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Efficient Thermal Management in Processor Cooling Using Lauric Acid and Copper Foam-based PCM Composite

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ABSTRACT

Thermal management is critical in most industries to maintain optimal temperatures and improve system efficiency. This study focuses on creating a composite phase change material (PCM) using lauric acid (LA) and copper foam (CF) to enhance thermal management performance. Lauric acid was chosen because it melts at a practical temperature range (43–46℃) and has a high capacity to store and release energy during phase changes. Copper foam was added for its good thermal conductivity and porosity, thus allowing for an even distribution of heat and enhancement of the performance. The composite PCM gave promising results in terms of latent heat capacity (190 J/g) and thermal conductivity. Its properties make it suitable for applications such as cooling electronics, managing battery temperatures, and renewable energy systems. Testing confirmed stability and effectiveness. Structural stability was verified through XRD analysis. Differential Scanning Calorimetry cycling tests showed constant thermal performance across repeated heating and cooling cycles. Field Emission Scanning Electron Microscopy images showed that lauric acid was distributed uniformly in the copper foam allowing effective heat transfer. Thus, the composite can regulate temperature well, extend the lifetime of hardware, and show great potential for heat-dissipation. When compared with the lauric acid phase change alone, copper foam can decrease the time for a phase change to as low as 45%. Such an innovative material can bring about practical and effective solutions in the fields requiring efficient and reliable thermal management systems.

Keywords: Thermal management; Phase change materials; Lauric acid; Copper foam.

1. INTRODUCTION

Phase Change Materials (PCMs) are very attractive as they can absorb and release heat efficiently during phase transitions, that is a direct, simple efficient cooling method. Lauric acid, which melts in the range 43-46℃, has high heat capacity and good stability. It is easily available and safe. However, its ability to transfer heat is relatively poor, which slows down the process of absorbing and releasing heat, limiting its effectiveness. To address this, a composite material combining lauric acid with copper foam is proposed. Copper foam's high thermal conductivity can enhance the heat transfer of lauric acid, creating a material that combines excellent heat storage with improved heat dissipation. This study examines how this composite performs compared to traditional cooling materials, with a focus on its potential to manage high heat output in advanced processors.

Paraffin-based composite phase change materials are reinforced with copper foam for high heat transfer applications. It focuses on the improvement of thermal conductivity and fast dissipation of heat for electronic processor cooling (Zheng *et al*. 2018). Lauric acid has been doped with graphene nanoplatelets (GNP) to enhance thermal conductivity and stability for electronic processors. (Harish *et al*. 2015). The hybrid PCM composed of lauric acid and expanded graphite was fabricated to enhance thermal conductivity, primarily for electronic cooling applications. Similarly, copper foam-based PCM composites using paraffin exhibit rapid heat dissipation, demonstrating significant heat transfer enhancement (Bhutto et al. 2024). Leifer *et al* (2024) studied the thermal conductivity of lauric acid-based nanocomposite enhanced with CuO and Al_2O_3 nanoparticles.

Lauric acid and nano-zinc oxide (ZnO) are used as a thermal management elements in processing PCMs. ZnO increases thermal conductivity but keeps latent heat properties (Fan *et al.* 2022). Researchers have reported paraffin-based PCMs reinforced with copper foam for heat dissipation in processors. Copper foam could improve thermal conductivity and phase change rate. Lauric acid and nano-copper oxide (CuO) composites were developed to enhance thermal conductivity for cooling applications (Ayyasamy *et al.* 2022; Peng *et al.* 2024).

Lauric acid doped with boron nitride nanosheets was shown to enhance the conductivity and stability, making it suitable for processor applications (Mishra *et al.* 2020). Lauric acid-based phase change material embedded with expanded graphite was investigated for heat dissipation in processors. A combination of lauric acid and aluminium oxide (Al_2O_3) nanoparticles was reported to have high thermal conductivity as well as stability under cyclic thermal loading (Wu *et al*. 2020a; Zheng *et al.* 2018). Lauric acid-based hybrid PCMs with carbon nanotubes enhance conductivity and heat storage ability. Copper foam also is shown to enhance thermal conductivity (Sun *et al.* 2023).

The study addresses lauric acid-CuO nanoparticle composites that enhance thermal conductivity for heat storage in processors. (Zheng *et al.* 2018; Pugalenthi *et al*. 2024). Lauric acid doped with nano-silicon carbide (SiC) particles has been investigated in electronic cooling applications. The incorporation of SiC greatly enhances the thermal conductivity and energy storage (Roy *et al.* 2019). Lauric acid filled with titanium dioxide (TiO_2) nanoparticles is used for processor applications. The increased thermal conductivity makes it suitable for thermal management systems. (Yuan *et al*. 2014). Copper foam-based paraffin composites are used for processor cooling applications. Copper foam enhances the thermal conductivity and decreases the melting time, Lauric acid and stearic acid-based nanocomposites containing CuO nanoparticles are studied for energy storage applications. Improved thermal conductivity and latent heat performance are reported (El-Hadek *et al.* 2018; Tan *et al.* 2024). Paraffin-copper foam composites for processor heat management. Though copper foam is an effective material for thermal enhancement, the work does not include lauric acid (Rezaie and Montazer, 2018).

A study with lauric acid doped with MgO nanoparticles has shown improved conductivity and stability (Zuo *et al*. 2024). This study explores the structure determination of low-melting n-alkyl methyl esters using in situ cry crystallization and single-crystal X-ray diffraction. It identifies two isostructural groups (triclinic for odd-numbered and orthorhombic for even-numbered esters) and highlights an odd–even effect in melting points and unit cell parameters. Structural trends and intermolecular interactions were analysed using Hirshfeld surface analysis and AA-CLP lattice energy calculations for deeper insights. (Prathapa *et al*. 2019).

To balance thermal conductivity and latent heat storage as well as improve the rates of phase change, investigators have analyzed the introduction of highly conductive materials, such as metal foams, nanoparticles, and carbon-based additives into PCM systems. Copper foam emerges as a particularly suitable supporting material for PCMs, as it possesses exceptional thermal conductivity and mechanical strength and is compatible with phase-change material. It produces a lauric acid-copper foam composite. This work developed the composite in its preparation and characterized it to explore its thermal performances, such as thermal conductivity and cycling stability, to mention a few. The results indicate that the inclusion of copper foam enhances the heat dissipation performance of lauric acid considerably, making it appropriate for demanding applications like electronics cooling, battery thermal management, and renewable energy systems.

2. MATERIALS AND METHODS

The materials used in this study (Fig. 1) included Lauric acid (LA) and Copper foam (CF). Lauric acid, a saturated fatty acid, was chosen as a primary phase-change material because it has a middle-range melting point and very high latent-heat capacity. It is chemically stable during thermal cycling processes. These properties make lauric acid favored for managing thermal energy associated with passive cooling. Copper foam, an open-cell metallic foam, was chosen as the enhancement material for the composite. Its high thermal conductivity and porous structure make it an excellent medium for improving heat transfer within the PCM. The foam's open-cell structure allows lauric acid to infiltrate and integrate with the copper matrix, forming a composite with enhanced thermal conductivity.

Fig. 1: Lauric acid and copper foam

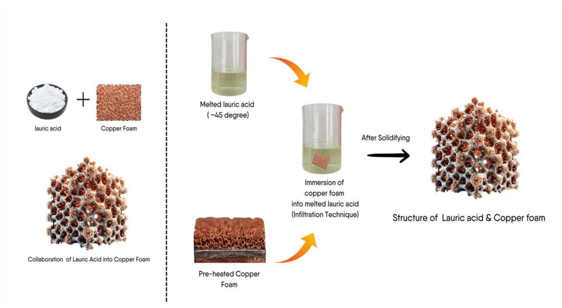

Fig. 2: Schematic diagram of LA-CF PCM composite preparation

Lauric acid was melted. The molten lauric acid was filled in the copper foam. During this step, the 85:15 weight ratio was maintained. Molten lauric acid fills the pores in the structure of the copper foam. After infiltration, the composite was allowed to cool and harden. Fig. 2 shows the scheme of synthesis of the composite.

3. CHARACTERISATION

The prepared composite material was characterized using several techniques such as XRD, SEM and DSC to evaluate its structural and thermal properties.

3.1 X-ray Diffraction (XRD) Analysis

The XRD pattern gives an indication of the dispersion of crystalline phases within the composite. Hence, it would be possible to identify the crystalline phase of lauric acid and potential interactions with the copper foam matrix. This was the analysis for verifying the homogeneous integration of lauric acid into the composite without changing the fundamental structure of the composite.

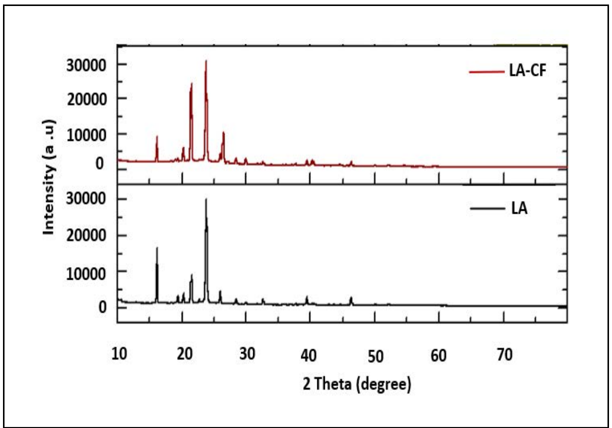

Fig. 3: XRD analysis of lauric acid and lauric acid with copper foam composite

3.2 Field Emission Scanning Electron Microscopy (FE-SEM)

The microstructure of the composite was visualized by employing Field Emission Scanning Electron Microscopy (FE-SEM), which focused on the interface between lauric acid and copper foam. FE-SEM gave high-resolution images of the extent of lauric acid infiltration into the porous structure of the copper foam. It also enabled the detection of microstructural defects, pores, and regions where the lauric acid had not penetrated completely. The images obtained from FE-SEM were critical in assessing the homogeneity and physical stability of the composite, both of which are critical for effective thermal performance.

3.3 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) was conducted to study the thermal behaviour of the lauric acid-copper foam composite with an interest in its melting and solidification features. The analysis offered detailed information about the phase-change temperatures and latent heat of the composite material, which reflect the material's capacity for storing heat. The influence of copper foam on the thermal behavior of the PCM was quantified by comparing the DSC results of the composite with pure lauric acid. This analysis was important to understand how the composite would perform under repeated heating and cooling conditions.

4. RESULTS AND DISCUSSION

4.1 X-ray Diffraction (XRD) Analysis

The XRD analysis revealed (Fig. 3) the crystalline structure of the lauric acid-copper foam composite, confirming the presence of distinct peaks that correspond to the crystalline phase of lauric acid. These peaks were generally consistent with those observed in pure lauric acid, indicating that its phase structure was largely preserved in the composite

The X-ray diffraction (XRD) analysis of Lauric Acid (LA) and Copper Foam (CF) confirms their crystalline nature through distinct diffraction peaks. The LA sample exhibits peaks at 16.32°, 20.39°, 21.63°, 20.04°, 30.12°, and 40.39° (2θ), indicating a well-ordered molecular structure typical of long-chain fatty acids. These peaks suggest the presence of strong molecular interactions and a stable crystalline phase.

For CF, the diffraction peaks at 43.4°, 50.5°, and 74.2° (2θ) correspond to the characteristic reflections of metallic copper. These peaks are associated with the (111), (200), and (220) planes of its face-centered cubic (FCC) structure, confirming its high crystallinity. The sharp intensity of these reflections indicates that the copper foam maintains its structural integrity without significant oxidation or amorphous content.

The XRD findings highlight the lamellar packing arrangement in LA, which is essential for its thermal and chemical stability, while the CF structure demonstrates a strong metallic framework (Kim *et al.* 2001). These properties make both materials suitable for applications in thermal energy storage, catalysis, and composite materials, where crystalline structure plays a critical role in performance.

4.2 Field Emission Scanning Electron Microscopy (FE-SEM) Analysis

FE-SEM images (Fig. 4) PCM composite provided clear visualization of the microstructure, and it was seen that lauric acid is uniformly distributed throughout the porous matrix of copper foam. High-magnification images showed extensive infiltration of lauric acid into the interconnected pores of the copper foam, thereby confirming a consistent filling process

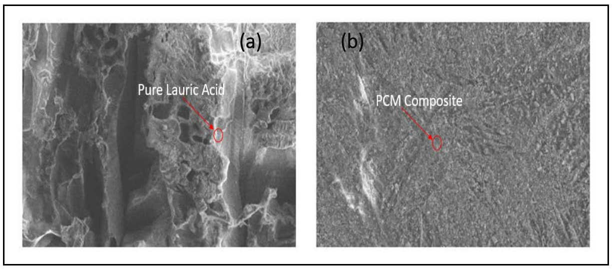

Fig. 4: FE-SEM structure of the materials (a) pure lauric acid (b) PCM composite with CF

The porous structure of copper foam contributed to an even distribution of lauric acid, enhancing the contact area and allowing efficient heat distribution across the composite. The uniformity observed in the microstructure indicates that the preparation method successfully facilitated full infiltration and bonding, which is crucial for maintaining thermal conductivity and stability. The foam's interconnected pores appear to act as channels for rapid heat dispersion, allowing the composite to perform well under conditions of high heat flux, as encountered in high-performance processors.

This even distribution and high interfacial contact support the capacity of the composite to stably manage heat for an extended period of usage. The FESEM images also clearly reveal a strong interfacial interaction between the lauric acid and the copper foam matrix (Li, 2013). In addition, the copper foam has a high thermal conductivity that supports quick absorption and release, thus making the composite highly effective for applications in the storage of thermal energy. FESEM analysis shows the microstructural stability of the PCM. This ensures constant performance over extended usage, a critical factor for practical applications.

4.3 Differential Scanning Calorimetry (DSC) Analysis

As per DSC analysis, the improvements in thermal properties of the lauric acid-copper foam composite are more compared to pure lauric acid. Melting point has been observed to lower somewhat, which may be because of the better heat transfer attributes being provided with the help of the conductive copper foam framework. The addition of copper foam results in faster and more uniform distribution of thermal energy throughout the composite. This is ideal for applications like processor cooling where fast dissipation of heat is needed. In fact, the results obtained have shown that apart from providing a structural reinforcement function, the foam actually enhances thermal performance, meaning that the composite was superior to that of standalone PCMs at such high temperatures. Fig. 5 shows the DSC curve for the PCM composite.

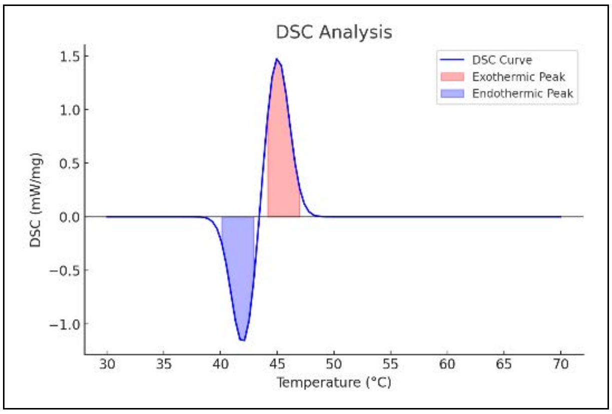

Fig. 5: DSC analysis of PCM composite

The latent heat of fusion for pure lauric acid was found to be about 185-200 J/g.

$$Q = mLf$$

Where:

Q = Heat energy absorbed or released (Joules)
m = Mass of the substance (grams)
Lf = Latent heat of fusion (J/g)

Given that,

Mass of lauric acid, m = 5 g
Heat energy supplied, Q = 950 J

$$Lf = mQ$$
$$Lf = 950/5$$
$$Lf = 190 \text{ J/g}$$

This value falls within the reported range (185–200 J/g), thus justifying the given range. The actual experimental value depends on factors such as purity, measurement precision, and heat losses.

A reduction of up to 45% in phase transition time is observed, attributed to the enhanced thermal conductivity of copper foam.

Differential Scanning Calorimetry (DSC) results indicate distinct thermal transitions in the analysed fatty acid ester biofuel. An endothermic peak appears between 40–45°C, signifying a phase change that requires energy absorption, likely corresponding to the melting process. This suggests the disruption of intermolecular forces as the ester transitions from a solid to a liquid state. Following this, an exothermic peak is observed between 45–50°C, indicating a crystallization process where energy is released as the material reorganizes into a more stable form (Ling and Poon, 2013). The sharpness of these peaks suggests a high level of purity and crystallinity in the sample. Additionally, variations in melting behaviour, possibly due to differences in molecular arrangement, highlight an odd–even effect in the homologous series. These thermal transitions provide valuable insights into the structural characteristics and stability of the ester compounds, reinforcing the trends observed in molecular interactions and phase behaviour.

5.CONCLUSIONS

This work has successfully demonstrated the integration of lauric acid with copper foam to enhance significantly the thermal management properties of phase change materials (PCMs).

XRD analysis showed that lauric acid within the copper foam matrix is structurally compatible; it shows almost no disturbance of the crystalline nature of lauric acid. FE-SEM analysis further ascertained uniform lauric acid dispersion inside the porous structure of copper foam. DSC analysis results indicated that the composite had retained a high latent heat capacity while, at the same time, having improved specific heat, which allowed for quicker and more even temperature control. The lauric acid-copper foam composite displayed consistent thermal performance. Such resilience makes it suitable for repeated thermal loading applications, such as electronic cooling and energy storage systems.

This work provides a basic research on the PCM-metallic foam composites. Further investigation may involve optimising the structural parameters of the foam, improving encapsulation procedures, and incorporating advanced additives such as nanoparticles in the solution to enhance its thermal and mechanical properties for particular uses.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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