NUMERICAL STUDY ON SOLIDIFICATION/MELTING OF PHASE CHANGE MATERIAL IN THERMAL MANAGEMENT SYSTEM

12/09/2021

Term Project for MAE-8311 Heat Transfer-Convection

Submitted By

Meftah Uddin

Supervisor

Dr. Chanwoo Park

Department of Mechanical and Aerospace Engineering

University of Missouri, Columbia, MO 65211, USA

Abstract

Thermal management of electronic systems is becoming challenging because of the integrated and complex design of the components. Electronic components generate heat during their operation, and the heat should be driven out to surroundings on a continuous basis to achieve proper functioning. Solid-liquid phase change materials (PCM) have been widely examined for active thermal management of electronic devices. The advantages of PCM for thermal management are high specific heat, high latent heat of fusion, and small volume changes on phase change [1]. PCM absorbs heat during power-on operation and releases heat at another time. The phase change of PCM is important because PCM absorbs latent heat of fusion from electronics when it melts, and it can be solidified once it can release heat to its surroundings. The effectiveness of latent heat storage system depends on efficient heat transfer to and from PCM during melting and solidification, respectively. In this study, we will numerically assess the effect of natural convection during melting process of PCM at vertical orientation.

1. Introduction

Global energy demands are rising gradually. Researchers and engineers are struggling to find alternative energy sources to replace conventional fossil fuels and reduce the emission of CO2. A thermal energy storage system (TESS) is one of the most promising alternatives to replace conventional energy sources. There are mainly three types of TESS depending on the way heat is stored: thermochemical, sensible, latent. Latent heat storage system provides high energy storage density compared to sensible storage system and absorbs & delivers heat at nearly constant temperature.

Among several TEES, solid-liquid phage changes material (PCM) based latent thermal energy storage system (LTESS) are most attractive and promising. PCM has a very high thermal storage capacity. However, due to low thermal conductivity, an effective heat exchanger design is required. The commonly used shell and tubes heat exchangers are tested as prototypes for LTESS in some studies [2]. To simplify the study, this type of heat exchanger can be modeled as a sum of annular PCM storage [3,4]. The PCM fills the annular space, and heat transfer fluid (HTF) circulates through the inside tube.

Although natural convection takes place during the melting/charging process of PCM, numerical results obtained by Chiu and Martin [5] without modeling the natural convection correspond to their experimental results. This finding represents that the effect of natural convection during melting/solidification depends on the properties and thickness of PCM.

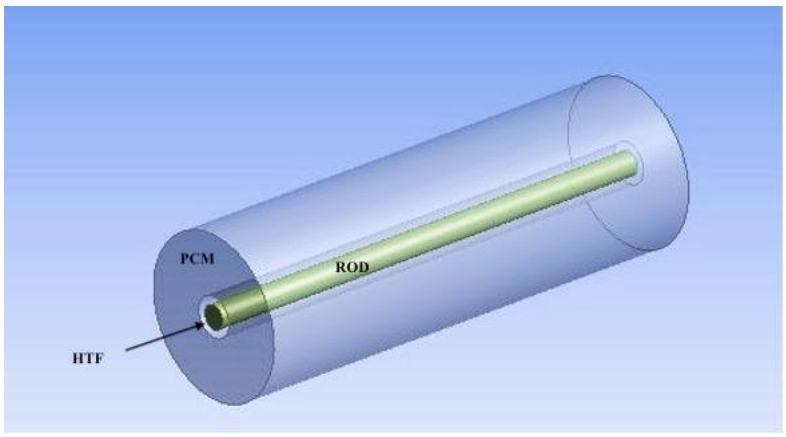
The proposed study is of the calculation of transient mass fraction of PCM, in which the liquid fraction of PCM will be measured with respect to time during its phase change/melting. The liquid fraction inside PCM will be calculated numerically using ANSYS Fluent 2019. The effect of natural convection on the phase change for vertical orientation of heat exchangers were observed.

2. Model Description

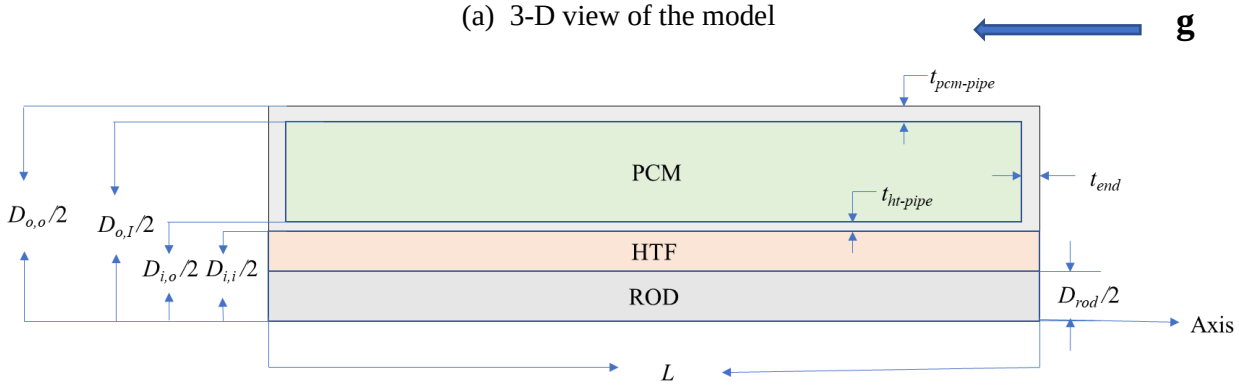
In our model, 50 % (v/v) ethylene glycol-water is use as HTF and gallium is used PCM. Properties of these materials are given in table 2. Both the pipes containing PCM and HTF are made of stainless-steel of different dimensions. The dimensions of the model are represented in figure 1 and corresponding values are given in table 1. HTF enters the system with an inlet velocity of v_i and circulates through the inner pipe having diameter $D_{i,i.}$ To make the flow laminar, a rod is places inside the inner pipe. Heat is transfer from HTF to PCM contour via conduction through the coupling pipe wall between HTF & PCM. The outer walls of PCM contour are insulated.

Study [5] shows that we can model the CFD simulation of 3-D annular problem as 2-D without any compromise of the results. In our study, 2-D axisymmetric model is used to numerically simulate the melting process in ANSYS fluent. The SIMPLE method was used for the pressure-velocity coupling in

the continuity equation, second-order upwind schemes were used for the mass, momentum, and energy equations. PRESTO was used for pressure correlation equation. The relaxation factors were used as default: 0.3 for pressure, 0.7 for momentum, 0.9 for the melt fraction, and 1 for energy.



(a) 3-D view of the model



(a) 2-D axisymmetric view

Fig 1. Model of the annular heat exchanger.

The convergence criteria for continuity and three momentum equations were 10^{-6} and 10^{-9} for energy equation.

Table 1. Dimensions of the annular heat exchanger model.

L (mm)	$D_{0,0}$ (mm)	$D_{o,i}$ (mm)	$D_{i,o}$ (mm)	$D_{i,i}$ (mm)	D_{rod} (mm)	t_{end} (mm)	$t_{pcm-pipe}$ (mm)	$t_{ht-pipe}$ (mm)
150.5	50.8	47.4	12.7	10.922	7.62	2.023	1.7	0.889

For this CFD simulation a suitable meshing is necessary. In our study, quadrilateral mesh of element size 16,500 was used. ANSYS fluent uses pressure based solver for the numerical calculation of solidification/melting.

Table 2. Thermophysical properties of PCM (Gallium) and HTF (50 % v/v ethylene glycol-water).

Property	PCM	HTF
Latent heat of fusion (ΔH_f)	80,160 kJ/kg	0 kJ/kg
Melting temperature (T_m) (Used for both solidus & liquidus temperature)	302.93 K	0 K
Thermal conductivity (k)	32 W/m-K	0.4 W/m-K
Specific heat at constant pressure (c_p)	381.5 kJ/kg-k	3565 KJ/kg-K
Density (ρ)	6093 kg/m^3	1060 kg/m^3
Dynamic viscosity (μ)	0.0018 Pa-s	0.00157 Pa-s

3. Mathematical formulation

In our CFD problem, HFT and PCM are the fluid domain, and pipe walls and stainless rod are solid domain. The governing equations of conservation of mass, momentum, and energy used for fluid domain are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\, \bar{u}) = 0 \qquad (1)$$

$$\frac{\partial \rho \bar{u}}{\partial t} + \nabla.(\rho \bar{u}\bar{u}) = \nabla(\rho) + \nabla(\bar{\tau}) + \rho\bar{g} + F \qquad (2)$$

$$\frac{\partial (\rho h)}{\partial t} + \nabla.\ (\rho \bar{u} h) = \nabla(k\ \nabla T) \qquad (3)$$

Where, ρ is the density, $\bar{u}$ is the velocity vector, T is the temperature, P is the static pressure, and t is the time. F, $\bar{\tau}$, $\rho\bar{g}$ are the momentum source term, stress tensor, and gravitational body force respectively. In our case unidirectional flow was considered, so $\bar{\tau}$ is equal to ∞. The "solidification and melting" model in ANSYS is based on enthalpy-porosity method. In this method, a porous region called "mushy zone" [8] represents a zone where both sold and liquid phases coexist. The porosity of each meshing element in mushy zone is described by the liquid mass fraction (f). The value of f is described as follow:

$$f = \begin{cases} 0 & if \quad T < T_{sol} \\ \dfrac{T - T_{sol}}{T_{liq} - T_{sol}} & if \quad T_{sol} < T < T_{liq} \\ 1 & if \quad T > T_{liq} \end{cases} \qquad (4)$$

In equation (4), T_{sol} *and* T_{liq} are the solidus and liquidus temperature of PCM. Since gallium is a pure metal, we considered both T_{sol} *and* T_{liq} their melting temperature (T_m) [9]. The source term F is expressed as,

$$F = \frac{(1-f)^2}{f^3+\epsilon} A_{mush} \bar{u} \qquad (5)$$

In equation (5), ϵ is a small numerical constant (usually the value is 10^{-3}) used to avoid floating point error during division. A_{mush} is mushy zone constant. Study [6] shows that changing A_{mush} value has little effect on the rate of melting for low Prandtl PCM like gallium (Pr = 0.025), A_{mush} value of 10^{-9} was chosen for our study. The specific enthalpy h_{en} of PCM is the sum of latent enthalpy h_{lat} and sensible enthalpy h_{sen} which is given by, $h_{en} = h_{sen} + h_{lat}$.

Sensible heat is the amount of energy required to increase the temperature of a material as follow:

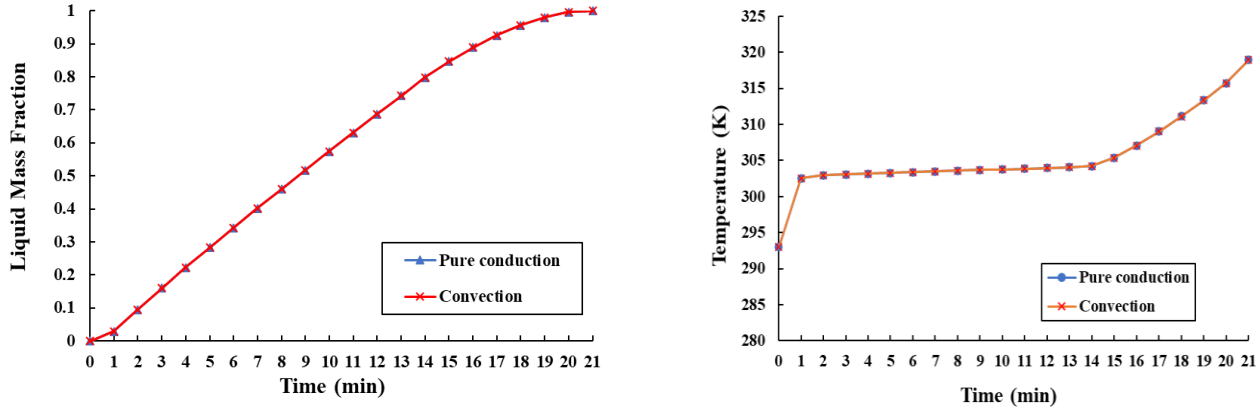
$$h_{sen} = \int_{T_{ref}}^{T} c_p dT, \text{ and} \quad (6)$$

$$h_{lat} = f L_{fusion} \quad (7)$$

Where, L_{fusion} stands for the latent heat of fusion that is energy required to change the phase from solid to its liquid state.

4. Results

In our CFD model, we considered the heat exchanger on vertical orientation. HTF flow from bottom with an inlet velocity (v_i) of 0.5 *m/s* and temperature (T_i) of 323 K. The PCM pipe outside walls (thickness $t_{pcm\text{-}pipe}$ = 1.7 mm), two end caps (thickness t_{end} = 2.023 mm) are insulated and heat is transferred from HTF pipe to PCM via couple wall. We ran the simulation for pure conduction case (without gravity) and for natural convection case (with gravity). The results were given in figure 2.

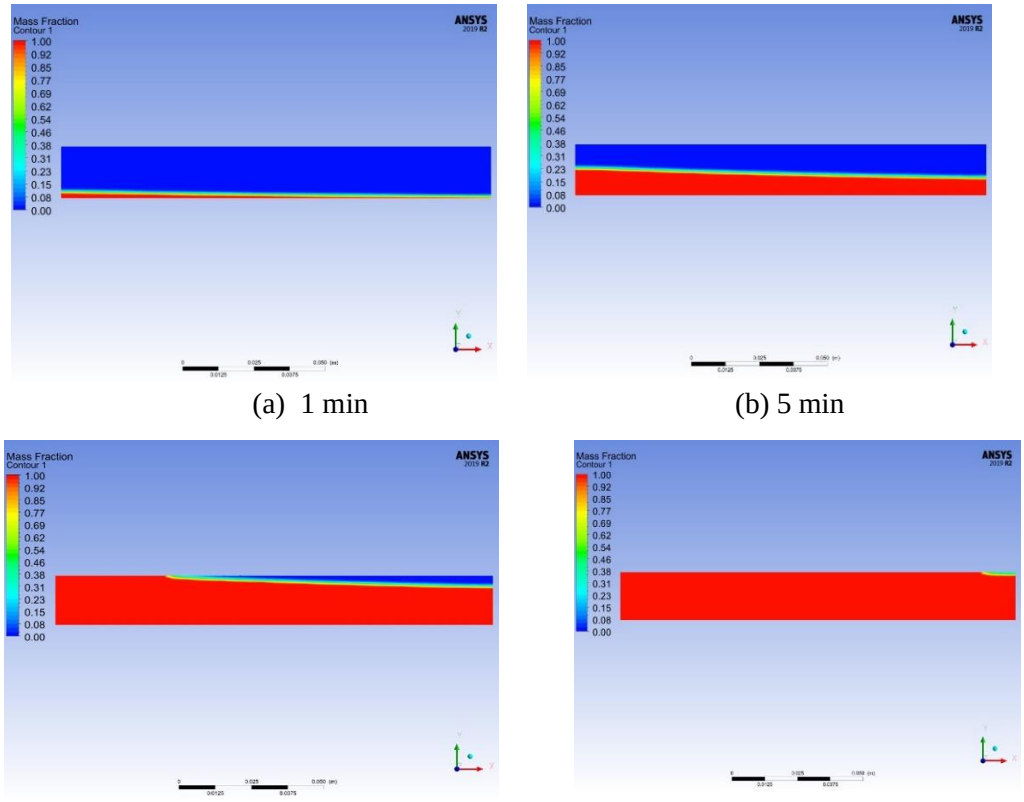


(a) (b)

Fig 2. (a) Liquid mass fraction (*f*) of PCM versus flow time (*t*), (b) average temperature (T_{avg}) of PCM contour versus flow time.

From Fig 3, we can see that melting (red) started from left portion (bottom side of the heat exchanger) of the PCM contour. HTF flows through this side inside HTF pipe. We got negligible effects for those orientations and directions, and so we only represented the vertical orientations with flow direction from bottom. Our study can be expended to study the effect of reciprocating flow on the melting time of PCM. We can also increase the dimensions of our PCM domain to observe the effect of natural convection.

From Fig 2, we can see that the curves for pure conduction and convection coincided for both melt fraction and average temperature. We can conclude that for our model, the effect of natural convection is negligible. In Fig 2 (a), around 20 mins time were required for complete melting of the PCM. We can also see that the average temperature of PCM remained almost constant between 302-303K (for gallium, T_m =302.93K) from 1 min to 14 min of flow time. The initial temperature rise is due to the sensible heat gain of the PCM. This results completely agree with the fact that PCM melts at nearly constant temperature close to its melting temperature.



(a) 1 min (b) 5 min

(c) 15 min (d) 20 min

Fig 3. Liquid mass fraction (red zone) of PCM versus flow time for pure conduction case.

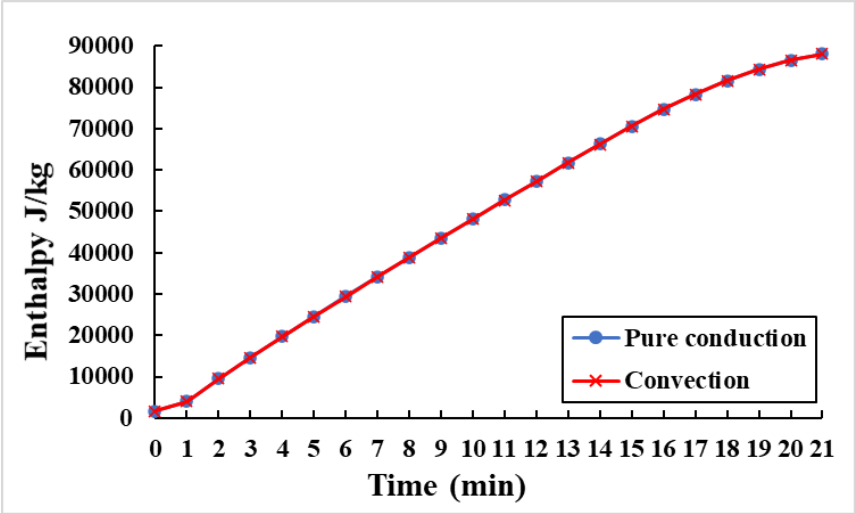
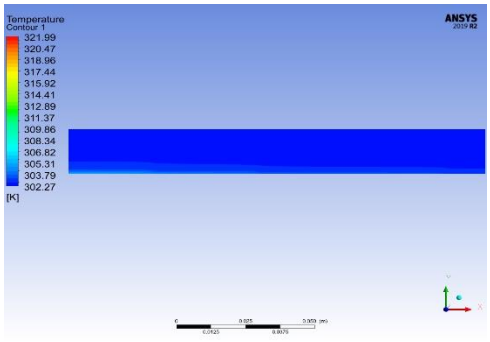
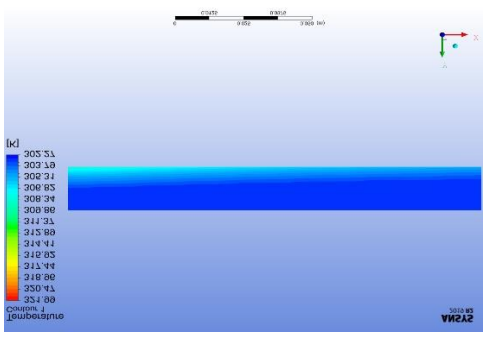


Fig 4. Enthalpy of PCM contour versus flow time.

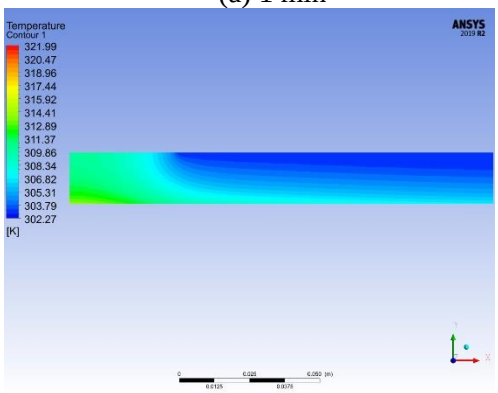
From Fig 5, we can see that temperature firstly increases near the corner that is adjacent to HTF flow inlet and then propagates to inside portion of the PCM contour. The melting patterns (see Fig 3.) also follow the similar path.



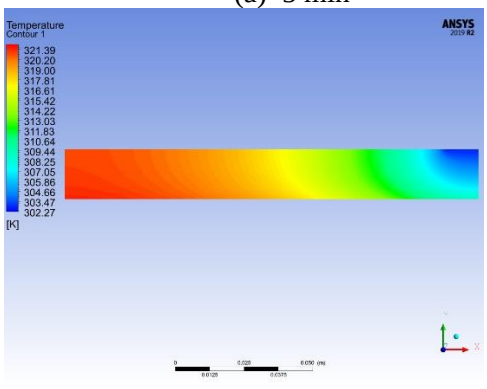
(a) 1 min



(a) 5 min



(c) 15 min



(d) 20 min

Fig 5. Temperature of PCM versus flow time for pure conduction case.

5. Conclusion

LTESS based on PCM can be an excellent energy source alternative to conventional energy sources. PCM absorbs huge enthalpy during its melting process. This energy will be driven out during solidification process. LTESS can be used at cooling system for electronic devices to absorb heat energy and later this absorbed energy can be utilized for other purposes. In our study it has been shown that for small geometry, there is negligible effect of natural convection during melting process of PCM. This simple model can be used design of small-scale cooling system in various electronic components. We have run our CFD simulation for different orientations and different flow directions.

6. Acknowledgement

I would like to thank Dr. Park to give me the opportunity to complete the project with some satisfying results. I am thankful to Dr. Virk to guide me to run ANSYS simulation and provide me sufficient data required.

7. References

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