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Optimization of Phase Change Material (PCM)-Based Heat Sink for Electronics Cooling Application

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Optimization of Phase Change Material (PCM)-Based Heat Sink for Electronics Cooling Application

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by

Nahal Taremi

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Committee Chairperson

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This thesis is dedicated to my valuable treasure in life, my beloved family:

My father who always has supported me,

My sister, my first teacher and who always has encouraged me to be brave,

And my lovely mom, my hero, who always has faith on me and was my hope in darkest day.

ABSTRACT OF THE THESIS

Optimization of Phase Change Material (PCM)-Based Heat Sink for Electronic Cooling Applications

by

Nahal Taremi

Master of Science Graduate program in Material Science and Engineering
University of California, Riverside, December 2017
Dr. Kambiz Vafai, Chairperson

The size of electronic devices is continually decreasing while the power consumption by these devices is increasing. As such the microchips in these devices dissipate more heat. Therefore, thermal management has become a challenging factor for designing electronic devices. With smaller electronic devices, the conventional air-cooled systems are not applicable for many cases. Therefore, new techniques are developed to keep the electronic packages in an acceptable operative temperature range. One of the alternative systems for conventional air cooling system is phase change material (PCM)-based heat sinks. In this work, innovative geometries of plate type fin and different materials were investigated. Our analysis has revealed that triangular cross-section and RT28HC organic PCM are the most efficient among investigated materials and geometries. The associated increased contact surface area in triangular cross-sectioned fin with PCM part and suitable melting temperature and latent heat of fusion of RT28HC with the selected processors make this cooling system more efficient.

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1. Introduction

Thermal management utilizing phase change materials have become attractive due to their ability to store and release heat during peak operations and idle times respectively. PCMs can be used in a number of ways, such as thermal energy storage whereby heat can be stored from one process or period in time, and used at a later time. PCMs are also very useful in providing thermal barriers or insulation especially in, temperature controlled transport. [1] Examples of these applications can be mentioned as, heat storage in buildings for energy saving, temperature control of high tech electronic devices, solar energy, stabilizing spacecraft temperature due to large temperature differences.

For electronic devices, thermal management become ever more critical in the developement of devices such as digital cameras, cellular phones and notebook. Since these devices operating system is categorized as a pulsed operative system, phase change materials can be the proper choice for thermal management of these electronic equipment.

Fundamental studies on latent heat storage and design of heat transfer enhancement, has been performed in recent decades to analyze the effectiveness of PCM in thermal management of electronic equipment [3]. PCMs are attractive due to their ability to have high latent heat, small volume change and wide range of melting temperatures.

PCM based cooling systems are good candidates for pulsed operative system since they can absorb extra heat during peak loads and thermally stabilize the device by phase transition at a constant temperature. The peak load ends after fully phased transition and PCM can re-solidify during normal operation of device or off period by releasing the heat to the ambient.

2. Thermal Energy Storage

Thermal energy storage can be stored as a change in internal energy of a material as sensible heat, latent heat and thermochemical or combination of these.[4]

2.1. Sensible Heat Storage

Sensible heat storage is the heat stored by temperature change of a medium. Sensible heat storage is dependent on the heat capacity and the change in temperature of the material during heat storage or heat release.[5]

$$Q_{sensible} = \int_{T_i}^{T_f} mC_p dT$$

2.2. Latent Heat Storage

Latent heat storage is the heat stored or release among phase transition such as solid to liquid, liquid to gas, etc. [5] The total heat that stored in latent heat storage system is

$$Q_{total} = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT$$

Which, a_m is fraction melted and Δh_m is heat of fusion per unit mass.

2.3. Thermochemical Heat Storage

Thermochemical heat storage is heat stored or released based on breaking or reforming molecular bonds in a completely reversible reaction.[4]

$$Q_{thermochemical} = a_r m \Delta h_r$$

Which, a_r is fraction reacted and Δh_r is endothermic heat of reaction

Latent heat storage ability to store a considerable amount of heat storage particularly in constant temperature makes it more attractive among other thermal storage mentioned above. In addition, it can be mentioned that materials in latent heat storage system can absorb 5-14 times higher heat per unit volume than sensible materials in almost same temperature.[4]

3. Latent Heat Storage Materials

After choosing the proper thermal storage technique it's better to analyze the materials for selected technique and their requirements. Phase change materials are the name that entitled to materials have been used in latent heat storage technique. The Thermal energy stored during phase change can occur in several forms such as solid-solid, solid-liquid, solid-gas, liquid- gas and vice versa.

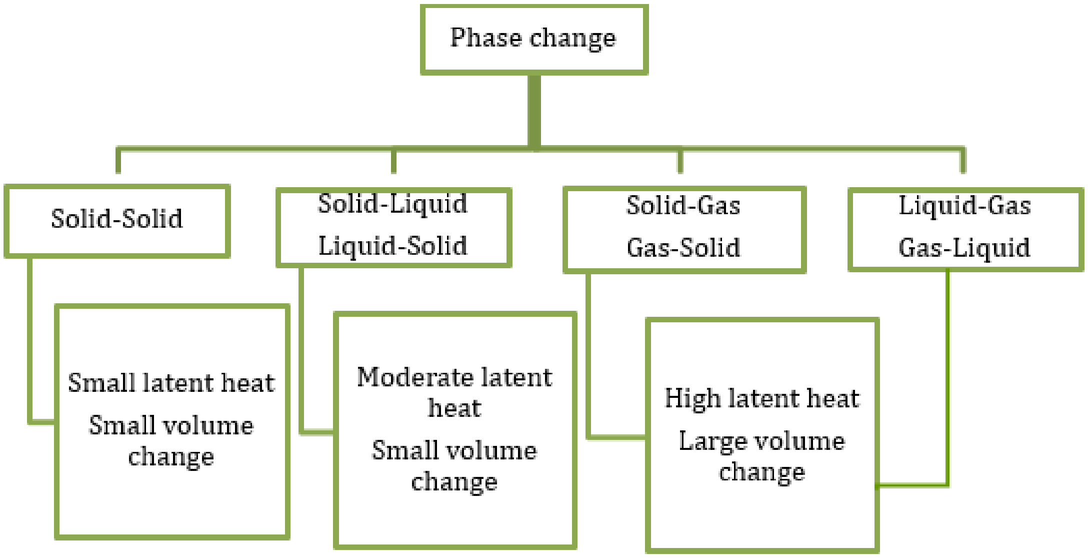


Figure 1 Phase change forms and their properties

As shown in Fig.1, solid-solid phase change has poor latent heat storage and due to the transition of one form of crystalline to another, it has low volume change. In addition, phase change in solid-gas or liquid-gas are accompanied by large volume change and contaminant problem. Therefore, they are not attractive for heat storage systems although they have high latent heat. After all, the remaining one is solid-liquid phase transition which is the most proper form due to its small volume change and moderate latent heat, smaller than liquid-gas but still considerable.

Phase change materials must exhibit certain required properties regarding their employment in latent heat storage system. For instance, suitable phase transition temperature (different for each application due difference in proper operating temperature), high latent heat and good thermal conduction for better heat transfer as thermodynamic properties. Also, small volume change and high density can prevent critical issues in designing the system. Other desired properties from phase change materials are chemical properties such as, chemical stability, compatibility with other component in the system and no toxicity and fire hazard which are very critical specially for electronic systems. Moreover, it is important to evaluate the material abundant and cost for marketing aspects.

4. Classification of Phase Change Materials (PCMs)

As it mentioned in previous section, PCMs divided into mainly three groups: solid– solid PCMs, solid–liquid PCMs and liquid–gas PCMs. Among them, the solid–liquid PCMs are most suitable because of their overall preferred properties for thermal energy storage. The solid–liquid PCMs are also divided into three categories, organic, inorganic and eutectics.[6]

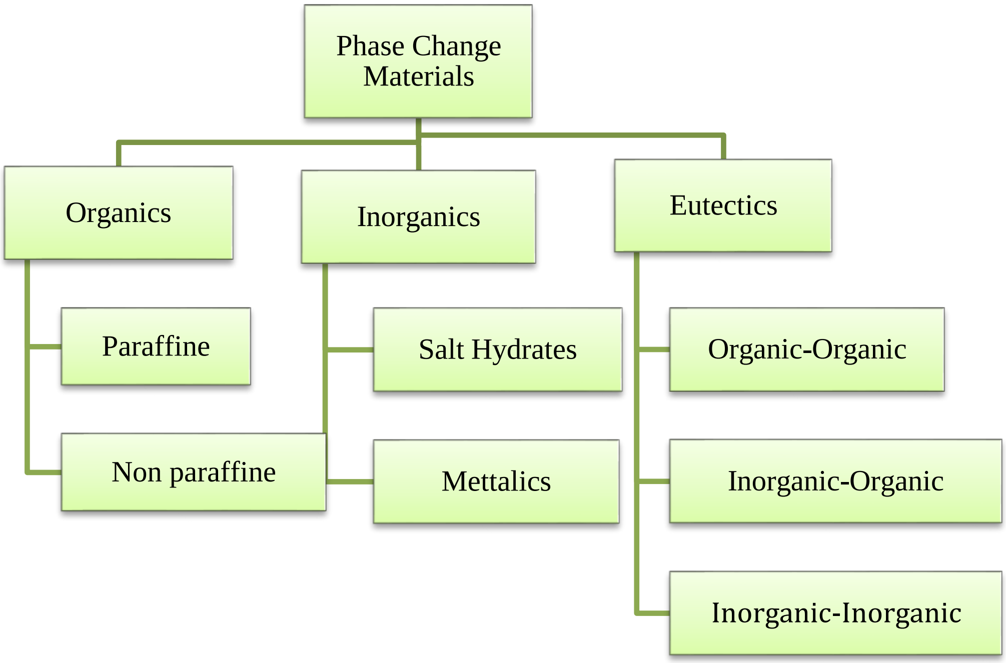


Figure 2 Phase change forms and their properties

4.1. Organic

Organic materials are classified as paraffin and non-paraffin.

4.1.1. Paraffins

Paraffins are known as linear n-alkanes (CH3–(CH2) CH3) with a number of carbons between 12 and 14. The crystallization of the (CH3)- chain release a large amount of latent heat which increases with chain length.[7] Paraffins are safe, reliable, predictable, less expensive and non-corrosive, chemically inert and stable below 500 ^{o}C, show little volume changes on melting and have a low vapor pressure in the melt form.

But their low thermal conductivity, no compatibility with the plastic container and be moderately flammable have limited their applications.[8]

4.1.2. Non-Paraffins

The non-paraffin organics consist of many different type materials with different properties. Unlike paraffins, these materials properties are totally different from each other, therefore, they need to be evaluated separately. These materials include fatty acids, alcohols and glycols. For instance, Glycols have low thermal conductivity and instability in the melting as well as weak compatibility with other materials.[9] The other example of non-paraffins PCMs is fatty acids which consist of CH3(CH2)2nCOOH. CH2 groups provide their high latent heat although it's not higher than paraffins. Fatty acids have low thermal conductivity, mild corrosiveness and high cost among all type of PCMs. In addition, the evaluated temperature can be critical for them due to their decomposition in high temperature and their flammability at very high temperature.[10]

4.2. Inorganic

Inorganic PCMs are salt hydrates. Although they have high latent heat and are non-flammable, low cost and abundant, they are not suitable for using in thermal management systems due to their corrosiveness specially with metals, instability, improper re-solidification and tendency to supercool.[4] Their improper re-solidification is due to separation of salt and water during charging cycle. As solid salts have a higher density than water they settle down on the bottom of the container and it is hard to recombine in the discharge cycle. Thus, it results in decreasing the latent heat with time.

4.3. Eutectic

The eutectics are mixture of 2 or more PCMs to build new PCMs with enhanced properties and melting temperature. Regarding the type of PCMs that includes in mixture, eutectics categorized as organic-organic, organic-inorganic and inorganic-inorganic. Achieving ideal material from the mixture of PCMs demands hard work and experience for finding two or more materials with proper properties and efficient percentage of their mixture which can make PCM with desired melting behavior and thermal conductivity.

As mentioned previously, one of the desired thermal properties of phase change materials is high thermal conductivity in order to enhance the heat transfer. Unfortunately, most of the phase change materials have poor thermal conductivity. In order to overcome the low thermal conductivity, additional element is needed.

Moreover, a proper heat transfer medium must be designed for heat storage unit to transfer heat from the heat source to phase change materials. Since the low thermal conductivity causes low thermal diffusivity, proper heat exchanger design can improve the distribution of heat through phase change materials section. The heat storage unit should include heat exchanger which is called thermal conductivity enhancer (TCE) and phase change materials in contact with the heat source. With this configuration, mentioned issues, such as compatibility and low thermal conductivity can be solved.

Many efforts have been done for enhancing phase change materials thermal conductivity so far such, modeling different shape and dimension of thermal conductivity enhancers (TCEs)[11], using graphite matrix[12] (in case of improving the PCM properties instead of adding an additional part to storage system). Adding high thermal conductive material to PCMs structure is not common due to its side effects such as decreasing latent heat which is the most important parameter in latent heat storage.

Therefore, any latent heat energy storage system possesses at least following four components:

(i) A suitable PCM with its melting point in the desired temperature range,
(ii) High duration index which is how long the PCM remains in constant temperature during absorbing heat,
(iii) A suitable heat exchange surface, and
(iv) A suitable container compatible with the PCM.[4]

To sum it up, development of latent heat storage needs investigations over suitable materials and heat exchanger design. Fig 3 shows practical summary of all steps have to be placed to design and produce efficient heat storage.

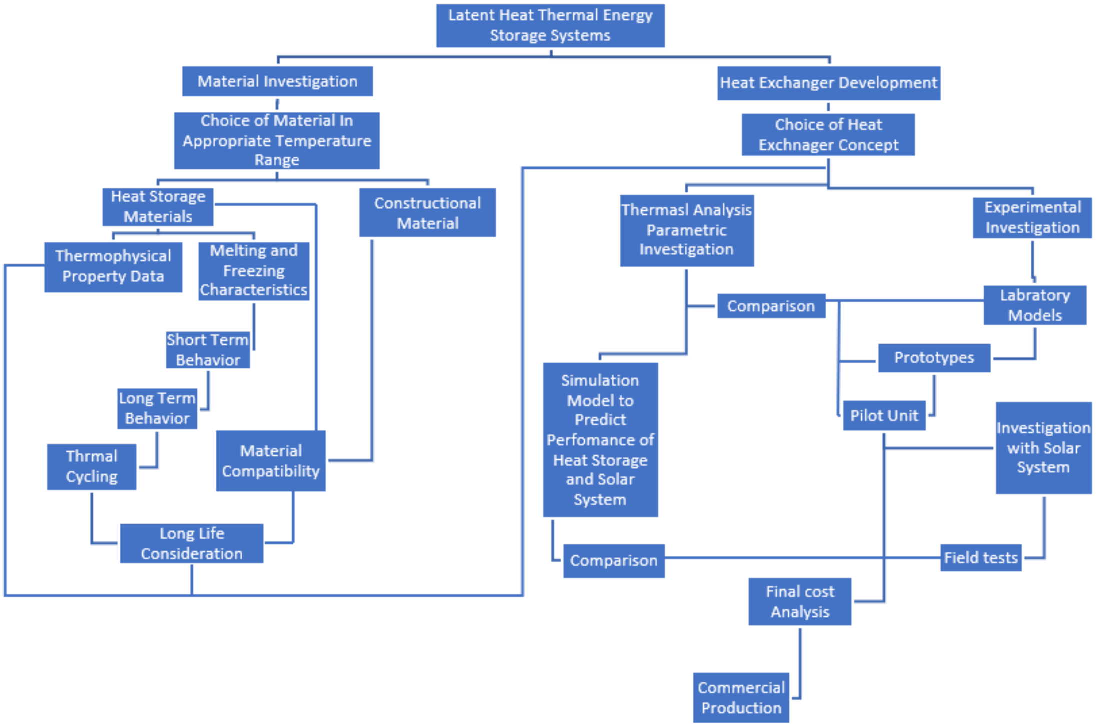


Figure 3 Different stages involved in the development of latent heat storage systems. [13]

5. Enthalpy-Porosity Method

5.1. Introduction

Phase change material problems are challenging due to their main feature, the moving interface at which the phase change occurs. Most of the developed numerical techniques are based on models which only consider heat transfer via diffusion. Although, the importance of convective heat transfer has been confirmed experimentally in physical situation involve solid/liquid phase change.

The modeling methodologies developed for melting or solidification studies - may broadly be classified into three groups, empirical, classical and enthalpy.[14] In Empirical method, heat transfer is only considered as conduction and energy enhancement because of convective heat transfer applied by boosting the liquid phase conductivity. In the other hand, fully elucidate of the liquid region convection is challenging. This approach bounds to driving heat and mass transfer equations and also the development of numerical techniques to solve them. For accounting phase transition conditions based on temperature, velocity and latent heat evolution in this region, temperature based heat transfer equations should be derived. Furthermore, using fix-grid numerical solution is impossible due to grid deformation or coordinate system transformation for accounting the position of the phase front.

To substitute above approaches because of their complexity and deficiency to fully simulate heat transfer through a phase transition, is Enthalpy method. By this approach conditions at the phase front are not study in detail. Thus, usage of fix-grid numerical solution is possible and standard fluid energy and momentum equations are used.

5.2. Enthalpy Porosity-Method

In this method, the latent heat is considered as a nodal value depending on the temperature of each cell. As phase change occurred, the nodal latent heat content of cell change regarding illustrate latent heat absorption from phase change material. Reflection of this change can be shown in energy equation of heat source and heat sink. Although this arrangement declares the need to accounting all conditions to energy equation explicitly, it has a problem that needs to be solved. Its main problem is accounting solid phase velocity which is zero.

Many researchers have done studies for solving this issue such as Voller et al. Among Voller et al studies on various method, enthalpy porosity method [14] has been followed in present work. Regarding this method, temperature based viscosity can be the solution for zero velocity problem. Therefore, consequence of considering high viscosity for the solid region based on temperature range that it occurs, will reflect as zero velocity. This method not only solves zero velocity but also helps to model phase change in a compatible manner to current fluid flow software. Based on this method, phase change transition can be modeled as a porous media with the porosity as a function of melt fraction.

For considering phase change of a material, three regions of, fully solid, fully liquid and mushy, which only part of structure molten and still some parts of it are in the solid state, should be accounted for. In this method, the mushy zone is assumed as a pseudo- porous media which its porosity is equal to the liquid fraction.

5.3. Governing Equations

To describe heat and mass transfer phenomena in a Newtonian incompressible fluid in the laminar flow regime the following general equations are required in a two-dimensional Cartesian system[14]:

Conservation of mass

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

where u and v are the velocities in the x and y directions, respectively.

Conservation of momentum

$$\frac{\partial}{\partial t}(\rho u)+\nabla(\rho uv)=\nabla(\mu\nabla u)-\frac{\partial p}{\partial x}+S_x \qquad (2)$$

and

$$\frac{\partial}{\partial t}(\rho v)+\nabla(\rho uv)=\nabla(\mu\nabla v)-\frac{\partial p}{\partial y}+\rho\beta g(T-T_{ref})+S_y \;\rho\;\mu \qquad (3)$$

where p is pressure, ρ density, μ viscosity and S_x, and S_y, are source terms which are defined as:

$$S_x=\frac{A(1-\Phi)^2}{\Phi^3+B}u\,,\quad S_y=\frac{A(1-\Phi)^2}{\Phi^3+B}v$$

Where A and B are arbitrary constants defined in a way that the source term can play as a damping term in the momentum equation. Term A usually takes large values $(A=10^4,10^5,etc)$ resulting in a very large source term as the melt fraction $\Phi(T)$ approaches zero. This reflects the zero velocity in the solid region. The source term disappears from the momentum equations as the melt fraction approaches 1. B takes small value as 10^3 to avoid division by 0 when $\Phi(T)$ has a value of 0 in the solid region. [15]

Conservation of energy

A suitable conservation of energy equation can be written in terms of the enthalpy[16]

$$\rho\frac{\partial h}{\partial t}+\rho u\nabla h-\nabla(\alpha\nabla h)+S_h=0 \qquad (4)$$

where α is the thermal diffusivity ($\alpha = k / \rho C_p$, where k is thermal conductivity and C_p is specific heat capacity at constant pressure), h is enthalpy and S is a source term which is defined as:

$$S_h = \rho \frac{\partial \Delta H_m}{\partial t} u \tag{5}$$

Therefore, simplified form of equation (4) can be written as

$$\rho C_p (\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}) = k_{eff} \nabla^2 T - S_h \tag{6}$$

The essential feature of the proposed enthalpy technique for convection/diffusion phase change will be the latent heat source term in equation (4). In a system which is undergoing a change of phase due to heat transfer, the total enthalpy is often expressed as

$$H = h + \Delta H_m \tag{7}$$

which is the sum of sensible enthalpy, h, and latent heat, ΔH_m. The latent heat contribution will be a function of temperature,

$$\Delta H_m = F(T) \tag{8}$$

The form of this function will depend on the problem. In isothermal melting, which is the case in this study, is defined as

$$F(T) = \begin{cases} 0 & T < T_s \\ L(1 - F_s) & T_L > T > T_s \ F_s \\ L & T > T_L \end{cases} \tag{9}$$

where F_S is the solid fraction, a non-linear function of temperature that will be explained in the next chapter, L is the latent heat of fusion and T_L and T_s are the liquidus and solidus temperatures, respectively.

6. Optimization of PCM-Based Heat Sink in Cooling System

6.1. Introduction

Thermal management has become a challenging factor for designing electronic devices. As electronic devices package have become smaller, the massive conventional air-cooled systems are not applicable anymore. Therefore, new techniques are developed to keep the electronic packages in the operating temperature range.

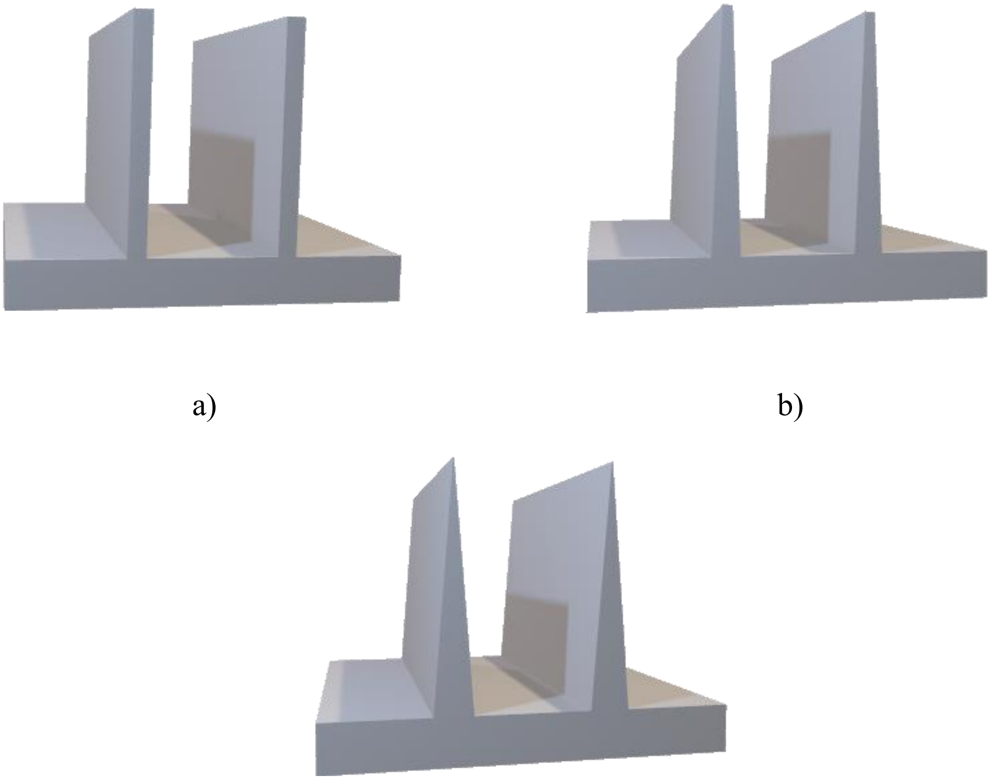
Using phase change materials has gained considerable attention. Solid-liquid phase change materials are more popular because of their high latent heat and small volume change during phase transition. In addition, among all types of solid-liquid PCMs, paraffin in organic PCMs category are quite useful due to their high latent heat, stability, compatibility with other materials, safety, etc. However, their low thermal conductivity is an undesirable characteristic which leads to a low rate of heat transfer. Many possibilities have been adopted to compensate for this weakness such as utilizing different forms of heat sink structure as a thermal conductivity enhancer (TCE), dispersing high thermally conductive materials to PCMs structure, etc. Although dispersing high thermal conductivity materials can considerably increase the thermal conductivity, it decreases the latent heat which is a crucial factor for this application.

Thus, collaboration of phase change materials and heat sinks is one of the best alternatives for conventional cooling systems. As mentioned earlier, phase change materials can absorb a considerable amount of overload heat without increasing the temperature during the peak chip operation. By selecting the proper phase change material the operational temperature range of a specific electronic package can be adjusted

6.2. Physical Model and Boundary Conditions

6.2.1. Physical Model

In this work, the heat storage unit includes $42 \times 42 \times 4\,mm^3$ heater made of silicon (a common material for electronic chips) with 4 W power and $42 \times 42 \times 34\ mm^3$ heat sink made of aluminum with 5 mm height base and fins with height of 25 mm.

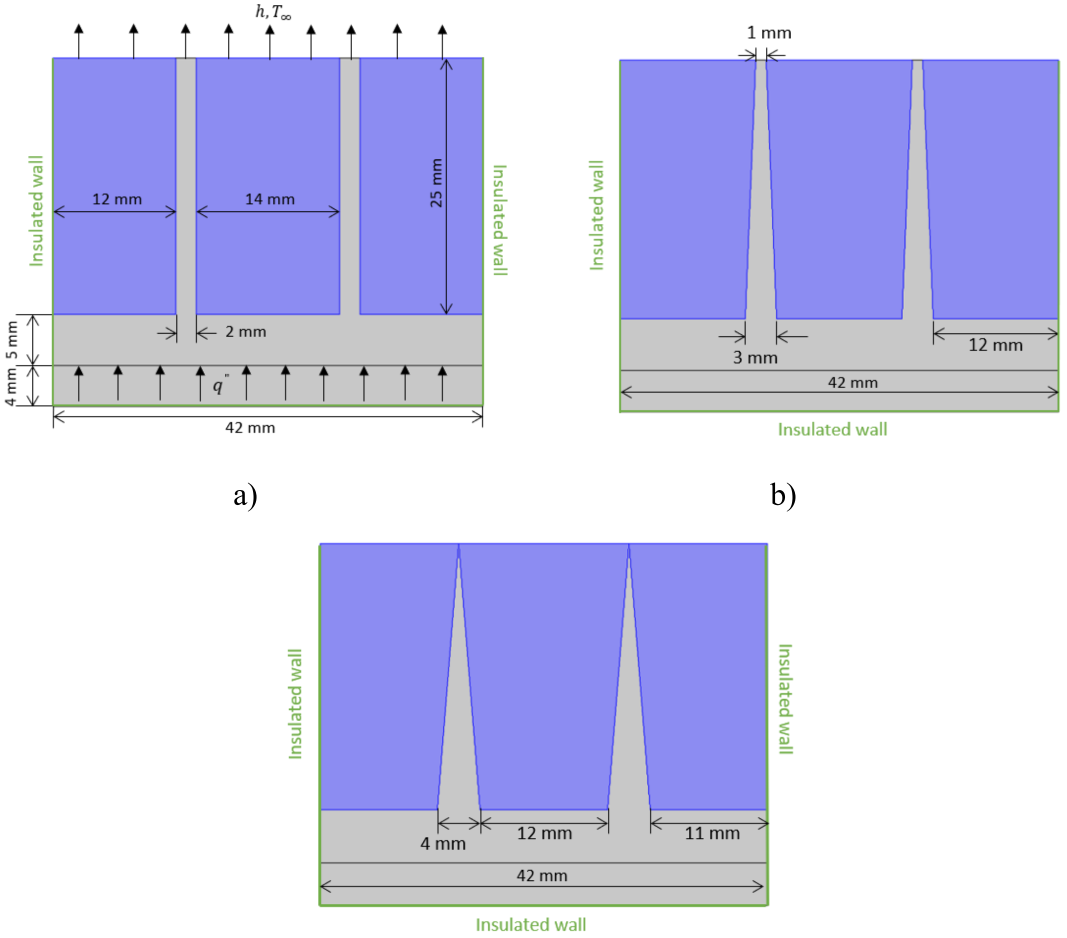


a) b)

c)

Figure 4 heat sink geometry with different fins a) Rectangular b) trapezoid c) Triangle

3D schematics of heat sinks with different cross-sections are shown in Fig 4. Heat sinks include 2 plate-type fins with volume fraction of 8% regardless of their cross section. Dimension of fins with different cross sections are defined as rectangular 2 × 25 × 42 mm^3, trapezoid a = 1, b = 3 and h = 25 (a and b are trapezoid bases and h is the height) and triangle b = 4 and h = 25 mm (b is the base and h is the height) Cavities between fins are filled with pure n-eicosane $(n-C_{20}H_{42})$ as a PCM.



a)

b)

c)

Figure 5 Dimension of cavities in different cross section a) Rectangular b) Trapezoid c) Triangle.

Properties of materials that have been used are shown below,

Table1. Thermo-physical properties of the PCM used by Nayak et al [17]

Eicosane	Density (kg/m^3)	Dynamic viscosity $(Pa.s)$	Thermal conductivity $(W/m.K)$	Specific heat $(J/kg.K)$	Melting point (℃)	Latent heat (J/kg)
Solid	810		0.39	1900	-	-
Liquid	770	3.465e-3	0.157	2200	37	241000

Table2. Thermo-physical properties of heat sink and chip used by Nayak et al[17]

	Density (kg/m^3)	Thermal conductivity $(W/m.K)$	Specific heat $(J/kg.K)$
Heat sink	2713.9	179.6	960
Chip	740	20	1830

6.2.2. Initial and Boundary conditions

The initial state of this model is:

At $t=0$, $T=T_0=293.15K$

Also, as shown in Fig 5, defined boundary conditions are as followings:

1. No slip condition at the walls, $u=v=0$
2. Natural convection with the ambient at the top surface

$$-k\left.\frac{\partial T}{\partial t}\right|_{y=34}=h(T|_{y=34}-T_\infty),\ T_\infty=293.15K,\ h=10\ \ W/(m^2.K)$$

3. Insulated side walls and bottom

$$\left.\frac{\partial T}{\partial x}\right|_{x=0,42}=0\ \text{ and }\ \left.\frac{\partial T}{\partial y}\right|_{y=0}=0$$

6.3. Governing Equations

As it is mentioned in previous chapters the enthalpy-porosity method is used to simulate the phase change. The followings are shown the governing equations and user-defined functions/material properties used in COMSOL Multiphysics for modeling such a method.[15]

Conservation of mass

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Conservation of momentum

$$\frac{\partial}{\partial t}(\rho u)+S(T).u=-\frac{\partial p}{\partial x}+\frac{2\partial}{\partial x}\left[\mu\frac{\partial v}{\partial x}\right]+\frac{\partial}{\partial y}\left[\mu(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})\right] \tag{2}$$

and

$$\frac{\partial}{\partial t}(\rho v)+S(T).v=-\frac{\partial p}{\partial y}+\frac{2\partial}{\partial y}\left[\mu\frac{\partial v}{\partial y}\right]+\frac{\partial}{\partial x}\left[\mu(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})\right]+F_B \tag{3}$$

The above momentum equations demonstrate incompressibility of PCM with variable viscosity. In order to consider the natural convection in the liquid PCM, the body force, F_B, is added to the momentum equation in y-direction and is defined by Boussinesq approximation[15]:

$$F_B=\rho_l\beta g(T-T_m) \tag{4}$$

S(T) in form of Carman-Kozeny equation is for showing the proportional dependency of flow to the fluid viscosity in momentum equations. This term is the solution for accounting 0 velocity of solid in momentum equation as it mentioned in introduction.

$$S(T) = \frac{A_{mush}(1-\Phi(T))^2}{\Phi^3 + \in} \tag{5}$$

$\Phi(T)$ is piecewise function demonstrating the melt fraction of PCM. It takes 0 value for solid state, 1 for Liquid, and linear function which varies between 0 and 1 for mushy region.

$$\Phi(T) = \begin{cases} 0 & T < T_m - \frac{\Delta T}{2} \\ \frac{T-(T_m - \Delta T/2)}{\Delta T} & T_m - \frac{\Delta T}{2} < T < T_m + \frac{\Delta T}{2} \\ 1 & T > T_m + \frac{\Delta T}{2} \end{cases} \tag{6}$$

Regarding equation (6), it can be determined that source term is effectively a damping term when the melting fraction is equal to 0 (Solid state) and its effect neglected when the melting fraction is 1 (Liquid state). The value of A_{mush} can be effective in result of simulation. Regarding to A. Kheirabadi et al work it is necessary to approach the best value of A_{mush} for each specific material and simulation. The value that has been used in this study is 10^4. $\in$ is also only for avoiding division by 0 for solid region.

In order to simulate heat transfer through the shown geometries, COMSOL Multiphysics has been used and in this finite element software basic equations for heat transfer and laminar flow which need to be complemented with following user-defined equation to account for phase change during the heat transfer.

In order to modify the overall heat capacity and shows its sudden increase provides by latent heat of fusion, following equation needs to be defined. [18]

$$D(T) = e^{-\frac{(T-T_m)^2}{(\frac{\Delta T}{4})^2}} / \sqrt{\pi(\Delta T / 4)^2} \tag{7}$$

This Gaussian function is defined to model the latent heat contribution to the specific heat capacity as phase change transition starts. Thus, this function has a value of zero except in range $T < T_m - \Delta T / 2$ and $T < T_m + \Delta T / 2$.

Therefore, modified form of the overall heat capacity can be defined as

$$C_p(T) = C_{p,s} + \Phi(T)(C_{p,l} - C_{p,s}) + L.D(T) \tag{8}$$

In addition, overall thermal conductivity and density of the PCM have modified in a similar manner as the overall heat capacity only without the additional effect of latent heat to have more realistic value during the phase transition.

$$k(T) = k_s + \Phi(T)(k_l - k_s) \tag{9}$$

$$\rho(T) = \rho_s + \Phi(T)(\rho_l - \rho_s) \tag{10}$$

Overall, all of these modified properties are implemented in heat transfer equation as shown below and solved with the continuity and Navier-Stokes equations. Also, as all of the properties varied by change of temperature, the overall system renders the simulation non-linear.[15]

$$\rho(T).\, C_p(T)\frac{\partial T}{\partial t} = \nabla.\,(k(T)\nabla T) \tag{11}$$

The other property that needs to be modified is viscosity. Modification of viscosity is due to accounting zero velocity of the solid state of PCM by forcing solid PCM with a large value of viscosity.

$$\rho(T) = \mu_l(1+S(T)) \tag{12}$$

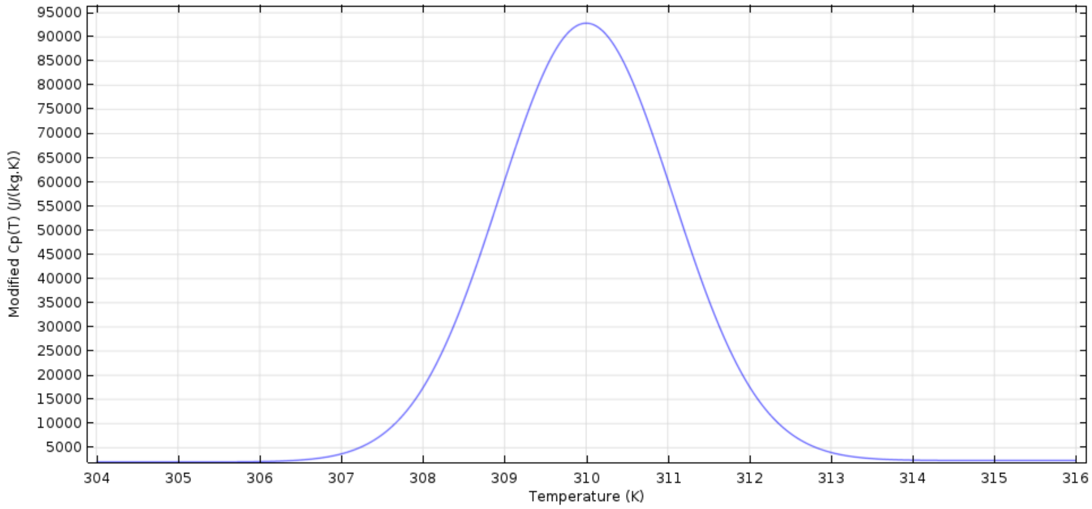


Figure 6 Modified C_p for $\Delta T = 3K$

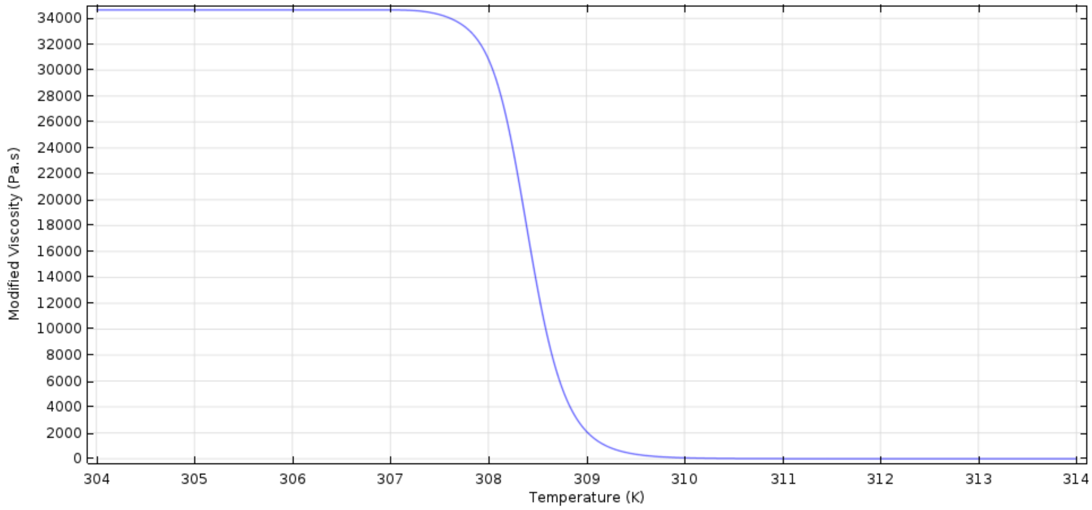


Figure 7 Modified Viscosity for $\Delta T = 3K$

6.4. Validation

The Numerical model in this sturdy has been validated with the numerical data of Nayak et al [17]. The different configurations of TSU have been considered in the validation. First, a TSU without any TCE is studied and the effect of natural convection is demonstrated. Second, a TSU with 2 plate-type fins with dimensions of $2 \times 25 \times 42 \ mm^3$ (10% volume fraction) is investigated.

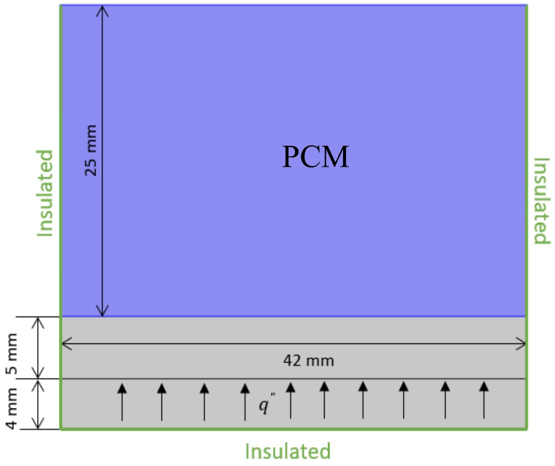


Figure 8 2D schematic of heat sink without fin

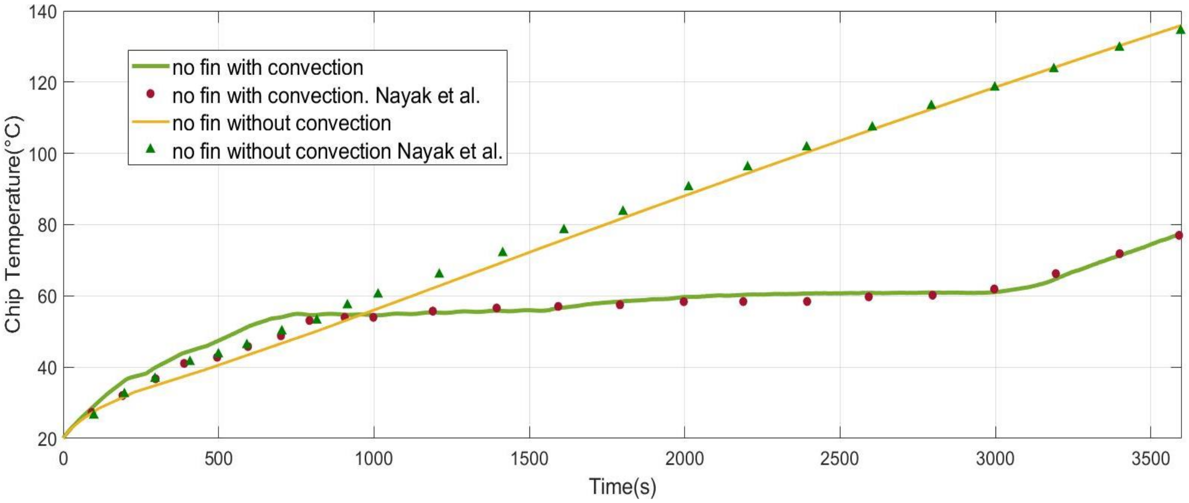


Figure 9 Effect of natural convection in TSE without TCE

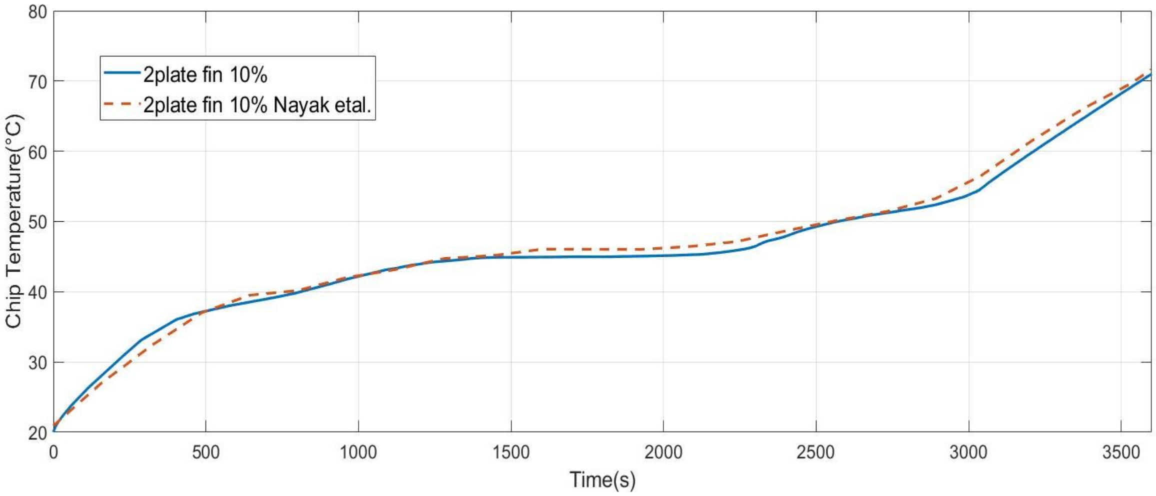


Figure 10 Evolution of the chip temperature with 2 plate-type fins heat sink

6.5. Results and Discussions

Nayak et al have established that 10% volume fraction for TCE in plate type heat sinks is the most efficient volume fraction. Regarding to their conclusion, different volume fractions have been compared as shown in Figure 11. However, 5% volume fraction has improved the system operation at the end of phase change transition and melting part, resulted low thermal conductivity is affected the heat transfer rate in solid state and beginning of phase transition. 10% volume fraction has chosen as selected volume fraction for TCE in the investigated unit to compare results with Nayak et al work.

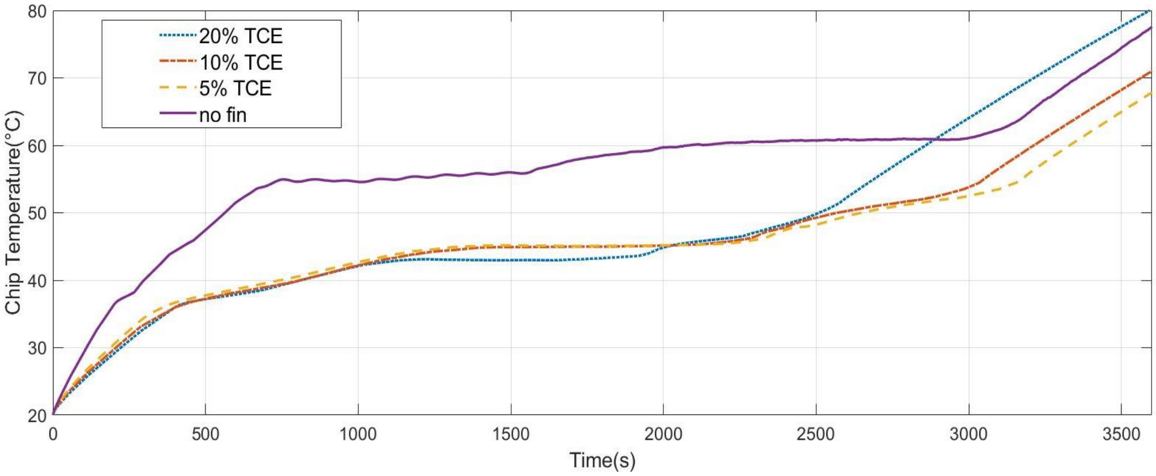


Figure 11 Different volume fraction of TCE in 2plate fin heat sink.

Subsequently, all the fin configurations considered in this study and shown in Figure 5 are corresponding to 10% TCE volume fraction. As demonstrated in Figure 12 the thermal conductivity of PCM parts has improved the most with triangular cross sectioned fins.

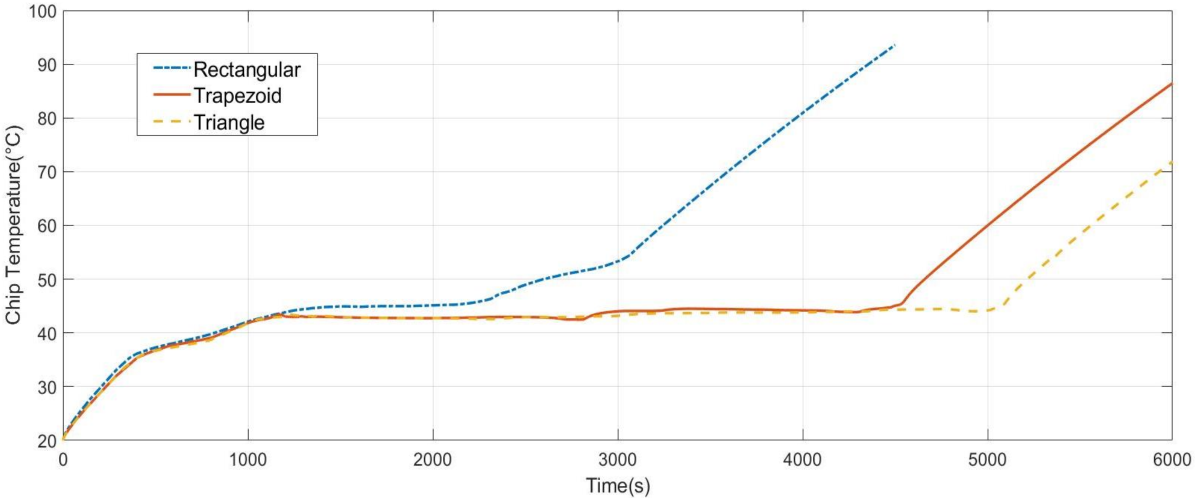


Figure 12 The effect of different cross sectioned fins in chip temperature.

This improvement is due to the increased surface area with PCM part from 25 mm in rectangular and 25.02 mm in trapezoid to 25.08 mm in triangular cross section.

Regarding to Figure 12, it can be observed that triangular cross section is not only has improved the thermal conductivity of PCM but also increased the phase change transition region by 3 times in comparison to rectangular. The increased phase change transition region is due to improved thermal diffusivity as a result of increased contact surface area. Thus, a cooling system with this type of heat sink can control the temperature of electronic processor in longer peak load period.

The other investigated aspect in this work is the effect of utilizing different material with different melting temperature and latent heat of fusion on the efficiency of the storage system. Materials have been chosen from Rubitherm phase change materials. This company has improved organic paraffins and build up a new category of them with a wide range of melting temperature and higher latent heat. Selected materials are from their RTHC PCMs which, according to Rubitherm company, have higher latent heat of fusion and wider range of melting temperature in comparison with their classic RT-line PCMs. Selected materials include, RT44HC with higher latent heat and melting temperature, RT35HC with lower latent heat and melting temperature and RT28HC with higher latent heat and lower melting temperature, in comparison with Nayak et al selected PCM, Eicosane.

Table 3. Selected material from Rubitherm products[19]

PCM	**RT28HC**	**RT35HC**	**RT44HC**
Density (kg / m^3)	Liquid 770	Liquid 778	Liquid 700
	Solid 880	Solid 830	Solid 800
Dynamic Viscosity $(Pa.s)$	0.0031	0.0044	0.008
Heat Capacity $(kJ / kg.K)$	2000	2000	2000
Thermal Conductivity $(W / m.K)$	0.2	0.2	0.2
Latent Heat of fusion (kJ / kg)	245	220	255
Melting Temperature $°C$	28	35	42
Melting bandwidth	2	2	3

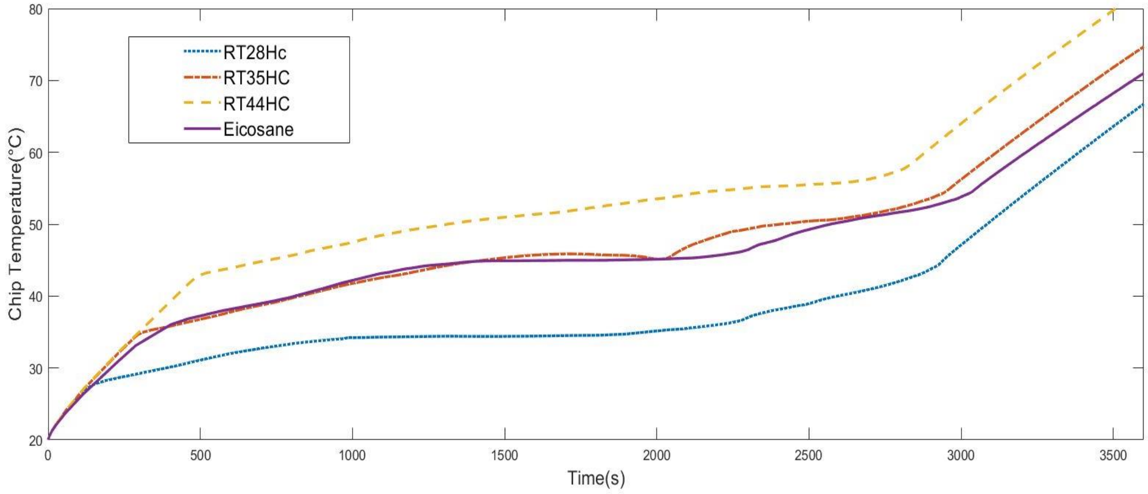


Figure 13 Comparison of different materials effect on chip temperature

The performance of the cooling system with each of these materials is compared in Figure 13 and it can be seen from this figure the significant effect of thermo-physical properties of the PCMs on controlling the temperature of the chip. By the comparison of RT44HC with Eicosane, it is observed that higher melting temperature not only increased the controlled temperature in phase change transition but also decreased the phase change region because of its influence in total enthalpy of material. The other selected material is RT35HC which although has lower latent heat but shows almost same performance as Eicosane. RT35HC results show lower melting temperature can improve low latent heat. Therefore, RT28HC with higher latent heat and lower melting temperature than Eicosane is the most efficient material among selected ones.

6.6. Conclusions

A two-dimensional numerical model has been employed to investigate the effect of different fin geometries and different materials on PCM-based heat sink performance. Among all designed geometries, triangular cross-sectioned fins are most effective in transferring the heat. In addition, comparison of chip temperature with selected material shows the significant effect of melting temperature on system efficiency. It was found that, RT28HC with lower melting temperature and higher latent heat is the best PCM among all selected. The combination of RT28HC along with triangular cross-section fin is shown in Figure 14. Developing triangular cross section in pin-fin type heat sinks can be the future work of this study.

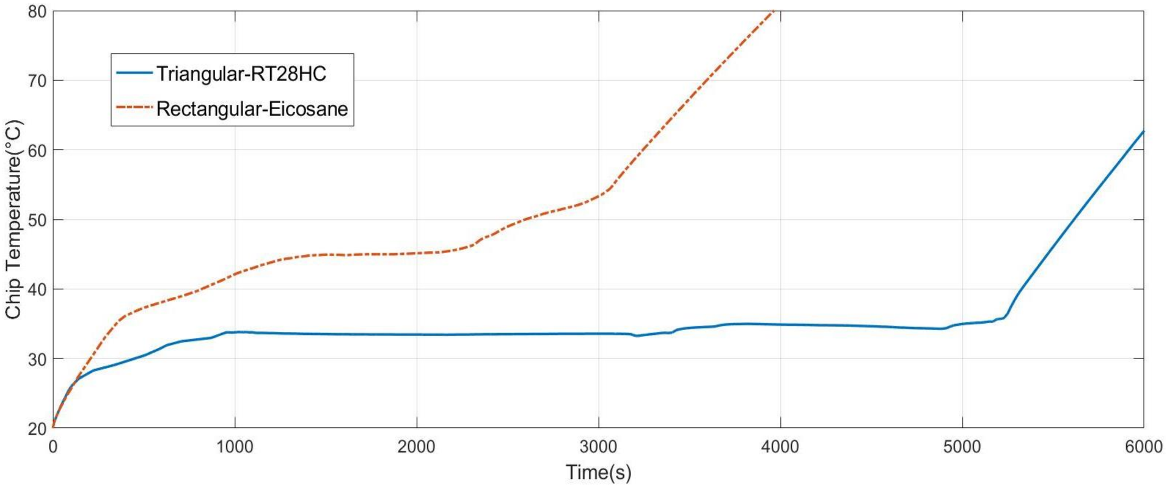


Figure 14 Comparison of Triangular-RT28HC heat sink and Rectangular-Eicosane heat sink.

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