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Experimental and Numerical Analysis of Phase Change Material (PCM) Heat Sinks and Determination of Mushy Zone Constant

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Abstract **-** Electronic packages with increased performance and process capability and decreased in size have been developed daily. High-performance chips include more circuits and this causes an increase in heat dissipation. To remove this heat from component and reduce the risk of overheating and damage, heat sinks filled with phase change material (PCM) can be used as passive cooling device. PCMs can absorb and store large amounts of heat energy and thanks to this, temperature of electronic devices can be regulated at the melting point of PCM. Since performing experiments and testing procedure of prototypes are costly, difficult and time consuming, numerical modelling saves time and reduces cost of prototyping. During phase transition of PCM, mushy zone, which is a two-phase mixed region between solid and liquid regions, is observed. Numerical modelling of this region is critical for PCMs because this region affects whole flow characteristics and heat transfer of PCM. To model this region, mushy zone constant is used in ANSYS Fluent Solidification&Melting option. This constant is accepted as 10^5 for all PCMs in ANSYS Fluent, however, each PCM has a specific mushy zone constant, which should be determined before flow analysis. In this paper, a 4-chambered PCM heatsink with different PCMs are investigated experimentally and numerically. Mushy zone constants are determined from experiments and then applied as an input to numerical analyses. Different trademarked phase change materials with codes A58H, RT-65 and S72 PCMs are used in the experiments. Experimental results are used for the validation of numerical studies. CFD results show good agreement with experiments, the highest error is obtained as 11%. In addition, from experimental results, it is observed that PCM provides a 30ºC temperature drop and therefore increases the operational time of IC package.
Keywords**:** PCM heatsink, Mushy zone constant, Dendrite length, Electronics cooling, Phase change phenomena.

1. Introduction

In today's life, electronic devices and products have become integrated into our lives. Due to the developments in electronics industry, the performance of the components increases while dimensions decrease. Therefore, the heat flux dissipates from the electronic components augment day by day. It can cause thermal failures and damages on components. To remove excess heat, different solutions based on active or passive cooling can be applied [1]. In passive cooling applications, there is no energy consumption and therefore there is no need for a complex structure or additional mechanical parts. Using phase change materials (PCM) is one of the applications of passive cooling. They are useful thorough the melting-solidification cycle and received energy taken from the component which dissipate heat is stored in phase changing period. Since phase change occurs in a certain temperature range, the component temperature maintained in melting temperature during the operations, thanks to the high-capacity heat storage, especially for time-dependent situations. In the literature, many studies are conducted to investigate PCM effects on heatsinks experimentally or numerically. Many studies have investigated the effects of PCM on the cooling of electronics. The common result was that PCM can stabilize and control the case temperature of the components subjected to cyclic heat loads. For steady loads, PCM provides a longer operation time by preventing IC package temperatures to reach the critical temperatures mentioned earlier. Since the thermal conductivity values of PCMs are low (<1 W/mK), the use of fin structures has been extensively studied in the literature. With this use, the heat transfer increases significantly and the high temperature gradients on the surface to be cooled are reduced.

Humphrey et al. [2] were the first to propose using a combination of PCM and a heat sink to improve the efficiency of the PCM. They applied the PCM to a heat sink with plate fins and analysed the results. The impact of the thickness of the fins on the effectiveness of the PCM was also examined by them. The study revealed that thinner fins resulted in greater heat transfer rates. In their research, Kandasamy et al. [3] conducted both experimental and numerical studies on heatsinks with phase change material (PCM). They investigated the impact of cyclic power levels, package inclination angle, and melting and solidification times of the PCM in their experiments. Paraffin wax was used as a PCM in their electronic cooling setup. They utilized Boussinesq approximation and the PISO algorithm in 2-D numerical simulations realised by ANSYS Fluent. The study observed that increasing power levels led to a higher melting rate but also longer solidification times. Wang and Yang [4] conducted 3-D numerical solution. In this study, transient simulations and enthalpy-porosity method was applied to ANSYS Fluent. In this case, the fin number, power inputs, and orientations were the main parameters. For the validation, they simulated the study in the literature and maximum 10.2% error was observed by comparing the results. The results indicated that static temperatures could be obtained by using paraffin wax. Better cooling performance and the lowest base temperature values were obtained by increasing the fin number and the orientation effect was found to be negligible. Fan et al. [5] studied on the effects of PCM type and internal fin. N-Eicosane and 1-Hexadecanol PCMs with different melting temperatures were used. As a result, two important inferences were concluded. First, as the melting temperature of the PCM was increased, the time for protection of the system from overheating increased. The other one was that PCM with lower melting temperature kept the system at lower temperatures and gave better thermal performance than others. Selection of the PCM was critically dependent on the conditions of the system and usage. Sridharan et al. [6] investigated the effects of radial fins and internal stem. Both numerical and experimental studies were performed. Also, mushy zone constant parameter was determined by trying different constants in analysis and comparing them with the experimental results. The minimum error was obtained when mushy zone constant was 10^7. It was suggested that further optimizations could be applied by using temperature distribution along the stem. Kabbara et al. [7] studied numerically on the effects of the fins and inclination angle. The main aim of this study was to obtain the effects of the natural convection on melting. The difference of this study was that 5 different mushy zone constants were tried in the analysis to obtain which constant is more appropriate for the dodeconaic acid PCM. Boussinesq approximation was applied to COMSOL to model the buoyancy forces. The most important observation from their analysis was that the mushy zone constant effect was negligible during conduction driven melting. However, during natural convection, dominant effects of mushy zone constant were obtained. This was because of the fact that mushy zone constant had a significant effect on the velocity term in Navier-Stokes momentum equations and therefore dominancy of mushy zone constant started during natural convection stage. Schematic of mushy zone is shown in Figure 1.

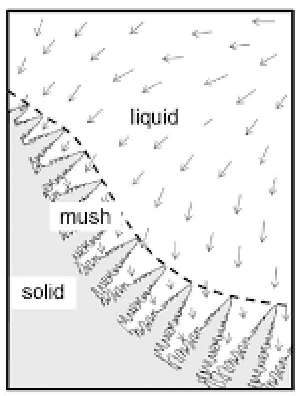

Figure 1: Schematic mushy region [8].

Yang et al. [9] investigated the mushy zone during the melting process for organic PCMs. After examining the experimental microscopic images using image processing, they established a general relation for mushy zone constant that is given in Equation 1.

$$C_{mush} = \frac{180\mu}{d^2} \tag{1}$$

In this study, three different PCMs are examined experimentally and numerically. Numerical solutions are performed by determining mushy zone constants from experiments conducted thorough this study. Thermal performance of the PCM heatsink is also compared with non-PCM heatsink. Analysis results are verified by using previous experimental results. Mushy zone constants are determined by using microscopic images obtained from experiments. Yang's method [9] is used to calculate them.

2. Experimental Setup and Numerical Methodology

2.1. Experimental Setup

The schematic view and photograph of experimental setup are shown in Figure 2 and Figure 3, respectively.

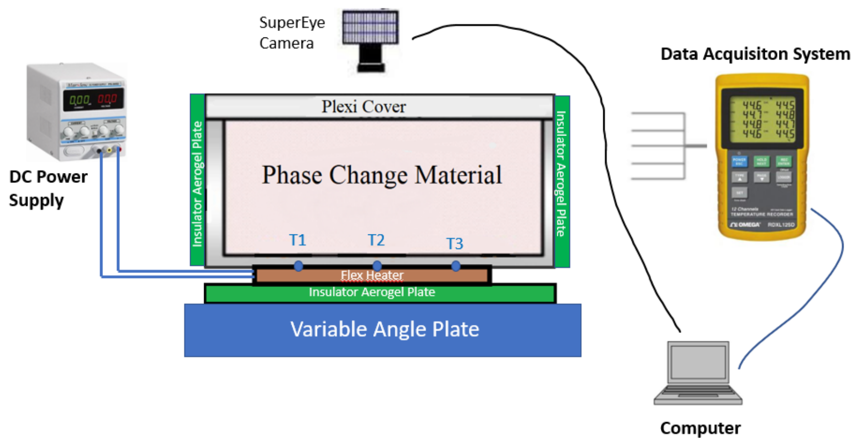

Figure 2: Schematic of the experimental setup.

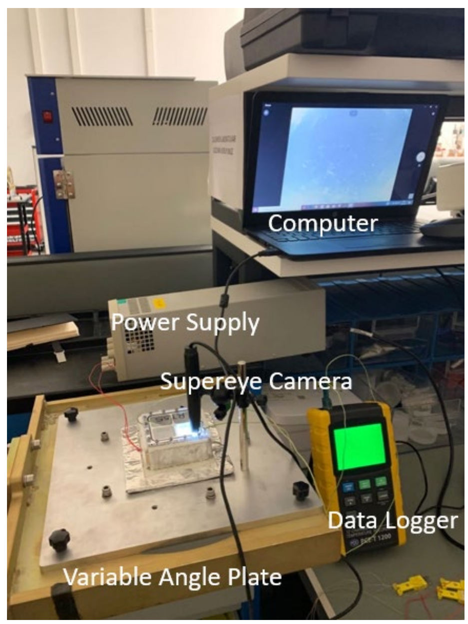

Figure 3: Experimental setup.

The heatsink with dimensions 75x75x25 mm is made from Al6061 and sides are covered with aerogel plates to ensure adiabatic surfaces. Flex heaters with dimensions 75x75 mm are used to simulate 21 W heat load. Homogenous temperature distribution is achieved bottom of the heatsink. Bottom of the heater is covered with aerogel to prevent heat loss from heater. K-type thermocouples are placed at the bottom of the heatsink to measure temperature. Plexiglass cover is used to investigate mushy region and melting phenomena in PCM by using microscopic camera. The material properties of used PCMs and materials are shown in Table 1.

Table 1: Physical properties of PCMs and materials [10,11].

Material	Density (kg/m^3)	Thermal Conductivity(W/mK)	Specific Heat (kJ/kgK)	Melting Temperature (ºC)	Latent Heat(kJ/kg)	Material Type
A58H	820	0.22	2.85	56-57.6	240	Organic
RT-65	830	0.20	2	58-65	150	Organic
S72	1650	0.58	2.13	72-73	285	Inorganic
Al 6061	2700	167	0.89	-	-	
Plexiglass	1180	0.19	1.5	-	-	
Aerogel	150	0.018	1.9	-	-	

2.2. Numerical Methodology

In the literature, different approximations are used in numerical solutions. Some researchers use their own codes while most of them use softwares like COMSOL or FLUENT. In this study, numerical solutions are performed by ANSYS Fluent 2022R1 which use control volume method. ANSYS Fluent has different options in order to model phase change phenomenon.

2.2.1 Governing Equations

For the melting of PCM, "Solidification & Melting" model option which uses "enthalpy-porosity" method is chosen. In the calculations of mushy zone and heat transfer between solid-liquid interfaces embedded equations are directly used. Mushy zone is modelled as a porous medium. The nodal latent heat is assigned according to the temperature value of each cell [9]. All governing equations (continuity, momentum, and energy) are given in Equation 2-4.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_i} = \mu \frac{\partial}{\partial x_j}\frac{u_i}{\partial x_j} - \frac{\partial p}{\partial x_i} + S_b + S_{mushy} \tag{3}$$

$$\frac{\partial}{\partial t}(\rho H) + \nabla.(\rho\vec{u}H) = \nabla.(k\nabla T) \tag{4}$$

The enthalpy term used in energy equation includes sensible and latent heat parts. Latent heat can be expressed in terms of liquid fraction which is defined by Equation 5 in Equation 6.

$$\gamma = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \tag{5}$$

$$\Delta H = \gamma L \tag{6}$$

Since the liquid fraction in Equation 5 depends on temperature, latent heat can be different in each volume cell. By this way heat transfer in mushy region can be accurately modelled. In momentum equation, Equation 3, buoyancy and mushy zone source terms are inserted. Bouyancy term provides modelling natural convection in liquid PCM and other term aims to model hydraulics of mushy zone. Mushy zone source term is defined in Equation 7. Mushy zone function is also shown in Equation 8 where C_{mushy} is the mushy zone constant. It can be changed from 10^3 to 10^9 and unique for each PCM. ε is a small value like 0.001 to prevent division by zero.

$$S_{mushy} = A_{mushy}\vec{v} \tag{7}$$

$$A_{mushy} = C_{mushy}\frac{(1-\gamma)^2}{(\gamma^3 + \varepsilon)} \tag{8}$$

Bouyancy term is given in Equation 9.

$$\rho = \frac{\rho_l}{(\beta(T - T_l) + 1)} \tag{9}$$

2.2.2 Numerical Model

Geometry used in the numerical study is shown in Figure 4. In order to make simplification of real model, screws and seal are ignored. In addition, volume expansion coefficient of PCMs are neglected.

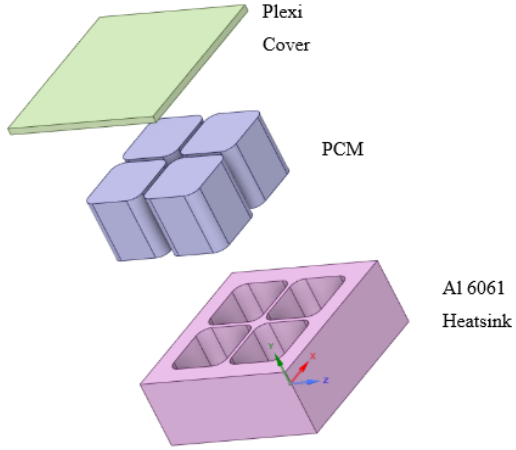

Figure 4: Numerical model of PCM heatsink.

The flow in liquid PCM is assumed laminar. Radiation and convection heat losses are neglected while the environment is 23ºC. The heat flux is uniform and liquid is incompressible fluid also. The boundary conditions are shown in Figure 5. 21 W heat load is applied to bottom of the heatsink.

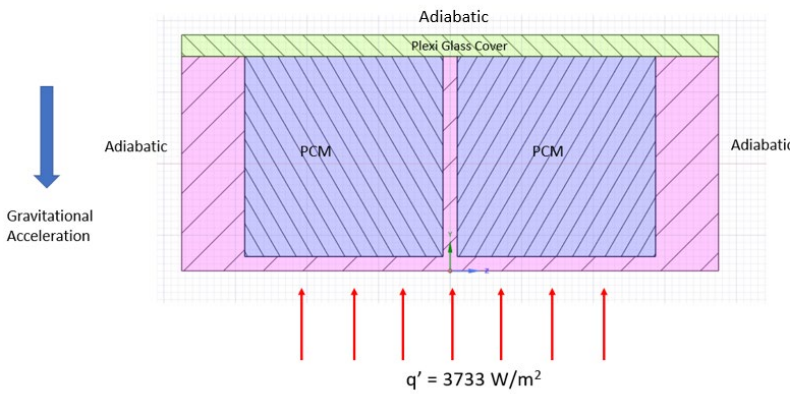

Figure 5: Boundary conditions of numerical model.

The SIMPLE algorithm is used for the solver option, which uses a relationship between pressure and velocity corrections to obtain pressure field. To correctly model natural convection effect, PRESTO! pressure discretization method gives more accurate results than other schemes [11]. This discretization method calculates pressure on the faces of volume cells by using staggered grids. In natural convection cases, therefore PRESTO! method is chosen for pressure correction [11]. For the momentum and energy equations, second order upwind scheme is used. For the transient analysis, time step is chosen as 0.5 s after achieving time independency study and 300,000 volume cells mesh structure with polyhedral is chosen after achieving mesh independency study.

3. Results&Discussion

3.1. Mushy Zone Constant Investigation

The mushy zone constant calculations are explained in this section. To calculate this constant, dendrite lengths of PCMs are measured during experiments. Dendrites are solid-form structures that give a tree-like appearance during the transition from solid to liquid form. Particles that separate from solid PCM during melting process are dendrites. The mushy zone constant values can be determined using the average dendrite length. While the dendrite separation in some PCMs could be seen very clearly in a crystalline form, in some PCMs it was observed that dendrites had a structure similar to a filamentous shape. Dendrites of A58H PCM is shown in Figure 6. Average dendrite length is calculated by choosing 11 different lengths from Figure 6. Mushy zones and dendrites of RT-65 and S72 are shown in Figure 7.

Figure 6: Dendrites of A58H PCM.

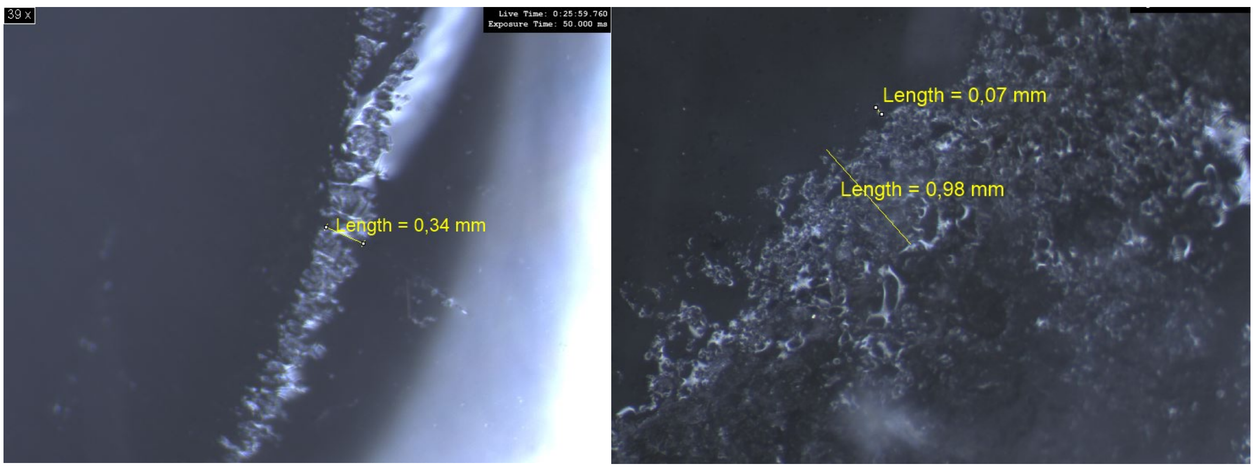

Figure 7: Dendrites of RT-65 and S72 PCMs.

In Table 2, selected three different dendrite lengths, average dendrite lengths and standard deviation of calculation is given. In addition, calculated mushy zone constants also given in Table 2.

Table 2: Observed dendrite lengths and calculated mushy zone constants of A58H, RT-65 and S72 PCMs.

Material	Dendrite Length-1 (mm)	Dendrite Length-2 (mm)	Dendrite Length-3 (mm)	Average Dendrite Length (mm)	Standard Deviation	Viscosity (kg/ms)	Mushy Zone Constant(kg/m^3s)
A58H	0.212	0.295	0.235	0.25	3%	0.007	$2.01x10^7$
RT-65	0.313	0.348	0.185	0.27	8.3%	0.005	$1.23x10^7$
S72	0.280	0.215	0.267	0.24	2.9%	0.02	$5.76x10^7$

3.2. Experimental and Numerical Results

Experimental and numerical result comparisons of PCMs are given in this section. From Figure 8, average base temperature results and comparisons can be seen. Maximum errors are 4.5%, 5.6% and 7.1% for A58H, RT-65 and S72, respectively.

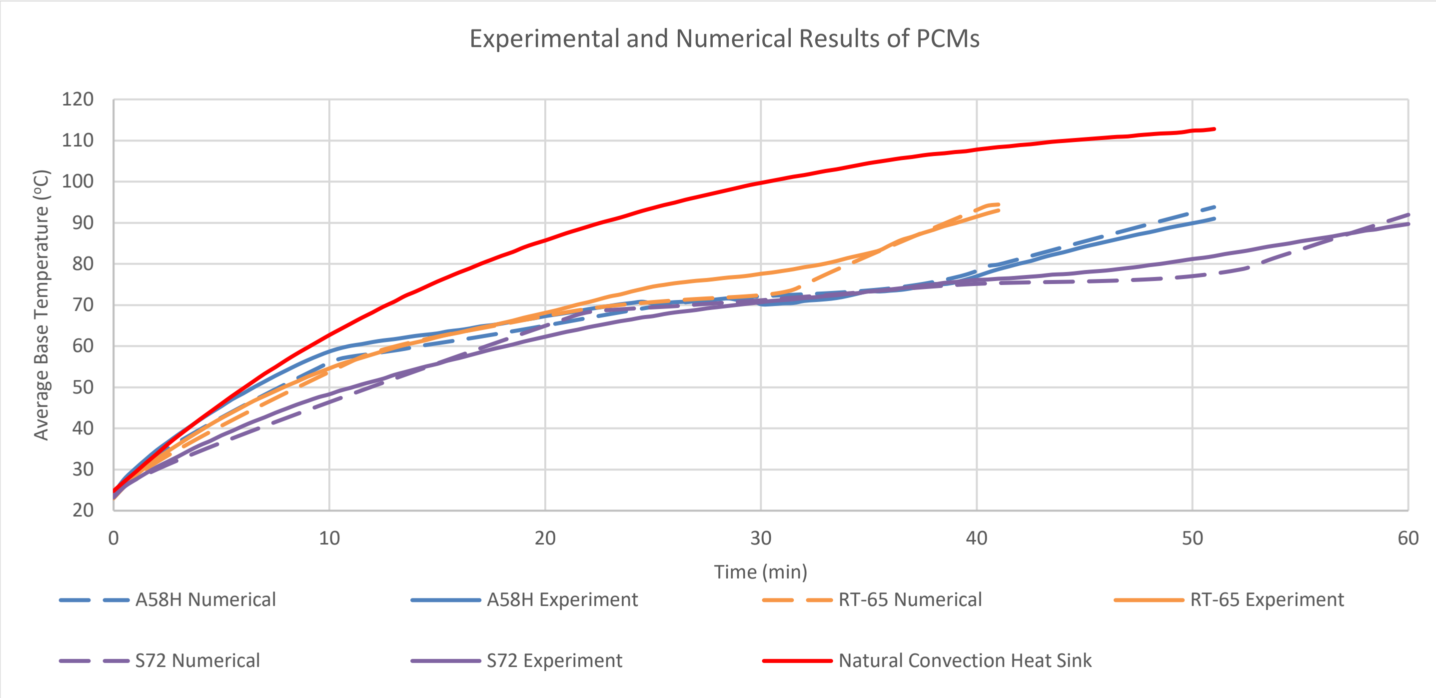

Figure 8: Experimental and numerical results of PCMs.

Liquid fraction contour comparison of three PCMs are also shown in Figure 9-10.

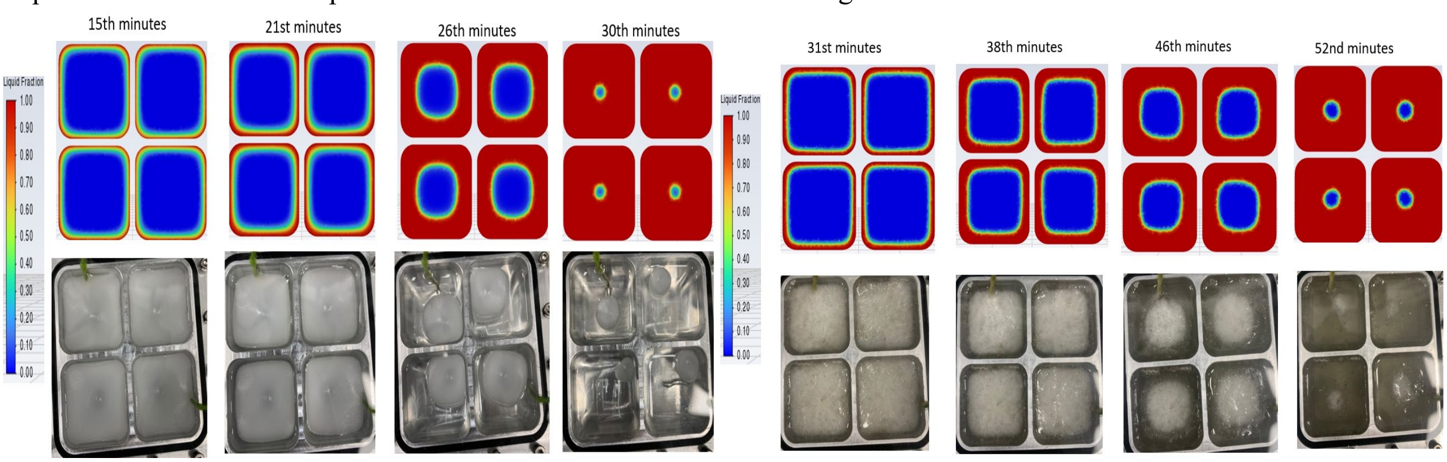

Figure 9: Liquid fraction contour comparison for RT-65 (left) and S72 (right) PCMs.

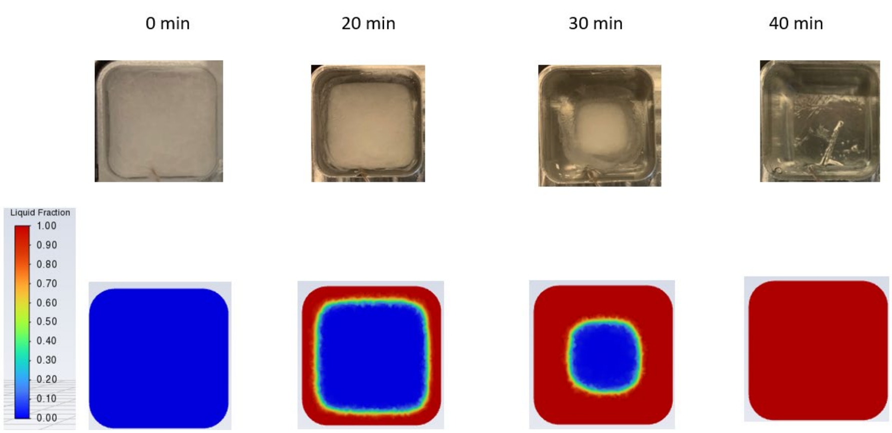

Figure 10: Liquid fraction contour comparison for A58H.

The liquid ratios of PCMs are compatible with experimental results as seen from Figure 9 and Figure 10. In addition, natural convection inside the liquid PCM causes the motion, and it affects the position of the solid PCM as shown in Figure 9. S72 PCM is an inorganic and ingredients of it is different than organic ones. From Figure 9, liquid S72 is observed blurry because of this reason.

Figure 9 also shows the effect of PCM in natural convection cooling. By using S72 PCM, base temperature can be reduced by 30ºC after 50 minutes operation time for IC package.

4. Conclusion

The main objective of this study is modelling of PCMs more accurately. Since having meaningful and comparable results by using three different PCMs, calculation method can be applied in all problems include PCMs. The important point is determination of mushy zone constant values in such kind of problems. In this study, these constants are calculated by measuring average dendrite length of PCMs from microscopic images. Average base temperature results and liquid fraction contours show that numerical results are in good agreement with experimental results. In order to more accurate modelling of systems includes PCM, the mushy zone constant value should be known and provided as an input to ANSYS Fluent. Since mushy zone constant has an important role on governing equations during phase change, the mushy zone constants should be known before initiation of analysis. Mushy zone constants can be determined by calculating average dendrite length values of PCMs.

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