

Thermal Regulation of PV Panels via Bio-Based Phase Change Materials

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Abstract. The degradation of photovoltaic performance due high operating temperature remains a major challenge in PV technology. The integration of phase change materials offers an effective solution by absorbing the excess heat through latent heat storage during PV operation. This study numerically investigates the impact of incorporating different PCM on PV temperature regulation and electrical efficiency, under varying solar irradiance and PCM thicknesses. A transient energy balance model was developed and solved using the finite difference method FDM. Results showed the PCM integration slows PV temperature rise and enhances electrical efficiency. Among the tested materials, the bio-based PCM BWCO demonstrated effective thermal performance even at low thicknesses.

1 Introduction

High operating temperature significantly impair the performance of PV systems, as the most of the absorbed solar irradiance converted into heat rather than electricity[1]. Leading to reduced electrical efficiency and accelerated material degradation.[2],[3] Phase change materials have gained considerable attention because they can absorbed a large amount of heat at nearly a constant temperature during phase transition. Thereby stabilising PV surface temperatures and improving energy yield [4],[5],[6]. Both experimental and numerical studies have demonstrated the effectiveness of PV-PCM hybrid system. Long-term field evaluation of PCM RT27 showed substantial temperature reduction and increased annual energy production [7], [8]. Experimental investigation have shown that RT35 PCM can significantly reduce PV operating temperature when applied with an optimal thickness [9],while passive eutectic cold PCMs have been reported to enhance power output through improved thermal regulation[10]. Numerical and experimental study further confirmed that PCM integration, particularly when combined with appropriate melting temperature; enhances heat dissipation and electrical efficiency in PV/T system[11],[12][13],[14]. Recent

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research has increasingly focused on advanced PV-PCM configuration incorporating Nano-enhanced PCMs to further improve system performance [15],[16],[17] However systematic comparison of different PCM types under varying solar irradiance remain limited, this study addressed this gap by numerically investigated the impact of different PCMs on PV temperature regulation and electrical efficiency using a one dimensional energy balance model solved via the Finite Difference Method in MATLAB

Table 1. Properties of different PCMs.

Thermo-physical properties	BWCO[18]	RT35[4]	RT42[19]	RT55[19]
Thermal Conductivity (w.m ⁻¹ .°C ⁻¹)	0.24	0.2	0.2	0.2
Density (kg/m ³)	928	800	880	880
Specific heat capacity(J.kg ⁻¹ .k ⁻¹)	2430	2000	2000	2000

Table 2. Properties of PV panel[5].

PV panel properties	Value
Electrical efficiency	17 %
Thermal conductivity	130 W/(m k)
Temperature coefficient β_{ref}	0.0045 1/K
Heat capacity	2090 J/ (kg k)
Density	2330 kg/m ³
T _{ref}	25 °C

2 Methodology and system configuration

2.1 Hybrid system structure description

Fig.1. illustrates the hybrid PV-PCM system, which consists of a monocrystalline photovoltaic PV panel integrated into a chamber containing PCM. The chamber’s lateral walls are thermally insulated, and an aluminium back cover is positioned beneath the PCM layer to enhance heat conduction[20]. The upper surface of PCM is in direct contact with PV panel, enabling efficient heat absorption. Four PCMs RT42, RT35, RT55 and BWCO table2 were selected to examine the effect of thermal conductivity, specific heat, melting point, and latent heat of fusion on the thermal regulation and electrical performance of the PV panel[21].

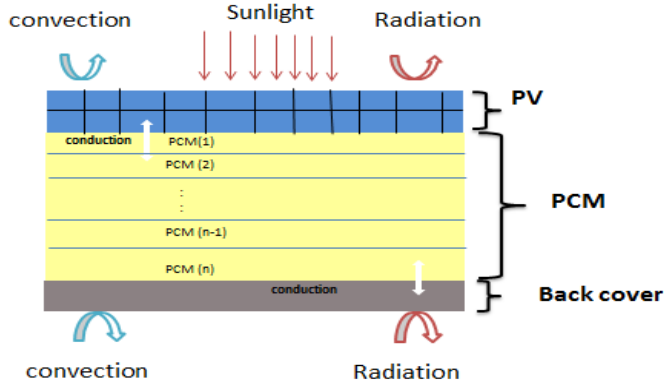


Fig.1. System configuration.

2.2 Mathematical model

A numerical model of the PV-PCM system was established using the energy balance. Equations for the PV panel, PCM layer, and back cover to assess system performance. The modelling details are provided below.

- PV panel:

$$c_p \rho_p t_p \frac{dT_p}{dt} = h_{p-sky}^{rad} (T_{sky} - T_p) + h_{p-amb}^{conv} (T_{amb} - T_p) + \alpha CG - CG \eta_{el} + \frac{k_p}{t_p} (T_{pcm} - T_p) + \frac{1}{dx} \int_{-x}^{+x} t_p k_p \frac{dT_p}{dx} \quad (1)$$

In this model the PV panel is characterized by its specific heat capacity c_p , density ρ_p , temperature T_p and thickness. The ambient temperature is denoted by T_{amb} , and the sky temperature T_{sky} , is estimated using Eq.2.

$$T_{sky} = 0.0375(T_{amb})^{1.5} + 0.32T_{amb} \quad (2)$$

The electrical efficiency of the PV panel depends on its operating temperature and is expressed as:

$$\eta_{el} = \eta_{ref} [1 - \beta_{ref} (T_{pv} - T_{ref})] \quad (3)$$

- Back cover

$$c_b \rho_b t_b \frac{dT_b}{dt} = h_{bc-gr}^{rad} (T_{gr} - T_b) + h_{bc-amb}^{conv} (T_{amb} - T_b) + \frac{k_b}{t_b} (T_{pcm} - T_b) + \frac{1}{dx} \int_{-x}^{+x} t_b k_b \frac{dT_b}{dx} \quad (4)$$

The back cover properties include specific heat capacity (c_b), density (ρ_b), temperature (T_b), and thickness (t_b). The PCM and ground temperature are denoted by T_{pcm} and T_{gr} . Radiative heat transfer is denoted by h_{p-sky}^{rad} between the PV panel and sky, and h_{bc-gr}^{rad} between the back cover and ground. Conductive heat transfer between layers is represented by $\frac{k_b}{t_b}$ and $\frac{k_p}{t_p}$ where k_b and k_p are the thermal conductivities of the back cover and PV panel.

- **PCM layer:** Under the PV panel

$$\frac{1}{dy} \int_{-y}^{+y} k_{pcm} \frac{\partial T_{pcm}}{\partial y} = \frac{1}{dy} \frac{k_{pv}}{t_{pv}} (T_{pv} - T_{pcm,1}) + \frac{1}{(dy)^2} (T_{pcm,2} - T_{pcm,1}) \quad (5)$$

- Above the back cover

$$\frac{1}{dy} \int_{-y}^{+y} k_{pcm} \frac{\partial T_{pcm}}{\partial y} = \frac{1}{dy} \frac{k_{bc}}{t_{bc}} (T_{bc} - T_{pcm,m}) + \frac{1}{(dy)^2} (T_{pcm,m-1} - T_{pcm,m}) \quad (6)$$

- Intermediate layer

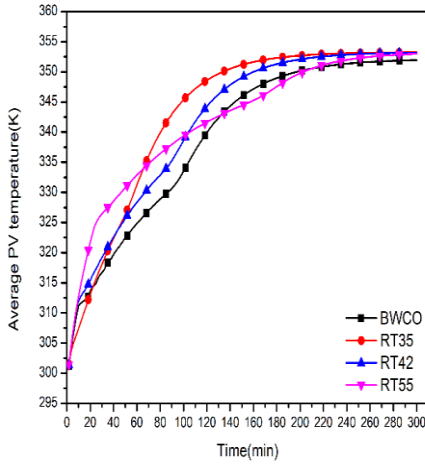


Fig.2. Influence of PCM type on PV temperature.

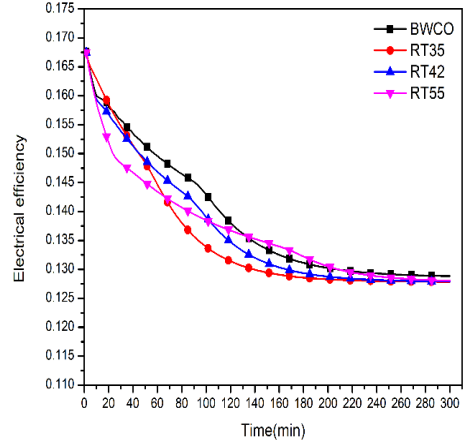


Fig.3. Influence of PCM type on electrical efficiency.

$$C_{pcm} \rho_{pcm} \frac{dT_{pcm}}{dt} = \frac{1}{dy} \int_{-y}^{+y} k_{pcm} \frac{\partial T_{pcm}}{\partial y} + \frac{1}{dx} \int_{-x}^{+x} k_{pcm} \frac{\partial T_{pcm}}{\partial x} \quad (7)$$

3 Results and Discussion

3.1 Effect of PCM type

The selection of an appropriate PCM is crucial for improving PV performance and mitigating temperature. This study examines four PCM types –RT35, RT42, RT55 and BWCO- to assess their impact on PV temperature. As shown in **Fig.2**, the PV system with BWCO exhibits the lowest temperature rise among the tested PCMs, reaching a maximum average temperature of 351.9K, indicating its superior thermal regulation capability. This slower temperature increase is attributed to BWCO’s high latent heat of fusion. **Fig.3** present the variation on the electrical efficiency of the hybrid PV-PCM for the different PCMs. An increase in the PCM temperature results in a reduction of electrical efficiency, reflecting the inverse relationship described in **Eq 3**. Among the tested PCMs evaluated BWCO demonstrates the most favourable performance.

3.2 effect of solar radiation

This section examines the impact of varying solar radiation on the performance of the hybrid PV-PCM system, as solar radiation increases, the PV panel temperature rises shortening the PCM melting period[22]. With temperature ranging from 352K to 355K at 1000 W/m², and decreasing to 317-323 K at 400 W/m² for different PCM. Higher radiation levels also reduce electrical efficiency for all PCM types, among them, WCO with highest latent heat, exhibit the smallest efficiency drop (1.46-4.1%), While RT55 shows slightly high reductions (1.87-4.19%).

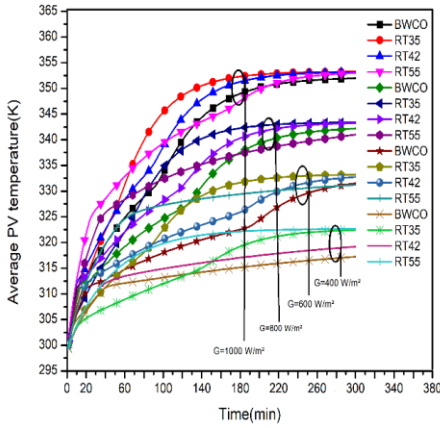


Fig.4. Impact of solar radiation on PV Temperature.

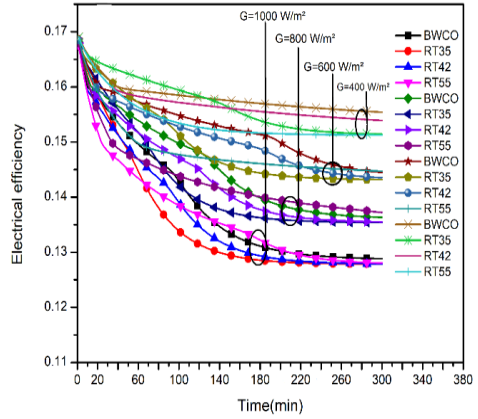


Fig.5. Impact of solar radiation on PV temperature.

3.3 Effect of PCM thickness

This section investigates the influence of PCM thicknesses on PV panel temperature; three PCM thicknesses (1- 3 cm) were tested. Increasing the PCM thickness from 1 cm to 2cm led to a higher average PV temperature: 353.28 K (RT55), 356.44 K (RT42), 357.84 K (RT35), and 353.18 K (BWCO). Further increase delayed the panel’s thermal stabilisation

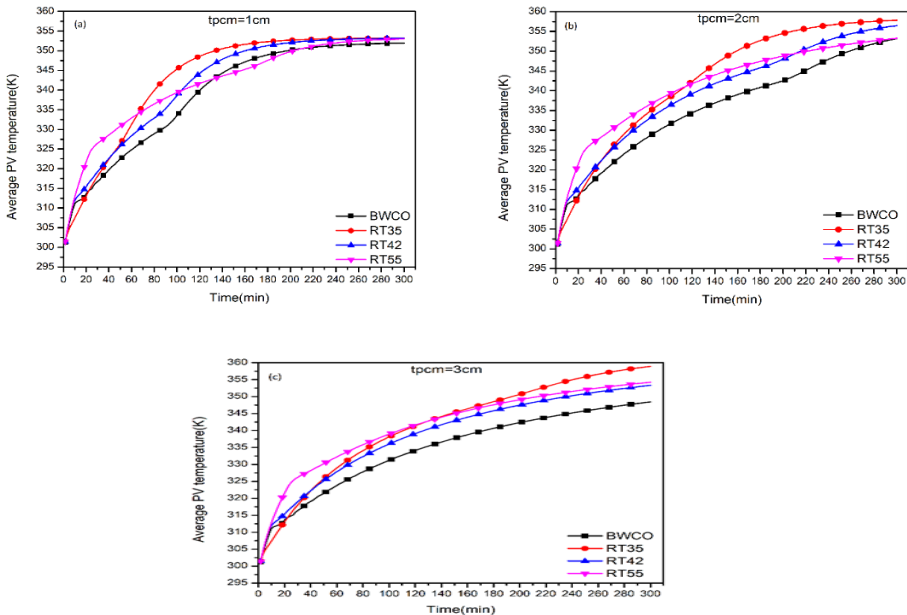


Fig.6. Effect of PCM thickness on PV temperature, (a) 1cm ,(b) 2cm,(c) 3cm.

4 Conclusion

This study developed a one-dimensional model to evaluate the thermal and electrical performance of PV-PCM system. The results confirm that PCM integration significantly reduces PV operating temperature and enhances electrical efficiency. System performance was found to be strongly dependent on PCM properties, operating conditions and PCM thickness, with high latent heat PCM and thinner layers providing superior cooling.

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