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Temperature of a metallic nanoparticle embedded in a phase change media exposed to radiation

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ABSTRACT

Over the past few years, researchers have introduced nanoparticles of varying sizes within a phase change material which enhances the thermal energy and the efficiency of the thermal capacity. A numerical analysis of a metallic nanoparticle embedded in a phase change material exposed to radiation is presented. This analysis includes plasmonic properties of metals when exposed to solar frequencies. Simulations of the model are initiated with a single metallic nanoparticle in a solid medium. When the particle temperature exceeds the phase change temperature an insulating liquid film forms around the particle. The temperature profiles of the solid medium, liquid film, and particle of different materials and particle diameters submerged in different mediums are presented. A thermal interface resistance between the particle and liquid film is included. It is shown that the larger particle heats faster, developing a smaller surrounding film and may eventually have a temperature that surpasses the melting temperature of the material. A compromise must be made between the thermal resistance caused by the particle/film interface and film as well as the absorption from radiation to determine the proper particle type, size, and medium for thermal storage.

1. Introduction

Thermal energy storage is captured when there is a change in internal energy of a material caused by latent heat, sensible heat, and/or heat caused by a thermal–chemical process. For the past ten years, latent heat storage has shown to be an attractive approach for thermal storage because large amounts of heat can be stored in small volumes with small temperature differences in the media. Thermal energy is accumulated in this material when a rise in temperature causes the phase change material (PCM) to change from a solid to liquid or liquid to vapor through the heat of fusion or heat of vaporization, respectively. Using a PCM provides a higher heat storage capacity with lower storage temperature.

Over the past decade, many people have studied the use of PCM for thermal storage [1–6]. Materials that utilize the phase change between solid and liquid have proved to be most effective. The solid–liquid PCMs comprise of organic, inorganic, and eutectic materials. Paraffins and salt hydrates are the typical choice for the PCM and more information on these types of materials can be found in [1–3]. Paraffins are compounds composed of hydrogen and carbon where all the atoms are linked by single bonds, i.e. C_nH_{2n+2}. All paraffins are colorless and odorless and are transparent in the visible range [7,8]. Paraffins between C_5 and C_{15} are liquids and the rest are waxy solids at room temperature with melting temperatures dependent on the number of carbons it contains ranging from 23–67 °C. The melting temperature increases as the number of carbons increases [9]. The paraffin used in these calculations is n-octadecane ($C_{18}H_{38}$). This material is commonly used to make crayons, candles, and electrical insulation and is affordable.

In 2007, Khodadadi and Hossenizadeh [10] proposed the idea of placing nanoparticles within the phase change material in order to improve thermal storage. In Khodadadi and Hossenizadeh's paper [10], they placed copper (Cu) nanoparticles of various concentrations into water and numerically simulated the solidification of a nanofluid in a square storage model. Fan and Khodadadi [11,12] and Nabil and Khodadadi [13] provided experimental insight of cyclohexane and eicosane both mixed with copper oxide (CuO_2) nanoparticles. This showed that the freezing rate was increased compared to the fluid with no nanoparticles because of the enhanced thermal conductivity. Hasadi and Khodadadi [14] numerically simulated the solidification of copper (Cu) nanoparticles in water. Dhaidan et al. [15] showed experimentally and numerically the increase of the thermal conductivity using the mixture of n-octadecane with copper oxide (CuO_2) nanoparticles

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Nomenclature

A	surface area (m^2)
a_0	molecular diameter (m)
C_{abs}	cross-sections (m^2)
c	specific heat (J/kg K)
d	diameter (m)
F	interfacial force (N)
g_o	gravity (m/s^2)
h_{sl}	latent heat of fusion (J/kg)
I_{inc}	incident intensity (W/m^2)
k	wavenumber (m^{-1})
$\hat{k}$	thermal conductivity (W/m K)
m''	mass flow rate (kg/m^2 s)
P	parameter for polarizability
p	pressure ($kg/m\ s^2$)
Q_{abs}	heat (W)
$\tilde{r}$	interface resistance (m^2 K/W)
$\tilde{R}$	resistance (K/W)
r	radial direction (m)
tot	total
θ	tangential direction
t	time (s)
V_p	volume (m^3)
v	velocity (m/s)

Greek variables

α	polarizability (m^3)
$\hat{\alpha}$	thermal diffusivity (m^2/s)
$\Delta\gamma_0$	interfacial energies (kg/s^2)
$\hat{\gamma}$	damping term (s^{-1})
ε	permittivity
ε_∞	permittivity bulk
θ	tangential direction
T	temperature (K)

Subscripts

$crit$	critical
f	film
ii	step in time
i	interface
j	type of medium
l	liquid
m	melting
n	step in space
p	particle
$plasma$	plasma
r	direction
s	solid
sl	solid/liquid interface
ρ	density (kg/m^3)
λ	wavelength (m)
ω	frequency (s^{-1})

Non-dimensional variables

R	radial direction
τ	time
Θ	temperature
$\hat{V}$	velocity
ϕ	film diameter
TLR	temperature loss ratio

in a square enclosure subjected to a constant heat flux from one side. Aluminum nanoparticles and silica oxide (SiO_2) nanoparticles were mixed with n-nonadecane, n-eicosane, n-heneicosane, and n-docosane in a molecular dynamic simulation to determine the size of the particle provided by Rao et al. [16]. Cingarapu et al. [17] studied the viscosity, thermal conductivity, and total heat absorption of silica encapsulated tin (Sn/SiO_2) nanoparticles dispersed in a synthetic HFT Therminol 66 (TH66) fluid. Chieruzzi et al. [18] studied the effect of heat capacity when the base fluid was the salt mixture $NaNO_3$–KNO_3 with nanoparticles of silica (SiO_2), alumina (Al_2O_3), titana (TiO_2), and a mix of silica alumina (SiO_2–Al_2O_3). A computational fluid dynamics program, FLUENT, was used by Jegadheeswaran and Pohekar [19] who explored the heat transfer characteristics of micron sized copper particles during both charging and discharging modes. Ho and Gao [20] experimentally investigated how the thermal physical properties such as density, viscosity, and thermal conductivity with alumina (Al_2O_3) nanoparticles in paraffin (n-octadecane) are affected. The melting/freezing characteristics of paraffin and copper nanoparticles were studied by Wu et al. [21,22]. Wu showed that the melting/freezing rates were enhanced due to adding the nanoparticles. Zeng et al. enhanced the thermal conductivity of paraffin (n-octadecane) using silver (Ag) particles [23], silver (Ag) nanowires [24], and multiwalled carbon nanotubes [25]. All of these papers presented above concentrated on the enhancement of the thermal properties of various combinations of mediums and particles.

Around the particle, the temperature may exceed the melting temperature causing a liquid film to form surrounding the metal sphere and begin the two phase process, see Fig. 1. When considering solid/liquid phase change there are numerical and experimental analysis of freezing and melting paraffin wax and water in spherical enclosures [26–29]. Only a few papers have concentrated on the single particle interaction between a solid and liquid film. Uhlmann and Chalmers [30] shows that there exists a force between the solid interface and the particle that prevents the particle to lay on the solid surface unless the force of gravity is greater than the buoyant force. Shangguan et al. [31] and Garvin and Udaykumar [32] provide numerical analysis of particles experiencing the interface forces against a planar solid surface. Bulunti and Arslanturk [33] numerically investigated an inward melting of a sphere subject to radiation and convection. The focus of this paper is to understand how one metallic nanoparticle of various sizes and compositions inside a phase change material is affected when exposed to radiation.

1.1. Plasmonic properties

Mechanical engineers, biologists, physicists, and chemists have all taken interest in studying metallic nanoparticles because they have unique, tunable absorption and scattering properties when interacting with photons. Gold (Au), silver (Ag), aluminum (Al),

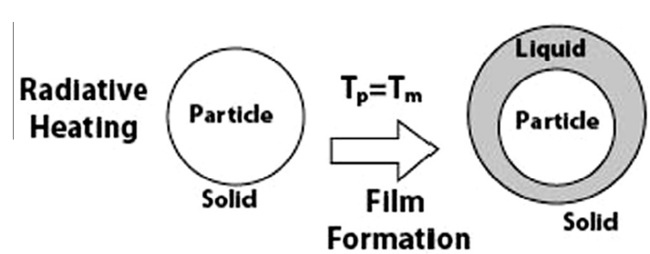

Fig. 1. Film formulations of one nanoparticle when it reaches the melting temperature.