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Thermal Analysis of PCM Composites Based on Paraffin Wax and Bamboo Carbon for Passive Cooling Applications of Electric Vehicle Batteries

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Abstract: This study aims to evaluate the thermal performance of Phase Change Material (PCM) composites based on paraffin wax. However, the use of paraffin alone as PCM has a drawback in terms of low thermal conductivity. To enhance the thermal conductivity of the PCM, additional elements need to be incorporated into the paraffin. Bamboo carbon, especially that produced through carbonization processes, holds great potential in various applications, including as a thermal energy storage material (PCM). The carbonization of bamboo at high temperatures produces materials with porous structures that can improve energy storage capacity. The use of bamboo carbon in energy storage systems not only provides a solution for renewable energy needs but also supports environmental sustainability by utilizing abundant and renewable natural resources Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), and Derivative Thermogravimetry (DTG) tests were conducted on PCM materials with varying bamboo carbon concentrations of 0%, 5%, 10%, and 15%. The test results showed that the addition of bamboo carbon influences the melting temperature, melting enthalpy, and thermal stability of the PCM. The sample containing 10% bamboo carbon exhibited the highest melting enthalpy value of 104.99 kJ/kg, which has the potential to enhance heat storage capacity and improve the cooling efficiency of electric vehicle batteries.

Keywords: Bamboo Carbon, Battery Cooling, Differential Scanning Calorimetry, Paraffin Wax, PCM

1 Introduction

The development of electric vehicle (EV) technology is advancing rapidly in line with the growing demand for environmentally friendly and energy-efficient transportation systems. One of the main challenges in the development of electric vehicles is thermal management of the battery system, where uncontrolled temperature increases can lead to reduced efficiency, accelerated battery degradation, and even thermal failure. Therefore, an effective and efficient cooling system is required to maintain the battery temperature within its optimal operating range.

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One of the widely developed solutions is the utilization of Phase Change Material (PCM) as a passive cooling medium. PCM can absorb and release heat energy in the form of latent heat during the phase change process, making it highly effective in mitigating temperature spikes. Paraffin wax is one of the most commonly used types of PCM due to its several advantages, including chemical stability, non-corrosive properties, and relatively low cost (Khan et al., 2016; Meng & Zhang, 2017). However, paraffin wax has a limitation in the form of low thermal conductivity, which hinders the efficiency of heat transfer during the melting and solidification processes (Arshad et al., 2021; Lin et al., 2018; Mhiri et al., 2020).

To overcome the limitation of paraffin's low thermal conductivity, PCM composites have been developed by adding materials with high thermal conductivity, such as expanded graphite, aluminum, nano TiO_2, coconut shell carbon, and others. The addition of these materials to paraffin as PCM can enhance the performance of the PCM (Chen et al., 2021; Goli et al., 2014; Malik et al., 2017; Patel & Rathod, 2020; Li et al., 2019; Bahiraei et al., 2017). The addition of bamboo carbon was explored in this study. Bamboo carbon possesses good thermal conductivity, is lightweight, and environmentally friendly, making it capable of improving the efficiency of heat storage and release in paraffin-based PCM. Bamboo carbon, particularly the carbon obtained through the carbonization process, holds great potential in various application fields, including as a material for Thermal Energy Storage (TES). Bamboo is known as a fast-growing plant that efficiently absorbs carbon dioxide, has high energy density, and is effective as a thermal energy absorber (Xu et al., 2022). The combination of paraffin wax and bamboo carbon as PCM is expected to produce a more effective, stable, and sustainable thermal energy storage material for various renewable energy applications. It represents an innovative solution in the development of efficient and environmentally friendly thermal energy storage technology, while also enhancing the efficiency of modern thermal systems.

2 Methodology

2.1 Material

The materials used in this study are PCM materials consisting of paraffin and bamboo carbon. The paraffin used is paraffin wax, with characteristics including a melting temperature of 64°C, heat of fusion of 266 kJ/kg, thermal conductivity of 0.339 W/mK, and density of 916 kg/m^3. The bamboo carbon used is derived from bamboo waste produced by small-scale industries in the form of bamboo shavings. This bamboo waste undergoes a series of treatments, starting with shredding into smaller dimensions, followed by washing with distilled water, then drying under sunlight for 5 hours, and further drying at a temperature of 100°C for 2 hours. The next step involves the carbonization process of the bamboo waste.

2.2 Research Variables

The variables in this study consist of independent variables and dependent variables. The independent variable is the PCM material in the form of bamboo carbon concentration in the paraffin, while the dependent variable is the thermal characteristics of the PCM material.

2.3 Preparation of Composite PCM

This research begins with the preparation of the test material in the form of bamboo carbon. The bamboo is cut into small pieces (5 cm x 1 cm x 0.2 cm) and washed using distilled water, then dried in the sunlight for 5 hours. Next, the bamboo is further dried in an oven at a temperature of 100°C for 2 hours. The following step involves placing the bamboo waste into a heating furnace to undergo carbonization at 400°C with a holding time of 2 hours. The bamboo is removed from the furnace once the furnace temperature returns to room temperature.

The next step is grinding the bamboo carbon into fine particles. The fine bamboo particles are then sieved using a 0.05 mm mesh, resulting in bamboo carbon with a particle size of 0.05 mm. After obtaining the bamboo carbon material, the process continues with the preparation of the paraffin and bamboo carbon mixture in several composition ratios to form the PCM composite. The mixture is prepared using a magnetic stirrer.

The procedure for making the mixture involves placing paraffin wax into a beaker and heating it to 100°C on the magnetic stirrer until it reaches a liquid state. The magnetic stirrer is then set to a temperature of 70°C with a stirring speed of 60 rpm. Bamboo carbon is gradually added to the paraffin according to the desired concentration until a homogeneous PCM mixture of Paraffin and Bamboo carbon (PC) is formed. The mixing process is carried out for 2 hours. After 2 hours, the mixture is molded into two different molds, one for samples to be tested for their characteristics and the other for a cooling box used as a medium for battery cooling performance testing. The detailed process is illustrated in Figure 1. The sample testing was conducted on several PCM variations with different compositions, and the sample compositions are presented in Table 1. The concentrations of 5%, 10%, and 15% were chosen because they are considered to significantly enhance thermal conductivity without altering the functional properties of paraffin as a thermal energy storage material. These concentrations allow researchers to optimize the thermal energy storage capacity without compromising thermal stability or efficiency. Overall, the selection of 5%, 10%, and 15% carbon concentrations in paraffin aims to achieve an optimal balance between improved thermal conductivity, melting point regulation, energy storage capacity, and cost efficiency in PCM applications.

Figure 1. Schematic Diagram of PCM Composite Preparation

Table 1. Sample Composition

No	Sample Name	Paraffin (%)	Bamboo Carbon (%)
1	Pure Paraffin (P)	100	0
2	Paraffin with 5% Bamboo Carbon (PC 5%)	95	5
3	Paraffin with 10% Bamboo Carbon (PC 10%)	90	10
4	Paraffin with 15% Bamboo Carbon (PC 15%)	85	15

2.4 Characterization

The characterization of PCM materials was carried out to determine the properties of each sample prepared. The thermal properties of paraffin and the shape-stable PCM composites were tested using Differential Scanning Calorimetry (DSC). The thermal stability of the PCM composites was analyzed using Thermogravimetric Analysis (TGA, Q50), and the rate of mass change with respect to temperature was analyzed using Derivative Thermogravimetry (DTG).

3 Results and discussion

3.1 Result

PCM's Ability to Absorb Heat. Based on the results of the DSC testing, the addition of bamboo carbon to paraffin can alter the thermal properties of the PCM, as shown in Figure 2. From Figure 2, it can be seen that there is a shift in the onset melting, melting point, and endset melting values after the paraffin wax is combined with bamboo carbon. The observed shifts are presented in Table 2.

Table 2. Onset, Endset, and Melting Point of PCM Materials.

Sampel	Onset melting (˚C)	Melting point (˚C)	Endset melting (˚C)	ΔH (kJ/kg)
PCM PP (0%)	53.15	63.3	88.18	92.454
PCM PC 5%	50.03	64.39	81.32	84.42
PCM PC 10%	54.58	66.73	95.27	104.99
PCM PC 15%	52.47	62.30	82.01	89.91

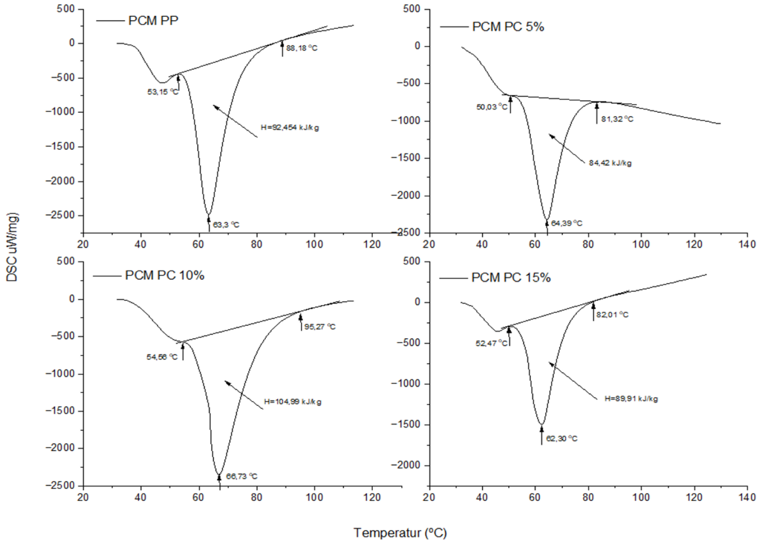

Figure 2. DSC Test Results of PCM Materials

Thermal Stability of PCM. The thermal stability of the PCM can be observed from the TGA and DTG test results of the PCM samples, as shown in Figures 3 and 4.

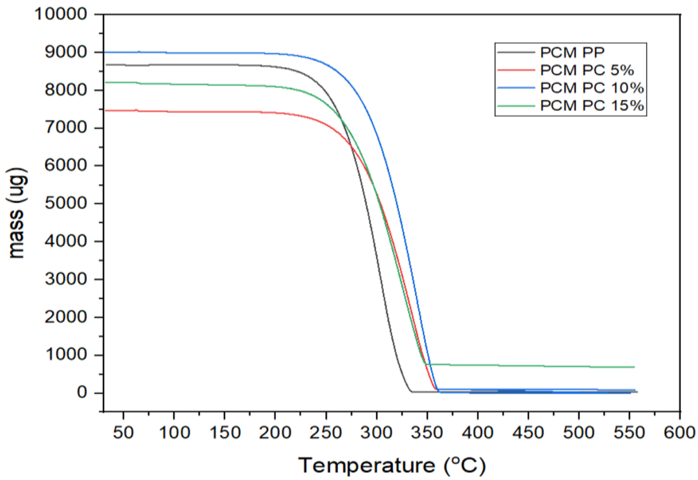

Figure 3. TGA Test Results of PCM Samples

Figure 3 shows the results of Thermogravimetric Analysis (TGA) of four types of PCM materials, namely PCM PP (pure paraffin) and PCMs modified with the addition of 5%, 10%, and 15% bamboo carbon. The graph illustrates the relationship between mass (µg) and temperature (°C), reflecting the thermal stability and thermal degradation characteristics of each sample. The test results indicate that up to a temperature of 250°C, the samples remain relatively stable as no significant mass reduction occurs.

All samples exhibit a sharp decrease in mass within the temperature range of approximately 250°C to 350°C, indicating the main thermal degradation of the PCM materials.

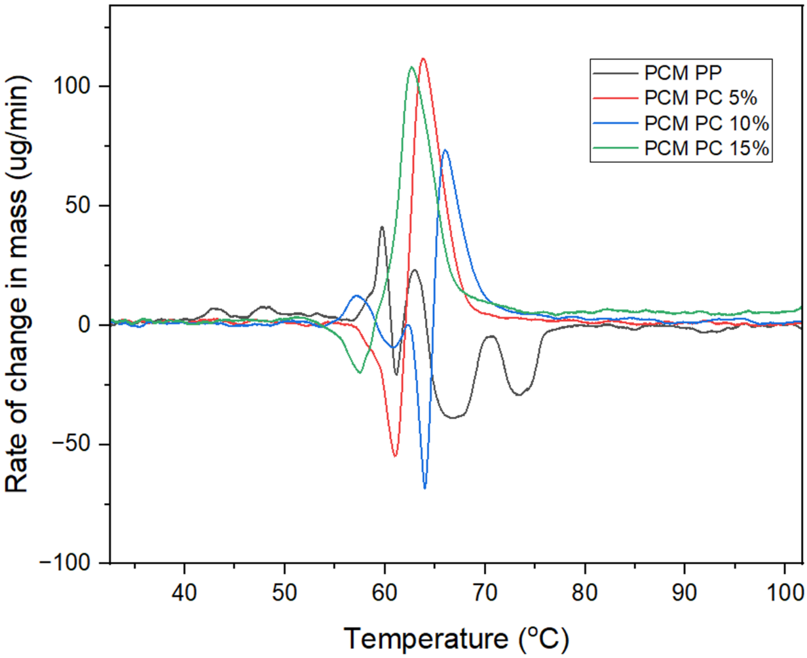

Figure 4. DTG Test Results of PCM Samples.

Figure 4 shows the results of Differential Thermogravimetric (DTG) analysis of PCM materials consisting of paraffin wax (PCM PP) and PCM composites with the addition of bamboo carbon at concentrations of 5%, 10%, and 15%. The graph illustrates the rate of mass change (µg/min) versus temperature (°C), representing the dynamics of the material's thermal degradation. It can be seen that all samples exhibit DTG peaks, indicating the most significant mass change occurring within the temperature range of approximately 55°C to 70°C. These peaks are associated with the phase transition process or the onset of PCM material degradation. The pure PCM exhibits a broader and lower peak of mass change compared to the bamboo carbon-modified PCMs. In contrast, the PCMs with bamboo carbon concentrations of 5%, 10%, and 15% display sharper and higher peaks, indicating a faster mass release process upon reaching the thermal transition point.

3.2 Discussion

The addition of 10% bamboo carbon, as shown in Figure 2, tends to improve the initial thermal stability, whereas bamboo carbon concentrations of 5% and 15% actually lower the onset temperature. A higher peak temperature (melting point) indicates the potential of the PCM to withstand heat for a longer period before reaching maximum melting. The PCM with 10% bamboo carbon (PCM PC 10%) demonstrates the best performance in this regard. A higher endset temperature indicates broader thermal stability, which is beneficial for applications with large temperature variations.

The value of ΔH is directly proportional to the latent heat storage capacity. The addition of 10% bamboo carbon significantly increases the heat storage capacity. In contrast, the addition of 5% and 15% bamboo carbon reduces the ΔH value. This is because adding carbon can disrupt the crystalline structure of paraffin. If the carbon particles are not homogeneously dispersed or are present in excessive amounts, they can hinder the movement of paraffin molecules during the freezing/melting process, leading to reduced latent heat release efficiency.

At 5% concentration, poor dispersion may cause microstructural irregularities that lower the enthalpy, while at 15% concentration, excessive carbon dominates the non-functional additive behavior during melting, causing the enthalpy to decrease. From the perspective of heat transfer and energy storage, carbon can enhance thermal conductivity, thereby accelerating heat release or absorption. However, an increased heat transfer rate does not always align with an increase in heat storage capacity (enthalpy). At carbon concentrations of 5% and 15%, the carbon content is either below or exceeds the optimal dose, resulting in reduced stored energy (ΔH) despite possibly better heat transfer rates. At the 10% concentration, an ideal balance is achieved, where the amount of carbon is sufficient to improve thermal conductivity without sacrificing heat storage capacity, and the distribution of carbon within the paraffin matrix is more uniform, thus increasing the enthalpy (Vasilyev et al., 2022).

The addition of bamboo carbon, as shown in Figure 3, clearly improves the thermal stability of the PCM material (Sun et al., 2022). PCMs with 5%, 10%, and 15% bamboo carbon exhibit degradation at higher temperatures. The PCM with 10% bamboo carbon exhibits the best thermal stability among all samples, as evidenced by the curve shifting to the right and the greater residual mass after degradation, particularly in PCM PC 10%. This difference indicates that bamboo carbon acts as an additive material capable of enhancing the thermal resistance of PCM by slowing down the thermal degradation process. This can also positively impact the reliability and lifespan of PCM materials in latent heat storage applications, particularly in passive cooling systems such as electric vehicle batteries.

The addition of bamboo carbon to paraffin tends to improve the thermal stability of the material, as shown in Figure 4 (Konuklu, Y., Yılmaz, A. A., & Güler, 2020), which is evident from the peak shift toward slightly higher temperatures and more controlled mass change rates. The addition of carbon also sharpens the transition peak, making the mass release process more focused and efficient. From Figure 4, it can be seen that the addition of bamboo carbon in PCM has the potential to enhance stability and improve the thermal characteristics of the material (Fatahi, B., & Sadeghian, 2022), which is essential for latent heat storage and passive cooling applications.

4 Conclusion

Based on the results of the thermal analysis of PCM materials using paraffin wax and bamboo carbon for electric vehicle battery cooling applications, several conclusions can be drawn. The addition of 10% bamboo carbon into paraffin wax enhances the PCM's ability to absorb heat. The mixture of paraffin wax and bamboo carbon also demonstrates sufficient thermal stability for thermal management applications below 200°C. Moreover, the incorporation of bamboo carbon improves stability and strengthens the thermal characteristics of the material. Overall, the combination of paraffin wax and bamboo carbon as PCM shows great potential as a passive cooling material for electric vehicle batteries.

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