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High power density thermal energy storage using additively manufactured heat exchangers and phase change material

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ABSTRACT

Thermal energy storage using phase change materials (PCMs) is an effective way to store thermal energy. PCMs store thermal energy in the form of latent heat, a promising thermal management methodology for intermittent heat loads. Because the thermal conductivity of many PCMs is relatively low (~0.1 W/(m·K)), high-power thermal storage is possible only when the PCM is integrated with a high thermal conductivity matrix. Enabled by recent advances in metal additive manufacturing (AM), we develop an ultra-compact high-power PCM heat exchanger and demonstrate its performance. The thermal storage device absorbs heat from, or rejects heat to, a flowing liquid coolant. Numerical simulations of heat transfer and phase change within the PCM were used to predict the device performance and evaluate potential designs. AM enabled three-dimensional (3D) metal structures were designed to serve as a matrix that conducts heat into the PCM or as extended surfaces that enhance convection to the liquid coolant. The 3D metal structures reduce conduction thermal resistance by 17X and convection thermal resistance by 3X compared to conventional designs. We fabricated three devices made of an aluminum silicon alloy (AlSi10Mg) and tested these devices with paraffin (C_nH_{2n+2}) PCM. Measurements validated the simulations and showed a 4X improvement in power density (0.58 W/cm^3) compared to conventional designs. This work demonstrates AM as a powerful technique for the development of PCM-based thermal storage systems and suggests design methods that aid the development of heat exchangers.

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1. Introduction

Thermal energy storage using phase change materials (PCMs) is a promising energy management technology capable of storing thermal energy from periodic or intermittent heat sources in the form of latent heat [1–5]. State-of-the-art (SOA) thermal management systems are typically designed to manage the maximum heat load, irrespective of its intermittency. Thermal management solutions that are designed to remove heat during peak power can be highly inefficient, since most of the time the rate of heat removal is well below the maximum capacity. Low efficiency is particularly problematic for transient heat loads such as those that occur in pulsed power applications [1–3,6]. Thermal energy storage using PCMs enables the lowering of the maximum heat dissipation required by storing thermal energy in the PCM, which allows size reduction of thermal management components such as radiators, heat exchangers, and pumps. Potential applications for thermal energy storage using PCMs include indoor-temperature management in buildings [7,8], thermal buffers in temperature sensitive electronics [1–3,9,10], and solar installations [11–13].

Polymeric PCMs are attractive due to the temperature range of their phase transition, typically around 40°C, compared to common metallic PCMs such as Bi-In that melt at 100°C. Paraffin (C_nH_{2n+2}) is a cost-effective and commonly used polymeric PCM and has a heat of fusion of 200 J/g, enabling it to store 400 times more energy in the form of latent heat when compared to raising the temperature of an equivalent mass of steel by 1°C. Paraffin has a thermal conductivity of 0.22 W/(m·K), which is typical for polymeric PCMs whose thermal conductivity can range between 0.1 to 1 W/(m·K) [14]. The low thermal conductivity of polymer PCMs limits the heat transfer rate into and out of the PCM and thus limits the power density (W/m^3) of the storage system. Previous research has focused on enhancing the thermal conductivity of PCMs

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