Transient Analysis of Phase Change Material for the Cooling of Discrete Heat Sources Under Mixed Convection

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ABSTRACT

The paper deals with the transient numerical analysis of phase change material (Paraffin wax) used for the cooling of seven non-identical protruding discrete heat sources (Aluminium) mounted on a substrate (Bakelite) board under mixed convection. The phase change materials (PCMs) are filled inside the protrude mini-channels (fabricated on the substrate board) and the heat sources are placed on the mini-channels. Transient heat transfer analysis is carried out using ANSYS Fluent to predict the temperature distribution of these heat sources. The melt fraction of the Paraffin wax is reported for both the charging (heating) and discharging (cooling) zone with respect to time. The results are validated with the existing numerical models. The study is extended using different PCMs (n-eicosane ($T_m - 36.5^\circ\text{C}$), paraffin wax ($T_m - 43$ to 49.5°C) and RT-54 ($T_m - 54^\circ\text{C}$)) to study the cooling characteristics of heat sources. It is seen that there is a temperature drop of $3 - 6^\circ\text{C}$ for the heat sources using the PCM. Thus it confirms that PCM can be used for better thermal management of heat sources. The study is also extended to determine the volume fraction of PCM inside the mini-channels and is seen that the mini-channels with 100% PCM volume shows the maximum temperature drop from the heat sources.

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Nomenclature

A	area of the heat sources, m^2
C	specific heat of PCM, J/kg K
F_o	Fourier number, α/L_c^2
g	gravitational acceleration, 9.81 m/s^2
h	convective heat transfer coefficient, $\text{W/m}^2\text{K}$
k	thermal conductivity, W/mK
L_c	characteristic length of the IC chip, m
M	mass of the PCM, kg
P	pressure, Pa
q	heat flux, W/m^2
Q	heat stored by the PCM, J
t	time, sec
T	temperature, K

Greek symbol

ΔT_{ref}	reference temperature, qL_c/k , K
θ	non-dimensional temperature, $(T_{max} - T_\infty) / \Delta T_{ref}$
ρ	density of air, kg/m^3
α	thermal diffusivity, m^2/s

Subscripts

∞	ambient
∞	melting point
max	maximum

1. Introduction

The increase in heat generation of the electronic components and the miniaturization of the ICs has led to the development of advanced cooling techniques to keep their temperature below the safe limit of 85°C (Murshed [2016]). One of the techniques is the use of phase change material (PCM) which acts as thermal energy storage as well as cools the ICs up to their melting point. The application of air and liquid cooling techniques are used with respect to input heat flux limitations in the ICs. Hence, the hybrid cooling technique using both air and PCM eliminates the challenges to handle the liquid used for the cooling of ICs.

Wang and Yang [2011] conducted transient numerical simulation on n-eicosane in a multi-fin heat sink. Different power levels with different orientation studies were carried out on the heat sink. They found that the heat sink with 6 fins showed better cooling ability, and the PCM with longer operating temperatures can be obtained using a multi-hybrid heat sink. Baby and Balaji [2012] performed the experimental investigation on n-eicosane based finned heat sinks for different heat loads ranging from $2 \text{ W} - 7 \text{ W}$ and found that the operating time of heat sink is enhanced by 18 times using n-eicosane. Qarnia et al. [2013] conducted the numerical investigation for three discrete protruded heat sources under natural convection using PCM based enclosures. They developed a correlation for the working time and volume fraction of PCM. Baby and Balaji [2013] performed the experimental investigation on PCM based pin-fin heat sinks. Paraffin wax and n-eicosane are used to maximize the operating time of the heat sink. They have used ANN - GA methodology to determine the optimum number of fins inside the heat sink. Thomas et al. [2016] conducted a numerical investigation of n-eicosane based heat sink on a portable electronic component. The analysis was performed under natural convection for different heat loads ranging from 4 W to 6 W and it was observed that; the operating time of heat sinks was increased significantly using the n-eicosane. Karvinkoppa and Hotta [2017] carried

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out numerical simulations on the optimal positioning of heat sources under natural and mixed convection heat transfer using Ansys Icepak and found that the mixed convection heat transfer is a better way for the cooling of heat sources. Gharbi et al. [2017] conducted experiments on paraffin wax with three discrete flush-mounted heat sources and found that the heat sources dissipating highest heat flux must be placed at the substrate bottom and the PCM fraction cycle increases the operating time of heat sources by 3 to 5 times of the critical time. Li et al. [2017] conducted numerical simulations on the melting of paraffin wax in a horizontal annulus and found that, with the increase in temperature, the convective heat transfer is initiated first, which lowers down the melting time of PCM. Kandasamy et al. [2008] investigated experimentally and numerically the use of paraffin wax in the heat sinks for the transient thermal management of plastic quad flat package (QFP) electronic device. They reported the increase in power input to QFP enhances the melting rate of PCM and ultimately the thermal performance of QFP has increased. Sridharan et al. [2018] carried out the experimental and numerical investigation on PCM based cylindrical heat sink. They used a multi-objective swarm optimization technique to optimize the geometric parameters of the heat sink. They found that there is a 4% increase in the charging time and a 13% increase in the discharging phase of PCM. Hafiz et al. [2018] studied experimentally the performance characteristics of the pin-fin heat sink using different PCMs (paraffin wax, RT-44, RT-35HC, SP-31, and n-eicosane). Rectangular, triangular and circular pin-fin cross-sections were used for the analysis. They found that RT-54 is more effective for the setpoint temperature of 60°C with a triangular cross-section pin-fin. Mathew and Hotta [2018] performed numerical investigations on ICs mounted on a switch-mode power supply (SMPS) board under mixed convection mode of heat transfer. They obtained the optimal distribution of ICs using a numerical data-driven ANN-GA based hybrid technique to maintain the ICs temperature below the critical limit of 85°C. Khanna and Sundaram [2018] conducted experiments on multiple PCM based heat sinks. They used RT50-RT55, RT58-RT47 and RT47-RT58 PCM combination and found that the RT58-RT47 gives the better thermal performance of heat sinks, which led to the increase in thermal regulation cycle and the heat sink temperature. Loganathan and Mani [2018] conducted fuzzy based multi-criteria methodology for appropriate selection of PCM. They used n-eicosane, Paraffin wax, 1-Hexadecimal, RT-80, Sodium hydrate, PCM-HS29P, PCM-HS34P, Rubitherm RT-42, Lauric Acid, and Suntech P116 PCMs. They found that RT-80 PCM is more suitable for better thermal management of the electronic device. Saha and Dutta [2011] and Saha et al. [2008] carried out numerical and experimental analysis on PCM based heat sink using n-eicosane in conjunction with thermal conductivity enhancer (TCE). They used the GA based optimization tool to predict the optimum width of heat sink fins. They have considered both conduction and convection effect on melting of PCM and suggested that the optimum width of fins gives better heat transfer rate and improvement in thermal cycle. Nayak et al. [2006] studied numerically the effectiveness of thermal conductivity enhancer (TCE) and found that the effectiveness of TCE improves with better thermal conductance of PCM. They also concluded that, the effect of melt convection is significant at high permeability and Rayleigh number.

From the above literature, it is clear that PCM is used extensively for the thermal energy storage and for the electronic cooling applications (especially heat sinks). However, the use of PCM in the passive cooling of ICs (heat sources) is scarce in the literature. The transient analysis of PCM under mixed convection is rarely reported in the literature. The study of PCM based mini-channels (fabricated on the substrate board) used for the cooling of heat sources is scarce in the literature. Hence, the present study focuses on the numerical investigation for the cooling ICs (for the optimal configuration, as reported by Mathew and Hotta [2018]) using PCM kept inside the protruded mini-channels.

2. Numerical Analysis

The transient analysis of PCM is carried out with the solidification-metritification model using ANSYS Fluent 16.0. It uses the enthalpy - porosity technique where the melt interface is not tracked explicitly. However, the liquid fraction that indicates the fraction of the cell volume in the liquid form that is associated with each cell in the domain can be predicted accurately. The liquid fraction is computed for each iteration based on the enthalpy balance. During the melting of PCM from solid to liquid, a mushy zone is formed for which the liquid fraction value lies between 0 and 1. When the material has fully solidified in a cell, the liquid fraction becomes zero, whereas when the material melts and turns into a liquid, the liquid fraction becomes 1 [Ansys Guide, 2013]. In the present study, the phase change material used is paraffin wax whose properties are given under Table 1 [Totten et al., 2003].

Table 1: Thermo-physical properties of Paraffin Wax (Mathew and Hotta [2019])

Property	Value
Density (kg/m ³)	818
Specific heat (J/ kgK)	2950
Thermal conductivity (W/mK)	0.24
Viscosity (m ² /s)	2.3227 x 10 ⁻³
Latent heat of fusion (kJ/kg)	266
Solidus temperature (K)	300
Melting temperature (K)	316

2.1 Computational domain

The transient analysis for the Paraffin wax used for the cooling of IC chips (heat sources) is carried out using ANSYS Fluent 16.0 for five different cases. The original substrate board has four rectangular mini-channels in which Paraffin wax is filled. Case A: substrate board without PCM in four mini-channels shown in Fig. 1. Case B: PCM in channel 1, Case C: PCM in all four mini-channels, Case D: PCM above the substrate board and Case E: PCM below the substrate board. The cases B - E are shown in Fig. 2. The methodology used for the analysis of all the five cases is the same as discussed under section 3. The 3D geometry and its mesh are created using the ANSYS Workbench Design Modeler. The mesh is imported to ANSYS Fluent 16.0; the simulations are carried out using 3D double precision. The Fluent is able to differentiate two different fluids, air and PCM using the solidification-melting model.

Figure 1: Schematic diagram of the substrate board without PCM in all the four mini-channels (Case A)

The following assumptions are considered to develop the numerical model used for the present study.

1. Thermo-physical properties of paraffin are dependent on temperature.
2. The effect of radiation and viscous dissipation are neglected.
3. The volume variation due to melting was neglected.
4. The Boussinesq approximation is valid.
5. The sharp interface between the solid and liquid phase of a real pure substance or a real eutectic mixture is represented by a narrow mushy region, where the material is neither solid nor liquid but a mixture of both phases.

Transient simulations are then carried out for all the above-mentioned cases under mixed convection mode and the initial condition ($t = 0$) of Paraffin wax is taken as solid at room temperature, $T = T_{\infty} = 25^{\circ}\text{C}$. The boundary condition with a velocity of air at the inlet ($Z=0$) is 31m/s (calculated using the mixed convection formulation with Richardson number = 1, as reported by Mathew and Hotta [2018]) and at the outlet ($Z=L$), the condition is $P=P_{\infty}$. The lateral walls of the substrate board are considered to be adiabatic. The specification and dimension of the different components of the numerical model are shown in Fig.1. The heat flux supplied for $U_1 - U_2 - U_3 - U_4 - U_5 - U_6 - U_7$ (U stands for the heat source) are 2.5182, 5.46, 0.0581, 0.0581, 2.005, 4.15 and 0.0822 W/cm² respectively. This is to simulate a practical case where all the heat sources have different sizes and all dissipating different power. The heat flux values are fetched from a data sheet [Texas instruments, 2014].

Figure 2: Different cases (B - E) of PCM on the substrate board

3.2 Governing equations

The modeling of PCM is carried out using the enthalpy - porosity technique suggested by Voller [1987] and Brent et al. [1988]. This technique uses the solidification-melting model in Fluent solver where the mushy zone constant is taken as $C = 10^5$. The liquid fraction (α) lies between 0 to 1 in this mushy region. The liquid fraction becomes zero (0) when the material is in solid-state and one (1) in the liquid state. The governing equations (equations of mass, momentum, and energy) used for the numerical modeling using the PCM based mini-channel is given under Eqs 1 - 6.

3.2.1 Continuity equation

The continuity equation for 3D, steady flow is given in Eq. 1. For incompressible flow, the density (ρ) can be taken as constant.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \quad (1)$$

3.2.2 Momentum equation

The enthalpy-porosity technique treats the mushy region (partially solidified region) as a porous medium. The porosity in each cell is set equal to the liquid fraction in that cell. The momentum sink due to the reduced porosity in the mushy zone takes the following form, as given in Eq. 2.

$$S = -A(\beta)V \quad (2)$$

Where ' $A(\beta)$ ' is the porosity function defined by Brent et al. [1988]. The source term is used to describe the flow in the porous medium in the momentum equation, and it has to be zero in the liquid phase to allow the free motion, but it has to be large in the solid phase to force the velocity values to near-zero (Vogel et al. [2016]), while different function full-fill this requirement, most often the Carman-Kozeny equation, which is derived from the Darcy law for fluid flow in porous media is used in the modified form.

$$A(\beta) = \frac{A_{mush}(1-\alpha)^2}{\alpha^3 + \epsilon} \quad (3)$$

Where ' α ' is the liquid volume fraction. ' ϵ ' value is taken to be very small ($\epsilon = 0.001$) to prevent the division by zero. ' A_{mush} ' is the mushy zone constant which measures how fast the fluid velocity approaches zero during solidification. The momentum equation is given in Eq 4.

$$\frac{\partial(\rho V)}{\partial t} + \nabla \cdot (\rho V) = -\nabla p + \mu \nabla^2 V + g\beta(T - T_{\infty}) + S \quad (4)$$

Where ' ρ ' is the density, ' k ' is the thermal conductivity, ' μ ' is the dynamic viscosity, ' S ' is the momentum source term, ' V ' is the fluid velocity, ' p ' is the pressure, ' g ' is the gravitational acceleration.

3.2.3 Energy equation

The total enthalpy of the material is computed as the sum of the sensible enthalpy ' S_h ', and the latent enthalpy ' L_h '.

$$H = S_h + L_h \text{ where}$$

$$S_h = S_{href} + \int_{T_{ref}}^T C_p dT \quad (5)$$

The liquid fraction (α) is defined as $\alpha=0$; if $T < T_{solidus}$, $\alpha=1$; if $T > T_{liquidus}$ and $\alpha = ((T - T_{solidus}) / (T_{liquidus} - T_{solidus}))$; if $T_{solidus} < T < T_{liquidus}$

The latent heat content is now written in terms of the latent heat of the material $H = \alpha L$. For the solidification and melting problems, the energy equation is written as given under Eq. 6.

$$\frac{\partial}{\partial t} (\rho H) + \nabla \cdot (\rho \vec{V} H) = \nabla \cdot (k \nabla T) + S_h \quad (6)$$

3.3 Grid independence study

While conducting the numerical analysis, the quality of the mesh and the number of elements play a vital role to obtain accurate results. The mesh must be optimum such that it will reduce the computational time. In the present study, the mesh elements generated are 757111. It is seen that increasing the mesh elements beyond this value increases the computational time but did not impact much on the results.

The numerical simulation was carried out using Fluent 16.0 with Semi-Implicit Pressure-Linked Equation (SIMPLE) algorithm. In PCM, the density changes with an increase in temperature during the melting and solidification process. Therefore the density was set as a piecewise linear function of temperature and the mushy zone constant is taken as $C = 10^6$. The time step analysis is carried out and found that 1 sec is appropriate to track the melting of PCM. The convergence criteria are set at 10^{-4} for mass and momentum conservation equations respectively and at 10^{-6} for the energy conservation equation.

4. Results and Discussion

Initial simulations are carried out for Case A. The temperature of the ICs obtained is shown in Fig.3. It is seen that the ICs U_2 and U_6 have a maximum temperature of 70.73°C and 57.89°C followed by U_1 and U_5 with 40.95°C and 37.43°C respectively. The ICs U_3 , U_4 and U_7 have the lowest temperature as predicted from Fig.3. Now, in Case B, the PCM

(paraffin wax) is filled only inside the channel 1 as shown in Fig. 2. It is clear that PCM receives the heat gradually and starts melting with the increase of volume fraction from 0 to 1, where it melts entirely and turns into liquid in 60 secs. The time taken to melt the PCM and convert it again to liquid is the charging time; it remains as liquid up to 120 secs as shown in Fig. 4a. The heat transfer to PCM is by convection and the heat is conducted within the ICs. During the charging time, there is a temperature drop of 2 - 3°C of ICs as shown in Fig. 3.

Figure 3: Temperature variation of the ICs for the different cases A - E

In Case C, all four channels are filled with PCM (paraffin wax) as shown in Fig. 2. It is observed that PCM in channels 1, 2 and 4 get melted fast, as it receives the heat transferred from the surrounding ICs U_2 , U_6 , U_1 , and U_5 respectively. Channel 3 is surrounded by low powered ICs U_7 and U_3 and the amount of heat transfer through convection from these ICs is very less. Therefore the melt fraction of PCM on channels 1, 2 and 4 is higher than channel 3 as shown in Fig. 4b. There is a temperature drop of 1 - 3°C for Case C as shown in Fig. 3. In Case of D, PCM (paraffin wax) is placed above the substrate board using another board of thickness 1 mm and length and width equal to the original substrate board, as shown in Fig. 2. It is observed that for this case PCM is directly in contact with the ICs; they have more contact surface with the PCM which subsequently results in maximum heat supply to the PCM.

Figure 4 a: Volume fraction of the PCM for the cases B, D, and E

Figure 4b: Volume fraction of the PCM for the case C

The PCM then absorbs heat and starts melting which results in more temperature drop of 3 - 6°C from the ICs. The volume fraction for Case D is shown in Fig. 4a. The temperatures of the ICs and substrate board U_1 - U_2 - U_3 - U_4 - U_5 - U_6 - U_7 -PCB for this case are 39.56-64.52-29.03-28.49-36.86-54.29-28.01-34.32°C respectively as shown in Fig. 3. In Case E, the PCM is placed between two substrate boards to study the effect of heat transfer from the substrate board to the PCM as shown in Fig. 2.

It is seen that the temperature of the ICs remain almost similar to Case A as there is no PCM above the substrate board. As the substrate board is made of Bakelite (low thermal conductivity), the heat is not conducted to the PCM placed below it. This results in no-melting of PCM and the volume fraction remains zero in solid-state as shown in Fig. 4 a.

Figure 5 shows the temperature variation of the ICs using different PCMs. The PCM is kept in the left mini-channel with a volume content of 100%. Figure 5 shows that there is a temperature drop of 4 to 12.5% using the PCM, which signifies the increase in the operating time of the ICs. Again, n-eicosane leads to the lowest temperature of the ICs as compared to other PCMs due to its lowest melting point value.

Figure 5: Temperature variation of the ICs using the different PCM

The important analysis in the PCM is to calculate the amount of heat absorbed by the PCM that depicts the cooling of the ICs. The heat stored is calculated as $Q = [(M_{PCM} C_{PCM} (T_{melting} - T_{initial})) + M_{PCM} L_{PCM}]$. The mass flow rate of the PCM is calculated for the time taken by the PCM to change its phase from solid to liquid. The amount of heat stored is found

to be 292.83 J, 1171.33 J, and 3943.49 J for the cases, B, C, and D respectively. The maximum heat stored is for the case D and the maximum heat input given to the ICs is 1.99W (maximum heat flux converted to input power). Figure 6 shows the heat stored (J) by the PCM for different PCM used in the left and right mini-channel. The heat stored are calculated using equation $Q = [M_{PCM} C_{PCM} (T_{melting} - T_{initial}) + M_{PCM} L_{PCM}]$. The PCM absorbs the heat dissipated by the ICs and allows these to cool faster. Ultimately the temperature of the ICs drops down. The amount of heat stored is maximum 914.69 J for the PCM, P116 ($T_m = 49.5^\circ\text{C}$), for which the maximum heat input to the ICs is 13.66 W (maximum heat flux converted to input power).

Figure 6: Heat stored by the different PCM

4.1. Validation of results

The current numerical model is validated with the experimental results obtained by Mahmoud et al. [2013]. They conducted experiments for the cooling of heat sinks using paraffin wax and other phase change material by supplying different heat inputs. The present numerical model is validated by supplying one of the heat input values of 4 W for a single cavity heat sink with paraffin wax. Figure 7 shows the variation of PCM based single cavity heat sink temperature with time, and clearly suggests that the numerical results are in strong agreement with the experimental one with a maximum variation of 0.058%. The temperature obtained numerically has the same trend as that of the experimental one.

Figure 7: Validation of the present numerical study with Mahmoud et al. [2013]

4.2. Correlation

Figure 8 shows the variation of Fourier number, Fo ($Fo = \alpha_{PCM} t / L_c^2$) with the non-dimensional temperature excess θ , ($\theta = (T_{max} - T_{\infty}) / \Delta T_{ref}$). The figure clearly depicts the increase of Fo with θ . Fourier number is the non-dimensional parameter used to predict the time taken by the PCM for melting. Based on the transient analysis for the cooling of ICs using different PCM, a correlation is proposed for the non-dimensional temperature excess (θ) and Fourier number (Fo). The correlation is given in Eq. 7.

Figure 8: Variation of Fourier number (Fo) with non-dimensional temperature excess (θ)

$$\theta = 0.005(Fo)^{0.535} \quad (7)$$

Equation 7 has a regression coefficient of 0.97 and the root mean square error on the estimate is 0.0002. The Eq. 7 is valid for $0.00513 \leq Fo \leq 1.62734$, $0.000229 \leq \theta \leq 0.00604$.

5. Conclusions

The transient analysis of paraffin wax is carried out using ANSYS Fluent for five different cases for the cooling of seven non-identical ICs (Aluminium) mounted on a substrate (Bakelite). The paraffin wax (PCM) was placed inside the mini-channels on the substrate board. It is observed that conjugate heat transfer is predominant that results in the melting of PCM. Case D in which the PCM is placed above the substrate board has the maximum temperature drop of 3 - 6°C followed by Case C with PCM in all the four mini-channels. The results suggest that PCM (paraffin wax) can be used extensively for the cooling of ICs to keep them under the safe temperature limit of 85°C. For the comparison of temperature using different PCMs, it is seen that n-eicosane (lower melting point) has resulted in a maximum temperature drop from the ICs. However, Paraffin wax has resulted in storing the maximum amount of heat. The effect of PCM volume content is also studied for the cooling of ICs. The charging and discharging of ICs using PCM signifies that the cooling of ICs is much faster as compared to the heating one. This results in efficient working and thus increases the reliability of ICs.

6. References

- [1] S. M. Sohel Murshed, 2016, Introductory Chapter: Electronics Cooling - An Overview.
- [2] Y.H. Wang, Y.T. Yang, 2011, Three-Dimensional Transient Cooling Simulations of a Portable Electronic Device using PCM (Phase Change Materials) in the Multi-Fin Heat Sink, *Energy*. 36, 5214 - 5224.
- [3] R. Baby, C. Balaji, 2012, Experimental Investigations on Phase Change Material Based Finned Heat Sinks for Electronic Equipment Cooling, *International Journal of Heat and Mass Transfer*. 55 (5 - 6), 1642 - 1649.
- [4] H. El. Qarnia, A. Draoui, E. K. Lakhal, 2013, Computation of Melting with Natural Convection inside a Rectangular Enclosure Heated by Discrete Protruding Heat Sources, *Applied Mathematical Modelling*. 37 (6), 3968 - 3981.
- [5] R. Baby, C. Balaji, 2013, Thermal Optimization of PCM Based Pin Fin Heat Sinks: An Experimental Study, *Applied Thermal Engineering*. 54 (1), 65 - 77.
- [6] J. Thomas, P.V.S.S. Srivatsa, S. Ramesh Krishnan, R. Baby, 2016, Thermal Performance Evaluation of a Phase Change Material Based Heat Sink: A Numerical Study, *Procedia Technology*. 25, 1182 - 90.
- [7] M. V. Karvinkoppa, T.K. Hotta, 2017, Numerical Investigation of Natural and Mixed Convection Heat Transfer on Optimal Distribution of Discrete Heat Sources

- Mounted on a Substrate, IOP Conference Series in Material Science and Engineering. 263.
- [8] S. Gharbi, S. Harmand, S. Ben Jabrallah, 2017, Experimental Study of the Cooling Performance of Phase Change Material with Discrete Heat Sources – Continuous and Intermittent Regimes, *Applied Thermal Engineering*. 111, 103 - 111.
- [9] S. Li, Y. Chen, Z. Sun, 2017, Numerical Simulation and Optimization of the Melting Process of Phase Change Material Inside Horizontal Annulus, *Energies*. 10, 1249.
- [10] R. Kandasamy, X.Q. Wang, A.S. Mujumdar, 2008, Transient Cooling of Electronics Using Phase Change Material (PCM)-Based Heat Sinks, *Applied Thermal Engineering*. 28, 1047 - 1057.
- [11] S. Sridharan, R. Srikanth, C Balaji, 2018, Multi-Objective Geometric Optimization of Phase Change Material Based Cylindrical Heat Sinks with Internal Stem and Radial Fins, *Thermal Science and Engineering Progress*. 5, 238 - 251.
- [12] M. Hafiz, M. Junaid, A. Giovannelli, M. Irfan, T. Bin, H. Muhammad, F. Hassan, A. Arshad, 2018, Thermal Management of Electronics/ : An Experimental Analysis of Triangular, Rectangular and Circular Pin-Fin Heat Sinks for Various PCMs, *International Journal of Heat and Mass Transfer*. 123, 272 - 284.
- [13] V. K. Mathew, T. K. Hotta, 2018, Numerical Investigation on Optimal Arrangement of IC Chips Mounted on an SMPS Board Cooled under Mixed Convection, *Thermal Science and Engineering Progress*. 7.
- [14] S. Khanna, S. Sundaram, 2018, Multiple Phase Change Material (PCM) Configuration for PCM-Based Heat Sinks - An Experimental Study, *Energies*. 11(7), 1629.
- [15] A. Loganathan, I. Mani, 2018, A Fuzzy Based Hybrid Multi-Criteria Decision Making Methodology for Phase Change Material Selection in Electronics Cooling System, *Ain Shams Engineering Journal*. 9(4), 2943 - 2950.
- [16] S. K. Saha, P. Dutta, 2011, Effect of Melt Convection on the Optimum Thermal Design of Heat Sinks With Phase Change Material, *Journal of Enhanced Heat Transfer*. 18 (3).
- [17] S. K. Saha, K. Srinivasan, P. Dutta, 2008, Studies on the Optimum Distribution of Fins in Heat Sinks Filled With Phase Change Materials, *ASME Journal of Heat transfer*, 130 (3).
- [18] K. C. Nayak, S. K. Saha, K. Srinivasan, P. Dutta, 2006, A Numerical Model for Heat Sinks With Phase Change Materials and Thermal Conductivity Enhancers, *International Journal of Heat and Mass Transfer*. 49 (11-12), 1833 - 1844.
- [19] Ansys. Fluent, Release 16.0, 2013, Theory Guide. November.
- [20] G.E. Totten, S.R. Westbrook, R.J. Shah, *Fuels and lubricants handbook*, 2003. ASTM Int.
- [21] Texas Instruments. LMx58 - N Low - Power, 2014, Dual - Operational Amplifiers.
- [22] R. V. Voller, C. Prakash, 1987, A Fixed Grid Numerical Modelling Methodology for Convection-Diffusion Mushy Region Phase-Change Problems, *International Journal of Heat and Mass Transfer*. 30 (8), 1709 - 1719.
- [23] A. D. Brent, V. R. Voller, K. J. Reid, 1988, Enthalpy-Porosity Technique for Modeling Convection-Diffusion Phase Change: Application to the Melting of a Pure Metal. *Numerical Heat Transfer* 13 (3), 297 - 318.
- [24] J. Vogel, J. Felbinger, M. Johnson, 2016, Natural Convection in High-Temperature Flat Plate Latent Heat Thermal Energy Storage Systems, *Applied Energy*. 184, 184 - 196.
- [25] S. Mahmoud, A. Tang, C. Toh, R. Al-dadah, S.L. Soo, 2013, Experimental Investigation of Inserts Configurations and PCM Type on the Thermal Performance of PCM Based Heat Sinks, *Applied Energy*. 112, 1349 - 1356.
- [26] V. K. Mathew, T. K. Hotta, 2019, Role of PCM Based Mini-Channels for the Cooling of Multiple Protruding IC Chips Mounted on the SMPS Board - A Numerical Study, *Journal of Energy Storage*. 26.