



## Two-phase heat and mass transfer of phase change materials in thermal management systems



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### ABSTRACT

This paper experimentally and numerically studies the solid–liquid heat transfer mechanism of octadecane which is a phase change material (PCM) with the melting temperature of 28 °C in thermal management systems. This study finds that the convective heat transfer driven by the buoyancy force could be dominant during the melting of pure PCM: the time to melt 30 mm of PCM decreases from 453 min to 13 min when the heating direction changes from downwards to upwards. The use of porous materials such as metal foams (made from Cu, Al or C) with various porosities and pore sizes in the thermal management system significantly increases the overall heat transfer rate due to the increase of effective conductivity. The amount of heat absorption within 60 min significantly increases from 105.6 kJ to 248.9 kJ after using the Al foam with 0.97 porosity. Further decreasing the porosity to 0.925 and 0.88, however, will decrease the amount of absorbed heat to 230.7 kJ and 179.7 kJ because of the decrease of natural convection and the decrease of overall heat capacity. Considering the increase of weight and cost of the thermal management system by using porous materials, the Al foam (compared with C and Cu foams) with the porosity of 0.97 (compared with 0.88 and 0.925) and the pore size of 5.08 mm (compared with 0.64 mm, 1.27 mm, 2.54 mm) is preferred within the porous materials investigated by this study.

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### 1. Introduction

Carbon emissions have been consistently increasing since the Industrial Revolution and show little signs of reversal [1]. In response to this rising trend, the US Environmental Protection Agency (EPA) has developed various regulatory standards for cars; e.g., the Corporate Average Fuel Economy (CAFE) [2]. The upcoming average standard of 54.5 miles per gallon for the fleet by model year 2025 has resulted in turning to hybrid, plug-in hybrid, and electric vehicles. The EPA is even incentivizing these types of vehicles along with fuel cell and compressed natural gas vehicles sold in model years 2017–2021 [3]. This is leading to an increase in interest from the public for electric and fuel cell vehicle technology [4]. However, vehicles that use battery packs and fuel cells have numerous operational challenges including, but not limited to, cold winter weather and prolonged usage that leads to relatively high temperatures [5]. A proton exchange membrane fuel cell (PEMFC) operates through a chemical reaction between hydrogen and oxygen that generates electricity and water. The water freezes in

sub-zero conditions and impairs the fuel cell's cold-start ability and efficiency [6]. Cold winter temperatures also pose a challenge to lithium-ion batteries [7]. Most of these temperature related issues, however, can be eliminated by the development of a proper thermal management system. The desired thermal management system for a fuel cell or battery pack will prevent it from overheating, its by-products from freezing, and ideally maximize its efficiency.

With the goal of encouraging the use of fuel cells and battery packs in electric vehicles, research and development of both active and passive thermal management systems have been carried out. Unlike typical active thermal management systems that employ convective air or liquid cooling, this study is centered on passive thermal management systems using phase change materials (PCMs). Passive thermal management is more cost-effective and reliable because it does not require auxiliary devices such as pumps or blowers [8–10]. However, PCM alone is difficult to employ efficiently due to the fact that PCM, like paraffin waxes, tend to have relatively low thermal conductivities. Furthermore, the expansion and contraction of PCM due to its density change leads to air bubbles or gaps which further decrease the heat transfer rate. It has been shown that the most significant driver of heat

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## Nomenclature

$c$	specific heat	<i>Greek</i>	
$d$	pore mean diameter	$\beta$	thermal expansion coefficient
$\bar{g}$	gravitational acceleration	$\gamma$	liquid fraction of PCM
$h$	enthalpy	$\delta T$	half width of mushy zone temperature range
$h_{sl}$	latent heat of fusion	$\varepsilon$	porosity
$K$	permeability	$\mu$	viscosity
$k$	thermal conductivity	$\nu$	kinematic viscosity
$Pr$	Prandtl number	$\rho$	density
$p$	pressure		
$s$	source term in temperature transforming model	<i>Subscripts</i>	
$T$	temperature	$c$	cold surface
$T_m$	melting temperature	$eff$	effective
$T^*$	relative temperature ( $T - T_m$ )	$h$	hot surface
$t$	time	$l$	liquid phase
$u, v$	superficial velocity components	$m$	metal foam
$u_i, v_i$	liquid velocity components	$s$	solid phase
$x, y$	coordinates		

transfer within a PCM is natural convection once the PCM melts [11]. In order to facilitate heat transfer, research on the inclusion of various aids (e.g., heat pipes, metal foams, nanofluid) to increase heat flow within the PCM has been performed.

Sharifi et al. [12], conducted an experiment in which vertical copper rods, copper hollow tubes, and copper water heat pipes were embedded in sodium nitrate (PCM) and the rate of melting of the sodium nitrate was compared. It was found that the melting rate of the PCM was the greatest through the utilization of the heat pipe when compared to the other options. Another experiment by Sharifi et al. [13] expanded on this result, showing that outfitting the embedded heat pipes with aluminum foil fins could further increase the heat transfer, as heat could now conduct through the fins into the PCM. The melting rates for the heat pipe with the aluminum foil fins were approximately 300% higher than for a copper rod, and 200% higher than an unadorned heat pipe. The increase in heat transfer was also demonstrated in the solidification processes with the finned heat pipe supplying a rate of solidification 900% higher than the copper rod, and 600% higher than the plain heat pipe.

Sari and Karaipekli [14] developed form-stable composite PCM by absorbing paraffin (*n*-docosane) into expanded graphite (EG). The thermal conductivity of the composite PCM increased from 0.40 to 0.52, 0.68 and 0.82 W/m K when the mass fraction of the EG was increased from 2 to 4, 7, and 10 wt% (the thermal conductivity of pure *n*-docosane is 0.22 W/m K). The increasing thermal conductivity of paraffin decreased its melting time by up to 32% (10 wt% EG) compared to the melting time of the pure paraffin. The study suggested that a form-stable composite PCM with a mass fraction of 10% EG as the most promising PCM for thermal energy storage using LHTES method considering its stability, thermal conductivity and latent heat capacity. The numerical study of Cu/paraffin nanofluids PCM carried out by Wu et al. [15] indicated that the melting time of the PCM can be saved by 13.1% when 1 wt % Cu nano particles are added in the paraffin. A comprehensive review of composite PCM made from paraffin and foam materials, expanded graphite, carbon nano materials and graphene based materials can be found from Zhang et al. [16].

Meanwhile, experiments and numerical simulations of solid–liquid phase change of PCM in porous media made from glass beads, aluminum beads, and stainless steel particles have been carried out. Ellinger and Beckerman and Viskanta [17] studied solid–liquid phase change of gallium–octadecane in porous matrix

composed of glass or aluminum beads with different sizes (5.98–11.02 mm) that partially fills a cavity by experiments. This study found that conduction is dominant at the initial melting period. The high effective thermal conductivity of the porous layer resulted in a faster melting. The convective flow is weaker in porous layer, relative to the pure PCM layer, due to the lower permeability. Due to the strong natural convection reduction caused by the low porosity (0.35–0.42) of porous layers, the investigated porous layers, however, did not enhance the melting rate compared to the pure PCM.

Damronglerd and Zhang [18] numerically investigated the melting of copper in stainless steel particles (the porosity is 0.385). They used a modified temperature-transforming model that considers the dependence of heat capacity on the fractions of a solid and liquid in the mushy zone. Their results showed that the conductive heat transfer could suppress the convective heat transfer if materials with high thermal conductivities are used (e.g. melting of copper in stainless steel particles). Both the increase of the Rayleigh number and the increase of Darcy number will increase the convective heat transfer due to the higher driven force (higher temperature gradient) and less resistance (less drag force from the porous wall), respectively. Similar conclusions are made by Chen et al. [19] using an interfacial tracking method to investigate a two-dimensional melting problems in porous media.

The porosity of the porous media in the above mentioned model studies, however, are low (less than 0.5). Considering the fact that thermal management systems of the power system needs to be compact and efficient, porous media with very high porosity (close to 1) are desirable. Although the single-phase heat transfer of fluid (e.g. air) in metal foams has been studied by experiments and numerical simulations [20,21], the solid–liquid phase change of PCM in porous media with high porosity such as metal foams requires more detailed studies [22,23]. The thermal management system in this study uses octadecane as the PCM and makes use of the latent heat of the PCM to store released thermal energy during operation and supply energy back to the energy source when dormant. Octadecane is chosen as the phase change material since the thermophysical properties of octadecane are well known and pure octadecane is commercially available. Although PCM materials other than octadecane may be used in real thermal management systems considering the safety, operating temperature, stability, cost etc, the mechanism of liquid–solid two phase transfer investigated in this study applies to other PCM as well.

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