

Numerical Investigation of Phase Change Materials for Thermal Management Systems

Taha Aldoss

Jordan University of Science & Technology

David J. Ewing, Yan Zhao and Lin Ma

Clemson University

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ABSTRACT

Phase change materials (PCMs) are extensively used in many engineering areas for thermal management purposes. This paper investigated the application of PCMs for vehicular systems, especially for the thermal protection of vehicle lighting systems based on light emitting diodes (LEDs). Lighting systems based on LEDs offer many advantages, however, also pose a smaller margin of error for thermal management. This paper analyzed the combined use of PCMs with metal foam for cooling systems. The cooling performance was studied numerically under different porosity values of the metal foam, and different boundary conditions. The cooling performance was also compared to a solid metal sink system (SMS) and was found to offer several distinct cooling characteristics.

NOMENCLATURE

b = half thickness of bump in hexagonal structure of metal foam
 CMS = cooling management system
 SMS = solid management system
 T = temperature
 T_M = melting temperature of PCM
 T_S = solidus temperature of PCM
 T_L = liquidus temperature of PCM
 D = Diameter of CMS and SMS unit
 H = height of CMS and SMS unit
 h = convective heat transfer

Q = heat added to system
 C_P = specific heat at constant pressure
 C_{Peff} = combined effective specific heat of conductor and PCM
 $(\rho C_P)_{MF}$ = (ρC_P) of the metal foam
 $(\rho C_P)_{PCM}$ = (ρC_P) of the PCM
 k = thermal conductivity
 k_{MF} = thermal conductivity of the metal foam
 k_s = thermal conductivity of solid metal foam
 k_f = thermal conductivity of PCM at its respective solid or liquid phase
 k_{PCM} = thermal conductivity of the PCM
 k_{eff} = combined effective thermal conductivity of conductor and PCM
 r = area ratio of the solid fiber to void area
 h_{ref} = reference enthalpy
 h_{sens} = sensible enthalpy
 T_{ref} = reference temperature
 L = latent heat
 L_f = half length of fiber of metal foam
 S_h = source term to correct the latent heat variation during the melting process
 ΔH = heat of fusion
 H_{tot} = total enthalpy of material
 Δt = time step
 FC = forced convection condition
 NC = natural convection condition
 AD = Adiabatic condition

GREEK SYMBOLS

- ρ = density
 ρ_{MF} = density of the metal foam
 ρ_{PCM} = density of the PCM
 ρ_{eff} = effective density
 ε = volume fraction of the PCM
 β = liquid fraction

INTRODUCTION

Phase change materials (PCMs) are extensively used in many engineering applications. They are used in energy storage systems¹, electronics cooling systems², building materials for energy storage improvement³, heat exchangers⁴, and many other similar applications. This paper investigated the applications of PMCs for the thermal management in vehicular systems, especially the thermal management of vehicle lighting systems based on light emitting diodes (LEDs). Lighting systems based on LEDs offer many advantages, including improved energy efficiency and potential for weight reduction. However, such lighting systems also pose a smaller margin of error for thermal management because LEDs can be permanently damaged if their operation temperature exceeds a critical temperature. Furthermore, the output power of LEDs varies significantly with the operation temperature. Therefore, a better thermal management technique is desired for such light systems.

A cooling management system (CMS) based on PCMs appear very attractive for this purpose because a PCM essentially behaves as a thermal switch. When the operation temperature of the lighting systems begins to exceed that of the melting temperature of the PCM, the temperature of the system stops increasing until the PCM is completely melted. Therefore, CMS based on PCMs show good promise to tightly control the temperature of LEDs. But as described above, the operation time of the CMS is fundamentally limited by the melting time of the PCM, which was a key parameter to be investigated in this study. The investigation was focused on maximizing the operation time of the CMS while still operating under specified sizing and other restraints.

More specifically, PCMs are characterized by their T_M , ΔH , and their T_S and T_L (Other properties may need to be considered for specific applications, e.g., ρ , chemical stability, safety, and flammability⁵). Once the operating temperature of the system being cooled reaches the T_L of the PCM, the PCM begins to melt and stores the thermal energy that the system releases during this process. The amount of thermal energy that the PCM can store depends on its ΔH and amount. During the melting process, the PCM and, therefore, the system temperature remain nearly constant. The duration of the melting process delays the system from reaching its maximum operational temperature, which prolongs the

operational time of the system where the operational time is defined as the amount of time it takes for the system to reach its maximum operational temperature. This operational time gain depends heavily on the PCM mass ratio and the PCM thermophysical properties k , ρ , ΔH , T_M , and C_P . The configuration of the unit containing the PCM, such as the thermal properties and the distribution of a thermal conductivity enhancer that encapsulates the PCM, also affects the system's performance^{6,7}.

It is known that the PCM's conductivity plays a very important role in the cooling system's performance⁷. Higher conductivity is usually preferred, because it aids in heat distribution, more uniform PCM melting process, and overall effectiveness of the CMS. Consequently, a higher conductivity of the PCM would increase the heat transfer rate and prolong the operational time of the lighting system. However, many PCMs have relatively low conductivity. For example, organic PCMs exhibit very low relatively conductivity, even though they, in comparison with metallic PCMs, are less corrosive, more readily available, and less costly. In order to improve the overall effective conductivity of the CMS to leverage the advantages of such organic PCMs, many researchers suggest filling the PCM into a honeycomb structure or mixing it with metal foam conductors^{8,9}. However, with a fixed size for the CMS unit, increasing the effective conductivity of the system will decrease the effective mass of the PCM material. This, in turn, reduces the heat storage potential of the system, thereby, reducing the operational time of the lighting system. Hence, this paper analyzed the optimal volume fraction of the PCM for attaining the maximum operational time at a fixed size for the CMS unit.

PROBLEM FORMULATION

During the phase change process (melting or solidification), the PCM encapsulated in a porous material, in this case, metal foam (MF), can exist in three states: solid, liquid, and a two phase mixture. Additionally, the thermal properties of a PCM-MF matrix are different from the constituent properties. To simplify the mathematical model, the PCM-MF combination can be treated as a body of uniform equivalent physical and thermal properties—principally C_P , ρ , and k of the PCM and MF. The effective properties of the mixture are calculated based on the volume ratio, ε , of the PCM material in the mixture, as follows:

$$(C_P)_{eff} = [(1 - \varepsilon)(\rho C_P)_{MF} + (\rho C_P)_{PCM}] / \rho_{eff} \quad (1)$$

$$\text{where } \rho_{eff} = (1 - \varepsilon)\rho_{MF} + \varepsilon \rho_{PCM} \quad (2)$$

and as derived in¹⁰

$$k_{eff} = \left(\left(\frac{2}{\sqrt{3}} \right) + \frac{\frac{r(b/L_f)}{k_f + (1/3)(1+b/L_f)(k_s - k_f)}}{\frac{(1-r)(b/L_f)}{k_f + (2/3)(b/L_f)(k_s - k_f)}} + \frac{\sqrt{3}/2 - b/L_f}{k_f + (4r/3\sqrt{3})(b/L_f)(k_s - k_f)} \right)^{-1} \quad (3)$$

where b/L_f is given by the following expression

$$\frac{b}{L_f} = \frac{-r + \sqrt{r^2 + \frac{2}{\sqrt{3}}(1-\varepsilon)\left(2-r\left(1+\frac{4}{\sqrt{3}}\right)\right)}}{\frac{2}{3}\left(2-r\left(1+\frac{4}{\sqrt{3}}\right)\right)} \quad (4)$$

Or, in a more simplified yet reasonably accurate form, k_{eff} can be calculated as follows¹¹:

$$k_{eff} = (1-\varepsilon)k_{MF} + \varepsilon k_{PCM} \quad (5)$$

This analysis performed in the paper was based on Equation (5). Also, instead of tracking the liquid-solid front explicitly, the enthalpy-porosity formulation can be used in this type of application. The two phase zone is treated as a porous zone with porosity equal to β , the liquid fraction, which is defined in the following Equation (6):

$$\begin{aligned} \beta &= 0 & \text{if } T < T_s \\ \beta &= 1 & \text{if } T > T_l \\ \beta &= \frac{T - T_s}{T_l - T_s} & \text{if } T < T_s \end{aligned} \quad (6)$$

With this definition (also referred to as the lever rule¹²), an enthalpy-porosity technique can be used for modeling the melting process⁹. The two phase zone is a region in which β of the PCM lies between 0 and 1, with 1 corresponding to the PCM being fully melted and 0 corresponding to the PCM being fully solid. The two phase zone is modeled as a "pseudo" porous medium in which the porosity decreases from 1 to 0 as the material melts. When the material has fully melted in the cell, the porosity becomes 0.

The enthalpy of the material is computed as the sum of h_{sens} , and ΔH :

$$H_{tot} = h_{sens} + \Delta H \quad (7)$$

where

$$h_{sens} = h_{ref} + \int_{T_{ref}}^T c_p dT \quad (8)$$

The latent heat content of the PCM (a mixture of melted liquid and unmelted solid), L , can now be written in terms of L and β as follows:

$$\Delta H = \beta L \quad (9)$$

Obviously, the latent heat content, L , varies between zero (for a pure solid) and L (for a liquid).

For solidification/melting problems, the energy equation can be written as¹²

$$\partial(\rho C_p T)/\partial T = \nabla \cdot (k \nabla T) + S_h \quad (10)$$

Where S_h is the source term to account for the latent heat variation during the melting process. It is represented by:

$$S_h = -\rho \partial(\Delta H)/\partial T \quad (11)$$

And ΔH is calculated utilizing the lever rule from Equation (6).

Now, temperature can be solved for by the interaction between the energy equation and the liquid fraction equation.

THE PHYSICAL PROBLEM AND THE PCM MATERIAL PROPERTIES

The physical problem was defined according to the design constraints of an LED light system. The heat input from the vehicle's lighting system was given to be a total of 73.5 W. The maximum permissible temperature of the lighting system was not to exceed 90°C and the ambient temperature was given to be 27°C. The problem is assumed to be conduction-dominated within the CMS unit, thus the internal natural convective heat transfer effect of the PCM can be neglected.

The geometry of the CMS consisted of a cylindrical container of aluminum material. The container contains a mixture of a PCM suspended in an aluminum metal foam. Figure 1 shows the sketch of the CMS unit. The diameter (D) and height (H) of the domain were 10 cm and 10 cm, respectively.

Three operating conditions were considered in this investigation, by assuming three different boundary conditions. In the first case the unit is assumed to be fitted outside the engine-hood, exposed to an ambient temperature of 27°C, and air velocity of 40 kilometers per hour (the average speed of the vehicle). This gave an average convective heat transfer rate of $14 \text{ W/m}^2\text{K}$.