Pressure-Enhanced Close-Contact Melting in Phase Change Materials: An Investigation of Butter as a Thermal Management Solution

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Phase-change materials (PCMs) offer a viable alternative for thermal management and thermal energy storage due to their capacity to store substantial latent heat. This study investigates pressure-enhanced close-contact melting in everyday materials like butter, where applied pressure significantly accelerates melting. During solid-to-liquid phase transition, PCMs absorb considerable energy as latent and sensible heat, providing promising alternatives to traditional passive thermal management solutions like heat sinks and radiative cooling. However, widespread industrial PCM adoption remains limited by costs, operational complexity, low thermal conductivity, and degraded heat transfer efficiency as the melt front recedes from the heat source, increasing thermal resistance between heat source and PCM cold source. To experimentally validate our concept and understand the underlying physics, we designed and developed a test setup from scratch. Results confirm our hypothesis that PCMs can reach steady-state under applied pressure, demonstrating that pressure-enhanced close-contact melting increases heat transfer rates by over 10× compared to traditional PCM melting simulated in COMSOL. To investigate the robust correlation found between heat source temperature and applied pressure, alongside effects of material properties and heat flux, we derive a physical model using Fourier's law for 1-D conduction, Navier-Stokes equations for fluid mechanics, and energy conservation principles. Our analysis demonstrates that pressure-enhanced close-contact melting not only accelerates butter's phase transition but also maintains thermal equilibrium, stabilizing heat source temperature over prolonged periods. Finally, we use COMSOL to simulate PCM integration with existing infrastructure.

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