Huang et al. [11] have analysed the effect of ambient temperature, insolation and the thickness of PCM layer on the performance of the system. Huang [12] has analysed the PV temperature in the PV-PCM system considering two different PCM materials in same container. Ho et al. [13] have studied the performance of the PV system integrated with microencapsulated PCM. Biwole et al. [14] and Groulx and Biwole [15] have presented a mathematical model to capture the rapid change in the thermal properties of the PCM during phase change period.

The above studies have considered the side walls of the PCM container to be thermally insulated (using adiabatic condition). Thus, the temperature variations are considered only along the thickness and the height of the system. Thus, the 2-d analysis have

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been carried out by them. However, Huang et al. [16-17] have considered the heat losses from the side walls of the container and, thus, presented the three-dimensional (3-d) analysis of the system. Ho et al. [18-19] have presented the 3-d analysis of the system. The following assumptions have been made in this work.

Apart from the numerical modelling, the following studies have carried out the experimental investigation of the PV-PCM system. Huang et al. [20] have analysed the effect of fins on the performance of the PV-PCM system. Huang et al. [21] have studied the effect of crystalline segregation of the PCM on the performance of the system. Hasan et al. [22] have investigated the PV-PCM system using various types of PCM. Indartono et al. [23] have analysed the PV-PCM system using yellow petroleum jelly as phase change material. Hachen et al. [24] have studied the system using pure PCM (white petroleum jelly) and compared with mixed PCM (mixture of white petroleum jelly, copper and graphite). Stropnik and Stritih [25] have studied the PV integrated with RT 28 HC phase change material. Hasan et al. [26] have analysed the performance of the PV-PCM system using white petroleum jelly, copper and graphite). Stropnik and Stritih [25] have studied the PV integrated with RT 28 HC phase change material.

From literature, it has been found out that the numerical studies are carried out for the vertical PV-PCM systems. However, the PV panels are generally tilted according to the latitude of the place. Thus, in the current work, the tilted PV-PCM system has been analysed. The mathematical model of the PV-PCM system is presented in section 2. The results obtained from the proposed model have been validated against the existing reported ones in section 3. The effects of the operating conditions (tilt angle of the system, wind direction, wind velocity, ambient temperature and melting temperature of the PCM) on the rate of heat extraction by PCM, melting process of PCM and temperature of PV-PCM system have been studied in section 4 and the only PV and PV-PCM systems have been compared. The conclusions have been listed down in section 5. Thus, from the current work, one can evaluate the system behaviour in different operating conditions.

2. Methodology

The system considered in this work consists of a polycrystalline PV panel integrated with a box containing PCM as shown in Fig. 1. The tilt angle of the system is denoted by $\beta$. The PV panel is considered to be made up of five layers. At the back of the panel, the PV panel is considered to be thermally insulated. Thus, the temperature variations are only along the thickness ($y$ direction) and height of the system ($x$ direction).

The following assumptions have been made in this work:
(i) The heat losses from the bottom and side walls are neglected as they are considered to be well insulated.
(ii) The incident solar flux is uniformly distributed over the surface of the PV.
(iii) The contact resistances in the PV cell are not considered.

The fraction of the incident solar radiation (\(I_T\)) that gets transmitted through the glass cover and absorbed by the solar cell can be written as \((\tau a)_{\text{eff}} \times I_T\) where \((\tau a)_{\text{eff}}\) is the effective product of transmissivity of the glass cover and absorptivity of the solar cell. Out of the absorbed one, only a small fraction gets converted into electricity and the rest of the solar radiation gets converted into

\[
Q_L = h [T_{at y=0} - T_0] + \sigma T_{F_s} \left[ T_{at y=0}^4 - T_s^4 \right] + \sigma T_{F_g} \left[ T_{at y=0}^4 - T_g^4 \right]
\]

Heat (\(S_h\)) which can be written as

\[
S_h = (\tau a)_{\text{eff}} I_T - \eta_{\text{cell}} I_T
\]

where \(\eta_{\text{cell}}\) is the solar radiation to electricity conversion efficiency of the cell. Some fraction of the heat is lost to surroundings due to convective and radiative losses from the top surface of the panel which can be written as

\[
h = \begin{cases} 
    \frac{h_{for}}{1 + \frac{h_{nat}}{h_{for}}} & \text{if } \frac{Gr}{Re^2} \leq 0.01 \\
    \left( \frac{h_{nat}^2 + h_{for}^2}{2} \right)^{1/3} & \text{if } 0.01 < \frac{Gr}{Re^2} < 100, \beta = 0^\circ \\
    \frac{h_{nat}^2 + \frac{h_{for}^2}{2}}{2} & \text{if } 0.01 < \frac{Gr}{Re^2} < 100, \beta > 0^\circ \\
    \frac{h_{nat}^2}{h_{for}} & \text{if } \frac{Gr}{Re^2} \geq 100 
\end{cases}
\]

where \(Gr\) is the Grashof number and \(Re\) is the Reynolds number. \(h_{nat}\) and \(h_{for}\) are the heat transfer coefficients of the top surface due to natural and forced convection respectively and can be written as follows

\[
h_{for} = 0.848 k_a |\sin \beta| \cos \gamma \nu_w Pr |\gamma^{0.5}/(L_{ch}/2)^{0.5}
\]

where \(Pr\) is the Prandtl number of air, \(Gr\) is the critical Grashof number = 1.327 \times 10^{10} \exp(-3.708(\pi/2 - \beta)), \(k_a\) is the thermal conductivity of air, \(L_{ch}\) is the characteristic length i.e. the length of the surface along the direction of air flow, \(\gamma\) is the wind azimuth angle (the angle made by wind stream with the projection of surface normal on horizontal plane), \(\nu_w\) is the wind velocity and \(r\) is the kinematic viscosity of air.

The temperature of the PV-PCM system and the velocities of the melted PCM in \(x\) and \(y\) directions at any time \(t\) can be found out by solving below equations and the values of the parameters used for the calculations are presented in Table 1 and Table 2.

\[
\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \kappa \frac{\partial T}{\partial x} - \rho C_p u_x T \right) + \frac{\partial}{\partial y} \left( \kappa \frac{\partial T}{\partial y} - \rho C_p u_y T \right) + G
\]

\[
\rho \left( \frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} \right) = \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} \right) + \rho g_x
\]

\[
\rho \left( \frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} \right) = \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} \right) + \rho g_y
\]

\[
\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = 0
\]

where \(\rho\) is the density, \(C_p\) is the specific heat capacity, \(k\) is the thermal conductivity, \(u_x\) and \(u_y\) are the velocities of melted PCM in \(x\) and \(y\) direction respectively, \(G\) is the heat generation, \(p\) is the pressure, \(\mu\) is the dynamic viscosity and \(g_x\) and \(g_y\) are the accelerations due to gravity in \(x\) and \(y\) direction respectively.

### Table 1
Thermo-physical properties of PV [37] and aluminium layer [14]

| Material   | Glass | EVA | Silicon | Tedlar | Aluminium |
|------------|-------|-----|---------|--------|-----------|
| \(C_p\) (J/kg·K) | 500   | 2090| 677     | 1250   | 903       |
| \(k\) (W/m·K)    | 1.8   | 0.35| 148     | 0.2    | 211       |
| Thickness (mm)   | 4     | 0.5 | 0.3     | 0.1    | 4         |
| \(\rho\) (kg/m³) | 3000  | 960 | 2330    | 1200   | 2675      |

![Fig. 1. View of the geometry of the system.](image)
For solid regions of the system (PV and aluminium layer), only Eq. (6) is solved by using $u_s = u_{w} = 0$ m/s. For PCM, all the above four equations (Eqs. (6)–(9)) are solved. The portion of PCM where temperature is below solidification temperature ($T_m - \Delta T/2$), the viscosity is used as $10^5$ kg/m-s so that the PCM portion will act as solid and the portion of PCM where temperature is above solidification temperature ($T_m + \Delta T/2$), the viscosity is used as $\mu$ (viscosity of PCM in liquid phase) so that it will act as liquid. $T_m$ is the peak melting temperature of PCM and $\Delta T$ is the phase change zone. During the period of phase change, PCM will absorb the latent heat and capture the latent heat during phase change. It has value 0 everywhere except in the phase change region and can be written as $D(T)$ in Eq. (10) is the Dirac delta function which is used to capture the latent heat during phase change. It has value 0 everywhere except in the phase change region and can be written as

$$ D(T) = \frac{e^{-2(T-T_m^2)/\Delta T^2}}{\sqrt{\pi}(\Delta T/4)^2} 	ag{12} $$

In Fig. 2, the graphical representation of Eq. (10) can be seen which shows the change in specific heat capacity of PCM with temperature. The area under the curve from $T_m - \Delta T/2$ to $T_m + \Delta T/2$ is almost equal to the latent heat which ensures that all the latent heat is captured in the phase change zone.

### 3. Validation

Biwole et al. [14] have analysed the thermal performance of PCM in a vertical aluminium box and reported the temperature of the front surface of the system. For validation, the calculations have been carried out using the methodology of the current work by using the same parameters as used by them. The variation in the temperature of the front surface with time is plotted in Fig. 3 along with their reported values. The results show that the values computed using the current work differ from those of Biwole et al. [14] within the range of $\pm 1.5$ °C.

### 4. Results and discussion

The variations in the temperature of the PV-PCM system with time, melting of the PCM, energy extraction by PCM, heat losses from the system and efficiency of PV in the PV-PCM system and only PV system have been computed. The effects of tilt angle of the system, wind azimuth angle (wind direction), wind velocity, ambient temperature and melting temperature of the PCM on the performance of the system have been analysed.

ANSYS Fluent 17.1 is used to solve the equations. It is found that the results do not change much with decrease in the values of energy, velocity and continuity residuals beyond $10^{-8}$, $10^{-4}$ and $10^{-4}$ respectively. Thus, for the convergence of the solution, these values of residuals are considered as the accepted ones.

#### 4.1. Grid independence study

The variations in the temperature of PV in PV-PCM system with time for various grid sizes are plotted in Fig. 4. The grid size is defined by the distance between successive nodes ($\Delta n$). The results show that the decrease in $\Delta n$ beyond 1 mm does not improve the results much. Thus, $\Delta n = 1$ mm is chosen for all calculations henceforth.

#### 4.2. Transient analysis of the system

The variation in the temperature of the PV-PCM system with time is presented in Fig. 5. The corresponding variations in the temperature of the PV with time and the rate of heat extraction by PCM are plotted in Fig. 6 respectively. The results show that, initially, the temperature of the PV increases rapidly with time. It is due to the fact that, initially, the PCM is in solid phase and its thermal conductivity is very low. Thus, the PCM extracts very less...
amount of heat from the PV and leads to rapid increase in the PV temperature with time. The results show that, beyond $t = 10\text{min}$, the increase in the PV temperature slows down because the PCM starts melting and absorbing the latent heat. Thus, the PCM starts extracting large amount of heat from the PV without increase in temperature. Beyond $t = 150\text{min}$, the temperature of the PV again increases rapidly with time. It is due to the fact that, now, the PCM is almost fully melted and absorbed all the latent heat which leads to decrease in the rate of heat extraction by PCM and increase in the PV temperature.
Fig. 6. Variations in the average temperature of PV (in PV-PCM system) and rate of heat extraction by PCM with time.

Fig. 7. Variation in the average temperature of PV (in PV-PCM system) with time for various tilt angles of system ($\beta$).

Fig. 8. Variation in the average temperature of PV (in PV-PCM system) with tilt angle at $t = 120$ min.
Fig. 9. Variation in the temperature of PV-PCM system with time for various tilt angles of system ($\beta$).

Fig. 10. Variation in the average temperature of PV (in PV-PCM system) with time for various wind azimuth angle ($\gamma$).
4.2.1. Effect of tilt angle of system

The variations in the temperature of the PV (in PV-PCM system) with time for various tilt angles of the system (β) are plotted in Figs. 7 and 8. The corresponding melting process of the PCM for various tilt angles is presented in Fig. 9. The results show that as tilt angle of the system increases, the PV temperature decreases. This is due to the fact that when tilt angle is very small, the energy flow inside the PCM due to convection is very less (Fig. 9). Energy flow is mainly due to conduction. Since conductivity of the PCM is very less, the energy extraction from PV is very low. With increase in tilt, the energy flow due to convection increases. Thus, the energy extraction by PCM increases which results in decrease in the PV temperature.

4.2.2. Effect of wind azimuth angle

The variations in the temperature of the PV (in PV-PCM system) with time for various values of wind azimuth angle (γ) are plotted in Fig. 10. The results show that as wind azimuth angle increases, the PV temperature increases. It is due to the fact that when wind azimuth angle is very less, wind flows almost normal to the surface which leads to larger heat losses due to forced convection and, thus, results in lesser temperature.

The variations in the rate of heat extraction by PCM with time for various values of wind azimuth angle (γ) are plotted in Fig. 11. The results show that, initially, the rate of heat extraction by PCM is higher for higher wind azimuth angle. However, after a certain time, the rate of heat extraction by PCM is lesser for higher wind azimuth angle. It is due to the fact that, initially, for higher wind azimuth angle, the heat losses are lesser which leads to higher rate of heat extraction by PCM. Thus, for higher wind azimuth angle, the PCM melts in shorter duration. After melting, the rate of heat extraction decreases. Thus, beyond a certain time, the PCM is fully melted for higher wind azimuth angle which leads to lesser rate of heat extraction by PCM.

4.2.3. Effect of wind velocity

The variations in the temperature of the PV (in PV-PCM system) with time for various values of wind velocity (vw) are plotted in Fig. 12 and the corresponding PV-IV curve is plotted in Fig. 13 for vw = 5 m/s. The results show that as wind velocity increases, the PV temperature decreases. It is due to the fact that when wind velocity is very less, the heat losses due to forced convection are very less which results in higher temperature.

The variations in the rate of heat extraction by PCM with time for various values of wind velocity (vw) are plotted in Fig. 14. The results show that, initially, the rate of heat extraction by PCM is higher for lesser wind velocity. However, after a certain time, the rate of heat extraction by PCM is lesser for lesser wind velocity. It is due to the fact that, initially, for lesser wind velocity, the heat losses are lesser which leads to higher rate of heat extraction by PCM.
**Fig. 13.** PV-IV curve for PV-PCM system at $t = 60\text{min}$ for $v_w = 5 \text{ m/s}$.

**Fig. 14.** Variation in the rate of heat extraction by PCM with time for various wind velocities ($v_w$).

**Fig. 15.** Variation in the average temperature of PV (in PV-PCM system) with time for various values of melting temperature of PCM ($T_m$).
Thus, for lesser wind velocity, the PCM melts in shorter duration. After melting, the rate of heat extraction decreases. Thus, beyond a certain time, the PCM is fully melted for lesser wind velocity which leads to lesser rate of heat extraction by PCM.

4.2.4. Effect of melting temperature of PCM

The variations in the temperature of the PV (in PV-PCM system) with time for various values of melting temperature of PCM \( (T_m) \) are plotted in Fig. 15. The corresponding variations in the rate of heat extraction by PCM with time are plotted in Fig. 16. The results show that the PCM with lesser \( T_m \) can maintain the PV at lower temperatures. Thus, the appropriate PCM will be the one having \( T_m \) closer to the ambient temperature. However, the results also show that after a certain time, the PV temperature becomes higher for the system with lesser \( T_m \). It is due to the fact that the system with lesser \( T_m \) experiences lesser heat losses and, thus, higher rate of heat extraction by PCM (Fig. 16) which leads to melting of the PCM in shorter duration. Thus, after melting, the PV temperature starts increasing rapidly. It should also be noted that the duration for which the PV is maintained at lower temperature can be increased by increasing the quantity of the PCM used (i.e. the depth of the PCM container) and the latent heat of the PCM.

4.2.5. Effect of ambient temperature

The variations in the temperature of the PV (in PV-PCM system) with time for various values of ambient temperature \( (T_a) \) are plotted in Fig. 17. The results show that as ambient temperature increases, the PV temperature increases because of decrease in the heat losses.

The variations in the rate of heat extraction by PCM with time for various values of ambient temperature \( (T_a) \) are plotted in Fig. 18. The results show that initially, the rate of heat extraction by PCM is higher for higher ambient temperature. However, after a certain time, the rate of heat extraction by PCM is lesser for higher ambient temperature. It is due to the fact that, initially, for higher ambient temperature, the heat losses are lesser which leads to higher rate of heat extraction by PCM. Thus, for higher ambient temperature, the PCM melts in shorter duration. After melting, the rate of heat extraction decreases. Thus, beyond a certain time, the PCM is fully melted for higher ambient temperature which leads to lesser rate of
It must also be noted that a PCM with lesser melting temperature can be used in winters to maintain the PV at lower temperature. But, this PCM cannot be used in summers as it will remain melted due to higher ambient temperature. Thus, in future work, two PCMs in same container will be explored which can work effectively in summers as well as in winters.

4.2.6. Comparison of PV-PCM system with only PV system

The variations in the temperature of the PV in PV-PCM system and only PV system with time are plotted in Fig. 19. The corresponding PV-IV curves and solar radiation to electricity conversion efficiencies of the PV are plotted in Figs. 20 and 21 respectively. The results show that the temperature of the PV reduces by 19 °C by using PCM and power increases from 171W to 190W and, thus, the solar to electricity conversion efficiency of the PV increases from 17.1% to 19%.

5. Conclusions

In the current work, a mathematical model for a tilted PV-PCM system has been presented. Heat transfer due to all the three modes (conduction, convection and radiation) is considered. The rapid change in the thermal properties of the PCM during phase change is smoothly captured by a mathematical model. The variations in the temperature of the PV in PV-PCM system with time, melting process of the PCM, energy extraction by PCM, heat losses from the system and comparison of the PV-PCM and only PV systems have been analysed. The effects of tilt angle of the system, wind azimuth angle (wind direction), wind velocity, ambient temperature and melting temperature of the PCM on the performance of the system have been studied. The conclusions are as follows
The temperature of PV can be reduced by using PCM and the solar to electricity conversion efficiency of PV can be increased.

Increase in tilt angle of the system leads to increase in the rate of heat extraction by PCM which results in the decrement of PV temperature.

Increase in wind azimuth angle/wind velocity leads to decrease/increase in heat losses from top which leads to increase/decrease in the rate of heat extraction by PCM.

PCM with lesser melting temperature can maintain the PV at lower temperatures. Thus, the appropriate PCM will be the one having melting temperature closer to ambient temperature.

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