

ANALYSIS OF PHASE CHANGE MATERIAL HEAT SINK

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ABSTRACT

ANALYSIS OF PHASE CHANGE MATERIAL HEATSINK

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In this thesis, the Phase Change Material (PCM) heatsink cooling performance is studied experimentally and numerically. Three parameters, the number of chambers, inclination angle, and different types of PCMs, are investigated to keep the integrated circuit (IC) that dissipates 21 W at safe temperatures and increase the thermal performance of heatsinks. In the experiments, heatsinks with 1, 4, 9, and 16 chambers are filled with PCMs, and the results obtained from experiments are used to validate numerical analyses conducted using Ansys Fluent. The conduction driven and natural convection driven melting phases are investigated using numerical analysis results. Seven different inclination angles and eight different types of PCMs are examined experimentally and numerically. Moreover, mushy zone constants required in the phase change model are determined using a microscope and an image processing program. Among all cases, the maximum error is 11% between CFD analyses and experimental studies.

From experimental results, it is observed that PCM provides a 24°C temperature drop and therefore increases the operational time of IC package. Moreover, as the number of chambers increases, the base temperature of PCM decreases however due to geometrical constraints, as the number of chambers increases the amount of PCM

decreases and therefore melting time becomes shorter. The numerical results show that reverse U shapes occur due to the natural convection effect on liquid PCM. Also, vortex type flow shapes are observed from velocity vectors. In addition, as the inclination angle increases the base temperature increases as well. T-shape occurs beyond 30° inclination angle due to gravity effects on natural convection. In addition, as PCM's melting temperature decreases, the heatsink's base temperature decreases. The results of experiments and numerical analysis show that, S72 PCM has the best thermal performance among eight different PCM and 1 and 4 chambers heatsink have the highest operational time. The inclination angle affects the thermal performance during melting, with the best thermal performance obtained at 0° inclination angle. The CFD analyses results show good agreement with the experimental results.

Keywords: Phase Change Material Heatsink, Number of Chamber, Inclination Angle, Mushy Zone Constant, Dendrite Length

ÖZ

FAZ DEĞİŞİM MALZEMELİ ISI YAYICILARIN ANALİZİ

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Bu tezde, faz değişim malzemeli (FDM) ısı yayıcıların soğutma performansı deneysel ve nümerik olarak çalışılmıştır. Odacık sayısı, açısı ve farklı tip FDMlerden oluşmak üzere üç farklı parametre, 21 W ısı yüküne sahip bir entegre devrenin (ED) güvenli sıcaklıklarda tutulması ve ısı yayıcıların termal performansını arttırmak amacıyla incelenmiştir. Deneylerde 1,4,9 ve 16 odacık sayısına sahip ısı yayıcılar FDMler ile doldurulmuştur. Ansys Fluent yazılımında gerçekleştirilen nümerik analizler, bu deneyler ile doğrulanmıştır. Analiz sonuçları kullanılarak iletim baskını ve doğal taşınım baskını erime aşamaları incelenmiştir. Yedi farklı açı ve sekiz farklı FDM deneysel ve nümerik olarak incelenmiştir. Ek olarak, Nikon marka mikroskop ve ImageJ renk analizi programı kullanılarak lapa bölgesi konumları ve lapa bölgesi sabitleri belirlenmiş, bu sabitler kullanılarak faz değişimi Ansys Fluent'te modellenmiştir. Bütün analizlerde, deneysel ve nümerik çalışmalar arasındaki elde edilen en yüksek hata oranı %11'dir.

FDMler 24°C'lik sıcaklık düşüşü sağlamış ve EDMlerin çalışma süresini arttırmıştır. Buna ek olarak, odacık sayısı arttıkça ısı yayıcı taban sıcaklığı azalmaktadır, ancak, boyutsal kısıtlamalardan dolayı odacık sayısı arttıkça ısı yayıcıların içerdiği FDM

oranı azalmaktadır ve bu sebeple, odacık sayısı arttıkça erime süresi de kısalmaktadır. Nümerik sonuçlar, FDM'nin eriyen kısımlarında doğal konveksiyon etkisinden dolayı ters U şekillerinin oluştuğunu göstermektedir. Ek olarak, vorteks benzeri akışlar hız vektörleri incelendiğinde görülebilmektedir. Sistem açısı arttıkça ısı yayıcı taban sıcaklığı artmaktadır. 30°'den büyük açı değerlerinde yer çekimi ivmesinin doğal konveksiyona etkisinden dolayı katı FDMlerde T şekli oluşmaktadır. İlaveten, FDM'nin erime sıcaklığı azaldığında ısı yayıcı taban sıcaklığı da azalmaktadır. MiniTab programı kullanılarak açı ve FDM tipi etkileri kapsamında kontürler çizdirilmiş ve yorumlanmıştır. Sonuç olarak, S72, sekiz farklı FDM arasında en iyi soğutma performansı göstermiştir. 1 ve 4 odacıklı ısı yayıcılar en yüksek çalışma zamanına sahiptirler. Açı etkisi erime esnasında fark oluşturmaktadır. 0° sistem açısı en iyi sonucu vermiştir. Yapılan Hesaplamalı Akışkanlar Dinamiği (HAD) analizleri deney sonuçlarıyla uyumludur.

Anahtar Kelimeler: Faz Değişim Malzemeli Isı Yayıcı, Odacık Sayısı, Eğim Açısı, Lapa Bölge Sabiti, Dendrit Uzunluğu



To World Peace

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LIST OF ABBREVIATIONS

ABBREVIATIONS

ANN	Artificial Neural Network
CFD	Computational Fluid Dynamics
IC	Integrated Circuit
PCM	Phase Change Material
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
TCE	Thermal Conductivity Enhancer

LIST OF SYMBOLS

SYMBOLS

A_{mushy}	Mushy Zone Function
C_{mushy}	Mushy Zone Constant (kg/m ³ s)
c_p	Specific Heat (kJ/kgK)
d	Dendrite Length (mm)
g	Gravitational Acceleration (m/s ²)
H	Total Enthalpy (J)
h	Sensible Enthalpy (J)
k	Thermal Conductivity (W/mK)
L	Latent Heat (kJ/kg)
m	Mass (kg)
p	Pressure (Pa)
Q	Heat Load (W)
S_b	Bouyancy Source Term
S_{mushy}	Mushy Zone Source Term
t	Time (s)
T	Temperature (°C)
T_m	Melting Temperature (°C)
u	Velocity (m/s)
β	Thermal Expansion Coefficient (1/K)

γ	Liquid Fraction Ratio
μ	Dynamic Viscosity (kg/ms)
ρ	Density (kg/m ³)



CHAPTER 1

INTRODUCTION

In today's life, electronic devices and products have become integrated into lives. Most of the time, these devices are used for simple and complex tasks; therefore, there has been a huge growth in the electronics market. In addition, electronic packages have been developed daily, whose performance and process capacity increase but decrease in size. In 1975, Moore's law emerged. Moore's law states that the number of components that can be placed on the integrated circuits will double every 18 months, creating large increases in the computing capacity of computers, while production costs will remain the same [1]. As can be seen from Figure 1.1, the processors produced to date have proven the validity of this law. High-performance chips include more dense circuits, and it causes an increase in the heat flux of the electronic components. From Figure 1.2, the heat power upward trend can be seen. For most electronic devices, especially for the IC (Integrated Circuit) packages, the maximum allowable temperature value ranges from 85°C to 120°C [2]. Considering the development of the IC packages and components, electronic parts of the devices can easily reach these temperature values unless there are cooling solutions. These excessive temperature values cause failures on components of electronic devices due to inadequate thermal management. US Air Force made a survey, demonstrating that the percentage of temperature-related failures in electronics is 55%. Other causes of failure are vibration, humidity, and dust [3]. Apart from this, 1 °C temperature drop in an electronic component can reduce the probability of failure of the components by up to 4% [4].

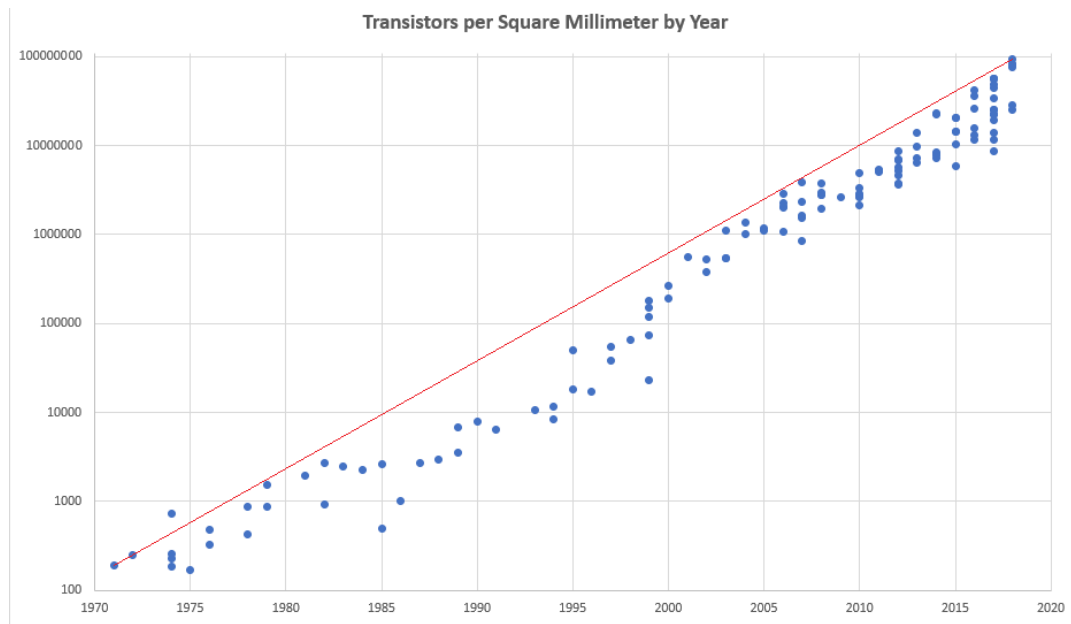


Figure 1.1. Microprocessor development according to Moore's Law [1].

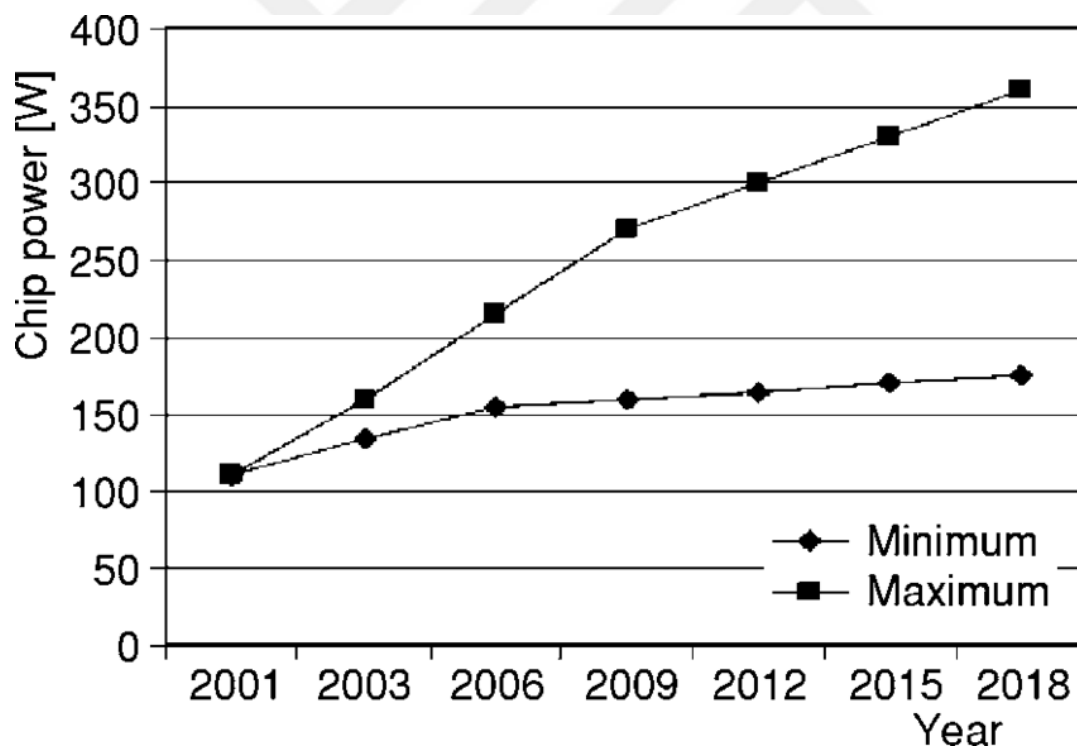


Figure 1.2. Power upward trend of processors [5].

Based on the information in the literature, it can be said that electronic systems' longevity and trouble-free operation depend on thermal control. To protect the

electronics from thermal failure and prevent them from reaching harmful temperatures, adequate heat transfer must be provided from components to the ambient. For this reason, one of the important issues focused on technologies in heat transfer is the thermal control of electronic devices. Within the scope of these thermal control studies, five different items were considered for electronic systems and technological developments were carried out by considering these five items [6]:

- i) Performance
- ii) Producibility
- iii) Serviceability
- iv) Compatibility
- v) Cost

1.1 Studies of the Electronics Cooling

The assembly structure created in electronic systems used in different industries is given in Figure 1.3. The main purpose of the thermal studies is cooling the IC packages, which are the heat source and consist of semiconductors. To provide this, both general and detailed cooling methods are used, either system-based or integrated circuit-based. The main purpose of the electronic cooling is to transfer the heat load at the integrated level to the external environment or the system and to ensure that the electronic component operates at the desired temperature. To provide this aim, different types of cooling methods were developed. Scott [7] classified these methods into four main categories:

- Natural convection and radiation
- Forced air cooling
- Forced liquid cooling
- Liquid evaporation

Also, Scott [7] lined up these methods according to their heat transfer capability as shown in Figure 1.4.

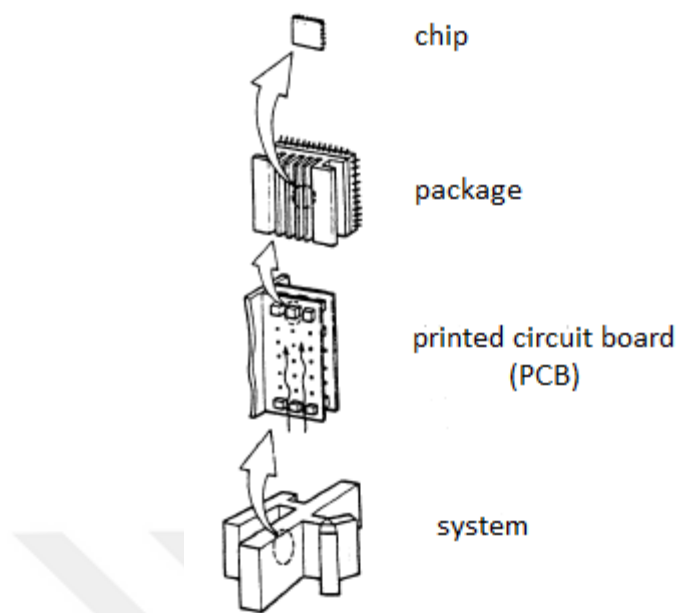


Figure 1.3. The structure of electronic system [6].

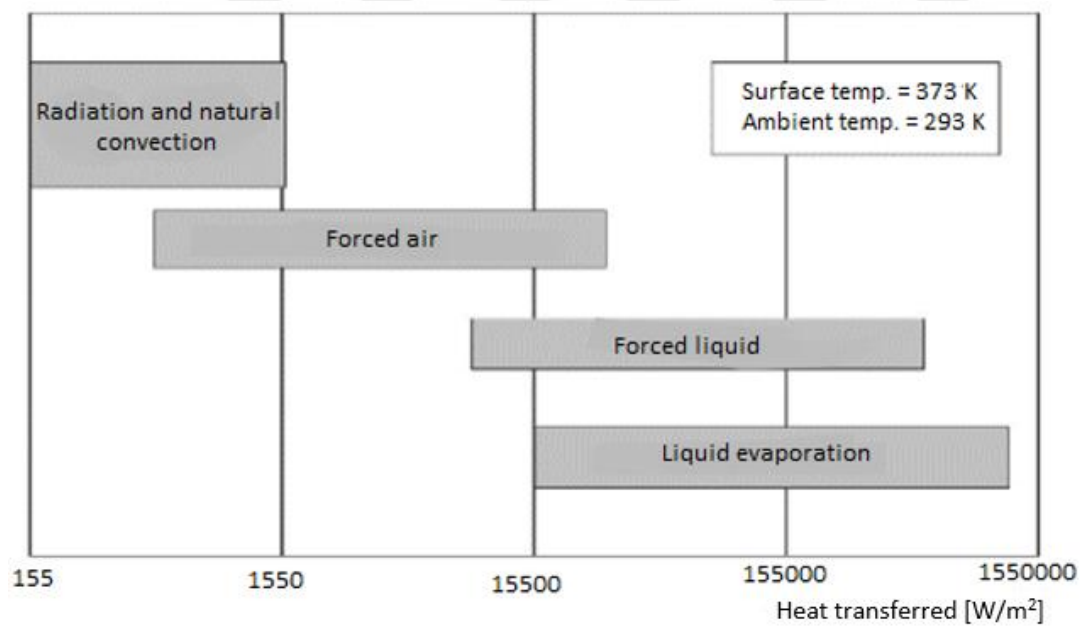


Figure 1.4. Effectiveness of cooling methods [5].

The specified cooling classification was created based on different needs. As the cooling capacity of the mentioned methods increases, their complexity level also

increases. Depending on the technological developments, different cooling methods are also included in this classification. The most well-known are heat pipes, thermoelectric coolers, microchannel heat sinks, spray cooling, and phase change materials [5].

In addition, another classification of the electronics cooling methods is active cooling and passive cooling. An external energy or device is needed in active cooling methods to enhance the heat transfer. Fans, thermoelectric coolers, or forced liquids (pump) can be given as an example. In this cooling method, the cost increases as an extra energy is required from the outside. In addition, more problematic structures occur in designs and ergonomics due to their complex structures. However, due to its high heat transfer coefficients, it can provide sufficient cooling for devices with high heat capacity.

For the passive cooling methods, there is no energy consumption and therefore there is no need for a complex structure or an extra mechanical part. The most used passive cooling methods are heat sinks, heat pipes, and phase change materials. Since spontaneous phenomenon (natural convection, phase change) are used in these methods, high heat transfer coefficients can be achieved with more energy efficiency and lower financial cost [8].

In recent years, electronic cards and systems with high power consumption have emerged in important industrial areas such as defence industry and aerospace. The mentioned electronic cooling methods are used for solution purposes. Active cooling methods, which have high cost, noise, and large volume occupancy features, have lost their popularity due to these reasons. For this reason, passive cooling methods have attracted attention. Phase change materials are preferred because of their high heat storage ability, as well as their quietness, low cost, and easy use. Phase change materials can be used with other thermal control systems simultaneously and provide temperature stabilization thanks to their high heat storage. They have been currently used and researched as a passive thermal cooling method in different applications.

1.2 Phase Change Materials (PCM) and Areas of Usage

Phase change materials (PCM) are passive cooling components that work with the melting-solidification cycle and store the energy it receives by changing phase in a certain temperature range.

1.2.1 Thermal Storage Methods

In different areas, thermal storage methods control the temperature and cool the devices. Different thermal storage methods are shown in Figure 1.5. As can be seen from this figure, thermal methods are divided into two parts: sensible heat and latent heat.

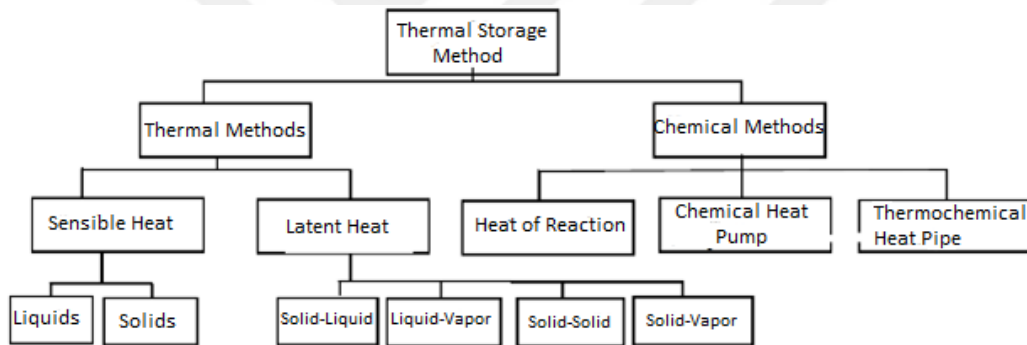


Figure 1.5. Classifications of thermal storage methods [9].

Thermal energy storage systems are based on storing the desired energy and its use when necessary. In summary this process could be explained by three steps: absorb, store, and release. While latent thermal energy storage is a more common technique in short-term storage, sensible heat storage is more preferred in long-term storage.

Along with the energy the material receives, the energy of the atoms and molecules in the material begins to increase. In this case, the materials start to store the energy they receive and show different reactions according to the storage type. Sensible and latent heat storages are classified according to these reactions.

1.2.1.1 Sensible Heat Storage

The process of storing energy in a substance which is in either solid or liquid state is called sensible heat storage. During this process, temperature of the material increases as the heat stored.

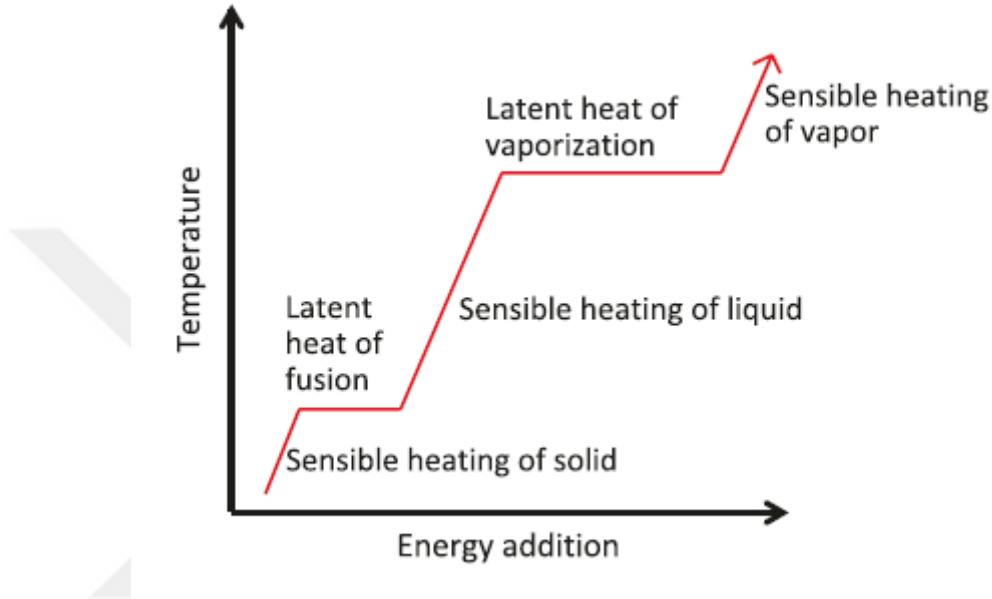


Figure 1.6. Latent and sensible heating curve of substances [10].

As seen from Figure 1.6, the temperature increases in the sensible heat part. The fundamental equation of the sensible heat storage is:

$$Q = \int_{T_0}^{T_1} mc_p dT \quad (1.1)$$

1.2.1.2 Latent Heat Storage

Every substance has specific properties such as melting point, latent heat, etc. After receiving heat from externals, the substance starts to store the heat on the phase

change points. In this process, different from the sensible heat storage, substance begins changing the phase. The chemical and atomic bonds are loosened; therefore, the substance transforms from solid to liquid. This process is called as phase change and during the phase change heat is stored. Latent heat capacities of substances determine the process time and during this time, temperature of the substance remains constant at the melting or solidification temperature. After this process, if the external heat vanishes or temperature starts to decrease, reverse process, which is solidification, occurs [11]. This process also shown in Figure 1.6. The basic equation of this process is:

$$Q = mL_{melting} \quad (1.2)$$

$L_{melting}$ is the latent heat capacity of the substance and the unit of this property is J/kg and therefore, this process can be classified as mass-based process.

1.2.2 Phase Change Materials and Fields of Usage

Phase change materials are used in heat storage systems due to their melting and solidification properties at different temperatures. They can keep the system's temperature constant during the working time, thanks to the high-capacity heat storage, especially for time-dependent situations.

Different types of PCMs can be found in nature according to different material properties, however generally PCMs are examined under three main headings: organics, inorganics, and metallic liquids [10]. In the thermal storage applications, generally organics and inorganics PCMs are chosen. This is because, they are advantageous than metallic liquids in terms of cost, easy usage, corrosion, etc. Different examples of the PCMs are given in the Figure 1.7.

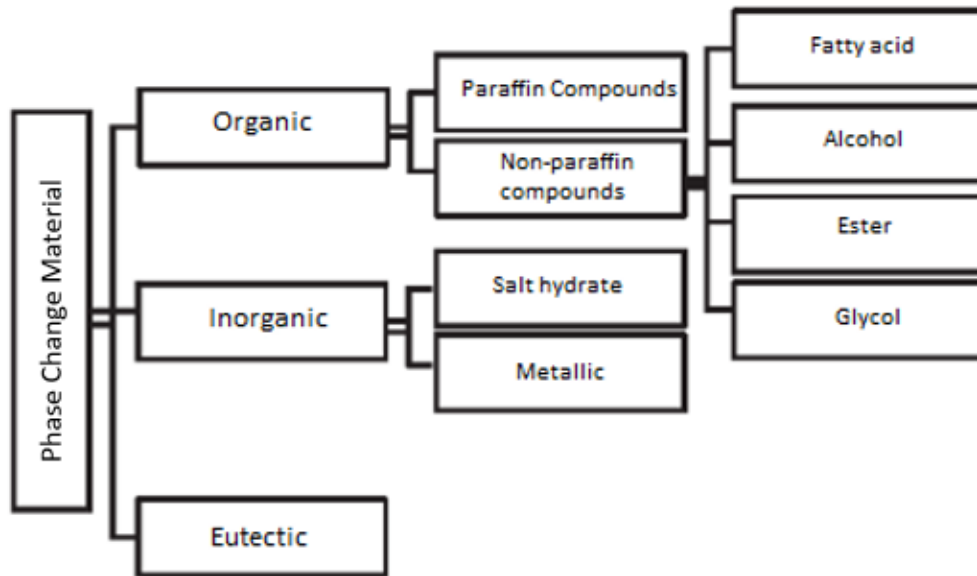


Figure 1.7. Examples of different PCM types [12].

Phase change materials have more than one characteristic feature. Material selection is made according to different properties such as density, latent heat, thermal conductivity, specific heat, melting temperature, etc. The most important criteria to be considered in the design process are the desired temperature value of the system, the operating time, and the system's heat capacity. In addition, phase change materials have volumetric expansion coefficient which causes 10-15% volumetric expansion during the transition from solid to liquid state. For this reason, it should be considered during the design [10].

Phase change materials are used in many different areas, as shown in Table 1.1, thanks to their heat storage capacity and ease of use.

Table 1.1. Fields of Usage of the PCM and Applications [10], [13].

Fields of Usage	Application
Thermal Management of Electronics	Cell phones, computers, electronic boxes
Thermal Management of Battery Systems	Li-ion packs, hybrid vehicles
Energy Storage in Buildings	HVAC systems in structures, Insulation
Solar Energy Systems	Concentrating Solar Power Plants, Domestic Solar Applications
Textile Designs	Thermally regulated vests, underwear, socks
Space and Aircraft Systems	Thermal capacitors in Apollo 15, 16 and 17.

1.3 Solidification & Melting Phenomena

In this section, theory of the solidification&melting phenomena is explained in detail.

In nature, different materials behave according to their different properties. According to these differences and different initial conditions, melting&solidification process was classified as three parts. These are one region, two region, and multiple regions melting (solidification) [74]. During phase change process, some materials store heat at a single temperature, however, some materials' melting occurs between two different temperatures. The reason for this phenomenon is the difference between the enthalpy changes of the materials [75]. For example, the pure crystalline or eutectic substances melt at a sharply defined temperature. These materials show discontinuous enthalpy as a function of temperature. From Figure 1.8, the A curve shows this process. During melting, temperature, T_m , has a

sharply defined value. However, the enthalpy of a mixture or glassy substance increases as a temperature function. In Figure 1.8, curve B represents this phenomenon. Unlike curve A, it has two different melting temperatures, solidus temperature and liquidus temperature. This kind of materials show continuous properties as a function of temperature in space.

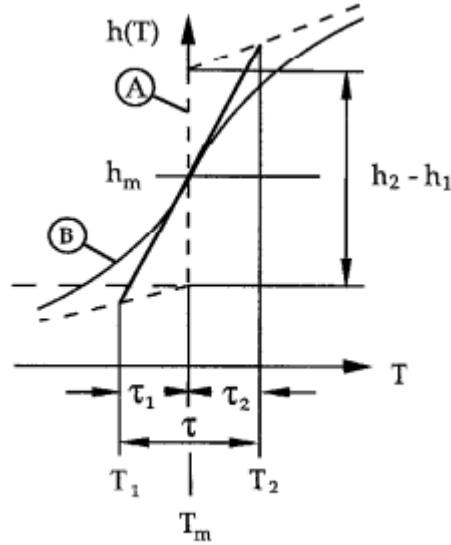


Figure 1.8. Enthalpy difference between different materials [75].

1.3.1 Melting&Solidification Classification

As mentioned previously, three main melting processes occur according to material properties and initial conditions. For the one-region problem, if the initial temperature of PCM equals to melting temperature of PCM and PCM has one and exact melting temperature, which means the material is pure crystalline or eutectic, solid region was known and only liquid region needs calculation. Therefore, one dimensional one region melting problem occurs. The example temperature distribution of this phenomena is shown in Figure 1.9. For the two-region melting problem, initial condition of the PCM is different from the phase change temperature and again material has only one certain phase change temperature. The initial

condition is the only difference between one region problem, which makes the solid and liquid phase temperature distribution unknown. It can be seen from Figure 1.10.

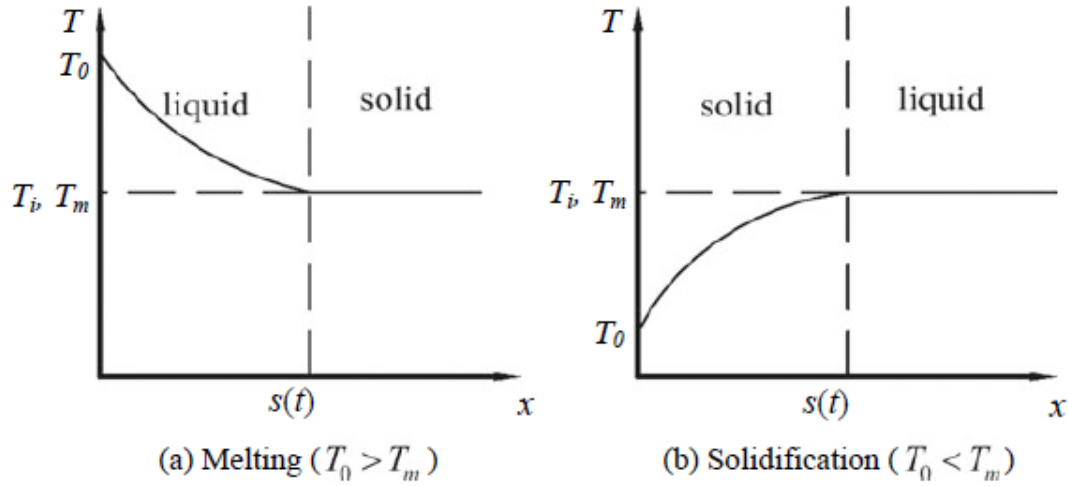


Figure 1.9. One region melting&solidification problem [74].

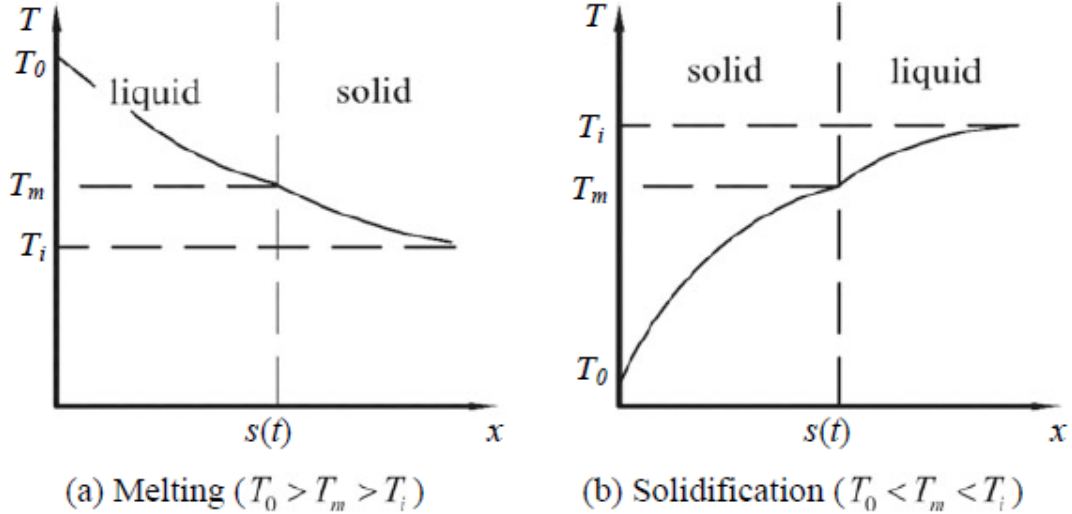


Figure 1.10. Two region melting&solidification problem [74].

In addition to these problems, the most difficult case to solve is the multiple regions melting. Because, for this case, PCM has two different melting temperatures like glassy substances and mixtures. Between these melting temperatures, material is

either solid or liquid. This region is called as mushy region. The temperature distribution should be determined for more than two regions; therefore, this case is called multiple regions melting. The temperature distribution graph is shown in Figure 1.11.

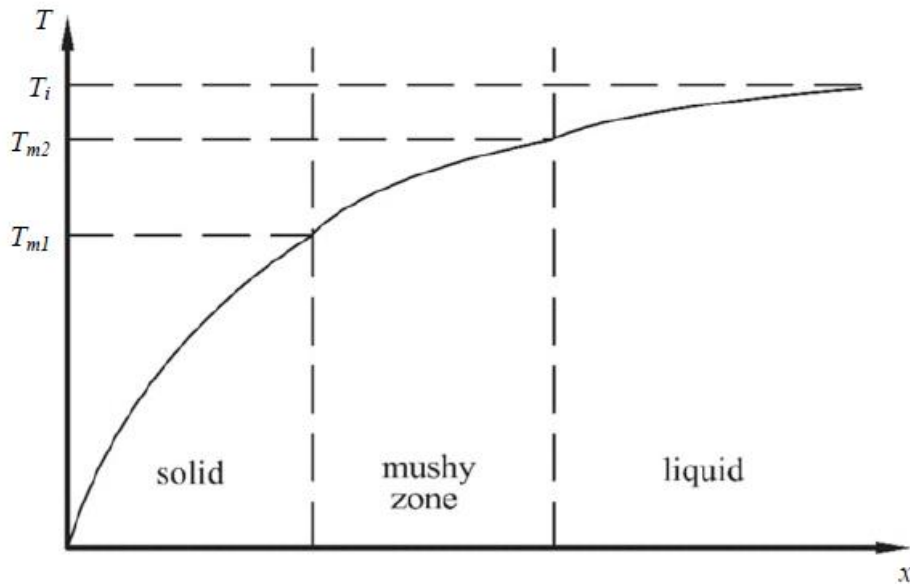


Figure 1.11. Solidification of multi-region case [74].

1.3.2 Mushy Zone

During melting or solidification processes, between liquid and solid, the mushy region is observed. In Figure 1.12, a schematic of mushy region is shown. This region influences the heat transfer and flow characteristic, so modelling this region is important for phase change.

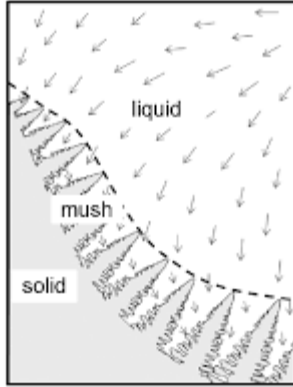


Figure 1.12. Mushy region schematic [75].

Mushy zone influences the heat transfer and flow characteristics between solid-liquid phases. Therefore, this region should be numerically simulated correctly to obtain accurate solutions. Also, the challenge is that the mushy zone characteristics are different for each phase change material.

For CFD analysis in Ansys Fluent or Comsol Multiphysics, to solve melting&solidification problems and mushy zone region, mushy zone constant is used. This constant affects the energy and momentum equations which will be mentioned later. Some studies have been conducted to determine this constant experimentally. Yang et. al. [76] investigated the mushy zone during the melting process. After examining the experimental microscopic images using image processing, they established a general relation for mushy zone constant that is given in Equation 1.3:

$$C_{mush} = \frac{180\mu}{d^2} \quad (1.3)$$

1.4 Thesis Objective

The thesis aims to design and numerically and experimentally investigate the PCM filled heatsink structures used in industrial applications where electronics with high heat generating components are used extensively, by examining various parameters to increase thermal performance. In design process, conducting experiments and testing of prototypes are costly, difficult and time consuming. Therefore, numerical modelling and analysis tools saves time and reduces prototype costs. In addition, working with different PCMs can be difficult in terms of cost, chemical storage requirement, and supply. Thus, for transient cases, correct modelling provides many advantages on PCM heatsink design. This thesis aims to provide a basis for the usage and numerical investigation of heatsinks with PCM in systems with time-dependent operating scenarios.

Three parameters were studied to design PCM heatsink to keep the IC with a heat load of 21 W at safe temperatures for about 1 hour. Number of chambers and amount of PCM effect, inclination angle effect, and different types of PCM effect were examined experimentally and numerically. Numerical analyses were validated with experiments. In addition, mushy zone constants were determined from experiments which were then used in numerical calculations.

1.5 Organization of Thesis

In Chapter 1, brief information about electronics cooling, PCM Heatsinks and field of usage of it is given. In Section 1.1, electronics cooling studies are explained. In Section 1.2, PCM and its usage areas are summarized and in Section 1.3, solidification&melting phenomena is explained, and mushy zone is defined and explained. Thesis objective is explained in Section 1.4.

In Chapter 2, the literature review is given. In Section 2.1, the studies about PCM heatsinks are summarized and explained. Section 2.2 summarizes the studies about PCM with metal foam matrices.

In Chapter 3, the experimental setup is explained and presented. In Section 3.1, detailed description of the experimental instrumentations and procedure are given. In Section 3.2, heat flux homogeneity experiments are explained, and results are given. Uncertainty analysis and calculations are explained in Section 3.3. In Section 3.4, the test matrix is given.

In Chapter 4, the numerical analysis is explained in detail. In Section 4.1, the governing equations are given. The physical model is explained in Section 4.2, and then the mesh and time independence studies are explained in Section 4.3.

In Chapter 5, results of experimental and numerical studies are given and discussed. Firstly, Section 5.1 presents the results on the effect of the number of chambers & amount of PCM. In Section 5.2, the results on the effect of inclination angle are presented and discussed by comparing numerical and experimental studies. Finally, in Section 5.3, the results on the effect of different PCM materials are given. Also, dendrite length calculation process and mushy zone constant calculations are presented.

In Chapter 6, the conclusions of the thesis and suggested studies for future work are given.

CHAPTER 2

LITERATURE REVIEW

PCM performance is critically limited by the material's low thermal conductivity. Different strategies have been considered to remedy this limitation. Many studies were conducted on passive electronics cooling using phase change materials and enhancing them using different methods. To overcome the low thermal conductivity limit, three main strategies are proposed in the literature; using metal fins (PCM-Heat Sinks), adding nanoparticles with high thermal conductivity into PCM, and using metal foam matrices. These proposals are also called as thermal conductivity enhancers (TCE) [14].

In electronics cooling studies, PCM and other techniques were mentioned as early as 1971 and since the 1990s, studies on PCM and electronics cooling applications have been ongoing [15]. Many studies have investigated the PCM effect 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.

As mentioned before, to enhance the thermal conductivity of PCM, one of the methods is using fins. They facilitate the heat transfer to the phase change material by increasing the heat transfer surface areas and prevent the IC package from reaching high temperatures by accelerating the heat transfer in the IC packages to the heat sink and PCM.

Many experimental and numerical studies have been conducted to investigate this phenomenon. These studies include fin and PCM optimization based on the parameters such as fin number, fin type, fin orientation, fin thickness, and fin height,

different power values and their types (constant, cyclic, etc.), ambient temperature, gravity effect, the volume of PCM, etc.

PCM-Heat sink combination was firstly mentioned by Humphrey et al. [16] to increase the effectiveness of PCM. PCM was implemented on the finned heat sink and the difference was observed. In addition, fin thickness's effect on PCM's effectiveness was investigated. As a result of this study, it was found that thin fins provided higher heat transfer rates.

In 2016, Sahoo et al. [17] published a review of TCE-PCM based usage of heat sinks. According to this review study, the statistical graph of the type of studies conducted until 2016, PCM used in these studies, and fin type parameters are given in Figures 2.1, 2.2 and 2.3. As can be seen from Figure 2.1, experimental studies are in majority. In addition, high percentage of organic PCM was used in investigations. The low use of inorganic PCM is striking.

2.1 PCM Heat Sinks

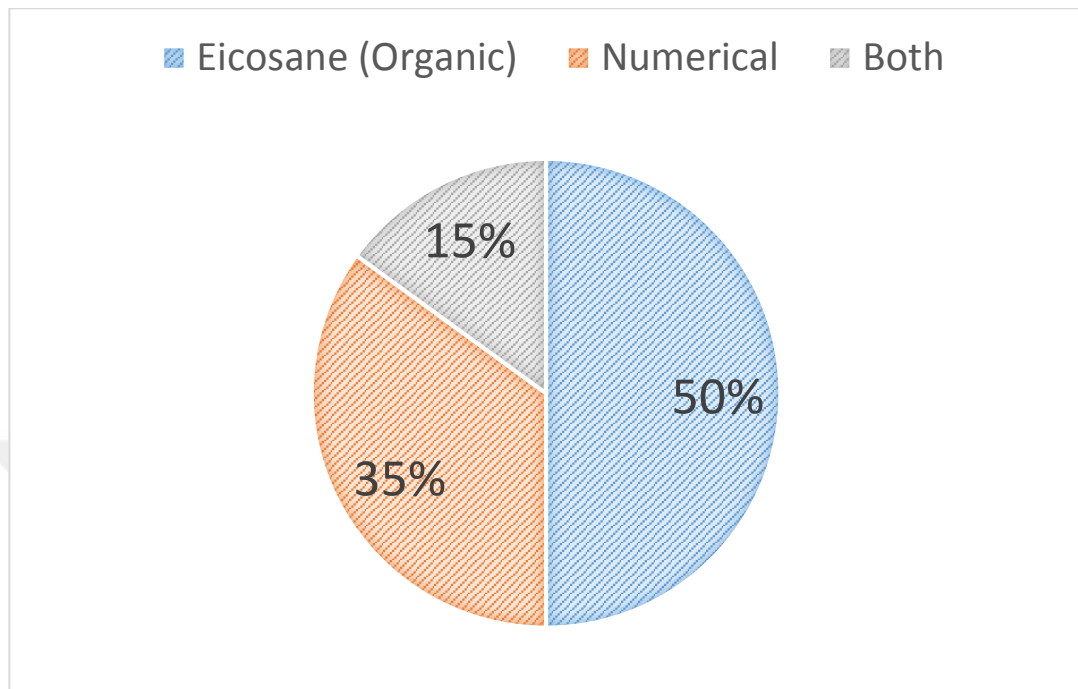


Figure 2.1. Percentage of the type of the studies on PCM Heat Sink [17].

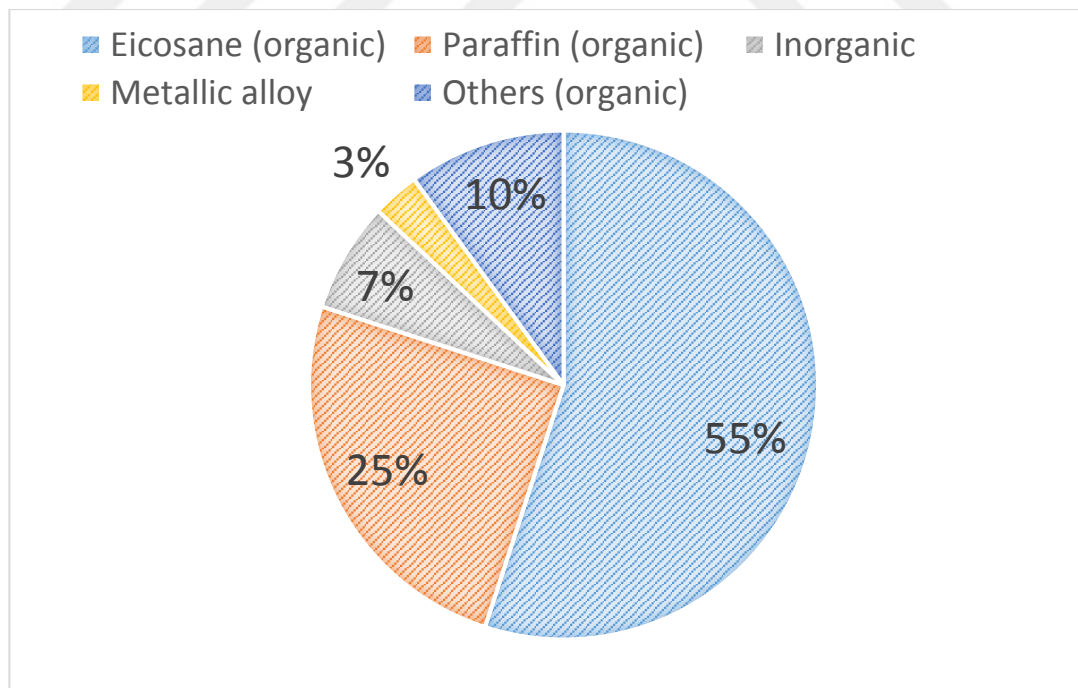


Figure 2.2. Percentage of the types of the PCM used on studies [17].

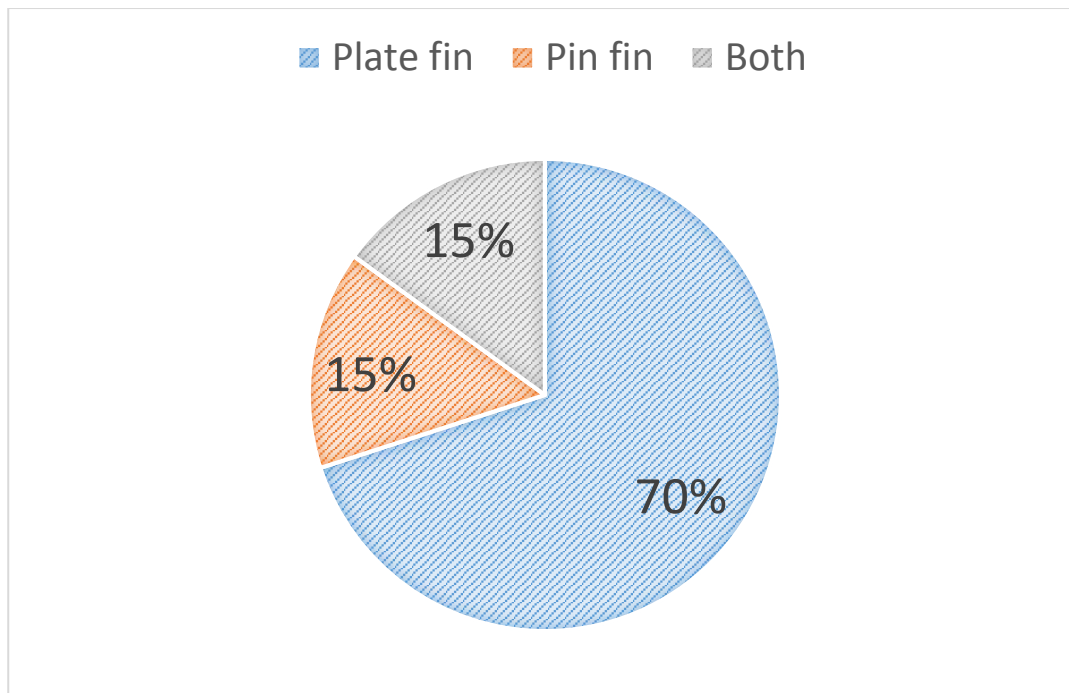


Figure 2.3. Percentage of fin types chosen in research [17].

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.

Alawadhi and Amon [18] developed Thermal Control Unit (TCU) for electronics cooling. This unit includes PCM and aluminum fins. This study examined the effects of the number of fins (2-6) and power level (3-6 W). 2-D numerical study was applied and only conduction in PCM was modeled. Plate type of fins were used in this study. Results demonstrated that as the power level was increased, the temperature also increased but melting time became shorter. In addition, as the fin number was increased, the homogeneity of the melting of PCM was improved.

Yoo and Joshi [19], studied the effect of fin type as plate fin and pin fin both experimentally and numerically. Plate fin and pin fin types were the parameters under the 35 W periodic heat load. Eicosane was selected as the PCM. In addition, they used fan to supply forced convection on the PCM-Heat sink system at different

air velocities such as 0.5, 1, and 1.5 m/s. It was observed that PCM usage in the system decreased the heat sink surface temperature compared to non-PCM one. Also, the time to reach the critical temperature values became longer thanks to PCM and thermal equilibrium was established during the melting process in the system. Since thermal equilibrium was succeeded, amount of PCM was not considered as a parameter in this study. Finally, the most important result they found was that pin fin geometry had better thermal performance than plate fins because pin fin could provide larger volume for PCM.

Akhilesh et al. [20] built up a relation between heat sink dimensions, fin thickness and PCM amount by scale analysis. This numerical analysis considered conduction, and natural convection was neglected. Pin fin configuration was chosen as heat sink geometry and eicosane PCM material was applied to analysis. By applying this scale analysis, useful correlations were developed.

Shatikian et al. [21] also studied numerically on the parameters of fin thickness, fin height, and PCM thickness for 2-D and 3-D cases. RT-25 was chosen as PCM. In this investigation, Ansys Fluent was used with the enthalpy-porosity method and VOF method. The system was modeled as 85% of PCM and 15% of air region because during the melting process, the volume of PCM increases. In addition, only conduction was considered for the heat sink, however for the PCM, convection and conduction were used together. The change in the volume, density, and viscosity of PCM were also considered in this study. Constant temperature boundary condition was used in their analysis of melting process. It was found from this study that, as the thickness of the fins increased, the uniformity of the temperature on the fins also increased. It was also observed that the melting time increased with the increase of the fin height. This was because of the fact that the amount of PCM increased as the fin height increased. Also, nondimensional analysis was applied to the results in terms of Stefan, Nusselt, and Reynolds numbers and generalized relationship between them was established.

The fin geometry, power level and number of fins effect were investigated numerically by Nayak et al. [22]. In this study also, natural convection was modeled in PCM. Enthalpy-porosity modeling was used and Eicosane was chosen as PCM. It was found that as the power level increased, the melting time became shorter, and temperature of the heat source increased as expected. Additionally, pin fin type performed better than plate fins by providing lower base temperature. For the last parameter, by keeping fin thickness constant, as the fin number was increased the base temperature of the heat sink decreased and melting time did not change significantly. The point is that these results contradict the results from Alawadhi and Amon [18] study. The reason behind that, Alawadhi and Amon [18] kept the PCM volume constant as the fin number was increased. Nevertheless, in the Nayak et al. [22] study, the PCM volume was changed as fin number was increased.

Kandasamy et al. [23] studied numerically and experimentally on PCM Heatsinks. Cyclic power levels, package inclination angle, and melting&solidification times for PCM were investigated experimentally. Paraffin wax was used as PCM, and basic electronic cooling setup was established. Also, 2-D numerical simulations were applied by using Ansys Fluent. PISO algorithm was used, and natural convection was solved by applying Boussinesq approximation. In this case it was observed that as the power level was increased, melting rate also increased. However, the solidification process became longer as the power level was increased. This investigation focused on orientation of the PCM heatsink and found that this effect could be negligible for the heatsink's performance. The critical conclusion to be drawn from this article was that for the smaller PCM Heatsink systems, TCE usage was not necessary. Nevertheless, for larger systems, TCE should be used to increase the thermal performance.

Kandasamy et al. [2] have applied another experimental study in 2008. In this research, they studied on usage of PCM in heatsinks. Also, different shapes of heatsinks (small plate fin, large plate fin, elliptical plate fin), shown in Figure 2.4, were investigated in this study.

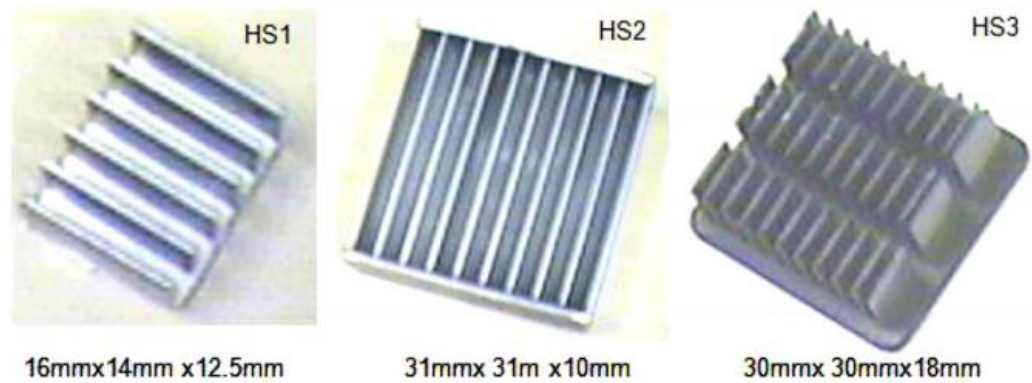


Figure 2.4. Different shapes of heat sinks used in the study of Kandasamy et. al. [2].

2-6 W power level input effect was also investigated in this research. Same PCM as previous work, paraffin wax, was used. It was found that PCM increased the thermal performance of the heatsinks when the power level was increased significantly (2, 4 and 6 W) In addition, when PCM was not used, elliptical and large plate fin structures gave better thermal performance than small plate fin.

Optimum fin distribution was studied by Saha et al. [24]. Fin shape and number were studied in this research experimentally and numerically. Volume fraction of the fin was the critical parameter. Eicosane was used as PCM and 8 W heat was applied. Results demonstrated that 8% of the fins' volume fraction had better thermal performance by providing lowest junction temperature on experiments. In addition, for the same PCM volume, as the fin number was increased the effectiveness of heatsink increased. Also, pin fin shape gave the best performance for the system.

Fok et al. [25] investigated the effects of fin number, orientation and PCM effect under constant and cyclic heat load for the portable electronic devices. Experimental and numerical studies were conducted. 5 W heat load was applied and eicosane was used as PCM. The results show that, by using PCM, the base temperature could be decreased; additionally, as the fin number was increased, the base temperature of the heatsink decreased. For the effect of orientation, it was concluded that this effect

could be negligible. For low heat loads and infrequently used electronic components, the use of PCM was not necessary. Different heatsink configurations and the results were given in Figure 2.5 and Figure 2.6.

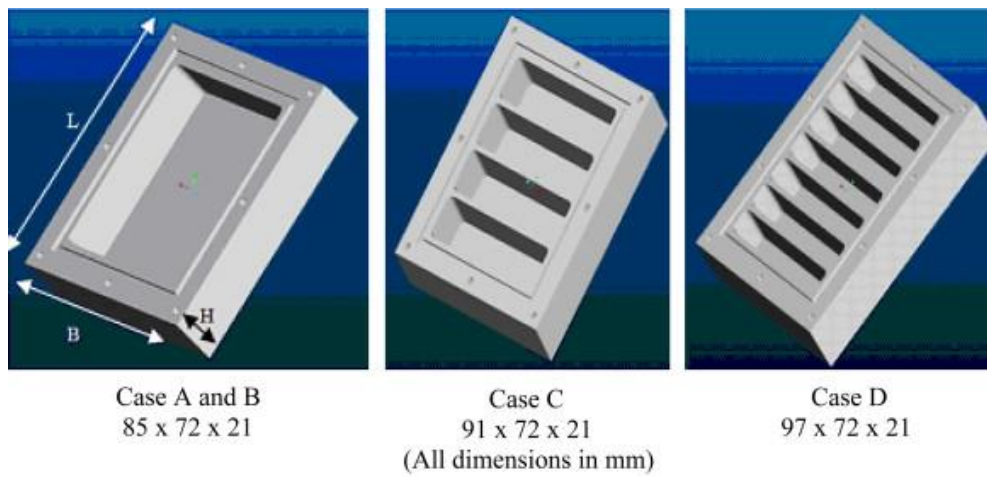


Figure 2.5. Heatsink dimensions in the study of Fok et al. [25]

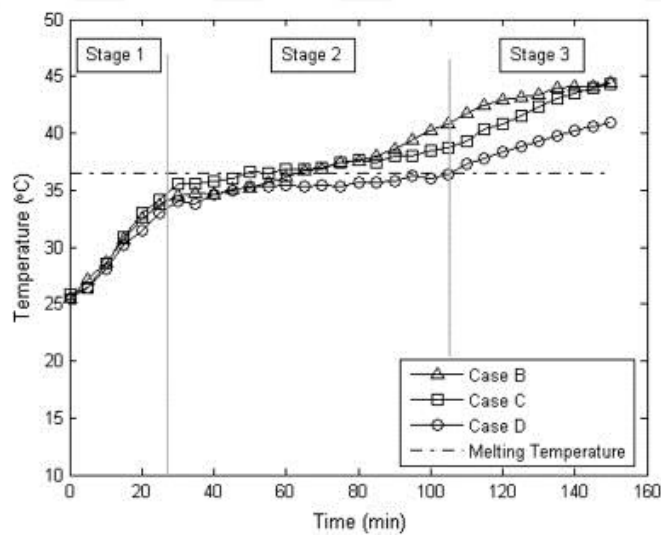


Figure 2.6. Results of the study of Fok. et al. [25]

Setoh et al. [26] researched a similar study about using PCM Heatsink on mobile phones. Melting and solidification process and internal plate fin number were

investigated. Eicosane was used for PCM, and 3-5 W power level was applied to PCM Heatsink. They found that solidification process took longer time than melting process and this was because of the fact that melting of the heat sink was managed dominantly by conduction; however, solidification process was adversely affected by convection and this problem should have been solved for cyclic operations. Additionally, this article concluded that as the internal fin number was increased, the heat sink's thermal performance increased.

Parlak and Etiz [27] conducted a study about applying PCM on electronics cooling in defense industry. Organic and inorganic PCMs were used in experiments. Two different locations were selected for applying PCM. Constant heat load of 12.9 W was applied on system. They observed that PCM usage could keep temperature lower compared to non-PCM usages. Also, the best thermal performance was seen using inorganic PCM due to high latent heat capacity. Results were examined for the system's critical time, which was 90 minutes.

Hossenizadeh et al. [4] conducted an experimental and numerical study. They investigated the effects of fin number, fin thickness, and fin height. Paraffin wax was chosen as PCM, and 45 W heat load was applied. They confirmed that as the fin height was increased the thermal performance of the heatsink increased and similar results were obtained for the fin number parameter. This was caused by the fact that the heat could not be transferred to upper regions of the heatsink due to low conductivity of PCM; therefore, local heating occurred at the bottom of the heatsink. 2, 4, and 6 mm fin thicknesses were examined also. The most effective results were obtained using 4 mm fin thickness, which showed an optimum thickness for the PCM heatsink. Furthermore, for the analysis part, enthalpy-porosity method was applied in Fluent software. The results showed similarity with experiments. The comparison was given in Figure 2.7.

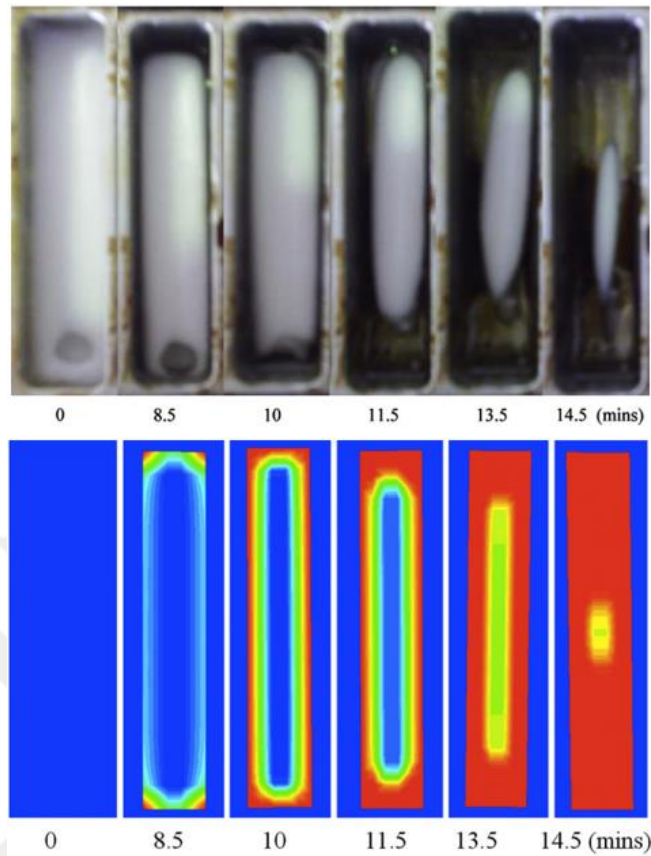


Figure 2.7. Experimental and numerical results comparison for the study of Hosseinizadeh et al. [4]

Huang et al. [28] investigated the natural convection effects and crystallization during solidification for the photovoltaic systems used in solar panels. In this experimental study, the structure included internal fins filled with PCM that is RT-35, RT-27, and Waksol-A. The results showed that PCM reduced the temperature of the system. Due to the density change during phase change from liquid to solid, crystallization occurred. In addition, PCM solidified first from the walls and finally in internal regions. Internal fins contributed to homogenous solidification of the PCM.

Wang and Yang [29] conducted 3-D numerical study. In this study, transient simulations and enthalpy-porosity method was applied using Fluent. In this case, the fin number, power inputs, and orientations were the parameters. For the validation, they simulated the study of Fok et al. [25] and maximum 10.2% error was observed

by comparing the results. The results indicated that static temperatures could be obtained by using PCM. 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.

In Reference [30], PCM was used for the military shelters to protect them from solar heat load. Different PCMs and amount of PCM were the parameters of the study. Military tests were applied on the system so that the effect of the PCM could be observed. Climsel C32, A32 and S32 types were used as PCM, among which S32 was an inorganic and others were organic PCMs.

In conclusion, PCM prevented overheating on military shelters due to solar load. The inorganic one gave the best thermal performance compared to organics. Also, thanks to PCMs, air conditioning inside the military vehicles were operated less.

Baby and Balaji [31] investigated different fin shapes (no fin, pin fin, and plate fin) with the same volumetric fraction of them for the PCM heatsink cooling method. The article investigated heatsink effect, different power level inputs, and various heat sink designs on cooling. For comparing fin shapes, they used heat sinks filled with PCM, having 72 pin fins, 3 plate fins and without fin for a 4-W heat load. Experimental results showed that, pin fin shape had longer time to reach desired temperature and therefore pin fin configuration gave better results. For the uniformity of the temperature, 4-W heat input and pin fin case was examined. Thermocouples were placed on different locations of the system and phase change process was followed. It was observed that the molten PCM region had uniform temperature distribution. In the other part of the study, the effect of heat load was examined by applying load from 3 W to 7 W for plate fins. It was observed that increasing the power level, melting process was shortened and melting occurred at the same temperature independently from the heat load. However, for 2-W heat input level, it was observed that PCM was not melted fully even at longer times. Therefore, the results proved that at low power input levels, the PCM temperature might not reach the melting values of PCM.

Stupar et al. [32] numerically investigated the PCM heat sink effect on cyclic loads. They developed thermal network approach to optimize air cooled PCM heatsink. This study aimed to design cooling modules for components with high heat loads and low duty cycles. In addition to thermal network simulations, another simulation study was done using COMSOL that works with finite element methods, and these results were compared with experimental results. There were differences between experimental results and thermal network simulations up to 10%. Using PCM, the peak temperature on the system was decreased by 10-20°C. The best performance of PCM was obtained by solidifying it until the next cycle of working. Therefore, if the time was too short for the PCM, the performance could decrease. Thermal network simulations showed that metal foam provided shorter solidification and melting times, thus better performance, compared to heat sink structure.

Another study for investigation of the cooling and solidification of the PCM heat sink after heating period was conducted by Saha and Dutta [33]. They studied the effect of heat flux on working cycle. The heating process was applied for 600 seconds and then the system was cooled. The heat transfer coefficient was the critical parameter to decrease the time to solidify PCM. Also, it was observed that cooling period to solidify all PCM volume took much longer than melting period. For the cyclic load studies, this period should be decreased for the efficient cooling performance of PCM heatsink.

Jaworski [34] studied PCM heatsink with different approach. Inspired by a radiator model, the PCM filled pipe heat sink model shown in Figure 2.8 was developed. By using this method, surface area for the cooling process was increased and the airflow could pass through the thin wall fins and thanks to this, solidification process took at a shorter time than other studies. This numerical study examined pipe number, external pipe diameter, pipe distance, and fin base thickness. By using these parameters, different thermal resistance values were calculated. To conclude, thanks to this design, more effective usage of PCM can be applied to fan-heat sink assemblies.

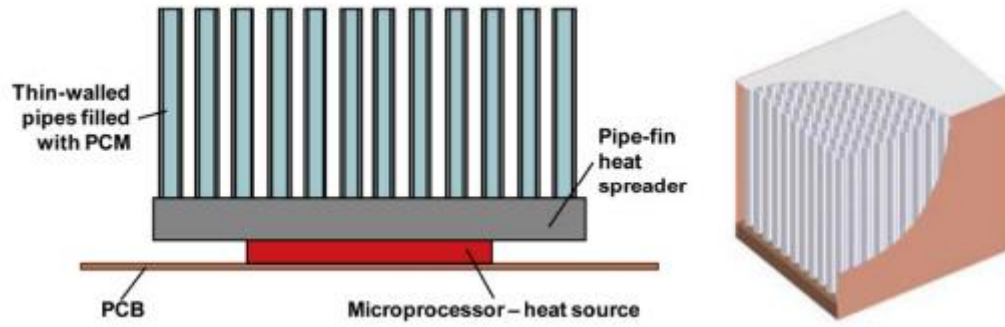


Figure 2.8. The developed model of PCM Heatsink by Jaworski [34].

Kozak et al. [35] also numerically investigated the fan-heatsink assembly model with PCM. The fan effect on PCM heatsink was investigated. For the validation of the Fluent analysis, experimental studies were also applied. The schematic model of the study was given in Figure 2.9. In Fluent, enthalpy-porosity approach was used to model the phase change phenomena. Due to the placement of the fan, results showed that temperature difference between the bottom and upper part of the heatsink was larger than no fan condition. Also, fan provided longer melting time than natural convection process. Also, due to the fan position, bottom parts of the PCM melted first and upper parts melted later. Therefore, the melting shape occurred like wedge shape. For the solidification phase, reverse process occurred. Thanks to the fan, upper parts solidified first, while the bottom ones solidified last.

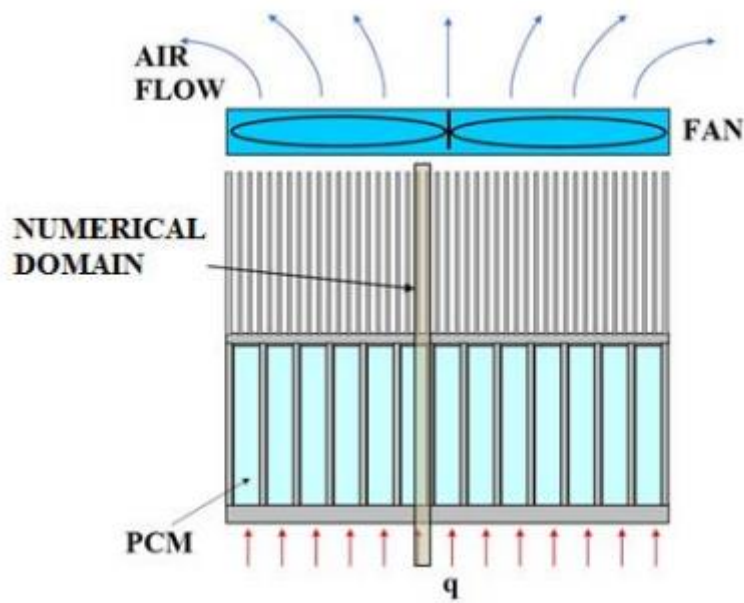


Figure 2.9. The schematic model of the study of Kozak et al. [35].

Another important parameter for the PCM heatsink is PCM type. Mahmoud et al. [36] studied the effects of different PCM types. In addition to PCM type, fin shape effect was also investigated. Parallel fins, crossed fins, and honeycombed fins were examined experimentally. 3 to 5 W power input levels were applied on PCM heatsink system. 6 different types of PCM were chosen according to different melting temperature and latent heat capacity. They observed that using PCM could decrease the peak temperature, but cooling heatsink system took longer due to PCM solidification. Additionally, honeycombed model showed the best thermal performance according to weight, easy assembly, and cost. For the PCM type, the lower melting temperature of PCM could keep the base temperature in lower values than others. As the latent heat increased, the system's temperature could be stabilized longer.

Fan et al. [37] also studied on PCM type effect and internal fin effect. By comparing other studies, higher heat loads (60-120 W) were applied to the system. 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. Another important result was that fins affected the melting process and thermal performance, however, the effect on the solidification was negligible.

Levin et al. [38] studied the effects of number of fins, height, and thickness using 2-D numerical analysis. The main purpose of this study was to minimize the dimensions and weight of the heat sink unit to cool an electronic device with time-dependent working scenario and 200-W heat load. In the numerical model, only conduction process was considered. It was found that after a certain number of fins, the fin effect became negligible and did not contribute to thermal performance. Also, as the melting temperature range of PCM was increased, the temperature contours inside PCM also differed, and this phenomenon negatively affected the heatsink performance.

Baby and Balaji [39], [40] conducted two different studies one year apart (2013, 2014). In the first article [39], they examined the effects of pin fin number and type of PCM experimentally. In this study, 36, 72, and 120 fins were studied at different power levels (5-8 W). For the 36 number of fins, enhancement in PCM was not sufficient and for 120 number of fins, the convection process was prevented by fins and therefore conduction driven melting occurred. Therefore, optimum fin number was found as 72 fins. Also, the Artificial Neural Network (ANN) method was applied in this study and the fin number was calculated as 77, which was close to 72. In the other study [40], they studied the effects of volume fraction of PCM, and the cyclic load experimentally. 5-10 W heat load was applied on the system during experiments. They concluded that when the cyclic load settings changed (8 cycles instead of 2 cycles with different operating times), the peak temperature could be decreased. Compared to constant heat loads, PCM was more useful for transient conditions. Also, by using ANN, optimum fin thickness was determined using results.

Lu et al. [41] investigated the inclination effect on PCM heatsink under cyclic heat loads. 1-hexadecanol PCM was chosen, and 20-40 W heat loads were applied on system. Experimental studies were conducted according to the inclination angle effect. The inclination angle was varied from 0° to 90° by incrementation of 15° . It was observed that as the inclination angle was increased, the peak temperature also increased due to the natural convection effect. The best thermal performance was obtained between 60° and 75° inclination angle for both heat loads. The difference between horizontal performance and the best performance was only 10%. The results showed that the inclination angle effect had no marginal effect on thermal performance of the PCM heatsink. Also, it was mentioned that the performance of the PCM heatsink was critically dependent on the conditions and desired temperature values of the system.

Crossed plate fin heatsink and metal foam matrices with PCM were examined numerically by Srivatsa et al. [42]. In this research, the analysis was validated using experimental results of Baby and Balaji [40]. 8-W heat load was simulated in Fluent and mushy zone constant was chosen as 10^5 . The velocity data of liquid PCM was obtained from the analysis and the results showed that 4.22 mm/s was the peak velocity of PCM. As expected, cross plate fins provided higher velocities than metal foam matrices due to providing more flexibility for liquid PCM. As a result of this study, as the contact surface area was increased between PCM and TCE, the system's cooling performance was also increased.

Kamkari et al. [43] experimentally investigated the inclination effect on PCM heatsink. 0° , 45° , and 90° inclination angles were chosen as parameters. The heat source was determined as constant wall temperature as 55, 60 and 70°C . The heatsink enclosure was insulated completely. It was observed that, until a certain time, conduction drove the melting process, however after that, convection dominated the process. Also, as the inclination angle was increased, the melting time was increased. During the vertical position (0°) test, the solid-liquid PCM interface was observed as wavy shaped, as shown in Figure 2.10.

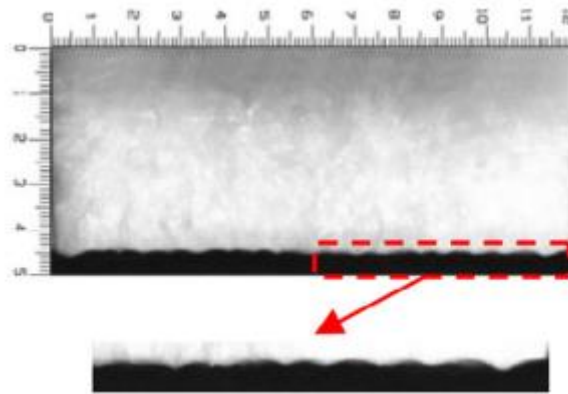


Figure 2.10. Wavy shape of melting interface during 0° angle study of Kamkari et al. [43]

Another important study about PCM Heatsink was conducted by Abu Muhammad Ayyan [15]. In this study, numerical validation was applied for the experimental studies. Four types of PCM heatsink were examined; under natural convection with no PCM, under natural convection with PCM, under forced convection with no PCM, and forced convection with PCM. Three different types of PCM were investigated; paraffin wax (organic), hydrated salt (inorganic), and milk-fat (organic). Different heat loads (4-10 W) were applied on system. It was observed from the study that, during the first 15 minutes of heating, natural convection with PCM showed better performance than forced convection with no PCM. Therefore, PCM can provide energy efficiency by preventing usage of fan. However, the best thermal performance for the whole process was obtained from forced convection with PCM scenario. This is because, in virtue of the forced convection effect and cyclic operation scenario, the time when the system was not working was sufficient for PCM to solidify completely. Therefore, PCM effectiveness was increased for the system. Optimization process was applied for the PCM heatsink numerically by using Ansys Fluent. It is recommended that PCM with narrow melting points gave better efficiency than others. If the temperature difference between melting and solidification temperatures of the PCM was lower than 2°C , PCM had a narrow melting point. Among four fin types (circular, rectangular, triangular, and square),

rectangular fins showed the best thermal performance. Also, as the fin height was increased, thermal performance of the PCM heatsink increased.

Pakrouh et al. [44] studied numerically on parametric fin analysis for the PCM heatsink. Fin number, fin thickness, and fin height parameters were studied. RT-44 PCM was chosen, and pin fin type was applied to study. Natural convection effects were considered in their analysis by applying Boussinesq approximation in Ansys Fluent. Enthalpy-Porosity method was also applied. The study was validated using the results of Hosseinizadeh et al. [4]. They observed that as the fin thickness was increased, the melting process of the PCM became shorter. Also, as the fin height was increased, melting time decreases and base temperature of the heatsink decreased. As a result of this study, the higher the values of the fin number, fin height and fin thickness, the higher the thermal performance of the PCM heatsink due to decrease in the base temperature of the heatsink. In another study, Pakrouh et al. [45] numerically studied on the optimization of PCM heatsink. The validation process was the same as the previous study [44]. The optimization method was chosen as Taguchi method. Pin fins and RT-44 PCM were used in the analysis. The fin number, fin thickness, fin height, and base thickness of heatsink were the parameters of this study. In Taguchi method, these parameters were evaluated and compared. The criterion for the optimization was the time to reach the critical temperature values 50°C, 60 °C, 70 °C, and 80°C. It was found from the study that the base thickness of the heatsink had the least effect on the thermal performance of PCM heatsink.

Another numerical research was conducted by Alayil and Balaji [46]. In this study, for the 5 W heat load, the most ideal parameters were determined using Artificial Neural Network (ANN), which used the results of CFD analysis. The number of fins and fin thickness were the parameters for the fixed volume of PCM and applied heat load. Fourier Number was used for the optimization. The optimized heatsink was used for the application and experimental study was conducted with the optimized heatsink.

Kabbara et al. [47] 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 validation of the numerical model was done using the experimental results of Kamkari et al. [43]. 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 dodecanoic acid PCM. Boussinesq approximation was applied to COMSOL CFD program to model the buoyancy forces. Constant surface temperature was applied to the system as a heat load. 3 different angles (0° , 45° , and 90°) and number of fin parameters were examined in this research. The most important observation from the 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 equations and therefore dominance of mushy zone constant started during natural convection stage. In addition, except 45° inclination angle, the simulation results got closer to experimental results. Kabbara suggested investigating this case in Ansys Fluent for future work. The mushy zone constant results are shown in Figure 2.11.

Arshad et al. [48] studied the effect of pin fin thickness and PCM volume fraction on the passive cooling of electronics experimentally. In this research, paraffin wax was used, and different heat loads were applied to bottom of the heatsink. They found that usage of PCM provided longer operational time for electronics system. The most critical result was that the investigated parameters, which were volume fraction of PCM and number of fins, had important influence on the performance of the PCM heatsinks. Also, as the fin thickness was increased, the performance of heatsink increased. In addition, as the heat load was increased, the time to reach the critical temperature decreased.

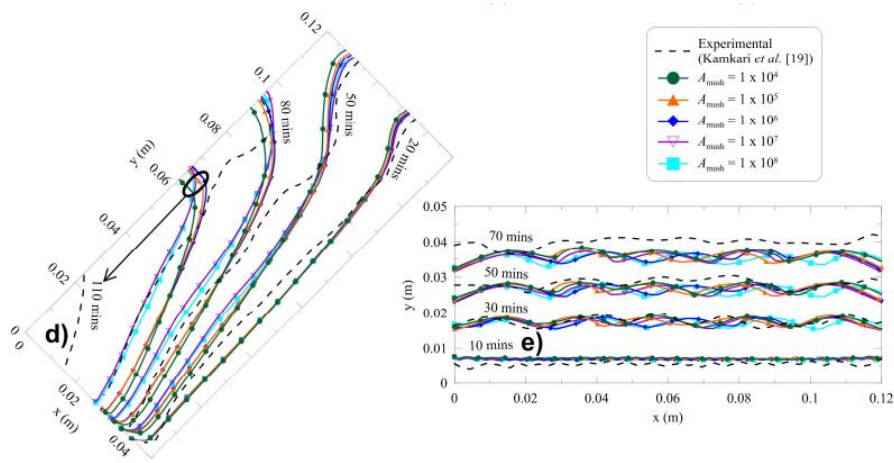


Figure 2.11. The mushy zone constant differences for 45° and 0° inclination angle of the study of Kabbara et. al. [47]

Ashraf et al. [49] expanded the study of Arshad et al. [48] by examining the parameters of PCM type and parametric pin-fin type heatsink geometries. The same experimental setup was used by Arshad et al. [49] and different types of Paraffin Wax PCM were compared. The volume fraction of PCM was constant and for the fin types, square and circular pin fins were investigated. In addition, inclined and staggered types were another optimization parameter of heatsink. 5 W and 8 W constant heat loads were applied on the system and just melting phase of the process was studied. The most effective pin fin type was found as square staggered pin fin in this study. From the study of the effect of PCM type, it was found that latent heat capacity had a more impact on the performance of PCM heatsink. This study concluded that, the requirements on the application of PCM heatsink were the most important factor for choosing the type of PCM.

Srikanth and Balaji [50] conducted a study on the effect of discrete heat load on pin fin PCM heatsink experimentally. Four different heaters were connected to base of the heatsink. 21 different experiments were conducted by distributing the heat loads on four heaters by keeping total heat load constant. The optimization of heat load distribution was made by artificial neural network (ANN) and the selected optimized parameter was the time to reach critical temperatures. The results are shown in Figure

2.12. As can be seen from the figure, equally distributed heat load gave the best results for the optimization process and, as the distribution becomes non-equal, the melting time of PCM became shorter. Therefore, it can be said that the uniform heat distribution on PCM heatsink has strong influence on thermal performance of PCM heatsink.

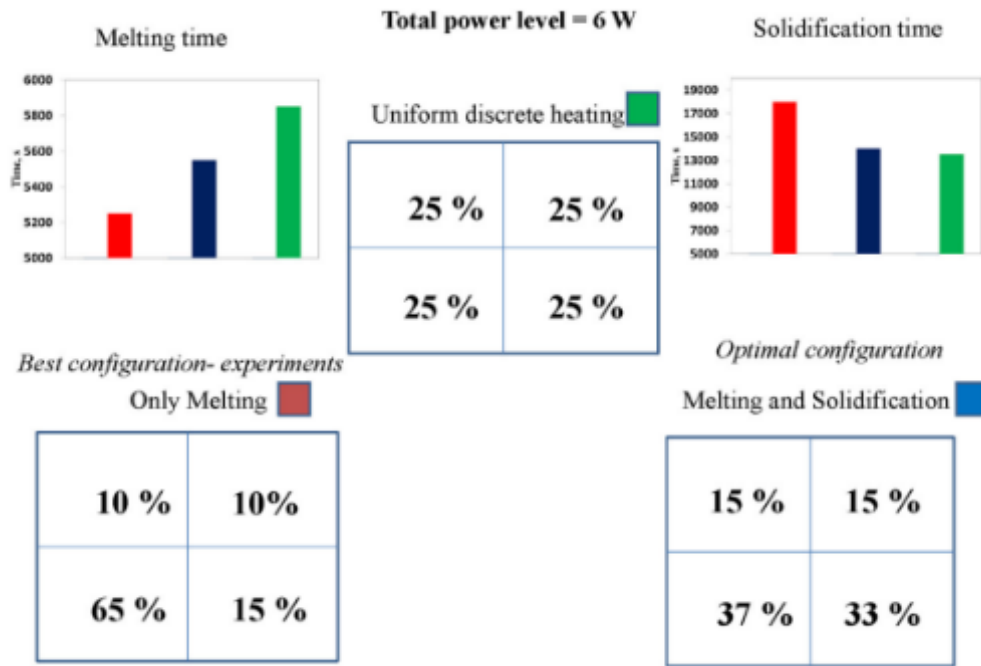


Figure 2.12. Results of discrete heating effect on PCM heatsink from the study of Srikanth and Balaji [50].

Emam and Ahmed [51] studied on different configurations of the PCM Heatsinks for the cooling of photovoltaic systems. In this 2-D transient numerical study, three different PCMs were used. To model the natural convection effect and buoyancy forces, Boussinesq approximation was applied to Fluent. From the results, as the fin number was increased, the temperature of the photovoltaic system decreased. In addition, the hybrid PCM usage was investigated in this research. From Figure 2.13, PCM 2 gave the best thermal performance; thus, hybrid PCMs not always give the best results. By applying this method, PCM selection can be suggested. Furthermore, latent heat capacity has the strongest effect on PCM selection parameters by

comparing other material properties of PCM and this phenomenon was also concluded by Ashraf et al. [49].

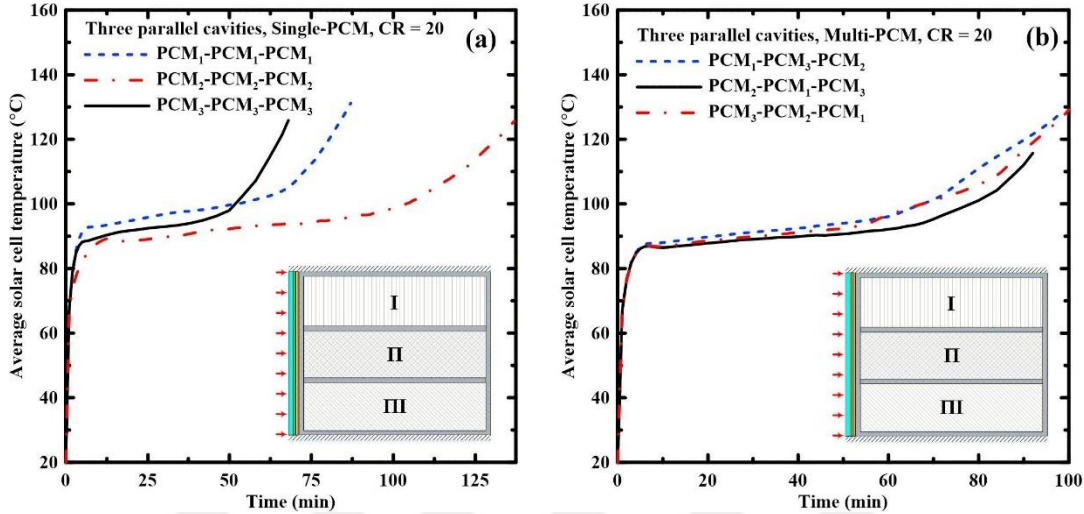


Figure 2.13. Hybrid PCM usage on the study of Emam and Ahmed [51].

Siyabi et al. [52] experimentally investigated the three types of PCM heatsinks to examine the effects of PCM arrangement, PCM combination, thickness of PCM, temperature of PCM melting, and heat load. PCM melting types and temperature data were the parameters for determining the efficient PCM heatsink. This study shows similarity with the Emam and Ahmed's [51]. In a heatsink, different PCMs were integrated into different chambers of heatsinks. It was observed that, using RT55-RT50 combination, extended the operation time for 20 minutes compared to single usage of RT55 and RT50. Also, by increasing the thickness of the heatsink from 30 mm to 60 mm, the operation time of PCM heatsink was increased 50 minutes for 1.5 W heat load. When the melting temperature of PCM was increased, operation time increased, however, the point was that the base temperature of heatsink increased also. In this study, as it was mentioned, similar results were obtained with Emam and Ahmed [51].

Mjallal et al. [53] studied the effects of PCM type on PCM heatsinks 3-D numerically. Three different heat loads were applied to system and inorganic (salt hydrate) and organic (paraffin wax) PCM types were chosen. The dimensions of the

heatsink was 20x20x6 mm. To validate the numerical study, experimental studies were conducted also. They found that PCM could extend the chip's operation time as 1000 seconds under 1250 W/m² heat load. Also, it was found that inorganic PCM performs better than organic PCM by delaying the time to reach the critical temperature.

Optimization study was conducted by Krishna [54]. In this numerical study, fraction of melting and operational time of PCM were chosen as investigation parameters. RT44HC was chosen as PCM, and Taguchi Method was chosen as optimization methodology. In Fluent, Melting&Solidification and Volume of Fluid (VOF) methods were used. The critical temperatures were chosen as 54.8 °C, 63 °C, and 72.6 °C. Longitudinal fins were designed for heatsink, and numerical model was validated using the experimental results of Kandasamy et al. [55]. SIMPLE algorithm was chosen, and pressure-based solver was applied on Fluent. In the optimization study, number of fins, fin thickness, fin height and base thickness were chosen as parameters. 9 different cases were analyzed, and it was concluded that after reaching the maximum critical temperature, total PCM volume did not melt completely; therefore, optimum operational time could not be determined. Further optimization calculations were conducted by removing the base thickness parameter due to its negligible effect. The main aim was that time for melting PCM completely should have been equal to time to reach the maximum critical temperature value. The results showed that the number of fins should have been increased to increase the operational time. Moreover, increasing fin thickness and fin number might not increase the thermal performance of PCM heatsink because it was valid for melting. Therefore, the improvement of thermal performance of PCM heatsink depended on different effects such as melting temperature of PCM, fin height, and other geometrical dimensions during the non-melting phases.

By applying geometric optimization, Sridharan et al. [56] investigated the effects of radial fins and internal stem. Both numerical and experimental studies were performed. 6 W heat input was applied constantly and eicosane was chosen as PCM. The internal stem shape PCM models were shown in Figure 2.14. 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 . Multi objective optimization study was also conducted using artificial neural networks (ANN). It was concluded that thanks to optimization process, 13% improvement was observed during solidification part. However, during melting period, only 4% improvement was obtained. Nonetheless, even this small increase is an important improvement practically for PCM heatsinks used in cyclic operations. Also, it was suggested that further optimizations could be applied by using temperature distribution along the stem and velocity flows inside PCM during natural convection.

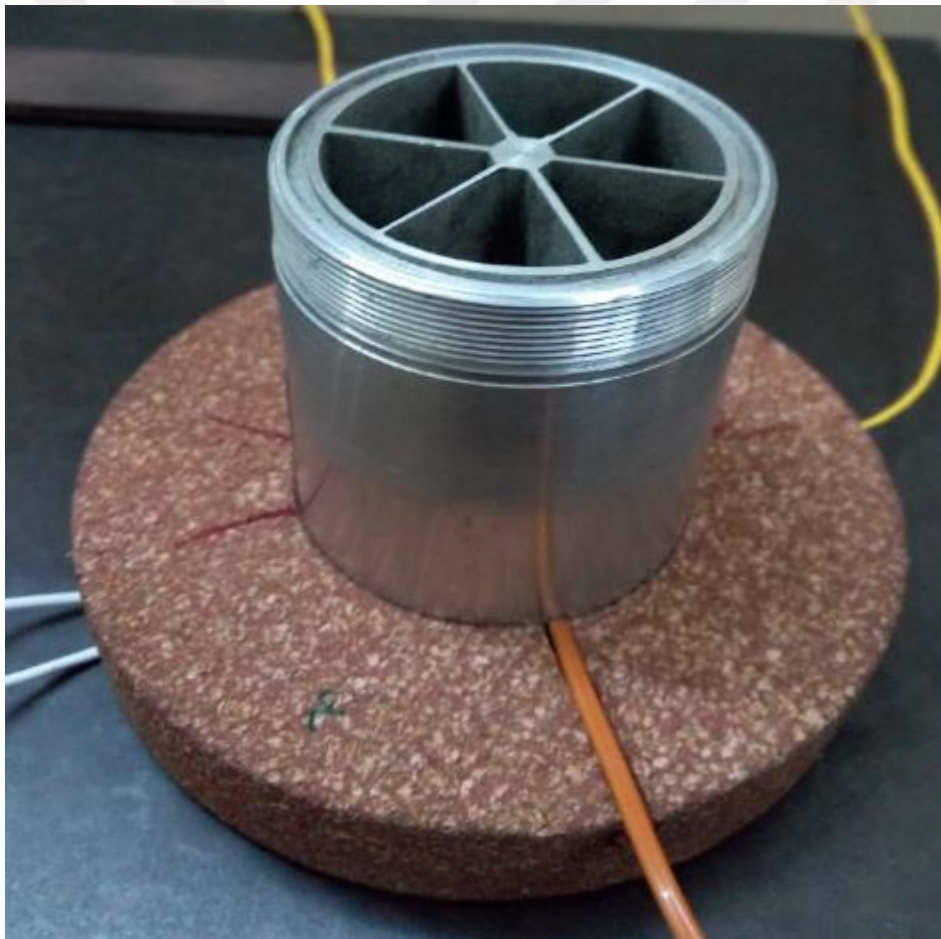


Figure 2.14. Internal fins and stem heatsink used in the study of Sridharan et al. [56].

Yazıcı [13] conducted an experimental study on the use of PCM heatsink for cooling electronic components. In this study, under constant heat load (16 W), the effects of inclination angle, fin number, and fin geometry (constant and variable thickness) were investigated. The importance of this study was that variable fin thickness was designed by considering both the natural convection and conduction effects on PCM melting period. Focus of this study was melting period of the system. The variable- and constant-fin-thickness shapes were shown in Figure 2.15. It was concluded that, in the initial period of the melting phase, conduction effect was dominant, however, after melting of certain amount of PCM, natural convection effect became dominant. During the conduction dominant period, uniform base temperatures and melting interface were observed. In addition, as the fin number was increased the base temperature of heatsink decreased. Also, until 60° of inclination angle, the temperature values of PCM heatsink decreased, however, after 60° , base temperature increased. Use of different types of PCM and numerical studies were suggested for further studies in this study.

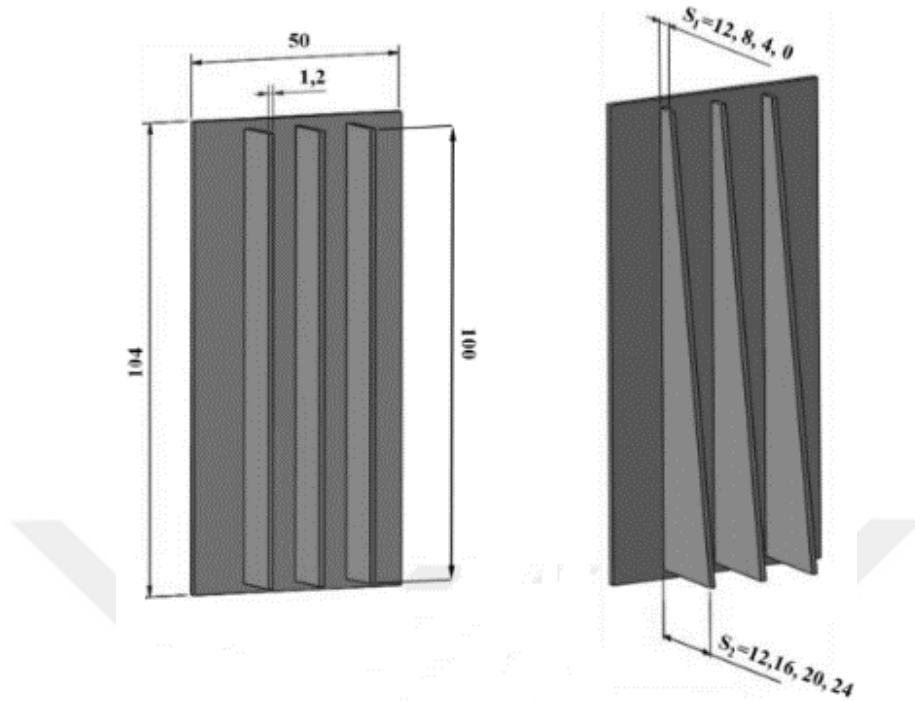


Figure 2.15. Constant and variable thickness of fin shape used in the study of Yazıcı [13].

Weng et al. [57] examined the optimization of internal fins for thermal management of battery modules. Rectangular, circular, and triangular types of fins were the parameters. In this experimental study, hybrid fin types were also investigated. Paraffin based PCM was chosen, and transient cyclic load was applied on the system. Rectangular type fins showed the best thermal performance in keeping the temperatures at the lowest level. Nevertheless, circular fins had better conduction because of having larger surface area. Also, optimized hybrid heatsink which consisted of circular fins at the bottom region and rectangular fins at the upper region showed 5.5% improvement on thermal performance compared to rectangular fin heatsink. This hybrid configuration was selected because in the bottom region conduction was more important and in the upper region, air convection was more important and therefore, by using experimental data, hybrid heatsink structure was created. This structure is shown in Figure 2.16.

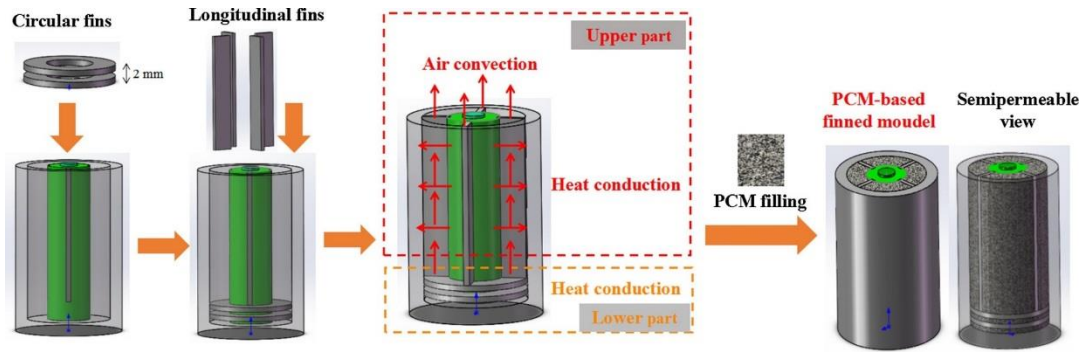


Figure 2.16. Hybrid heatsink structure of Weng et al. [57].

Emam et al. [58] investigated the PCM effects on heat sinks for thermal management of photovoltaic systems and electronic devices experimentally. In this study, three different types of PCM (RT-25HC, RT-35HC, and RT44HC) and three different heat fluxes (2000, 2950, and 3750 W/m²) were used. Ambient temperature effects on solidification were examined also. The important parameter studied in this paper was the creation of air cavities in PCM during solidification and their effects on cooling performance. Results showed that as the ambient temperature was increased, the solidification time increased also. Furthermore, solid PCM air cavities did not considerably affect PCM cooling performance. In this study, RT35HC demonstrated the best thermal performance for the system.

Groulx et al. [59] investigated 2-D numerically the effects of fin position and inclination angle for PCM heatsinks. RT-25 type of PCM was chosen and 1000 W/m² heat load was applied on the system for 2 hours so that just melting phase of process was examined. The dimensions of the heat sink were 132x28 mm. COMSOL Multiphysics simulation was used in this study and validation of the analysis model was conducted by comparing the results with the experimental study of Kamkari et al. [43]. It was concluded that melting was driven by conduction at 90°, however, between 0° – 45° natural convection played more important role on melting. Therefore, after inclination angle of 75°, melting time increased significantly. The reason was that natural convection effects on melting became important at later times for larger inclination angles compared to lower inclination angles. Also, it was

observed that as the fin number and height were increased, the thermal performance of system could be improved.

Kothari et al. [60] investigated the heatsink and metal foam effects on PCM as a TCE. In this research, 1.3, 2, and 2.7 kW/m² was applied on the heatsink with dimensions of 110x110x22 mm. Experiments were conducted using paraffin wax . The critical temperature value was chosen as optimization parameter. In addition, heatsink-metal foam combination was also experimented. Results showed that as the fin number was increased, the heat flux between PCM and heatsink increased and therefore thermal performance of system was improved. In addition, metal foam integration was advantageous at higher heat load values than using only heatsinks. The best performance was obtained for the case of 4 finned heatsink and metal foam combination.

Marri et al. [61] examined the PCM type and ambient temperature effects on overall performance of PCM heatsinks experimentally and numerically. Three different PCMs were used, and 6-W constant heat load was applied to the system. Radial fin heatsink structure included a stem shown in Figure 2.17, similar to the model of Sritharan et al. [56]. Latent heat of the PCMs were closer and difference between them was the melting temperature. Numerical validation was applied by comparing the results with study of Fok et al. [25]. Results show that, as the melting temperature of PCM was increased, heatsink temperature decreased after a while. In addition, as the ambient temperature was increased, the time to reach critical temperature values became shorter up to 2.3 times. However, for the solidification part, time for solidifying increased up to 3.33 times as the ambient temperature was increased from 20°C to 28°C.

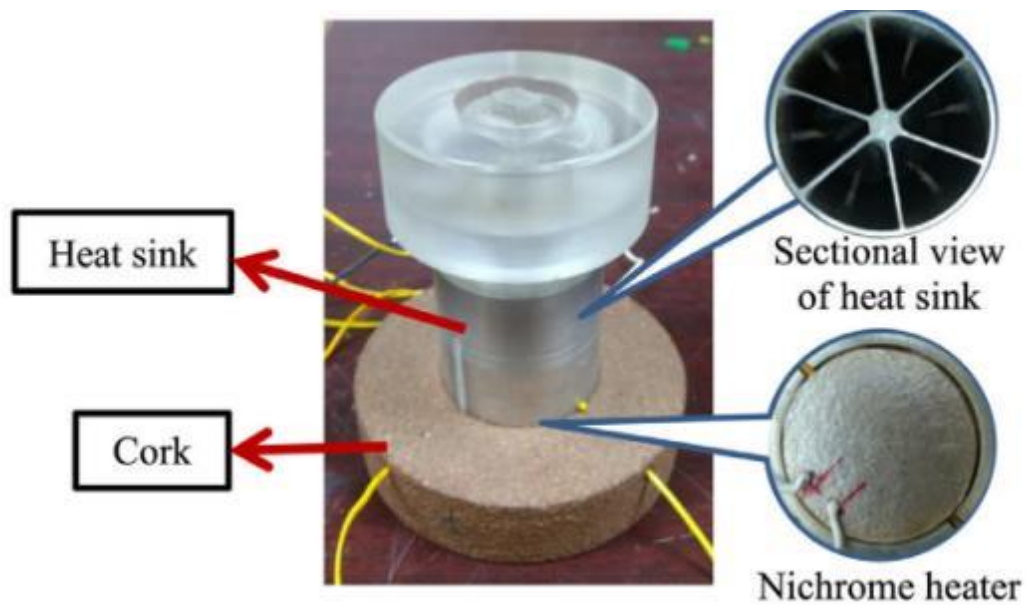


Figure 2.17. Structure of heatsink model in the study of Marri et al. [61].

Iradakunda et al. [62] developed a new approach to PCM heatsinks. By using additive manufacturing and topology optimization processes, new structural types of heatsinks were developed. As seen in Figure 2.18, these types of heatsinks showed similarity with metal foams, however, they were cheaper than metal foams by considering their production processes. The topology optimized heat sinks were studied regarding the effect of conduction, convection, and latent heat storage. Experimental studies were conducted, and topology optimized heatsinks were compared with plate fins. Cyclic 5-W heat load was applied on the system. The results showed that topology optimized heat sinks with PCM increased the operational time by a factor of 3.5, whereas plate fin heatsink increased the operational time by a factor of 3.2. The most important contribution of topology optimized heatsink was the shortening of the PCM's solidification time; therefore, for the cyclic load applications, this effect improved the PCM heatsink's thermal performance.

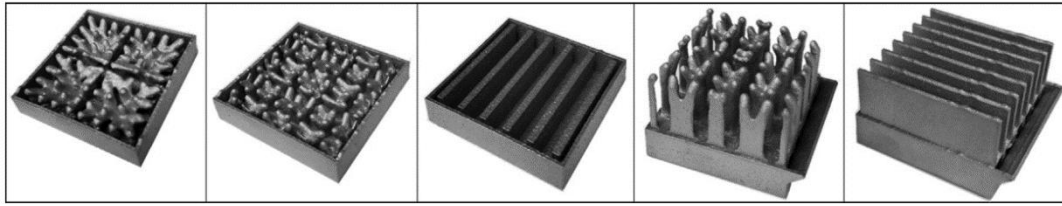


Figure 2.18. The topology optimized and plate fin heatsinks of the study of Iradakunda et al. [62].

Similar research was conducted by Guo et al. [63] in 2021. Thermal energy storage unit was created using lattice structure type heatsink that was produced by 3D printer filled with PCM. Lattice structure had less weight than other heatsinks and, thanks to high contact surface area, gave better results than other commercial heatsinks. Investigated parameters were the initial temperature distribution and heat load in this experimental study. Also, numerical model was established to calculate the thermal efficiency of lattice structure. Convection effects were neglected in the analysis. In conclusion of this research, at the solid connection nodes, PCM melted faster. Thanks to the distribution of the TCE by using lattice structure, distributed heat load effect could be pacificated. Therefore, it can be said that by using lattice or similar structures of heatsinks, distributed heat load effect could be controlled which was a problem in the study of Srikanth and Balaji [50].

Yang et al. [64] conducted a study to research the effects of PCM ratio, cyclic and constant loads, and heat transfer coefficient effects on the performance of PCM heatsinks. In this numerical study, n-eicosane was used as the PCM to cool a 50x50 mm chip. The maximum allowable temperature of the chip was 80°C and 10 kW/m² cyclic or constant heat load was applied. It was concluded that melting occurred faster during natural convection driven melting compared to conduction driven one. Also, upper region temperatures were higher than bottom parts because of natural convection effect. PCM showed better performance under constant loads compared to cyclic loads for $h < 20 \text{ Wm}^{-2}\text{K}^{-1}$ because solidification process took longer time than working scenario. During the forced convection case ($h > 20 \text{ Wm}^{-2}\text{K}^{-1}$), solidification time became shorter; therefore, for the cyclic load case, forced convection gave better performance.

Kumar et al. [65] conducted a study to examine the effects of heat load, fin number, and type of PCM on PCM heatsinks. In this numerical study, the validation was applied by comparing the results with those of Fok et al. [25]. 1, 1.5, and 2 kW/m² heat loads were applied on the heatsink with dimensions of 100x100x25 mm. As the fin number was increased, the heatsink's thermal performance increased and temperature distribution on the base of the heatsink became more uniform. As the heat load was increased, melting time of PCM decreased. By examining the melting phenomenon in terms of Nusselt Number, melting phase comprised of three main stages; conduction, strong convection, and weak convection. The fastest melting was observed during the strong convection part in this study. Finally, if the melting temperature range was nearly constant, the PCM demonstrated better thermal performance.

In 2022, See et al. [66] investigated the natural convection effect on topology optimized PCM heatsink. This research examined three different types of heatsinks: topology optimized heatsink, finned heatsink, and benchmark heatsink, shown in Figure 2.19. 27 and 48 W heat loads were applied on the system. Results showed that the topology optimized heatsink extended the operation time of PCM heatsink by 31% compared to finned heatsink. Also, the topology optimized heatsink provided longer melting time compared to other heatsinks because of the melting of side parts simultaneously with upper parts. This observation could not be obtained from other heatsinks.



Figure 2.19. Investigated types of heatsinks in the study of See et al. [66] (From top to bottom; topology optimized heatsink, finned heat sink, benchmark heatsink.)

2.2 PCM with Metal Foam Matrices

Another method to enhance thermal conductivity is using metal foams. Metal foam matrices, which have started to be used especially recently, attract attention due to their low weight and better thermal conductivity than other solutions. The most important feature is that it spreads the heat optimally, reaches all parts of the PCM, and provides a homogeneous melting cycle for PCMs. For investigating the metal foam effects, as can be seen from Figure 2.20 and Figure 2.1, experimental studies are mostly preferred in heatsink studies. This is because, numerical modeling of metal foams is more challenging than heatsink modeling. Generally, non-equilibrium thermal model was applied between metal foam and PCM because of huge difference between their conductivities. Main idea behind using metal foam is that it distributes the heat through all parts of PCM to provide homogeneity of melting inside PCM.

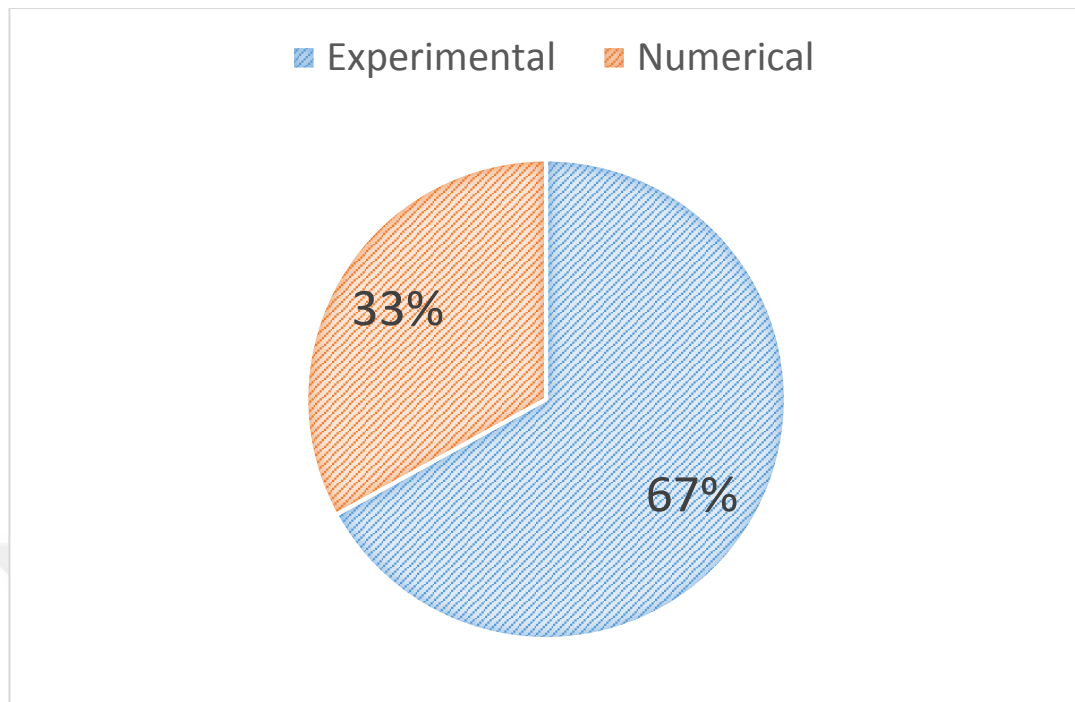


Figure 2.20. Fraction of studies on metal foam PCM integration [17].

Alawadhi and Amon [67] were the first who suggested the use of metal foam matrices and PCM integration in 2003. In this numerical and experimental study, constant and cyclic power loads were the parameters. Heat capacity method was used in the analysis. They observed that usage of metal foam matrices decreased temperature fluctuations in PCM under cyclic loads. Also, melting time became longer thanks to heat distribution through all parts of the PCM.

In 2007, Lafdi et al. [68] conducted a study on the effects of porosity and pore size of metal foam on PCM melting. In this experimental research, six different metal foam matrices were used. Paraffin wax was chosen as PCM, and material of metal foams was aluminum. 4x4 inches heater was used with power load of 28.9 W. As a result of this study, time to reach critical temperature became shorter using metal foam with higher porosity, compared to lower porosity. This effect was also valid for larger pore size of metal foams compared to smaller pore size since convection effect was dominant for larger porosity values or pore size. Nevertheless, base temperature decreased as the porosity ratio or pore size was decreased was due to

higher conduction rates in these metal foams. To summarize this research, optimization study should have been applied for convection and conduction processes to find the ideal metal foam properties.

Gharbi et al. [69] experimentally compared PCM heatsink with PCM metal foam structures for electronics cooling. Silicone and graphite matrix materials were used in this research to investigate the different metal foam material effects. The other investigated parameters were two different positions (vertical and horizontal) and different types of PCM. The dimensions were 51x25x16 mm and 4W- constant heat load was applied for 250 minutes. The results showed that PCM addition extended the operation time by a factor of 2. Also, metal foam was more advantageous than fins for the same volume fraction of copper. This was because, metal foam could reach even sides of the PCM and therefore more amount of PCM contacted with copper, and it provided higher heat transfer between the PCM and copper. Thanks to this, lower base temperatures and better thermal performance were obtained. Graphite metal foam also gave better results than silicon matrices.

Another investigation was conducted by Zheng et al. [70] in 2018. In this article metal foam effect on paraffin wax PCM was investigated. Experimental and numerical modelling were applied in their research. As can be seen from Figure 2.21, two different cases were experimented. First case included only PCM, on the other hand the second case included PCM with copper metal foam. Copper metal foam had 0.95 porosity and 5 PPI pore size. 100x100x30 mm case was designed for experiments and 3, 4, and 5 W constant heat load was applied. From experiments, it was concluded that the melting time of the metal foam case was 20% shorter than pure PCM. The results showed that metal foam increased the heat transfer rate inside PCM due to its higher thermal conductivity. Also, the addition of copper foam reduced the thermal resistance inside paraffin. Finally, numerical results showed consistency with experimental results.

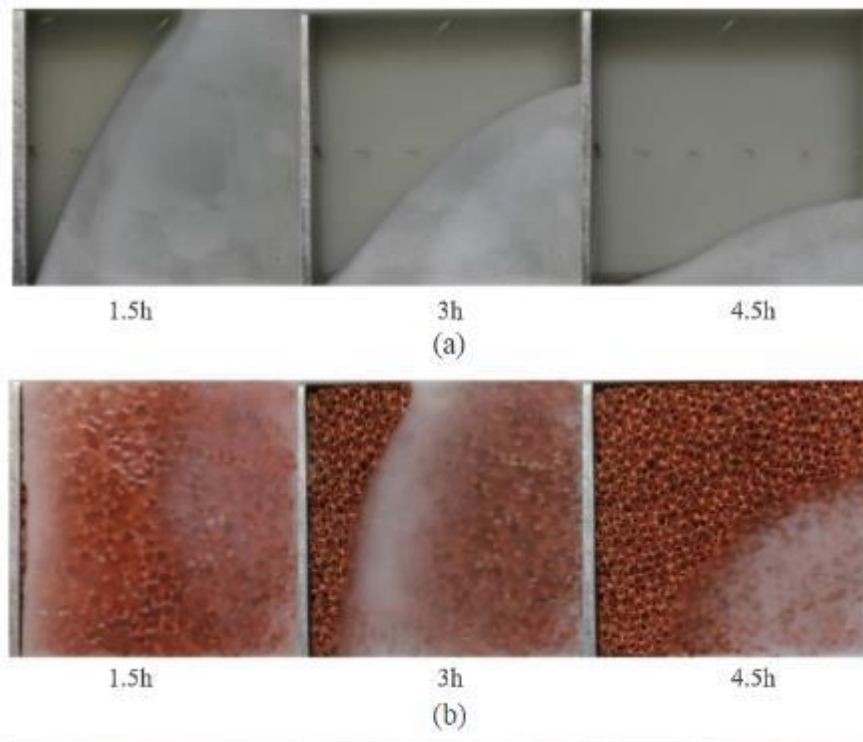


Figure 2.21. Experimental results of the study of Zheng et. al. [70].

Kumar et al. [71] investigated the effects of TCE type (finned heatsink or metal foam), fraction of PCM, and heat loads ($1.5\text{--}2.5\text{ kW/m}^2$) on PCM heatsinks. In this experimental study, $100\times100\times4\text{ mm}$ heatsinks were used. Paraffin wax was chosen as PCM. Optimization study was conducted by using VIKOR technique. Different fins, copper foam and carbon foam were experimented.

In conclusion of this research, for the melting process, the best thermal performance was obtained from the heatsink with carbon foam. In addition, as the TCE ratio was increased, the base temperature of heatsink increased. Results showed that if TCE ratio is 5% instead of 25%, the base temperature reduced by %17.5 compared to the %25 TCE ratio situation. Finally, VIKOR optimization found that the PCM with carbon metal foam demonstrated the best performances for all cases.

Hou et al. [72] investigated PCM-copper foam integrated heatsink for electronics cooling using printed circuit boards. In this numerical study, three types of PCM were optimized using ANN with two main purposes: maximizing the operation time,

which was the time to reach main components to 80 °C, and minimizing the total weight of PCM metal foam heatsink. The printed circuit board emitted 75 W heat load from different chips and the thickness of PCM, porosity, power level of chips, and height of heatsink were input parameters to find the best solution case from ANN. Optimization results showed that the best PCM performance was observed from RT44 HC because it has low density, high latent heat and relatively high melting range than others. The reason behind that was RT44 HC had lower density and it resulted in low weight, high melting temperature, and high latent heat. Also, from the pareto results, it was found that the best performance of PCM metal foam heatsink was obtained from RT44 HC PCM having 0.95 porosity and 9 mm height. During the tests, the local heating from printed circuit boards was observed because of discrete heating.

Another Pareto optimization study was conducted by Bianco et al. [73] to examine fin and metal foam PCM heatsink. The Pareto optimization was applied with the objectives of maximizing the time of operation and minimizing the cost of the system. A mathematical model was developed to solve porous media equations. 50x55 mm heat sinks subjected to 8W-constant heat load were used. In 2-D numerical analysis, COMSOL program was used. The Pareto optimization results ranged from 2000 s to 6000 s for operation time and from 200 € to 275 € for cost. The optimized case had a cost of 235 € and operation time of 3780 s. The porosity value was found to be 0.94. In addition, it was found that as the porosity ratio and heatsink height were decreased, and fin thickness was increased, operation time of the system decreased. Natural convection effects were also observed during analysis even there were very small spaces due to metal foams.

2.3 Summary of the Literature Review

In this section, conducted studies and research are presented. Different parameters were investigated by different methods. Experimental and numerical investigation of phase change material in electronic cooling and different applications has proven to be useful in time-dependent operating scenarios. In this section, where heat spreader and metal foam applications are examined, it is understood that Ansys Fluent and Comsol Multiphysics software are used in analysis studies. In this thesis, it is aimed to model phase change materials with different properties using the outputs from experimental studies and to find an answer to a specific cooling problem. In addition, the effects of inclination angle and chamber number are also investigated experimentally and numerically.



CHAPTER 3

EXPERIMENTAL SETUP

The detailed test setup, the devices used in the experiments and the procedures of the different experiments for different parameters are given in this section. In addition to these, uncertainty analysis and its details are also explained. In the studies, inclination angle, different types of phase change materials, number of chambers and metal foam effect are investigated experimentally. A camera system is used to observe the mushy zone behaviour of the different types of PCMs. Experimental setups are designed and used in accordance with all these experiments and analyzes. As mentioned in the previous sections, the main purpose is to measure and evaluate the thermal performance of PCM heatsinks to be used in electronic cooling applications.

3.1 Experimental Description

In the scope of the thesis, experiments are conducted to verify the analyzes and to measure the performance of PCM Heatsinks, which are planned to be used in defense industry. In experiments, four different types of heatsinks, eight different types of PCMs, seven different inclination angles, and three different types of metal foams are used to investigate their effects. The heat load, geometric boundaries, and ambient conditions are constant. In all experiments, the melting and solidification regions of the PCM are investigated. The schematic of the setup is shown in Figure 3.1 and the established experimental setup is shown in Figure 3.2, Figure 3.3 and Figure 3.4. The experimental setup used for the investigation of the effect of inclination, is shown in Figure 3.5.

To perform experiments, some steps are followed in this thesis. These steps are given below:

- i) Firstly, to provide adiabatic boundary condition, side surfaces of heatsinks are covered by aerogel plates.
- ii) Thermocouples are placed on base of the heatsinks.
- iii) Flex heater is placed at the bottom of the heatsinks and bottom of the heater is covered with aerogel to prevent heat loss from heater.
- iv) Then solid PCM is melted with the help of furnace and then liquid PCM is filled into preheated heatsinks. (Heatsinks are preheated to prevent solidification of liquid PCM)
- v) By using gasket and screws, heatsink cover is placed.
- vi) PCM heatsink is waited for solidification process.
- vii) After solidifying, heater is connected to power supply and thermocouples connected to data acquisition system. Microscope and camera start recording.
- viii) Power supply starts to give current to the heater and experiment starts.
- ix) After the melting of PCM completed, power supply is turned off and data is obtained from data acquisition unit to computer to examine.

The details of used tools and materials in experiments are explained below.

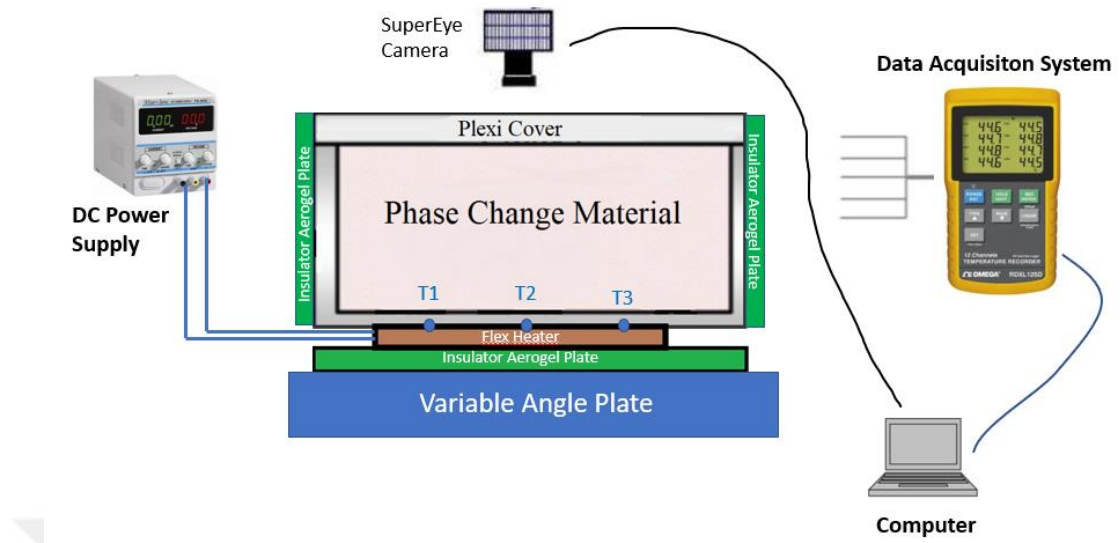


Figure 3.1. Schematic of the experimental setup.

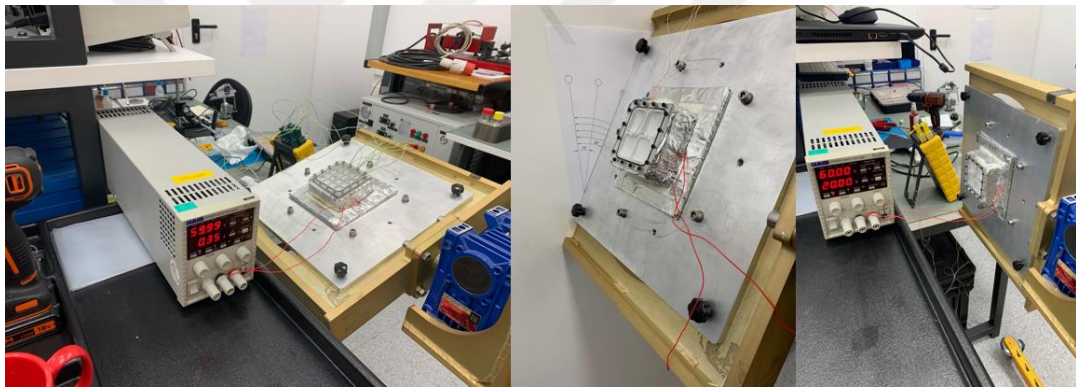


Figure 3.2. Different orientations of PCM Heatsinks.

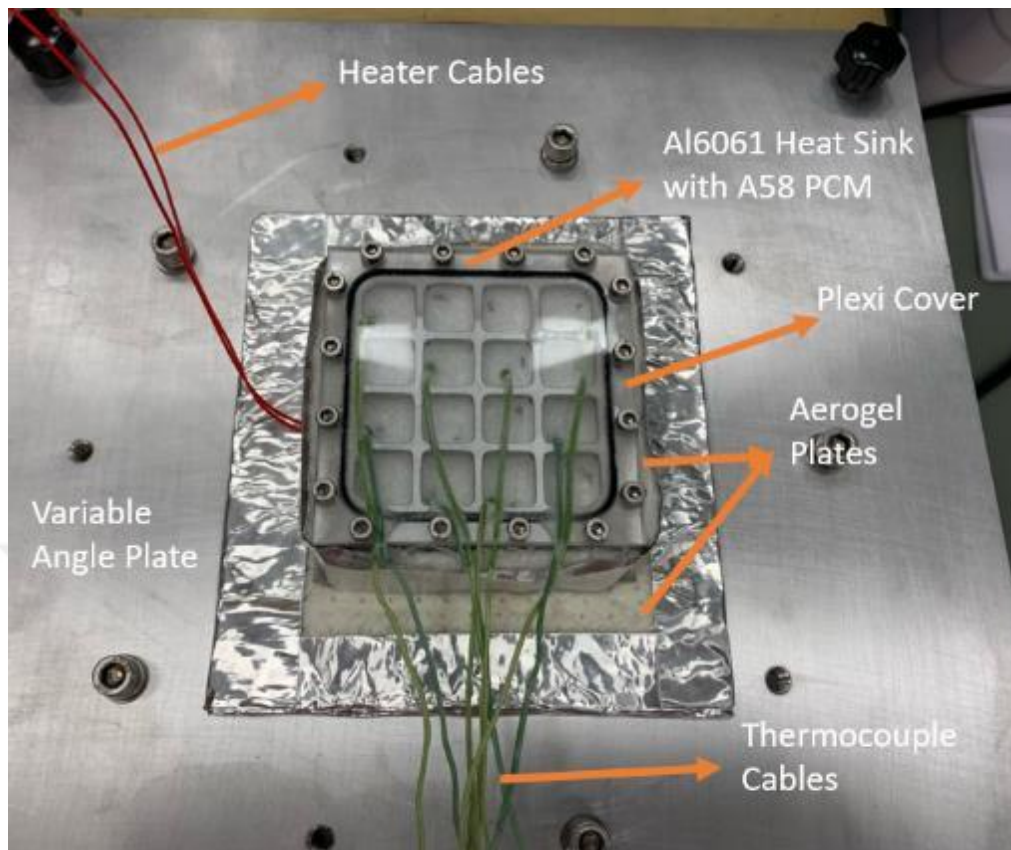


Figure 3.3. Experimental setup of the PCM Heatsink with 16 chambers.

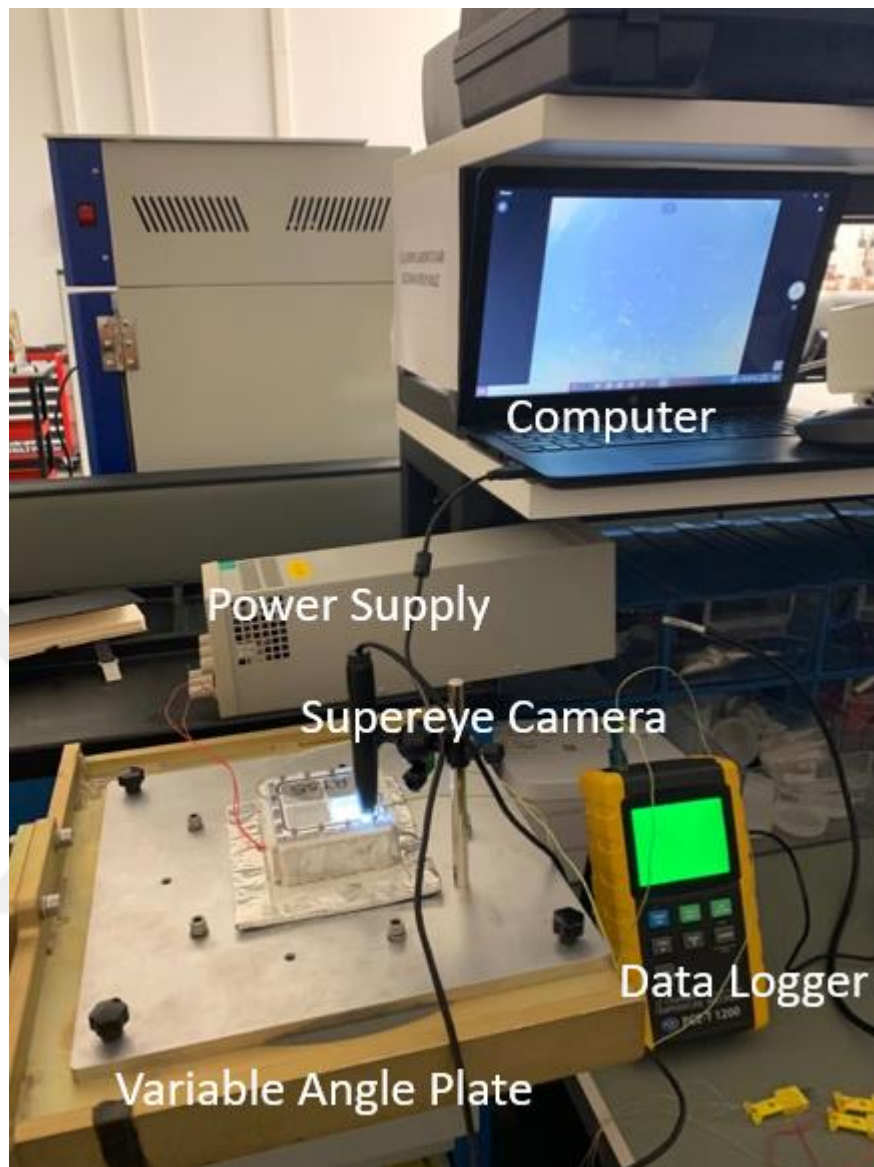


Figure 3.4. Experimental setup of the PCM Heatsink with 4 chambers.

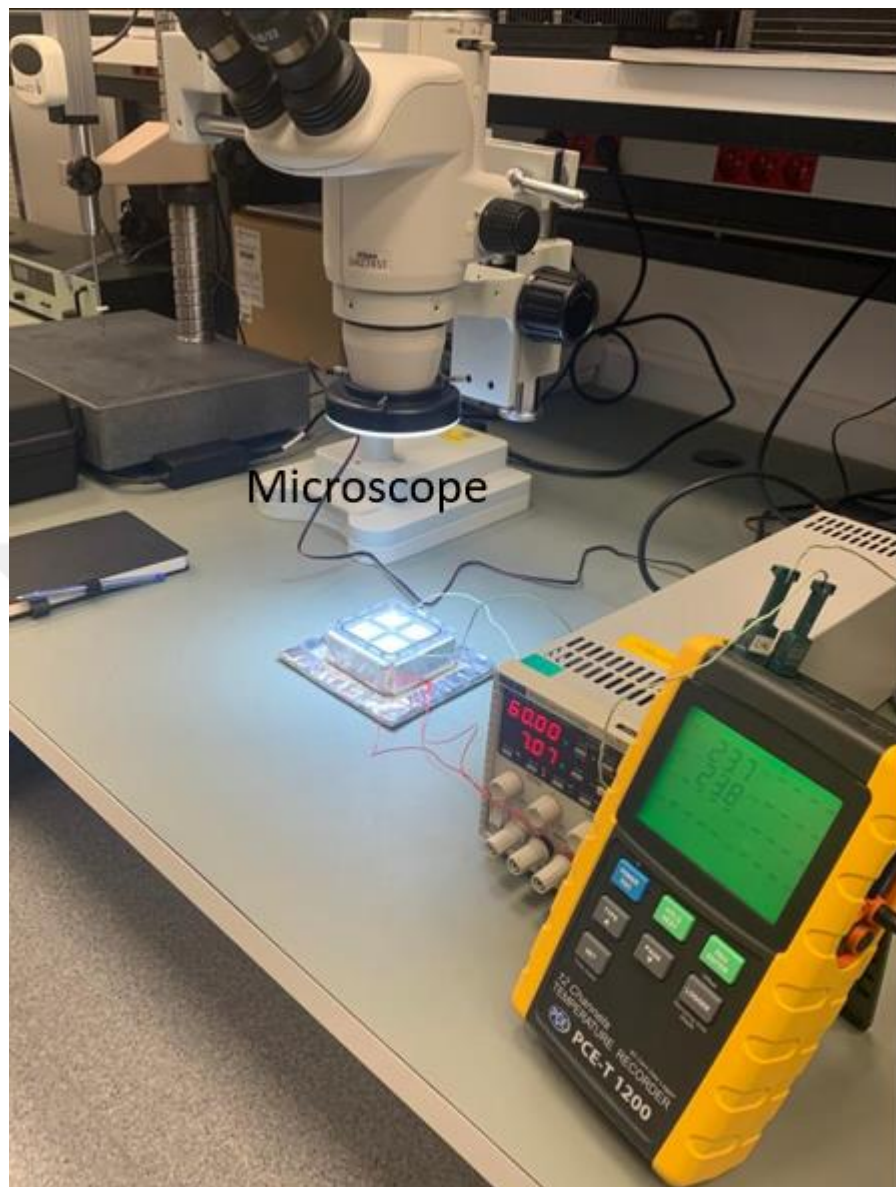


Figure 3.5. Experimental setup for investigating different types of PCMs.

3.1.1 Heatsinks

Heatsinks having 1, 4, 9, and 16 chambers are produced by milling. Al 6061 material is chosen, and its material properties are given in Table 3.1. The produced heatsinks are shown in Figure 3.6 and their dimensions are shown in Appendix A.

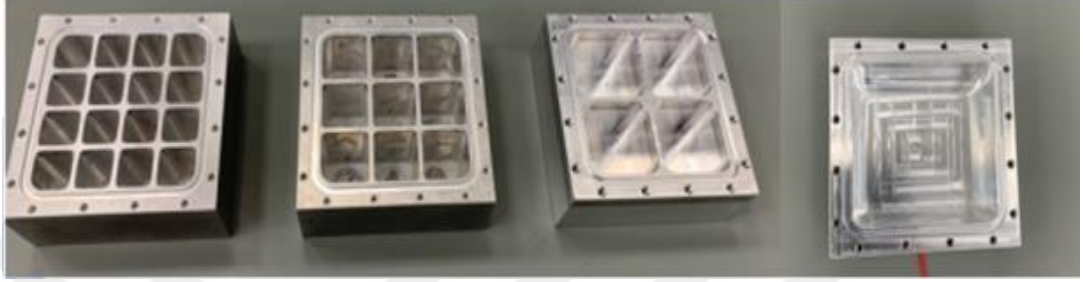


Figure 3.6. Al 6061 heatsinks with different number of chambers.

After filling with PCM, heatsinks are closed using plexiglass cover, seal, and screws. The plexiglass cover is shown with its dimensions in Figure 3.7. The thickness of the cover is 2 mm. The final assembly of the PCM heatsink is shown in Figure 3.8. For the insulation, the heatsink's sides are covered using aerogel plates. The material properties of Plexiglass and aerogel are shown in Table 3.1. Also, the amounts of PCMs for different number of chambers heatsinks are given in Table 3.2.

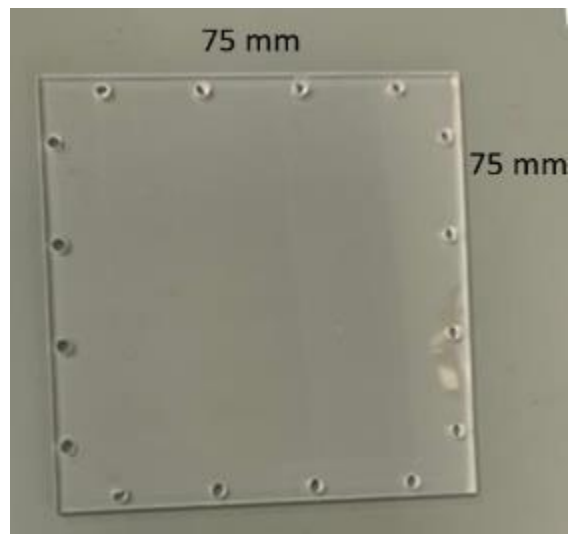


Figure 3.7. Plexiglass Cover.

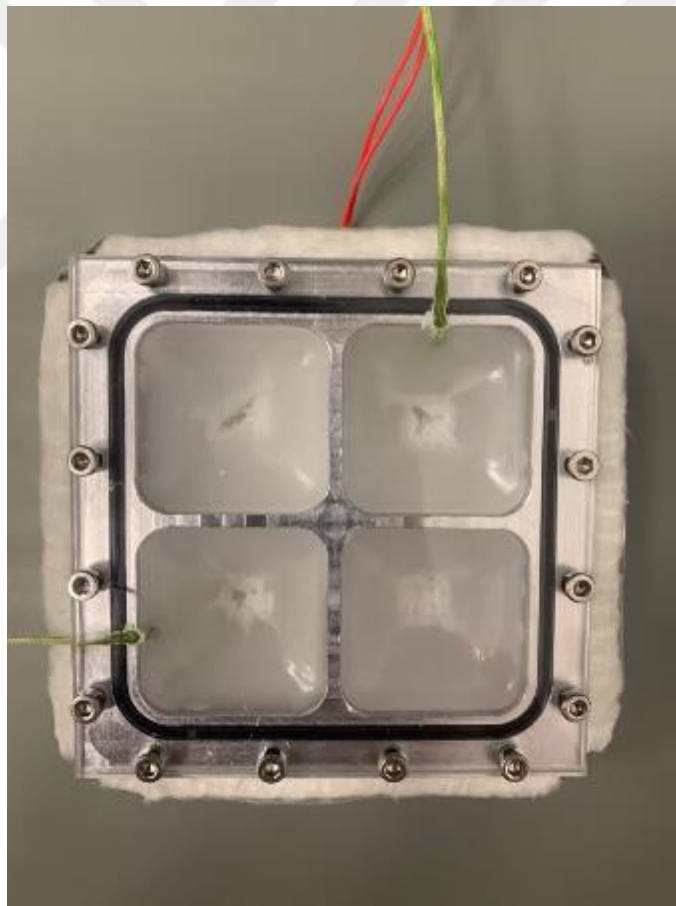


Figure 3.8. The final assembly of 4 chamber PCM Heatsink.

Table 3.1. Material properties of Al 6061, plexiglass, and aerogel.

Materials	Aluminum 6061	Plexi Glass	Aerogel
Density (kg/m^3)	2700	1180	150
Thermal Conductivity (W/mK)	167	0.19	0.018
Specific Heat (kJ/kgK)	0.896	1.5	1.9

Table 3.2. Amount of PCM according to the number of chambers.

Number of Chambers	Volume of PCM (m^3)	Weight of PCM (g)
1	9.16×10^{-5}	75.1
4	8.35×10^{-5}	68.5
9	7.89×10^{-5}	64.7
16	7.28×10^{-5}	59.7

3.1.2 Heaters

A flex heater is used to simulate the behaviour of the integrated circuit (IC) packages. Minco HK5174R294L12F model flex heater, shown in Figure 3.9, is attached at the bottom side of the heatsink. The resistance of the heater is 29.4 ohm. Dimensions of the heater is 76.5x76.5x1 mm. Resistances of the heater is distributed equally and homogenous temperature distribution can be obtained thanks to this.



Figure 3.9. Flex heater used in the experiments.

3.1.3 Thermocouples

K-type thermocouples having Nickel-Chromium /Nickel-Aluminum leads (shown in Figure 3.10) are used in experiments to measure heatsink base temperature values. Thermocouples have probe diameters of 0.254 mm, and the error of thermocouples is 0.4% above 0°C. K-type thermocouples can measure temperature from -100°C to 200°C.

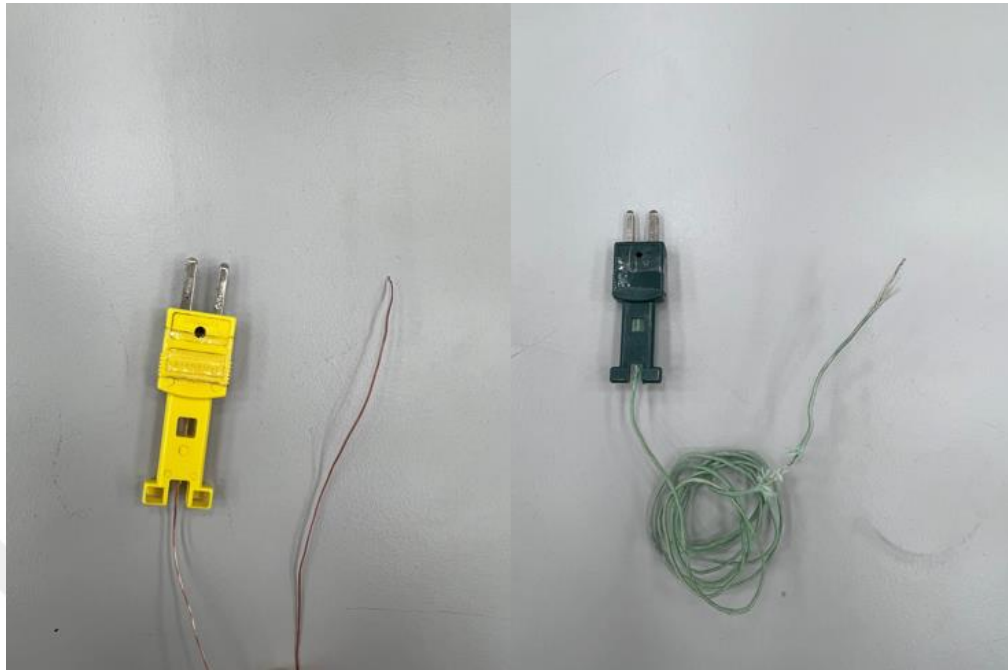


Figure 3.10. K-type thermocouples that were used in experiments.

3.1.4 Power Supply

The CPX400S model power supply, produced by AIM-TTI Instruments, is used in this study. Single DC output is provided and 0-60 V voltage range, 0-20 A current range can be applied. This device has an accuracy of $\pm 10\text{ mV}$ and $\pm 10\text{ mA}$, corresponding to $\pm 0.1\%$ for voltage and $\pm 0.3\%$ for current. The power supply, shown in Figure 3.11, can be controlled by setting the voltage as desired and according to the resistance value in the heater, current is delivered to the heater.



Figure 3.11. CPX400S power supply.

3.1.5 Data Acquisition Unit

To obtain temperature data from the thermocouples, PCE-T 1200 model multi-channel data logger is used in experiments. This unit can collect data from 12 thermocouples simultaneously and store them in an SD card. After the experiments, data is transferred from SD card to computer for further analysis. The device has a

battery and can work without a power cable. The data logger device is shown in Figure 3.12.



Figure 3.12. PCE-T 1200 data logger.

3.1.6 Nikon Microscope and SuperEye Camera

To investigate the mushy zone region in detail and measure the average dendrite length of solid particles during the melting phase, Nikon SMZ745T model microscope and SuperEYES B008 HD Digital Camera are used in experiments. The properties of Nikon SMZ745T [82] are:

- Zoom range: 0.67-5x
- Working distance: 115 mm

- Total magnification: 3.35-300x
- Optical system: Greenough optical system
- Eyepiece Inclination: 45°
- Zoom ratio: 7.5:1

The properties of SuperEYES B008 [83] are:

- Zoom Capability: 1-500x
- Sensor: 5.0 MP
- Image Capture Resolution: 2592x1944
- Display Speed: 30 f/s
- Focus Type: Manual

The Nikon Microscope is shown in Figure 3.13, and SuperEYES Camera is shown in Figure 3.14.



Figure 3.13. Nikon SMZ745T Microscope.

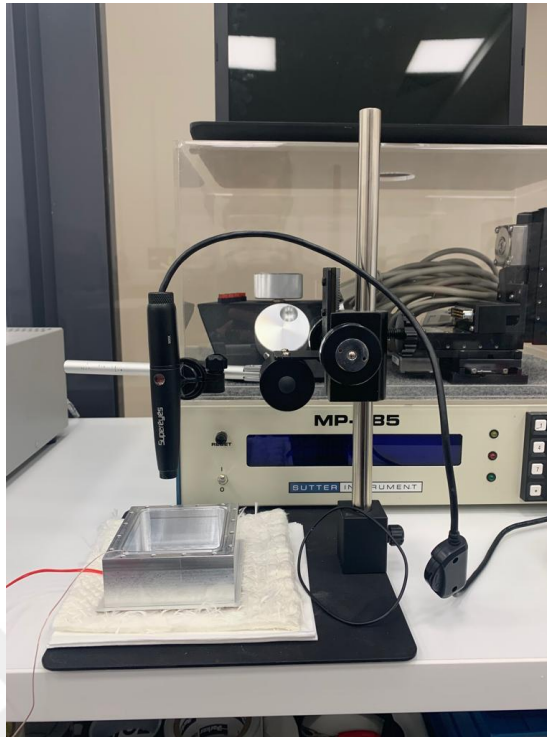


Figure 3.14. SuperEYES B008 Camera.

3.1.7 Phase Change Materials

8 different types of PCMs are examined in this study. Material properties of them are shown in Table 3.3. These properties are obtained from producers and their datasheets [80], [81]. Different concerns are considered when choosing PCM. The parameters for investigation of PCMs are melting temperature, material type (organic or inorganic), latent heat, specific heat. The PCMs are supplied from the producers Rubitherm and PCM Products.

Table 3.3. Physical properties of PCMs used in this study.

Materials	RT-55 [80]	S58 [81]	A58-H [81]	RT-62 HC [80]
Material Type	Organic	Inorganic	Organic	Organic
Solidus Temperature (°C)	51	57	56	62
Liquidus Temperature (°C)	57	58.4	57.6	63
Solid Density(kg/m³)	880	1520	810	850
Liquid Density(kg/m³)	770	1495	830	840
Thermal Conductivity (W/mK)	0.2	0.69	0.22	0.2
Specific Heat (kJ/kgK)	2	2.55	2.85	2
Volume Expansion Coefficient	14%	-	5%	-
Latent Heat (kJ/kg)	170	145	240	230

Table 3.3 (cont'd). Physical properties of PCMs used in this study.

Materials	RT-65 [80]	A70 [81]	RT70-HC [80]	S72 [81]
Material Type	Organic	Organic	Organic	Inorganic
Solidus Temperature (°C)	58	69	69	72
Liquidus Temperature (°C)	65	70	71	73
Solid Density(kg/m³)	880	900	880	1700
Liquid Density(kg/m³)	780	880	770	1600
Thermal Conductivity (W/mK)	0.2	0.23	0.2	0.58
Specific Heat (kJ/kgK)	2	2.2	2	2.13
Volume Expansion Coefficient	11.3%	5%	12.5%	-
Latent Heat (kJ/kg)	150	225	260	285

For these PCM properties, no experimental study is conducted to check the correction of these values. Shared values from producers are accepted as correct and calculations are made by using them.

Also, different PCMs are filled into the heatsinks and their physical appearances differ. The experimental setups with different PCMs are shown in Figure 3.15 and Figure 3.16.

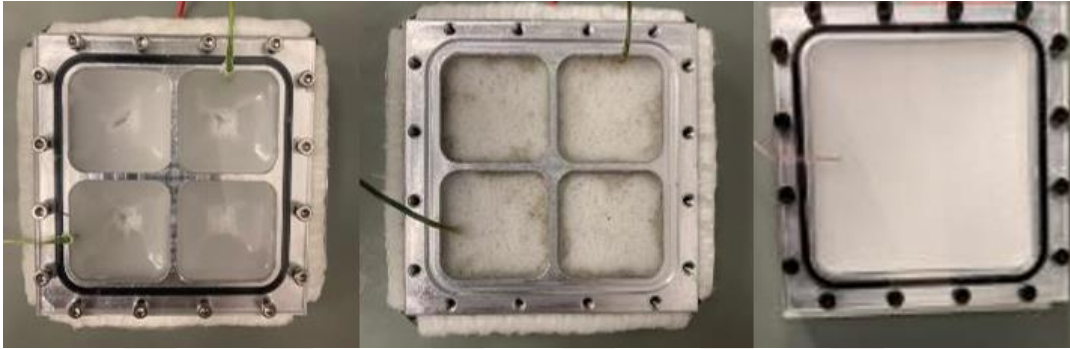


Figure 3.15. RT-55 and S-58 PCM filled into heatsinks.

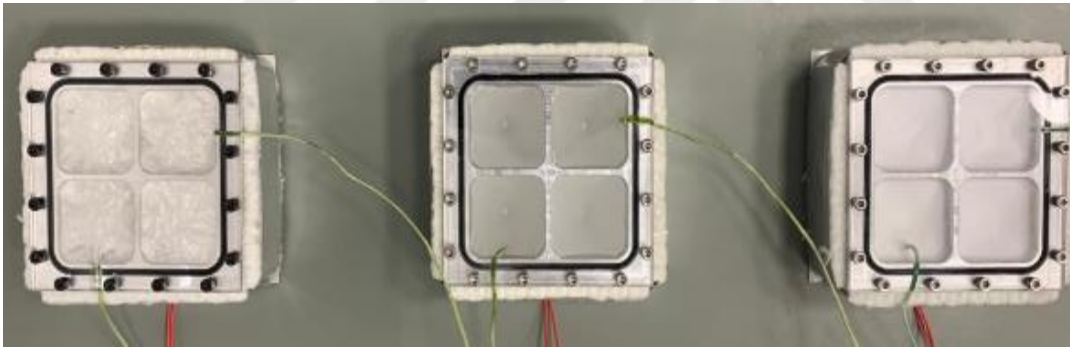


Figure 3.16. RT62-HC, RT-65, and RT-70 HC PCM filled into heatsinks.

3.2 Homogeneity of the Heat Flux

To provide uniform distribution of heat flux at the bottom of the heatsink, the heater should homogenously give the heat flow through the heat sink. By this way, the same melting process can be observed in every chamber. Therefore, before starting experiments, this phenomenon is checked by conducting simple experiments. K-type thermocouples are connected to the base of the heatsink. Heater is placed at

the bottom of the heatsink and no PCM is filled, and cover is not attached on heatsink. By giving power to the heater, temperatures obtained from the base of the heatsinks are compared then. The homogeneity is expected because of the uniform resistance distribution in the heater as shown previously in Figure 3.9. Thermocouples are placed at the bottom of the heatsink as shown in Figure 3.17 to Figure 3.20. As can be seen in these figures, different number of thermocouples are used in the chambers, such as 3 thermocouples for 1 chamber and 8 thermocouples for 16 chambers. Recorded temperatures during tests are shown in Figure 3.21 to Figure 3.24. As can be seen from these figures, temperature distribution is homogenous in the chambers; therefore, for PCM in each chamber, the same temperature profile is expected.

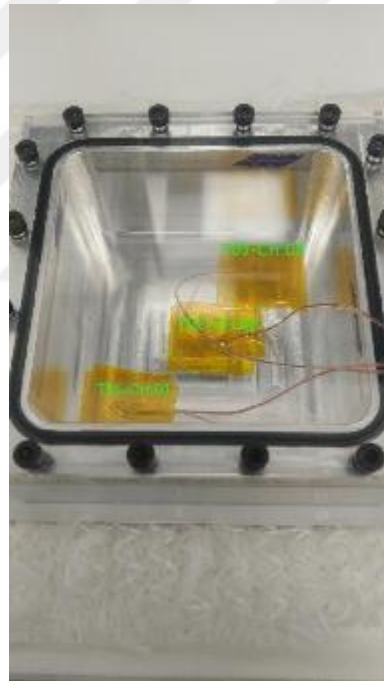


Figure 3.17. Thermocouple positions for 1 chamber heatsink.

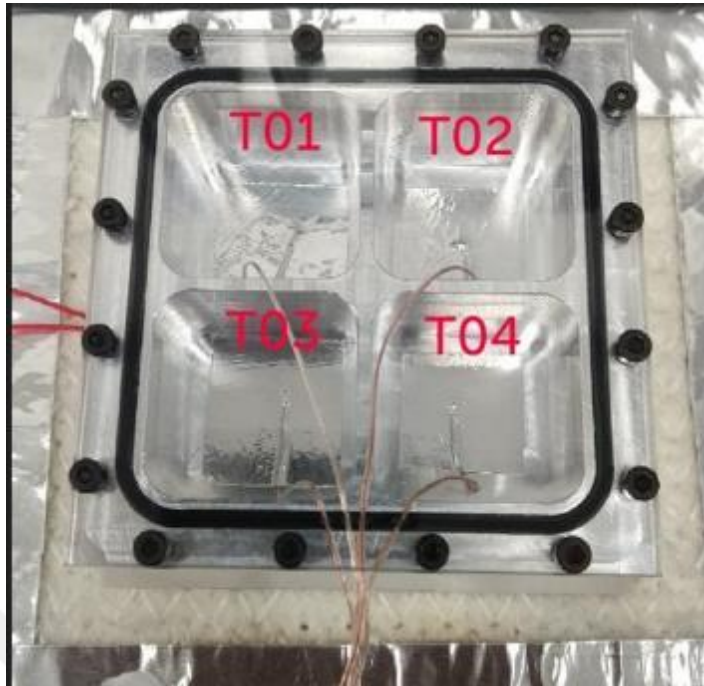


Figure 3.18. Thermocouple positions for 4 chambers heatsink.



Figure 3.19. Thermocouple positions for 9 chambers heatsink.

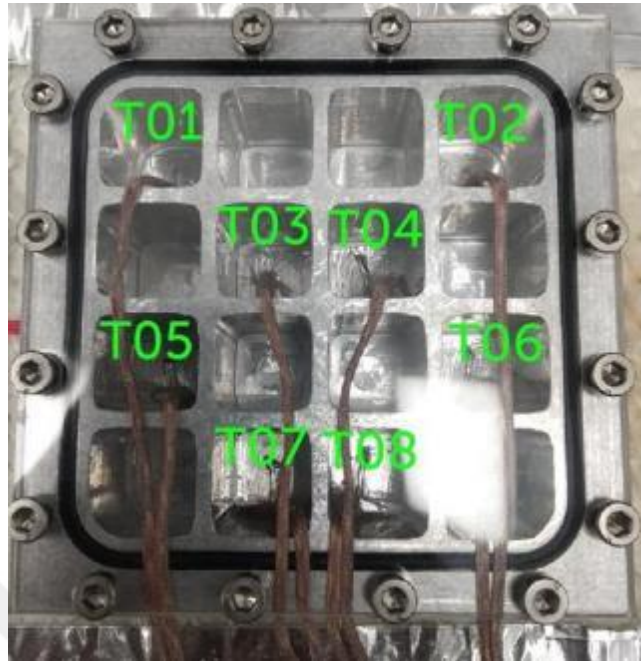


Figure 3.20. Thermocouple positions for 16 chambers heatsink.

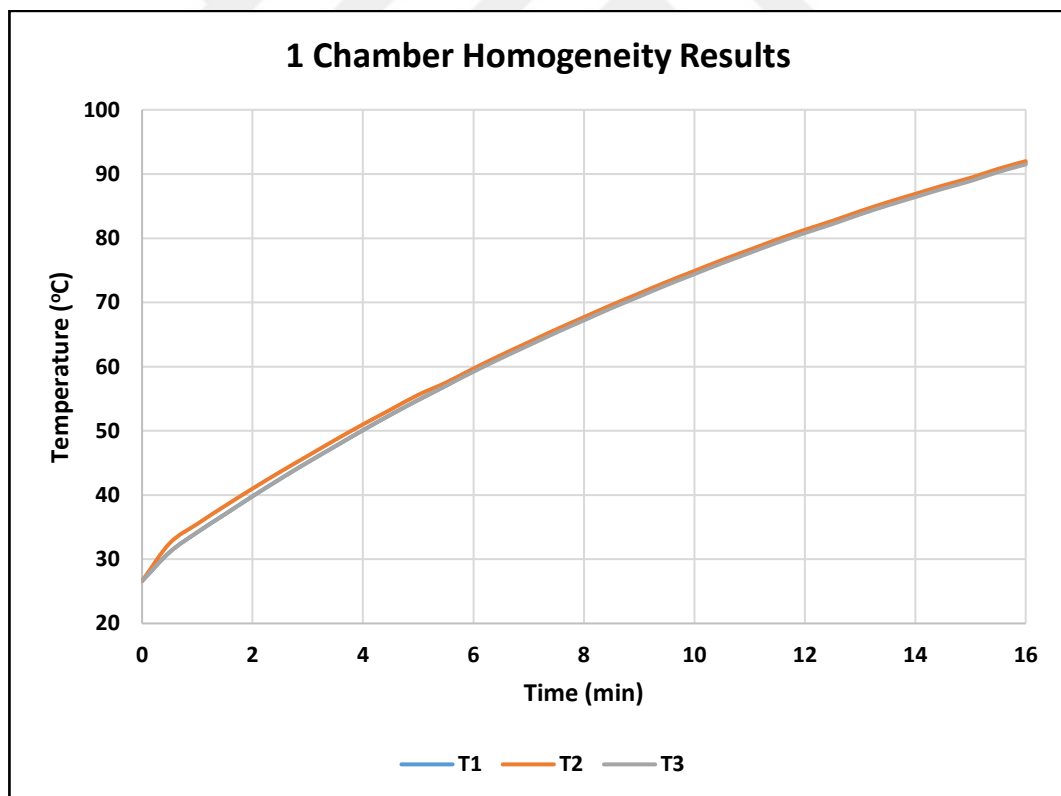


Figure 3.21. Homogeneity results of 1 chamber Heatsink.

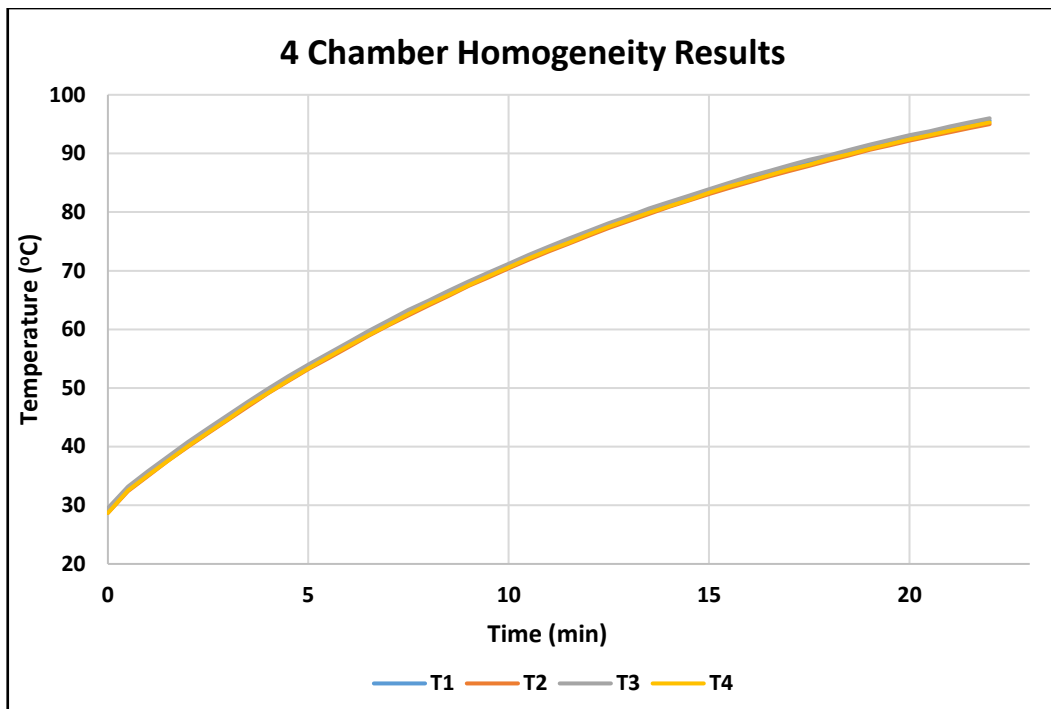


Figure 3.22. Homogeneity results of 4 chambers Heatsink.

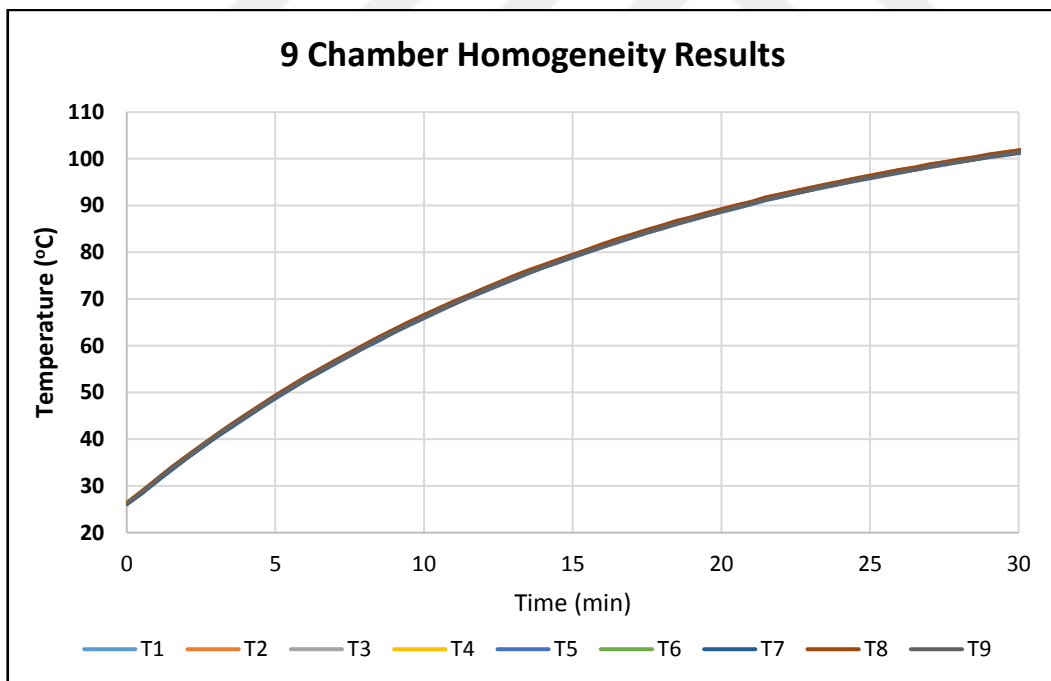


Figure 3.23. Homogeneity results of 9 chambers Heatsink

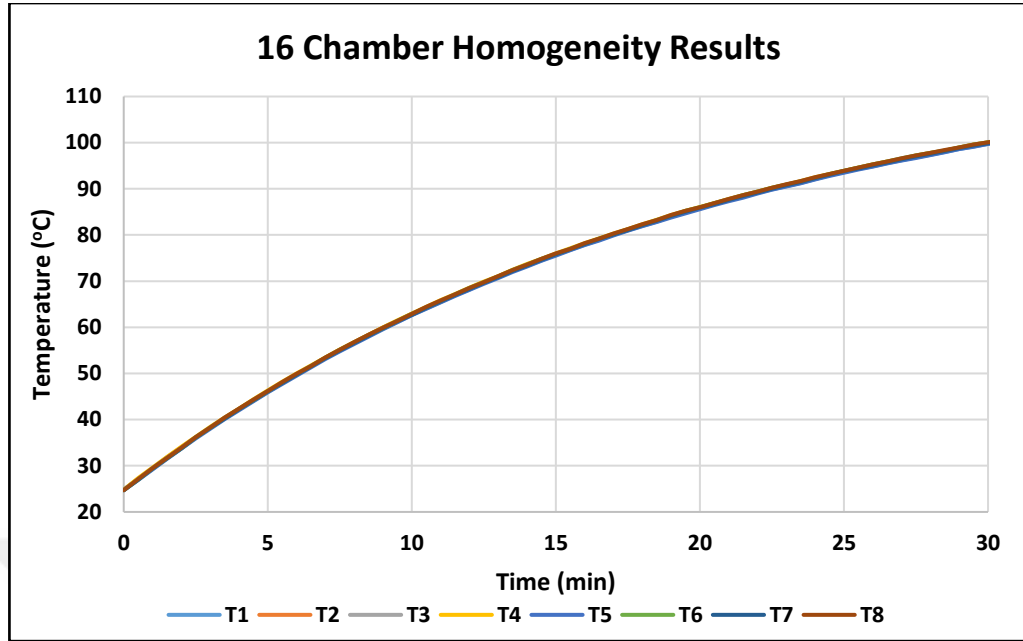


Figure 3.24. Homogeneity results of 16 chambers Heatsink.

3.3 Uncertainty Analysis

The accuracy values of thermocouple and power supply are given in Section 3.1 previously. To calculate the uncertainty in the magnitude of the heat input from the heater to the heatsink, the heat rate and power equations should be differentiated [15]. In this analysis, it is assumed that all power goes into heatsink because aerogel plate is placed the bottom of the heater and the measured temperature from the aerogel equals the ambient temperature. Therefore, this assumption is performed for uncertainty analysis. The power equation is given in Equation 3.1 and derivative of power equation is given in Equation 3.2.

$$Q = VI \quad (3.1)$$

$$dQ = \frac{\partial Q}{\partial V} dV + \frac{\partial Q}{\partial I} dI \quad (3.2)$$

Then, Equation 3.2 can be written by using Equation 3.1 as:

$$dQ = IdV + VdI \quad (3.3)$$

The right-hand side of Equation 3.3 is mentioned previously in Section 3.1.4.

Therefore, these terms become:

$$dV = 0.001 \quad (3.4)$$

$$dI = 0.003 \quad (3.5)$$

Then, Equation 3.3 becomes:

$$dQ = 0.001I + 0.003V \quad (3.6)$$

In addition, heat rate equation is given in Equation 3.7:

$$Q = mc_p\Delta T \quad (3.7)$$

The same procedure is applied on heat rate equation:

$$dQ = \frac{\partial Q}{\partial m} dm + \frac{\partial Q}{\partial \Delta T} d\Delta T \quad (3.8)$$

$$dQ = c_p\Delta T dm + mc_p d\Delta T \quad (3.9)$$

The temperature measurement error is given previously in Section 2.1.3 as:

$$d\Delta T = 0.004 \quad (3.10)$$

Uncertainty heat rate equation is given in Equation 3.11:

$$dQ = c_p\Delta T dm + mc_p 0.004 \quad (3.11)$$

Then, by considering Equation 3.6 and Equation 3.11, the total uncertainty for heat load is found to be 0.8%.

3.4 Test Matrix

In this section, the summary of the conducted experiments is given in Table 3.4. 25 different experiments are conducted to investigate number of chambers, inclination angle, and PCM type effects on thermal performance of PCM heatsinks.



Table 3.4. Test matrix of experiments.

Experiment No	Factor 1 / Number of Chambers	Factor 2 / Inclination Angle	Factor 3 / PCM Type
1	1	0°	A58H
2	4	0°	A58H
3	9	0°	A58H
4	16	0°	A58H
5-11	4	0° 15° 30° 45° 60° 75° 90°	A58H
12-18	16	0° 15° 30° 45° 60° 75° 90°	A58H
19	4	0°	RT-55
20	4	0°	S58
21	4	0°	RT62-HC
22	4	0°	RT-65
23	4	0°	RT70-HC
24	4	0°	A70
25	4	0°	S72

CHAPTER 4

NUMERICAL ANALYSIS

In this chapter, information about the numerical analysis is given. This chapter presents the analysis model and theoretical equations of the phase change problems. In addition, validation and independence studies are also mentioned.

4.1 Governing Equations

Firstly, the conservation equations are given in this section:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (4.1)$$

Momentum equation:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_j} = \mu \frac{\partial}{\partial x_j} \frac{u_i}{\partial x_j} - \frac{\partial p}{\partial x_i} + S_b + S_{mushy} \quad (4.2)$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{u} H) = \nabla \cdot (k \nabla T) \quad (4.3)$$

To model phase change phenomenon in Ansys Fluent, different options are provided. For the melting of PCM, “Solidification&Melting” model option will be used in this study. This model uses “enthalpy-porosity” method and equations to solve mushy zone and heat transfer between solid-liquid interfaces. In this method, mushy zone is modelled as a porous medium. This method assigns the nodal latent heat according to the temperature value in every volume cell [77]. To implement this method, liquid

fraction term is defined. As can be seen from Equation 4.4, this ratio depends on temperature of the volume cell and solidus and liquidus temperatures of the material. This ratio becomes 0 when the material is solid and 1 when the material is liquid. In mushy region, this value is between 0 and 1. It can be said that this method treats mushy zone as porous medium and liquid fraction represents the porosity. The enthalpy-porosity method was suggested by Voller et al. [77] in 1987. The liquid fraction is defined as:

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

$$\begin{aligned} \gamma &= 0, & \text{when } T \leq T_{solidus} \\ \gamma &= 1, & \text{when } T \geq T_{liquidus} \end{aligned} \quad (4.4)$$

Enthalpy affects the energy equations, and enthalpy changes in the mushy zone. Therefore, it should be modelled before solving energy equations. The enthalpy of the PCM comprises from sensible and the latent heat as shown in Equation 4.5:

$$H = h + \Delta H \quad (4.5)$$

In Equation 4.6, sensible enthalpy can be explained as:

$$h = h_{ref} + \int_{T_{ref}}^T c_p dT \quad (4.6)$$

Latent heat can be expressed in terms of liquid fraction as:

$$\Delta H = \gamma L \quad (4.7)$$

Equation 4.7 shows that for every volume cell in mushy region, latent heat capacity and so total enthalpy can change, and it provides correct simulation of heat transfer and melting or solidification in mushy zone.

The melting process is modelled using conservation equations of mass, momentum, and energy. During the initial melting phase, the process is driven by conduction until a certain amount of liquid PCM is formed, thereafter, natural convection starts to dominate the melting process [78]. Therefore, natural convection in PCM should be modelled correctly. To achieve this, in Fluent, Boussinesq Approximation method is used. Boussinesq Approximation is a model that assumes a constant density in governing equations except buoyancy term in momentum equations [79]. Therefore, density equation becomes:

$$\rho = \frac{\rho_l}{(\beta(T - T_l) + 1)} \quad (4.8)$$

Momentum equation is shown in Equation 4.2. In this equation, there are two source terms at the right-hand side. The first one is S_b that is buoyancy term. This term manipulates the momentum equation by using Boussinesq Approximation to model natural convection inside PCM:

$$S_b = \frac{\rho_{ref} g \beta (h - h_{ref})}{c_p} \quad (4.9)$$

The other source term aims to model mushy zone hydraulics:

$$S_{mushy} = A_{mushy} \vec{v} \quad (4.10)$$

$$A_{mushy} = C_{mushy} \frac{(1 - \gamma)^2}{(\gamma^3 + \varepsilon)} \quad (4.11)$$

In Equation 4.11, C_{mushy} is the mushy zone constant. This term is explained in Section 1.3 at Equation 1.3. This constant is special for every PCM type, and different methods are used to determine it. It represents the amplitude of the damping during phase change [78]. In Fluent, it can be changed from 10^3 to 10^9 . γ is the liquid fraction and it was introduced previously in Equation 4.4. The last term in this equation is ε , which is a small value like 0.0001 to prevent division by zero when PCM is in solid state, i.e. when $\gamma = 0$.

Enthalpy term also varies with the liquid fraction according to Equation 4.7.

4.2 Physical Model

4.2.1 Geometry

The geometry is obtained from the solid model of manufactured heatsinks which is mentioned in Chapter 3. The view of the geometry is shown in Figure 4.1. To simplify the model, seal and screws are not shown. The heat flux is applied at the bottom of the heatsink. For the A58H PCM, coefficient of volume expansion is neglected and therefore, heatsink is filled completely by A58H.

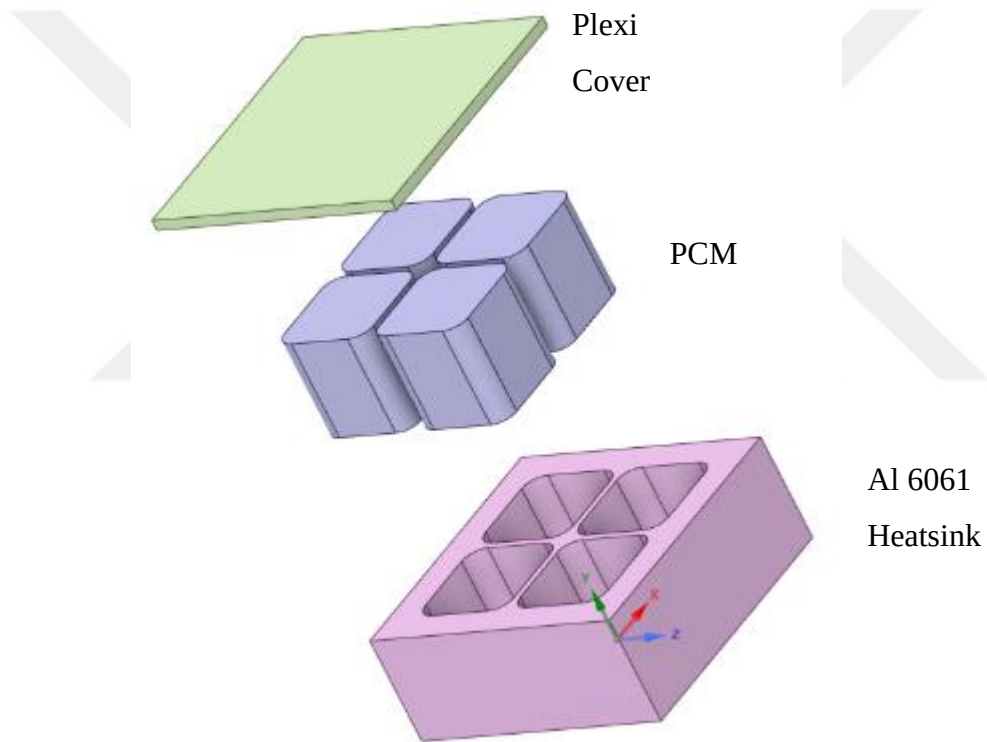


Figure 4.1. Analysis model of PCM Heatsink with 4 chambers.

4.2.2 Numerical Setup and Materials

Ansys Fluent 22.1 is used for numerical simulation by using Finite Volume Method. In numerical analysis, the effect of three parameters is investigated, which are:

- i. Number of Chambers
- ii. Inclination Angle
- iii. Different PCMs

Experimental studies are also conducted for these parameters. For all cases, eight different types of PCM are used and modelled.

4.2.3 Assumptions

The following assumptions are made in solving the governing equations for modelling the phase change phenomenon of PCM.

- i. Laminar flow
- ii. Constant and uniform heat flux
- iii. Incompressible fluid
- iv. Variable thermo-physical properties
- v. Negligible radiation and convection heat losses from the PCMs to the surroundings.
- vi. For each PCM, average density is assumed.

After analyses, the velocity of liquid PCM do not exceed 0.01 m/s for each case, by using Reynolds number equation, the Reynolds Numbers of PCMs are calculated. In Equation 4.12, the Reynolds Number equation is shown.

$$Re = \frac{\rho \vec{v} L}{\mu} \quad (4.12)$$

Applying Equation 4.12 for A58H PCM:

$$Re_{A58H} = \frac{820 \times 0.01 \times 9.5 \times 10^{-3}}{0.007} = 11.13 \quad (4.13)$$

Hence, the flow inside the chamber is assumed as laminar.

4.2.4 Boundary Conditions

The power is applied to the heatsink from the bottom side uniformly and constantly using a flex heater, which is in direct contact with the heatsink. The heat flux is calculated as follows:

$$\text{Current} \times \text{Voltage} = \text{Power} \quad (4.14)$$

$$0.35 \text{ Amper} \times 60 \text{ Volt} = 21 \text{ W} \quad (4.15)$$

$$\text{Heat Flux} = \frac{\text{Power}}{\text{Area}} = \frac{21 \text{ W}}{0.005625 \text{ m}^2} = 3733 \text{ W/m}^2 \quad (4.16)$$

For the top wall and side walls, the boundary condition is defined as adiabatic to provide aerogel effects. This condition is shown in Figure 4.2.

Initial condition of the system is 25°C for all zones in the analysis.

Gravity is also considered as shown in Figure 4.2. For the inclination cases, gravitational acceleration is kept constant.

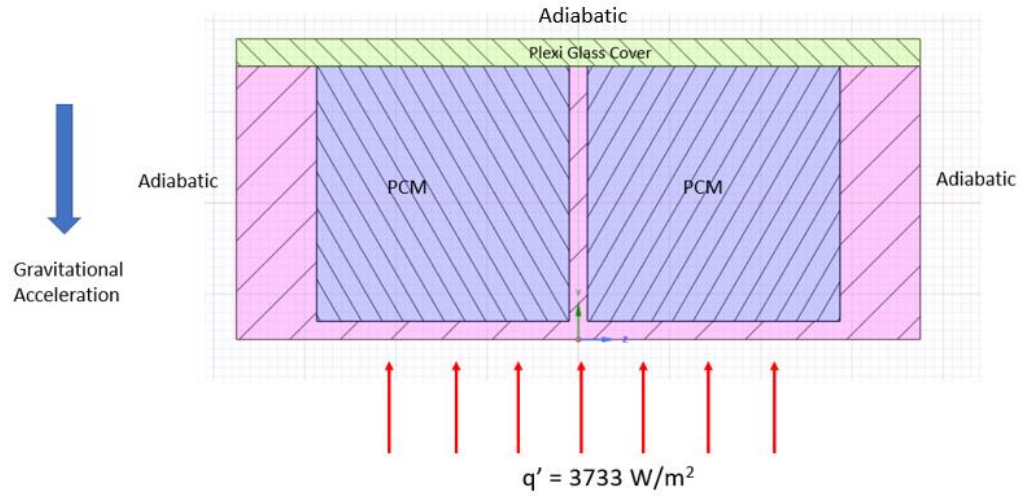


Figure 4.2. Boundary Conditions of analysis model.

4.2.5 CFD Analysis Setup

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 [79]. 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 [79]. For the momentum and energy equations, second order upwind scheme is used.

Time step is chosen as 0.5 seconds with 20 iterations for each time step and for each case, 3000 seconds (50 minutes) scenario is modelled according to the experimental results. The liquid fraction of PCMs and base temperature value are plotted during the transient analysis. In addition, temperature values and liquid fraction contours are recorded to compare with experimental results.

4.3 Mesh & Time Independence Studies

4.3.1 Mesh Settings

Meshing is applied on PCM Heatsink model using Fluent Meshing and “Watertight Meshing” option. Polyhedral mesh is applied to this model. The reason for choosing Polyhedral mesh is that although there are lower number of mesh cells, it gives more accurate results than other methods by contacting more side surfaces with neighbour cells [79]. The mesh structure is demonstrated in Figure 4.3 and Figure 4.4. Appropriate cell number is obtained after conducting a mesh independency study, which will be introduced in Section 4.3.2. Table 4.1 shows the selected cell number and qualities of mesh.

Table 4.1. The mesh statistics.

Volume Cell Count	Maximum Skewness	Minimum Orthogonal Quality
298,612	0.65	0.2

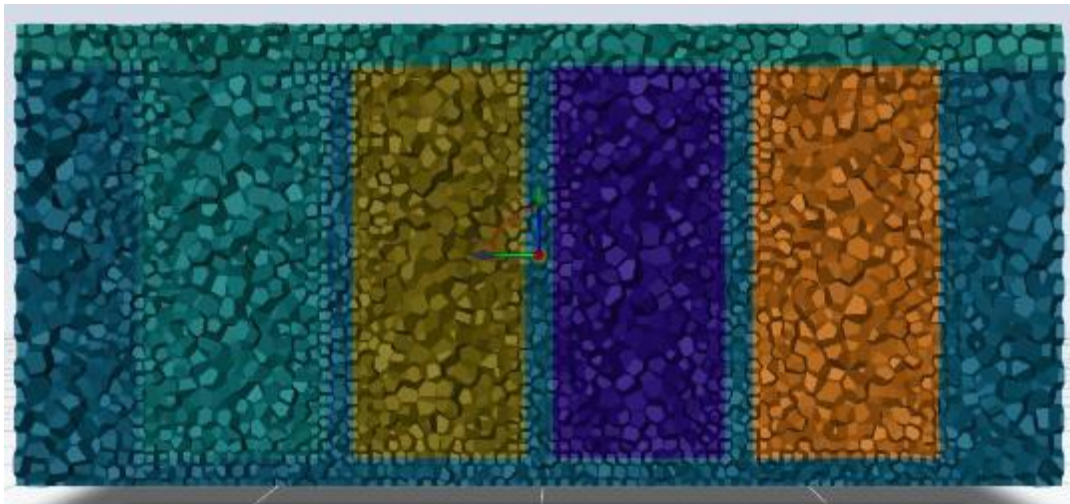


Figure 4.3. Mesh structure of 16 chamber PCM Heatsink.

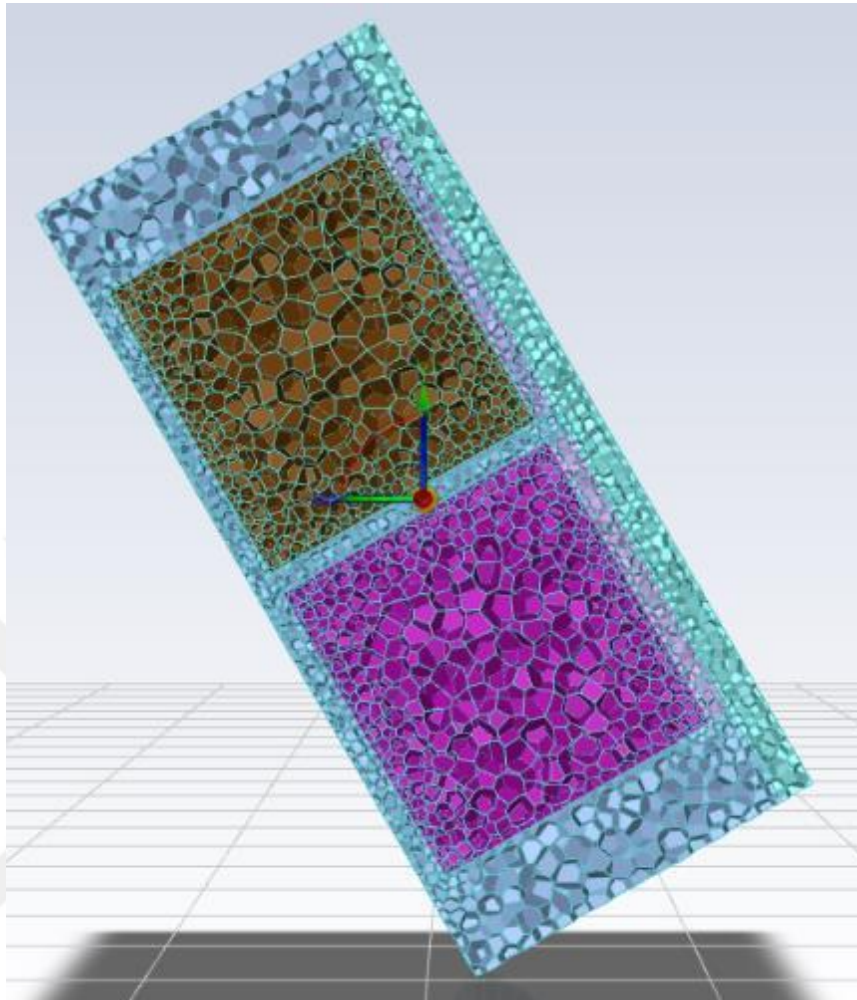


Figure 4.4. Mesh structure of 4 chamber PCM Heatsink at 60°.

4.3.2 Mesh&Time Independence

The mesh independence study aims to obtain the solution of the analysis by using finer mesh structures until the average temperature results at the heatsink base show difference lower than 2% and become independent from the mesh size. To obtain this independency, three different mesh sizes are tried. After completing the mesh process, for all three different meshes, the same analysis case is solved using the same analysis settings. Then, the results are plotted, and the independent cell number is determined by comparing them. Polyhedral mesh is applied to this model.

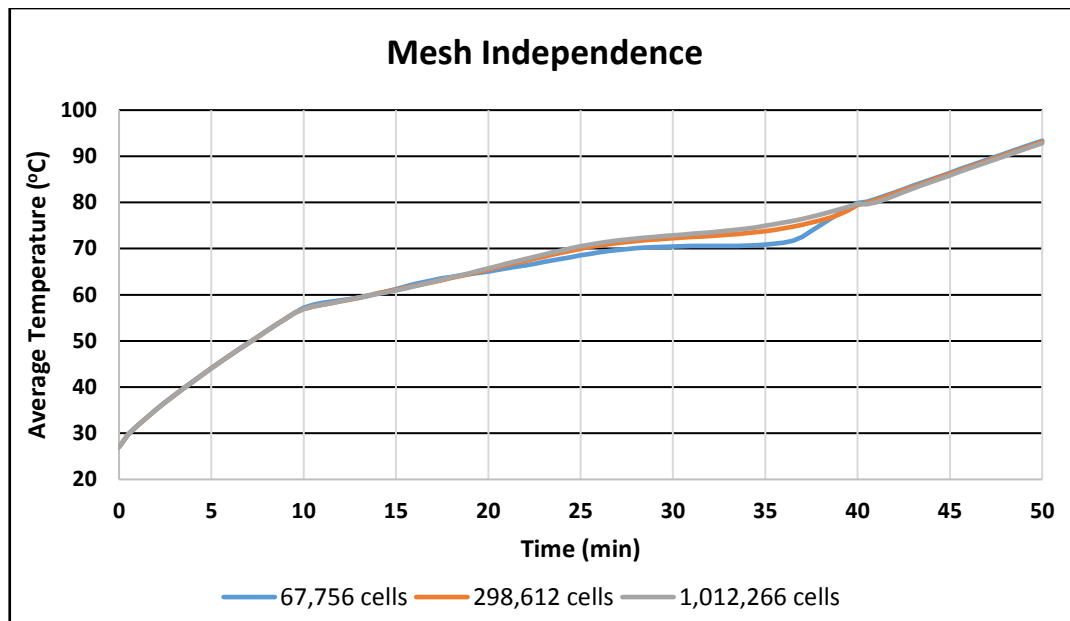


Figure 4.5. Results of mesh independence study.

The results are shown in Figure 4.5. The result of 298,612 cell number is very close to the result of fine mesh having 1,012,266 cells, therefore, for the CFD analysis to be conducted, the mesh size of 298,612 cells is selected.

For the time independency analysis, the independent mesh size of 298,612 is applied. Three different time step is studied; 0.1 s, 0.5 s, and 0.8 s. The same analysis case is solved using the three different time steps and the results are shown in Figure 4.6. As seen from the figure, 0.5 second can be chosen as time step.

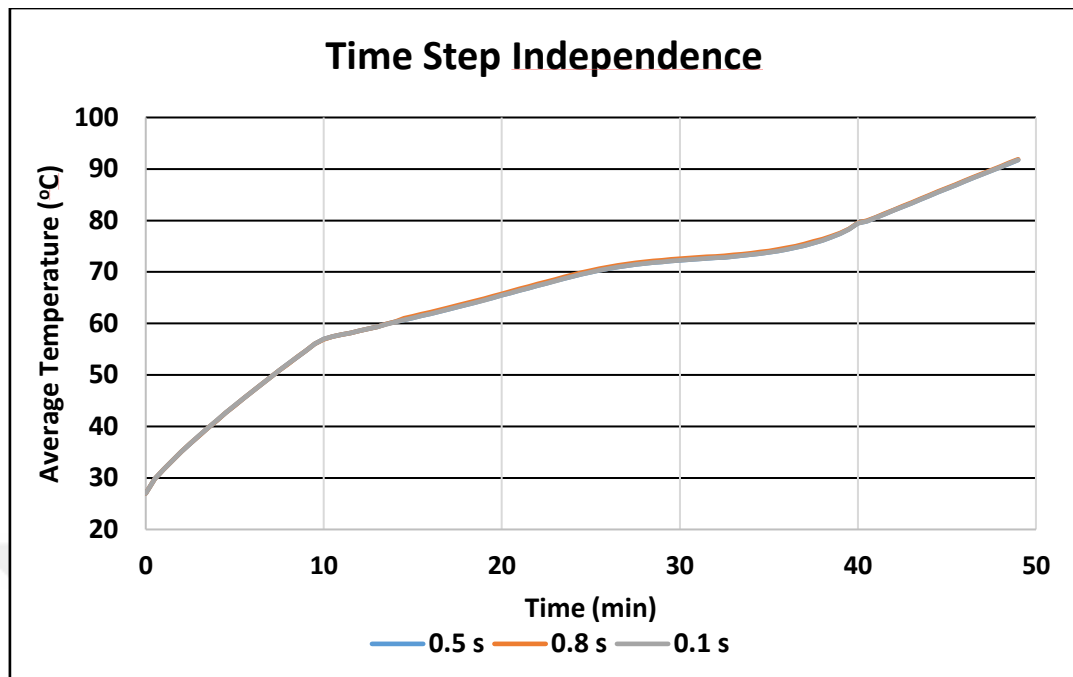


Figure 4.6. Results of time independence study.

4.3.3 Determination of Mushy Zone Constant for A58H PCM

Different values are tried numerically to determine the most appropriate mushy zone constant value, and they are compared with the experimental results of A58H PCM. Three different constants, 10^5 , 10^6 , and 10^7 are analysed in Fluent and results are shown in Figure 4.7. As can be seen from the results, 10^7 mushy zone constant shows coherency with experimental results. Therefore, in all analyses that used A58H, 10^7 mushy zone constant is used.

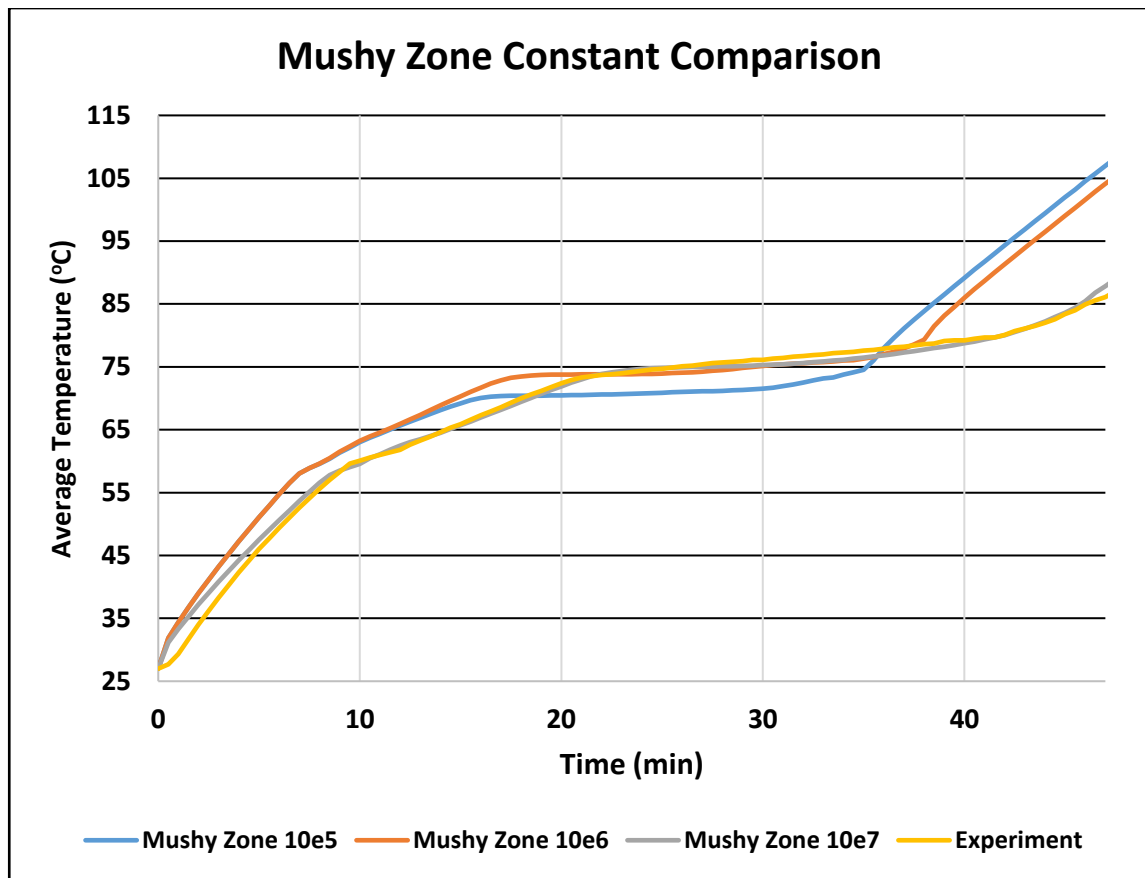


Figure 4.7. Mushy Zone Constant Comparison for A58H

CHAPTER 5

RESULTS & DISCUSSION

5.1 Results of Number of Chamber & Amount of PCM Effect

Due to geometric constraints, the amount of PCM placed inside the heatsink decreases when the number of chambers is increased, for this reason, for systems with limited geometrical properties, the chamber effect is examined and the ideal amount of PCM is determined. In this part, the results of this effect are given by using data of experiments and CFD analyses. To observe the effect of PCM, heatsink without PCM is also experimented and the results are compared.

5.1.1 Experimental Results

The experimental results of number of chamber effect are shown in Figure 5.1. Also, comparison between PCM and non-PCM heatsink result is shown in Figure 5.2. The data shown in the figures are the average temperature data obtained from each chamber for each heatsink. The experimental and analysis results of selected chambers for each heatsink are given in Appendix B.

PCM effect can be seen clearly from Figure 5.2. The comparison of PCM heatsink performed with natural convection cooling heatsink. 16 chambers heatsink is used for this experiment without PCM with no forced convection. After 40 minutes, by using the PCM, the temperature of the heatsink base is decreased by 24.4°C. This result shows that PCM heatsink cooling results in an important improvement in the transient operation of electronic devices over natural convection cooling.

From Figure 5.1, two important results can be obtained. First one is that as the number of chambers increases, the temperature of the heatsink base decreases. This

effect can be seen until the 30th minutes, when the melting of the 16-chamber heatsinks PCM is completed. As the number of chambers increases, the contact surface area between PCM and heatsink increases, localized heat diffusion in PCM increases and provides lower base temperature. After the first 30 minutes, PCM amount effect starts to dominate the base temperature. 16-chamber PCM heatsink has the lowest PCM amount; therefore, PCM melting finished earlier than others. As can be seen from Figure 5.1, the temperature of the heatsink that has melted PCM has a higher temperature than the heatsinks with PCM that continues to melt. Therefore, the first heatsink that reaches the critical temperature is 16-chamber heatsink and the last heatsink that reaches the critical temperature is 1-chamber heatsink.

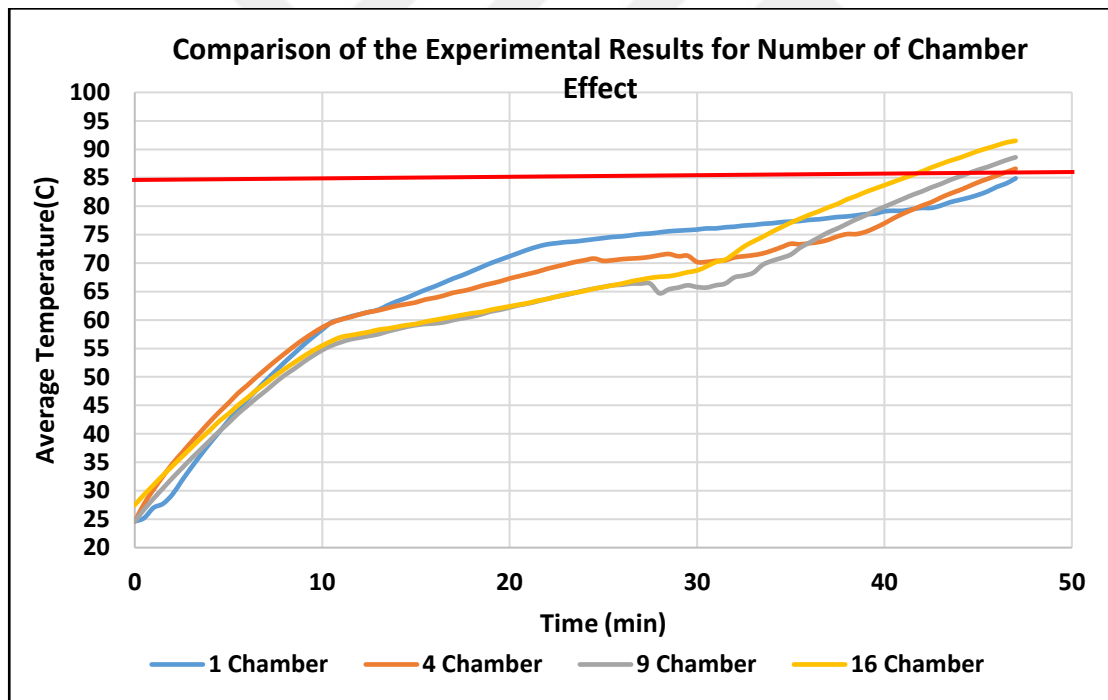


Figure 5.1. Graph of comparison of the Experimental results for number of chamber effect with A58H PCM at 0° inclination angle.

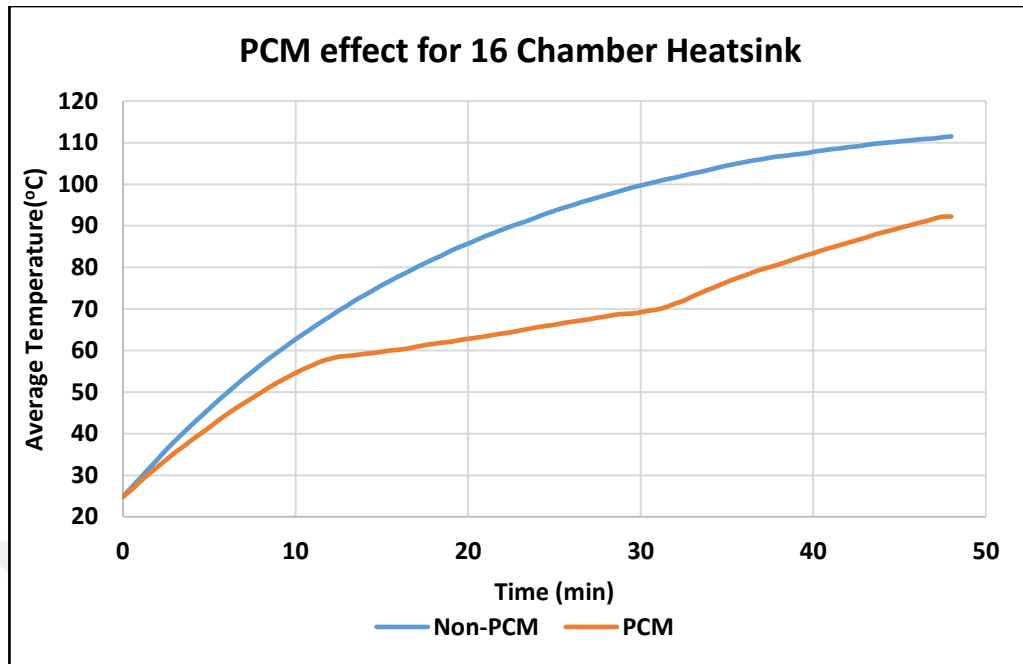


Figure 5.2. Graph of PCM effect for 16 chambers Heatsink with A58H PCM at 0°.

5.1.2 Numerical Results

4 different runs are performed for 4 different heatsinks. In this section, for all cases, experimental and numerical results are compared. In addition, liquid fraction contours are also given. The maximum error values for all cases are given in Table 5.1.

5.1.2.1 1 Chamber PCM Heatsink

The results of the 1-chamber PCM heatsink are shown in Figure 5.3. As can be seen from the graph, the melting starts at the same time in both numerical analysis and experiments and the lines perfectly match. For the A58H PCM material, at the 9th minute, base temperature reached 58 °C and after this point melting starts. As can be seen from the slope of the lines, after 40th minutes, increase of temperature became faster than melting phase because of the completion of melting.

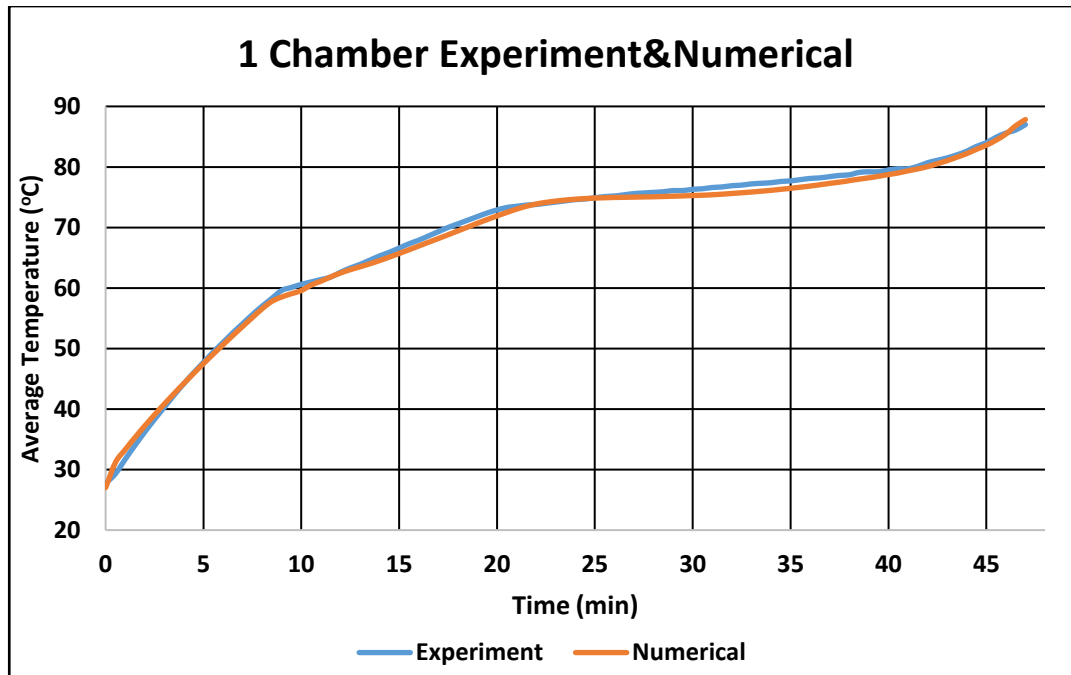


Figure 5.3. Comparison of 1-chamber experimental&numerical results with A58H PCM at 0° inclination.

The maximum error between experimental and numerical analyses results is found to be as 4.5%. The average error value is found to be as 1.1%. Therefore, it can be said that numerical analysis is successful for this case.

The liquid fraction contours obtained from numerical analysis at various times are shown in Figure 5.4. The cut section is taken from the middle of the heatsink. As can be seen from the contours, at the beginning of melting phase, conduction driven melting is observed, thus shape of the melting interface is formed to be in line with edges of the heatsink. After a certain period, natural convection starts to dominate the melting process and reverse U shapes are observed in cut sections. In this thesis, average density assumption is made for numerical analyses to observe natural convection effects on PCM. Therefore, solid PCM does not sink. However, as can be seen from Figure 5.3, the base temperature results are compatible. Therefore, for this study, this difference is neglected.

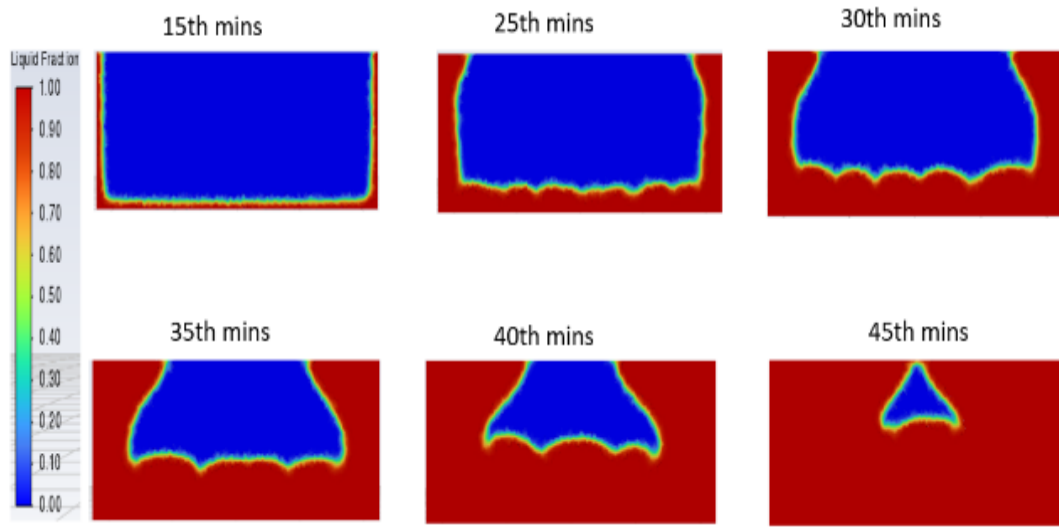


Figure 5.4. Liquid fraction contours from numerical analysis for 1-chamber PCM Heatsink with A58H PCM at 0° inclination angle.

5.1.2.2 4-Chamber PCM Heatsink

4-chamber PCM heatsink results are shown in Figure 5.5. The changes in the slope of the curves that occurred during the beginning of the melting and the completion of the melting show similar trends in analysis and experimental results. The maximum error for this case is found to be as 6%. There is a consistency between the results.

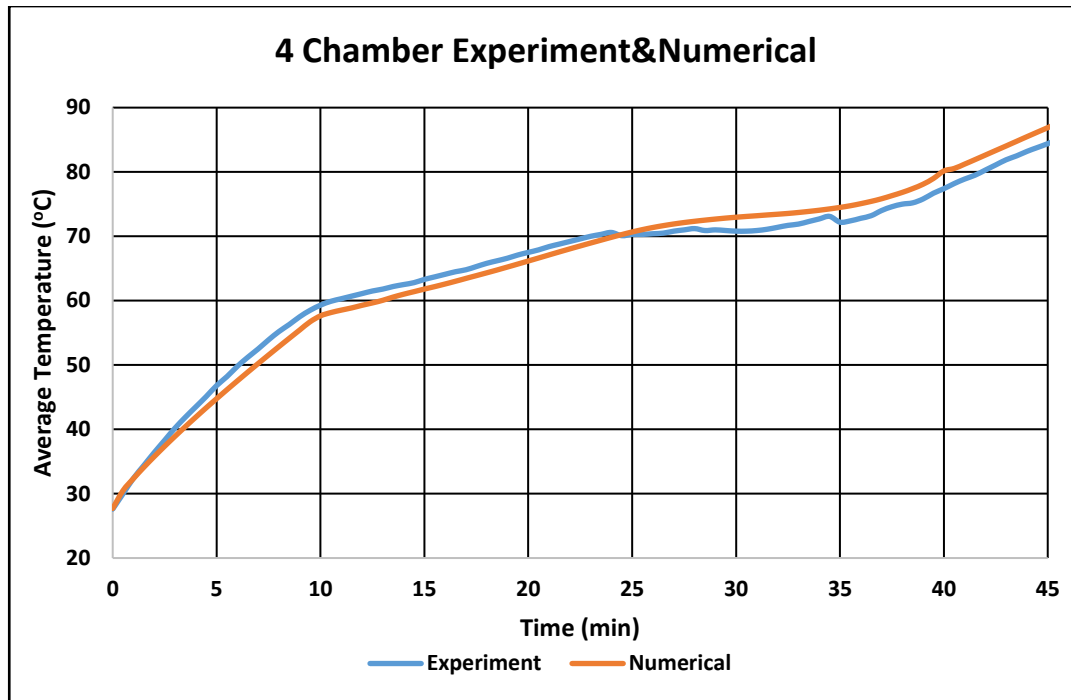


Figure 5.5. Comparison of 4-Chamber experiment&analysis results with A58H PCM at 0° inclination.

The liquid fraction contours of 4-chamber PCM Heatsink are shown in Figure 5.6. Melting is completed earlier compared to 1-chamber heatsink. Same melting phenomena is also observed in this case. At the 25th minute, natural convection effect can be seen in upper parts of the PCM, which resulted in early melting in these regions. At the 40th minute, melting is completed. Again, for the same reason as 1 chamber PCM heatsink, due to average density assumption, the solid PCM does not sink.

In addition, the comparison of numerical and experimental contours is given in Figure 5.7. The contours and images are obtained from the top view. The liquid and solid parts of the PCM in numerical and experimental contours show consistency.

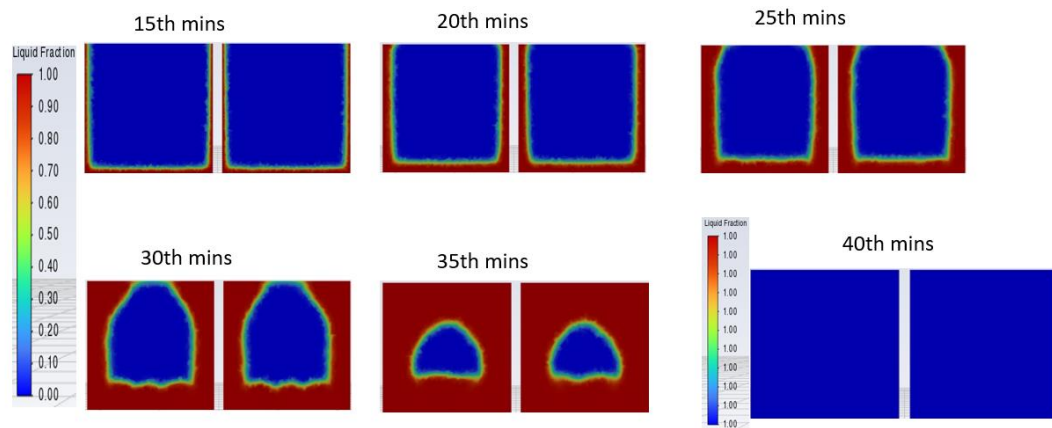


Figure 5.6. Liquid fraction contours from numerical analysis for 4-chamber PCM Heatsink with A58H PCM at 0° inclination.

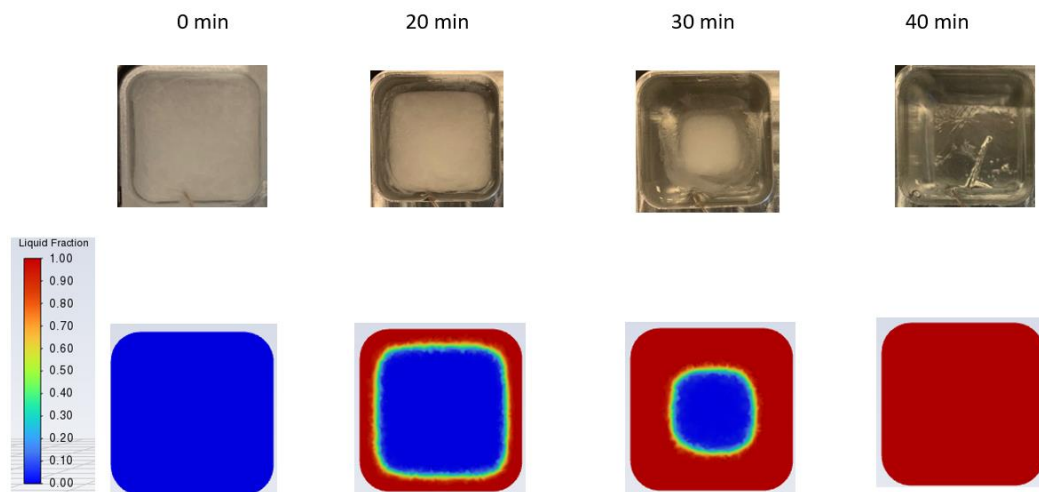


Figure 5.7. Experimental&numerical liquid fraction contours for 4-chamber PCM Heatsink.

5.1.2.3 9-Chamber PCM Heatsink

9-Chamber PCM Heatsink experimental and analysis results are given in Figure 5.8. The A58H PCM melts earlier in 9-chamber heatsink than 1- and 4-chamber

heatsinks. Numerical and experimental results show consistency and until the 30th minute, there is no difference between the results. The maximum error value is found to be as 4%. Therefore, it proves that correct numerical modelling is achieved. In addition, as can be seen from Figure 5.8, single slope is observed during melting. As the chamber sizes get smaller, the volume for the movement of the liquid PCM decreases. For this reason, the obvious effect of natural convection is not reflected in the average base temperature results as in 1- and 4- chambers heatsinks.

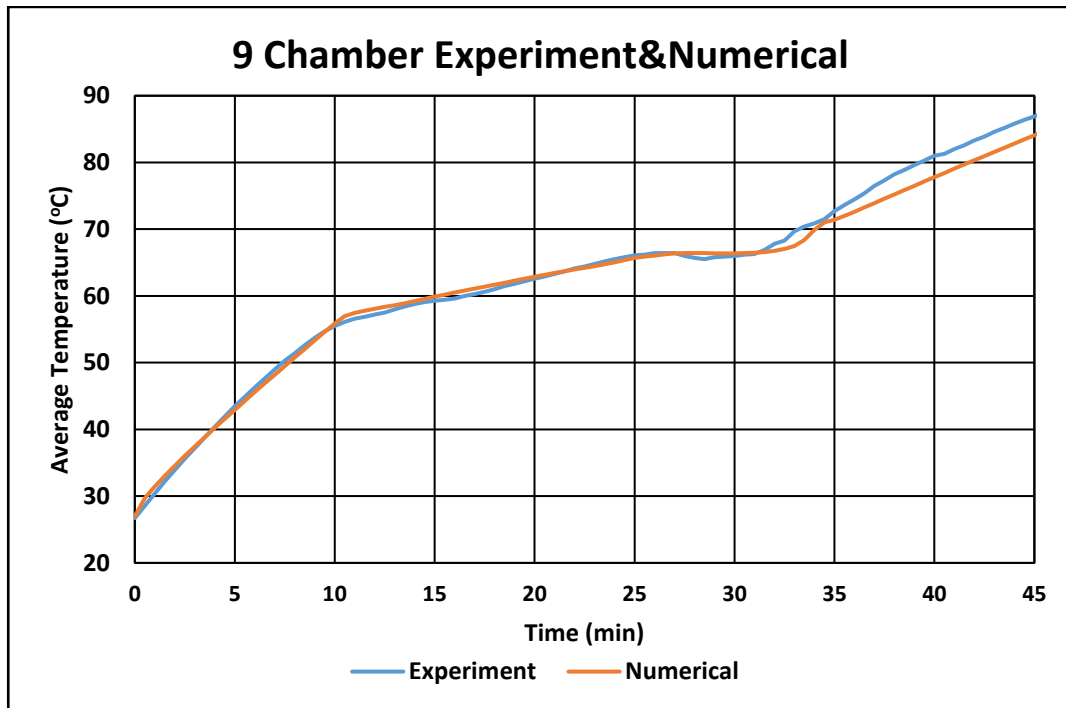


Figure 5.8. Comparison of 9-Chamber experimental&analysis results with A58H PCM at 0° inclination.

The liquid fraction section contours for 9-chamber PCM heatsink are given in Figure 5.9. Since it contains less PCM and has more chambers, the melting phase is shorter than the previous cases. At the 32nd minute, melting is completed and the shapes of the solid PCMs are coherent with natural convection phenomena.

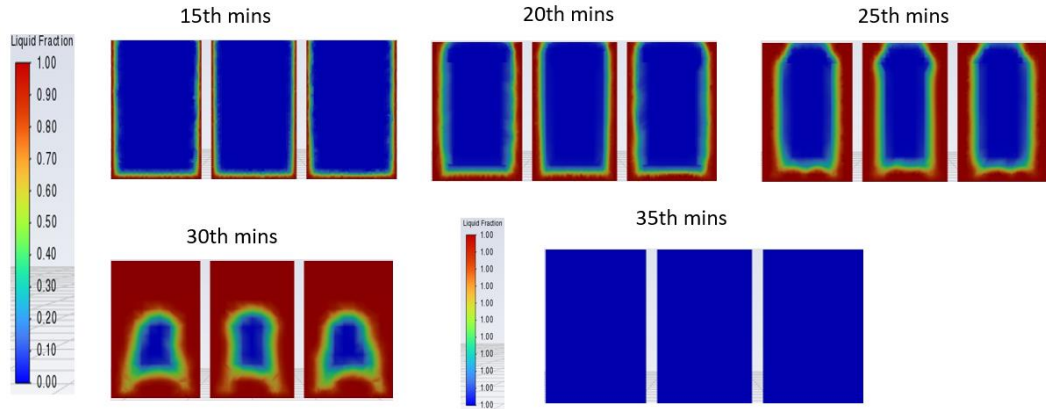


Figure 5.9. Liquid fraction contours from numerical analysis for 9-chamber PCM Heatsink with A58H PCM at 0° inclination.

5.1.2.4 16-Chamber PCM Heatsink

The last case for this part is 16-chamber PCM heatsink. The comparison result between numerical model and experimental study is given in Figure 5.10. There is a decent conformity between experimental and numerical results until the 35th minute. However, after melting is completed, difference occurs in slope of the curves. This could be caused by different liquid behaviour of PCM inside 16 chambers. The maximum error is found to be as 3.8%.

Liquid fraction contours for 16-chamber PCM heatsink are shown in Figure 5.11. The fastest melting occurs in this case and the lowest base temperature until the melting phase is obtained. Same reason with 9- chamber PCM heatsink, as the number of chambers increases, the motion of liquid PCM is confined in a very small volume in each chamber, which adversely affects the natural convection flows, and the shapes occur like conduction driven melting flow even in the last periods of the melting. Also, the slope of the line for average base temperature stay constant due to this reason, can be seen from Figure 5.10.

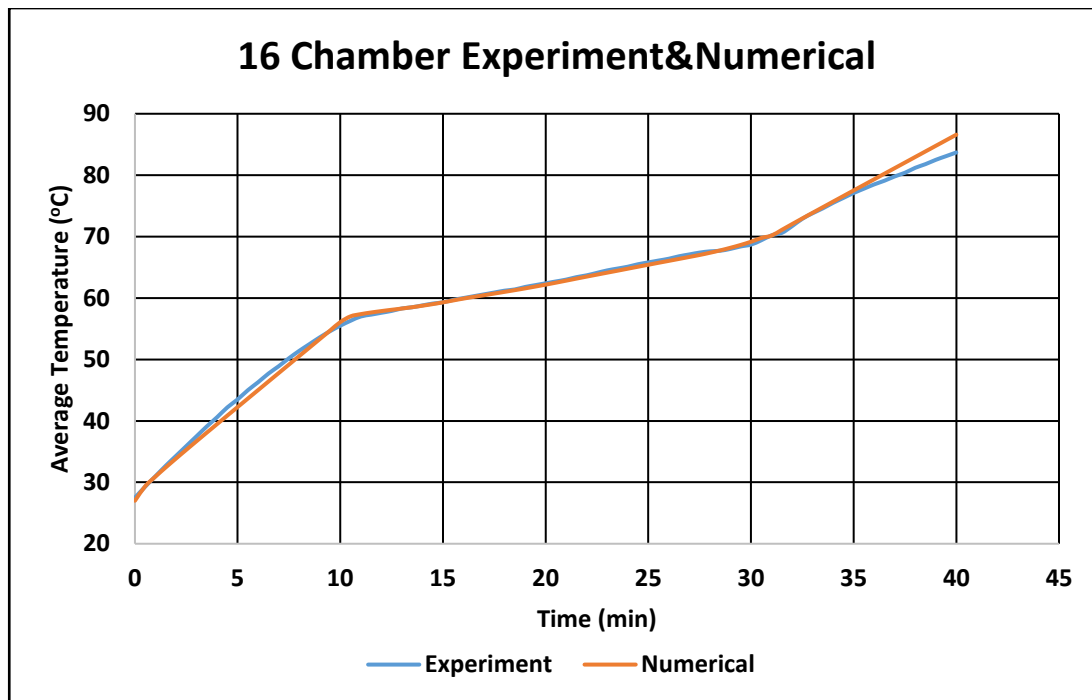


Figure 5.10. Comparison of 16-chamber experimental&analysis results with A58H PCM at 0° inclination.

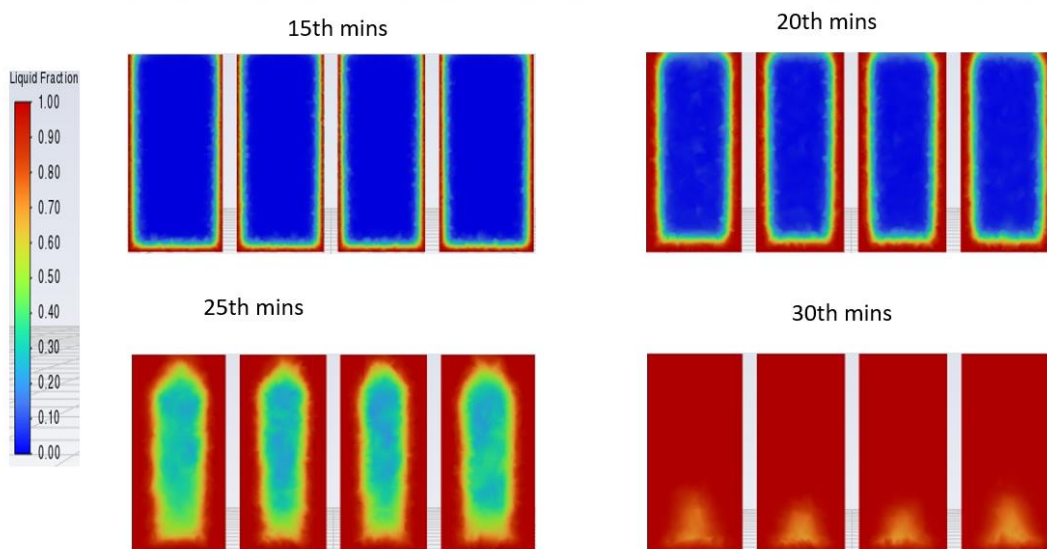


Figure 5.11. Liquid fraction contours from numerical analysis for 16-chamber PCM Heatsink with A58H PCM at 0° inclination.

The maximum errors between experimental and numerical analysis for all heatsinks are given in Table 5.1.

Table 5.1. The maximum errors obtained between analysis and experimental results for different number of chambers.

Case	The Maximum Error (%)
1 Chamber	4.5
4 Chamber	6
9 Chamber	4
16 Chamber	3.8

5.2 Results of Inclination Angle Effect

In this part, the inclination angle effect results are given. Inclination angle effect can be critical especially for rotating systems in air, naval, and land vehicles. Gravity influences the natural convection and therefore melting phenomena. 4- and 16-chamber PCM heatsinks are used to investigate the inclination angle effect on PCM heatsinks. A58-H PCM is used in these experiments and numerical analysis. 4-chamber PCM heatsinks are modelled numerically.

5.2.1 Experimental Results

5.2.1.1 Base Temperature Results

The experimental results for 16-chamber PCM heatsink are shown in Figure 5.12 and 4-chamber PCM heatsink are shown in Figure 5.13. The data shown in these figures are the average temperature data obtained from each chamber for each heatsink.

From the results, it is observed that up to a certain point, there is no difference between temperature values for different inclination angles. However, in the case of 16 chambers, the curves start to diverge after 25 minutes. This is because natural convection starts to dominate the melting process after 25 minutes. The buoyancy forces affect the liquid motion; therefore, the direction of gravitational acceleration begins to intervene on the melting phase. Same effect is observed in 4-chamber PCM heatsinks. As can be seen from Figure 5.13, after 17 minutes, temperature curve slopes become different from each other.

For both cases, as the inclination angle increases, base temperature of the heatsink increases until the completion of melting. Therefore, the highest base temperature values are observed at 90° inclination angle. Temperature values except horizontal case (0° inclination angle) reach the same value for both cases at the end of the phase change process. Thus, the inclination angle influences the thermal performance from 25th minutes of melting phase and until melting completed.

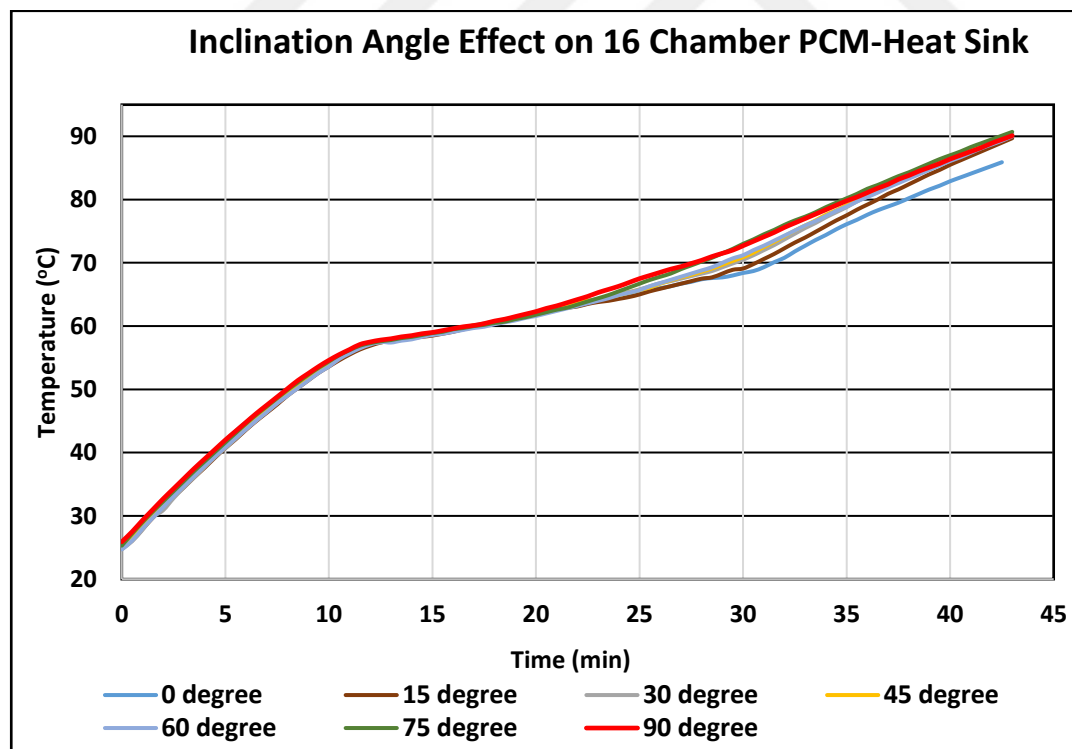


Figure 5.12. Experimental results of inclination angle effect on 16-chamber PCM heatsink with A58H PCM.

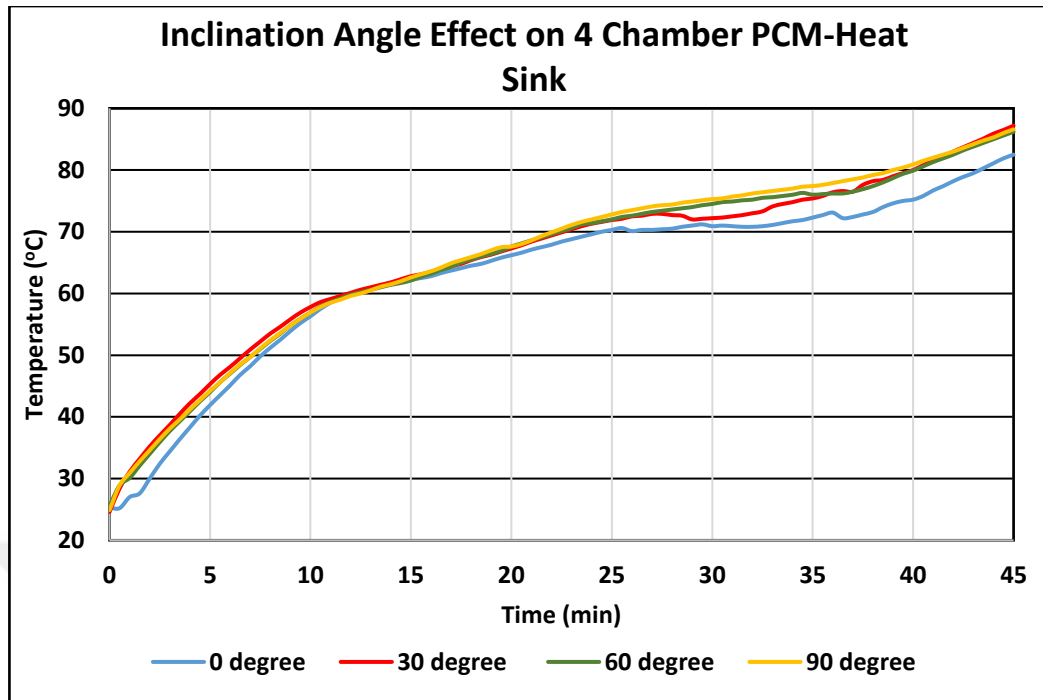


Figure 5.13. Experimental results of inclination angle effect on 4-chamber PCM heatsink with A58H PCM.

5.2.1.2 Liquid Fraction Contour Results

For the 4-chamber PCM heatsink, photographs are taken during the melting of the PCM. In Figure 5.14 to Figure 5.17, the contours at the 30th minute are shown for 0°, 15°, 60° and 90° inclination angles. As can be seen, after 30° inclination angle, the contours of the PCM start to differ from 0°. T-shape occurs due to the inclination effect and upper parts of the PCM melts later.



Figure 5.14. 4 Chamber PCM heatsink contours for 0° inclination angle at the 30th minute with A58H PCM.



Figure 5.15. 4-chamber PCM heatsink contours for 15° inclination angle at the 30th minute with A58H PCM.

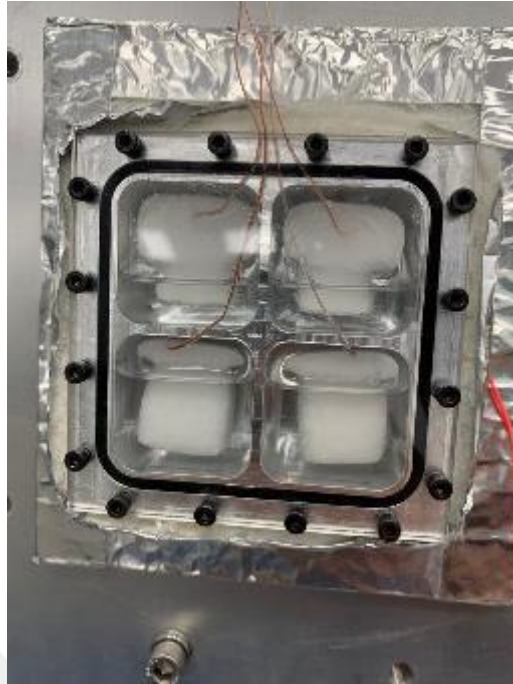


Figure 5.16. 4-chamber PCM heatsink contours for 60° inclination angle at the 30th minute with A58H PCM.

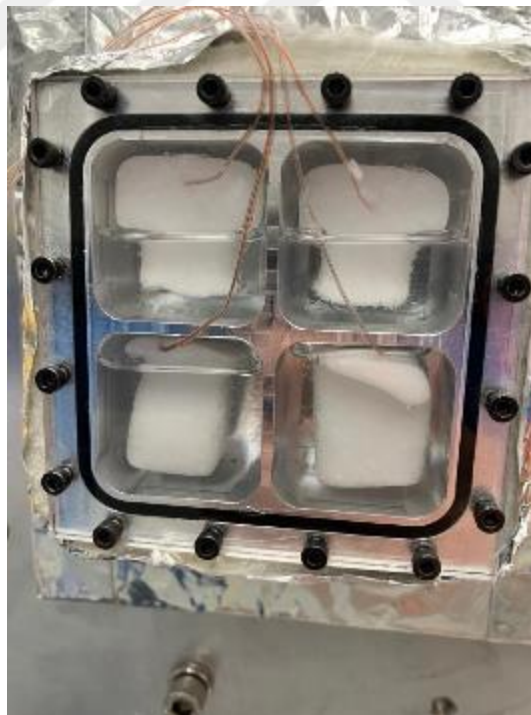
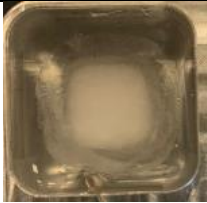


Figure 5.17. 4-chamber PCM heatsink contours for 90° inclination angle at the 30th minute with A58H PCM.

In addition, the PCM contours are shown with respect to time and inclination angle in Table 5.2. The PCM takes a welded-angle shape during melting. While the lower parts of this shape melt faster due to contact with the liquid PCM, the other regions melt late. For this reason, T shape formation is observed.



Table 5.2. 4-chamber PCM heatsink contours with respect to time and inclination angle with A58H PCM.

Inclination Angle / Time	Initial	20 th min	30 th min	40 th min
0°				
15°				
60°				
90°				

5.2.2 Numerical Results

Numerical analyses are performed for 6 different inclination angles (0° , 15° , 30° , 45° , 60° , 75° , and 90°). The temperature plots are obtained from the same points as in experiments. In this section, comparison between experimental and numerical results are given for all cases.

The results for the 15° inclination angle case can be seen in Figure 5.18. The results are consistent until melting is completed, which is at the 35th minute. However, after that, there is a little offset between the results. This is caused by density change modelling in Fluent.

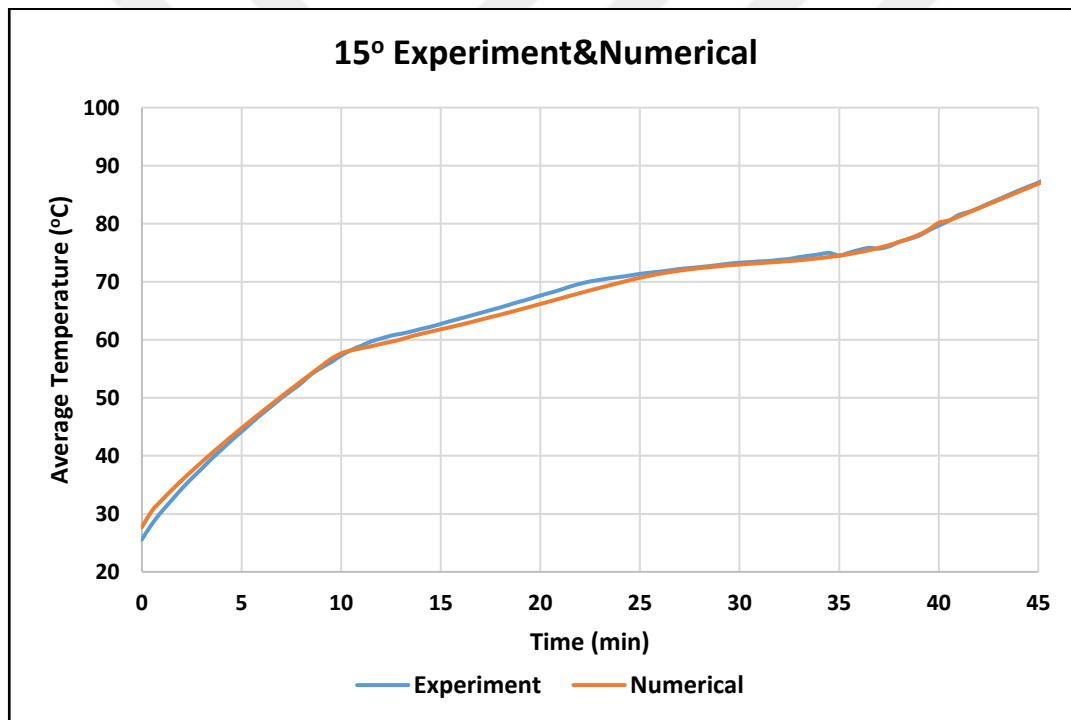


Figure 5.18. Comparison of experimental&analysis results of 15° inclination angle for 4-Chamber heatsink with A58H PCM.

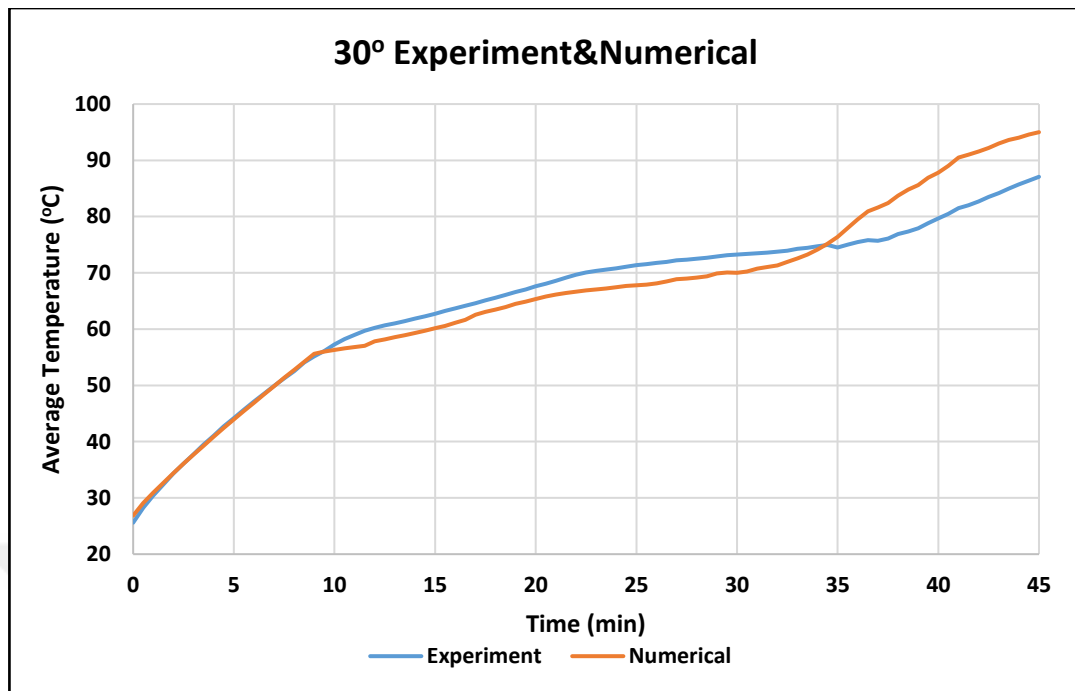


Figure 5.19. Comparison of experimental&analysis results of 30° inclination angle for 4-Chamber heatsink with A58H PCM.

Other case is 45° inclination angle. The results are shown in Figure 5.20. There is a consistency between the results as can be seen. In addition, the results are similar to 15° case. The error is small until the 40th minute when the melting is completed. However, after the completion of melting, there is a slight difference between the analysis and experimental results. The same reason as in the 15° case caused this difference in the results. The maximum error in this case is found to be as 4.8%.

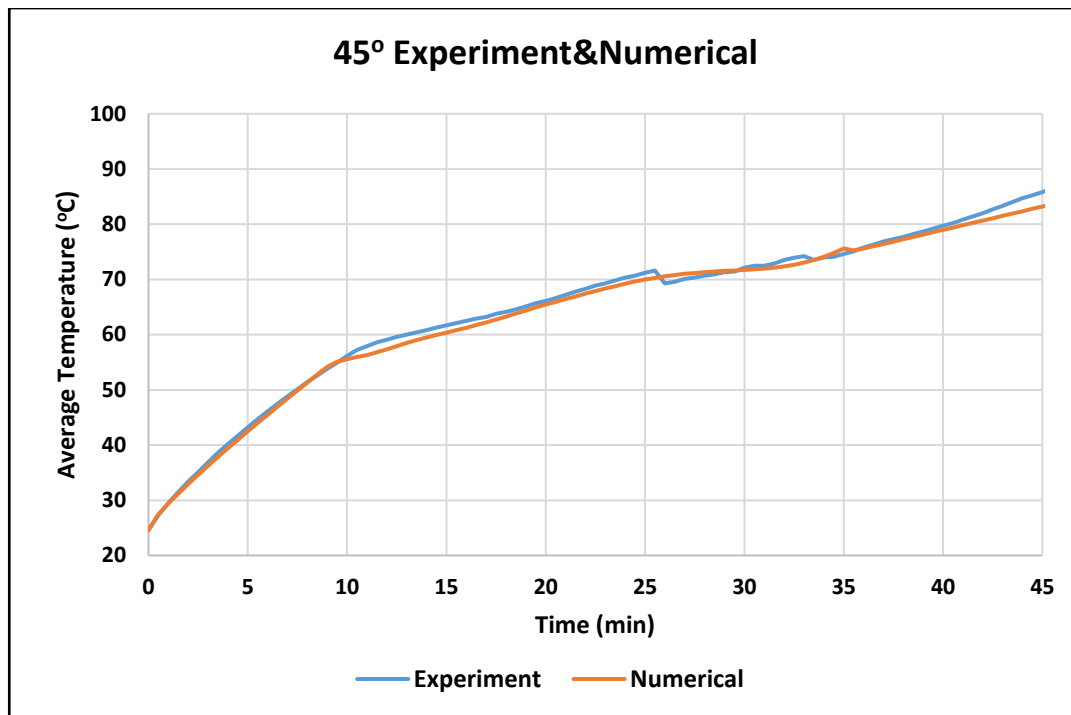


Figure 5.20. Comparison of experimental&analysis results of 45° inclination angle for 4-Chamber heatsink with A58H PCM.

The results from experiments and numerical analysis are compatible and the maximum error is found to be as 4.5% for the 60°, 75°, and 90° inclination angle cases. The lowest errors are obtained in 75° inclination angle case. The results for 60°, 75°, and 90° inclination angle cases are shown in Figure 5.21 to Figure 5.23.

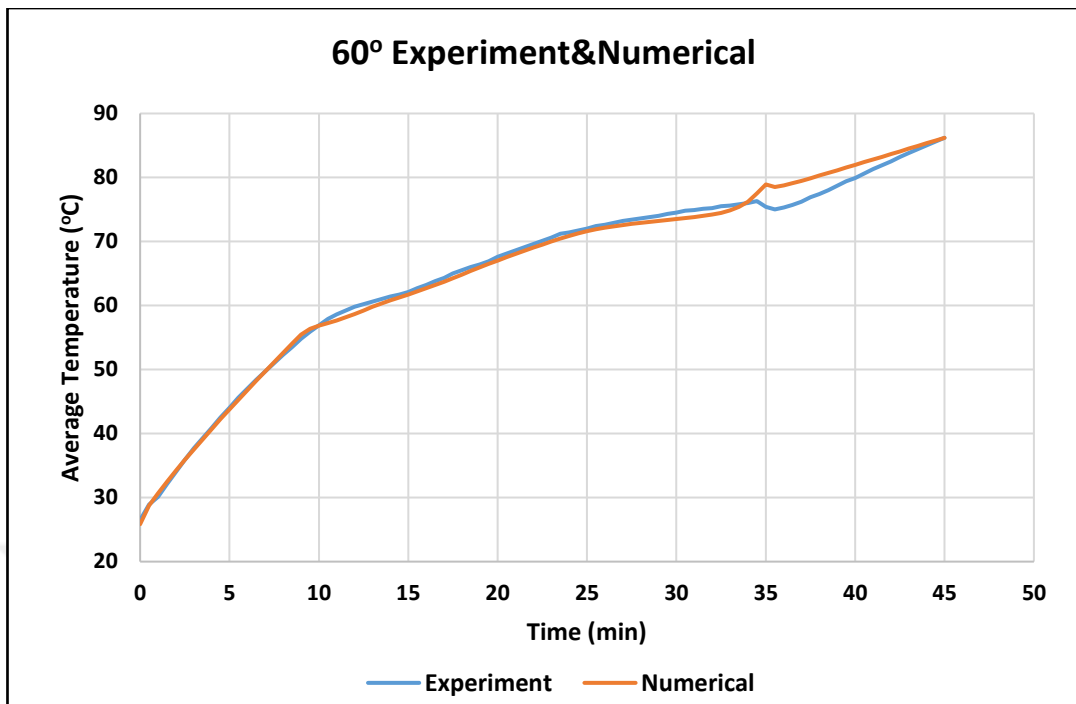


Figure 5.21. Comparison of experimental&analysis results of 60° inclination angle for 4-chamber heatsink with A58H PCM.

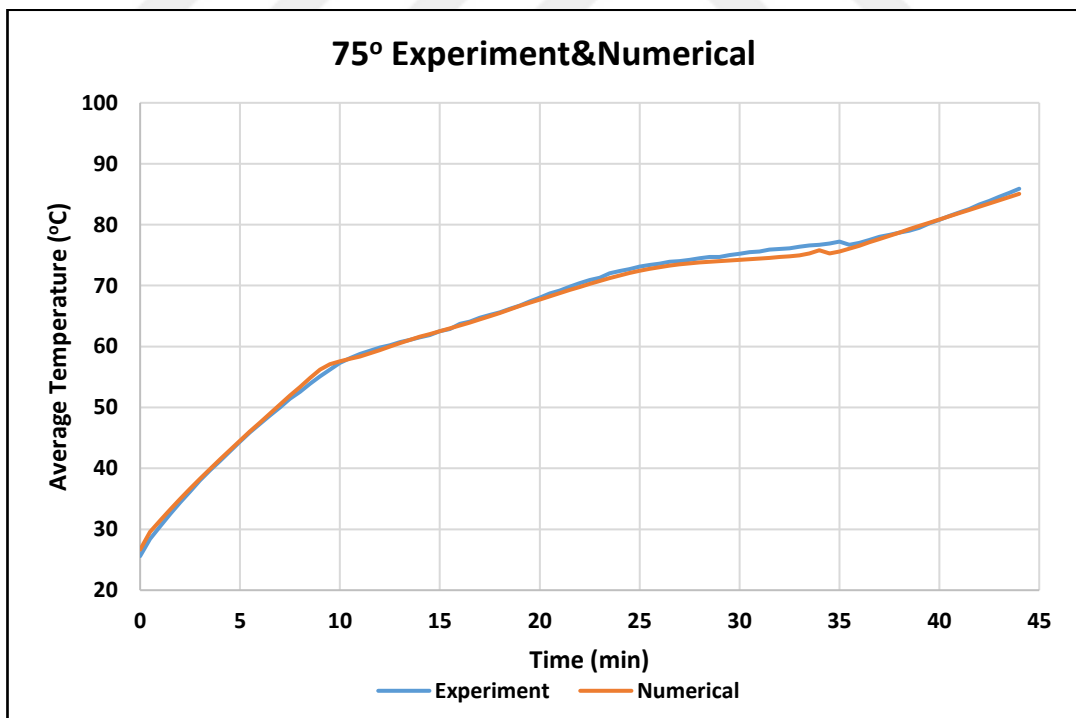


Figure 5.22. Comparison of experimental&analysis results of 75° inclination angle for 4-chamber heatsink with A58H PCM.

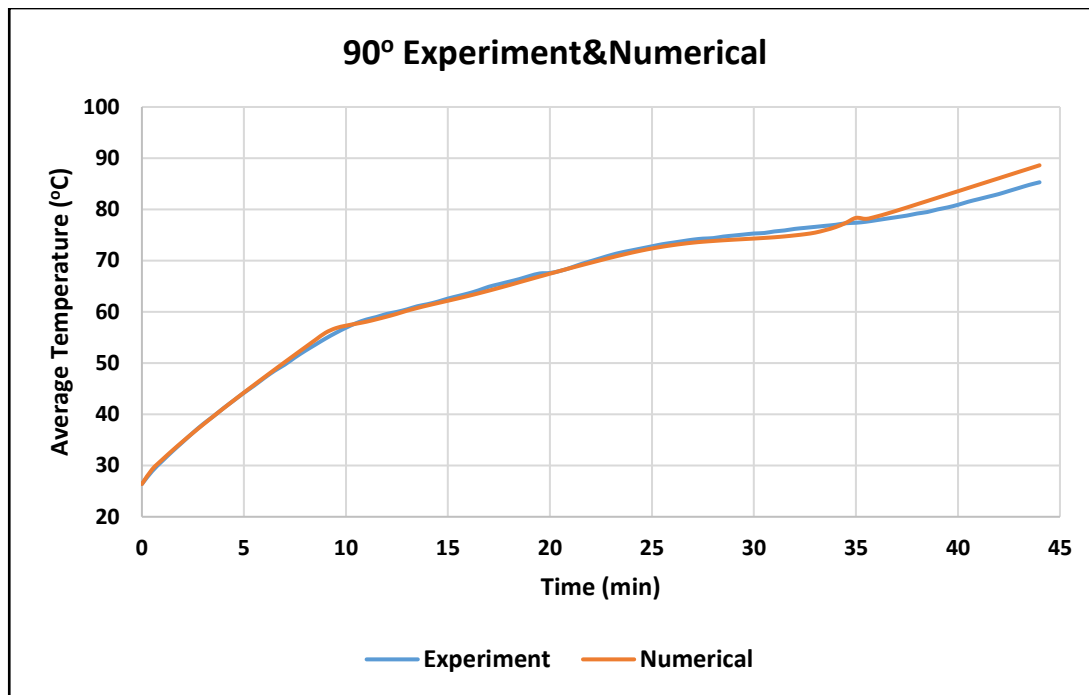


Figure 5.23. Comparison of experimental&analysis results of 90° inclination angle for 4-chamber heatsink with A58H PCM.

Table 5.3. Maximum error values for different inclination angles for 4-chamber PCM heatsink with A58H PCM.

Inclination Angle	Maximum Error (%)
15°	3.6
30°	11
45°	4.8
60°	4.7
75°	4.1
90°	3.6

Finally, the surface plot of the inclination angle vs number of chambers is extracted using the MiniTab Statistical Software and is shown in Figure 5.24. The main comparison factor is considered as the time to reach critical temperature value. This

plot demonstrates the dominant effect between two factors and reflects the change in the factors.

As can be seen from the contour plot, vertical and horizontal lines explain the effect of factors. For the white vertical line placed on the right, as the inclination angle increases, the time to reach 85°C decreases for the same number of chambers. Therefore, it can be said that inclination angle affects the thermal performance of the system negatively for higher number of chambers (>9) respectively. Nonetheless, as the number of chamber decreases, the inclination angle effect also decreases. By examining the vertical yellow line placed on the left, for the lower number of chambers cases (<9), time to reach 85°C does not change. In addition, upper parts of the contour plot are narrow compared to bottom parts. That means, as the inclination angle increases the angle effect starts to dominate compared to the number of chamber effects.

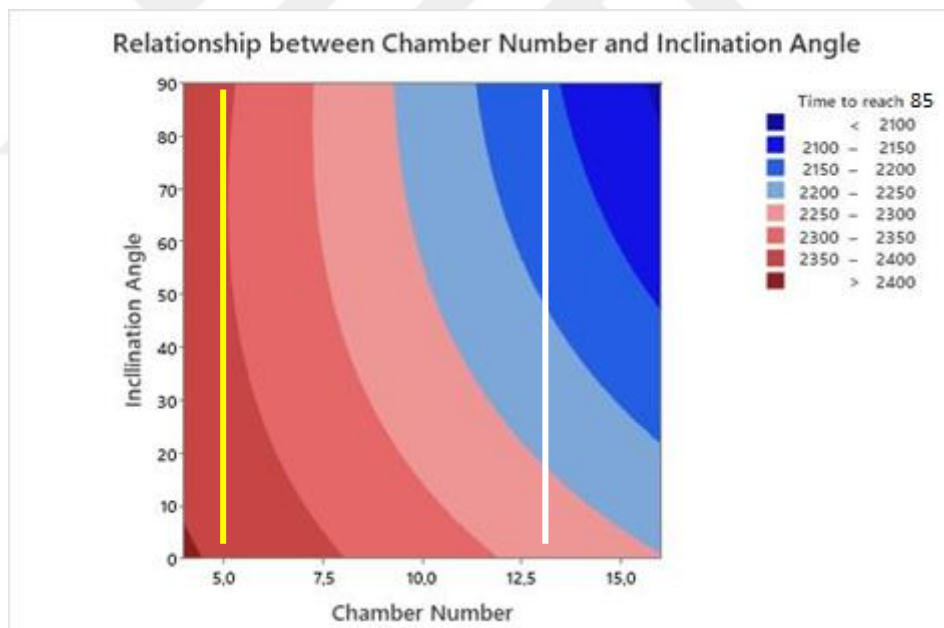


Figure 5.24. Surface Plot for number of chamber and inclination angle effects for 4-chamber PCM heatsink with A58H PCM.

5.3 Results of Different PCM Effect

In this section, the experimental and analysis results of the 4-chamber heatsink at 0° inclination angle with eight different PCMs, and the discussion of the results are given. In addition, investigation of the mushy region with the microscope and the camera to determine the mushy zone constant, is presented in this section. Detailed mushy zone contours and dendrites of solid particles are viewed and examined using the microscope. From this analysis, mushy zone constant of the PCMs is calculated using Equation 3.1. The calculated mushy zone constant is then used in numerical analyses.

The average temperature data, which is the average of measured temperatures with the thermocouples located in each chamber, for heatsinks having different PCM are presented in the below section. The experimental and analysis results of selected chambers for each heatsink are given in Appendix C.

5.3.1 Experimental & Analysis Results

5.3.1.1 RT-55 PCM

The experimental and analysis results are shown in Figure 5.25. RT-55 has the shortest melting time because it has less latent heat capacity than other PCMs. Therefore, it reaches the critical temperature values before 40 minutes. In addition, it has the lowest melting temperature, which affects the thermal performance of RT-55. The maximum analysis error is found to be as 3.2%.

The liquid fraction and temperature contours obtained from the analysis and experiment are shown in Figure 5.26 and Figure 5.27. Liquid fraction contours of analysis show similarity with the experimental results. Additionally, to obtain the movement of the liquid PCM, velocity vectors are drawn using analysis results.

These results are shown in Figure 5.28. From Figure 5.28, flow movements can be observed during the melting process at the bottom part of heatsink.

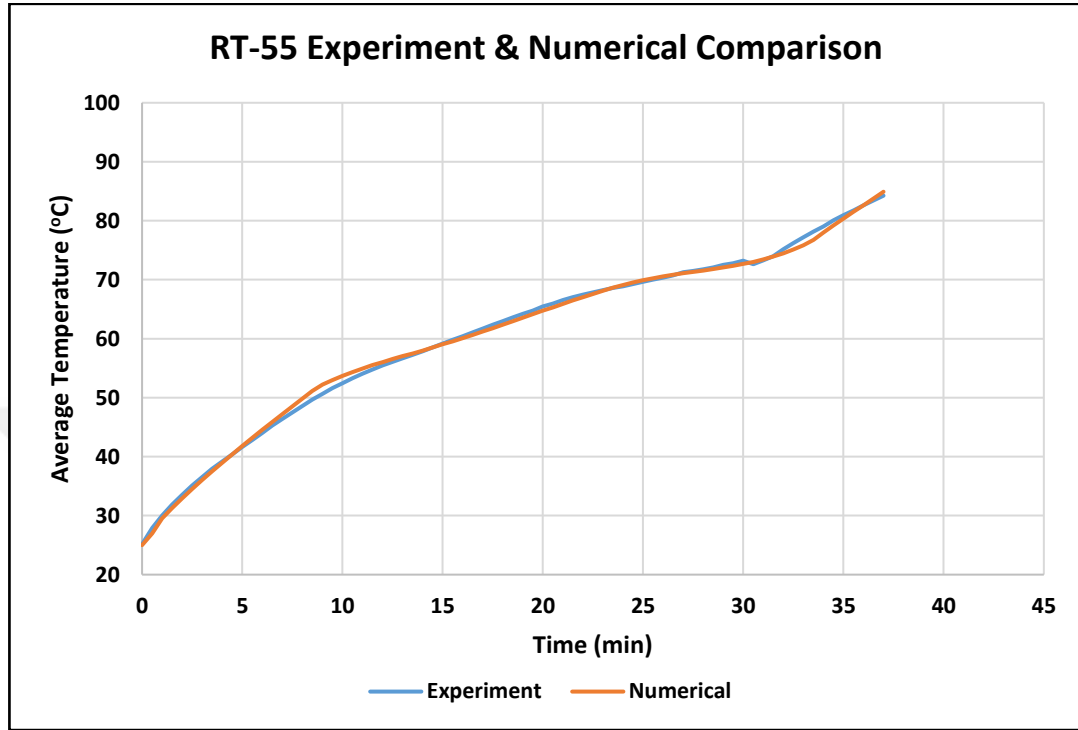


Figure 5.25. Experimental and analysis results of RT-55 PCM for 4-chambers heatsink at 0° inclination angle.

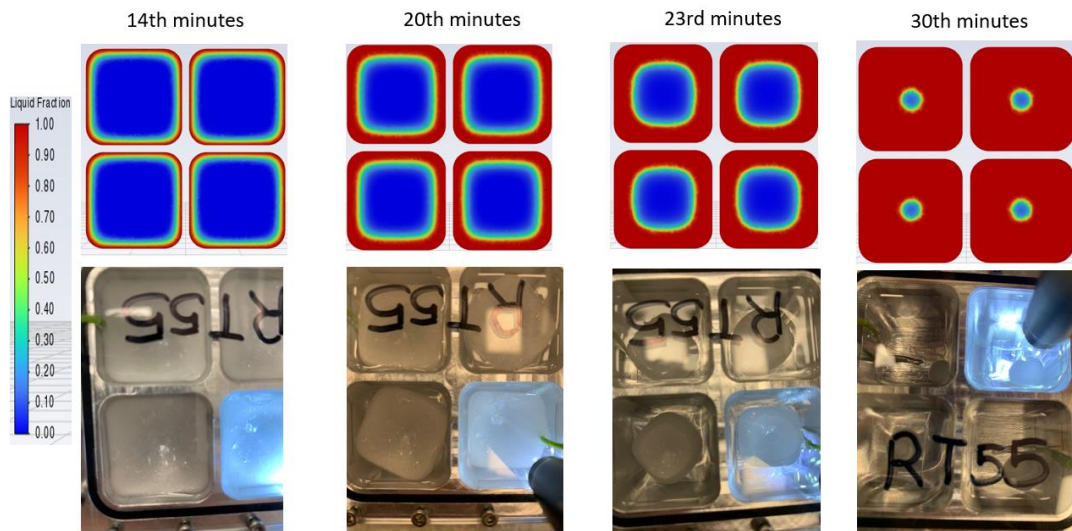


Figure 5.26. Liquid fraction comparison of RT-55 PCM for 4-chambers heatsink at 0° inclination angle.

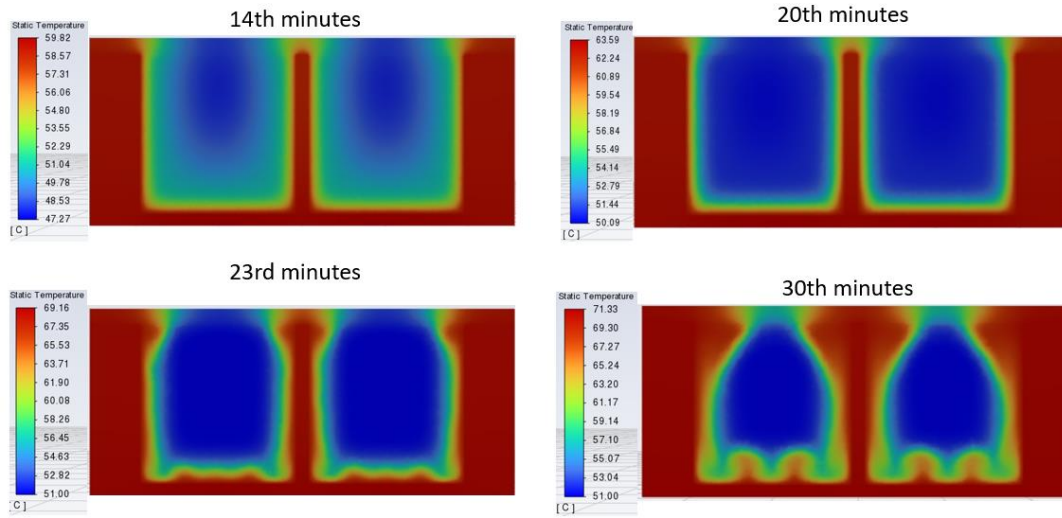


Figure 5.27. Calculated temperature contours obtained from the middle section of 4-chamber RT-55 PCM heatsink at 0° inclination angle.

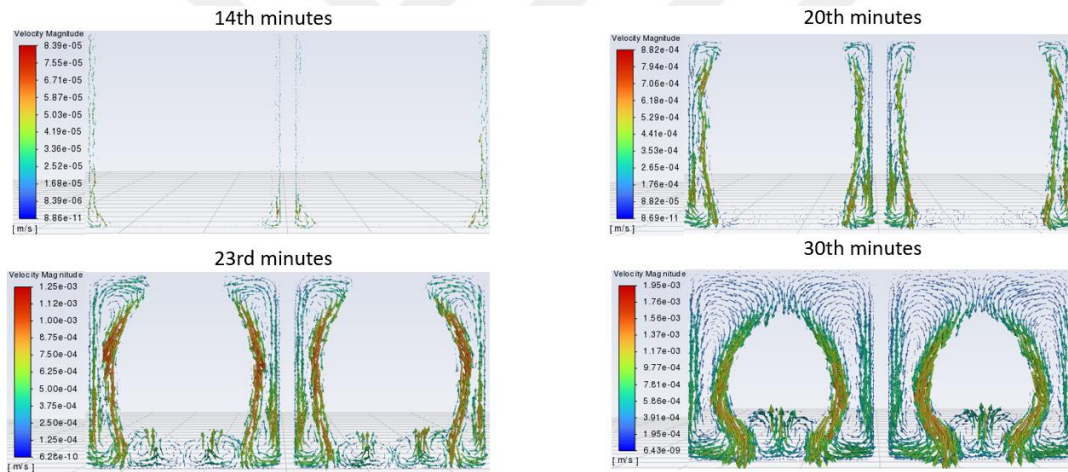


Figure 5.28. Velocity vector contours of RT-55 PCM for 4-chambers heatsink at 0° inclination angle.

5.3.1.2 S-58 PCM

S-58 is an inorganic PCM and therefore behaviour of it differs from organic ones. The experimental and analysis results of base temperature are shown in Figure 5.29. Experimental and analysis results show consistency. The maximum error for S58 is found to be as 6.8%. The liquid fraction and temperature contours of experiment and analysis are shown in Figure 5.30 and Figure 5.31, respectively. The natural

convection effects can be seen as reverse U shapes from the bottom parts of the temperature contours. Figure 5.32 shows the velocity vectors of S58 PCM. At the reverse U shape regions, secondary flows occur. The velocity values are smaller than 0.01 m/s.

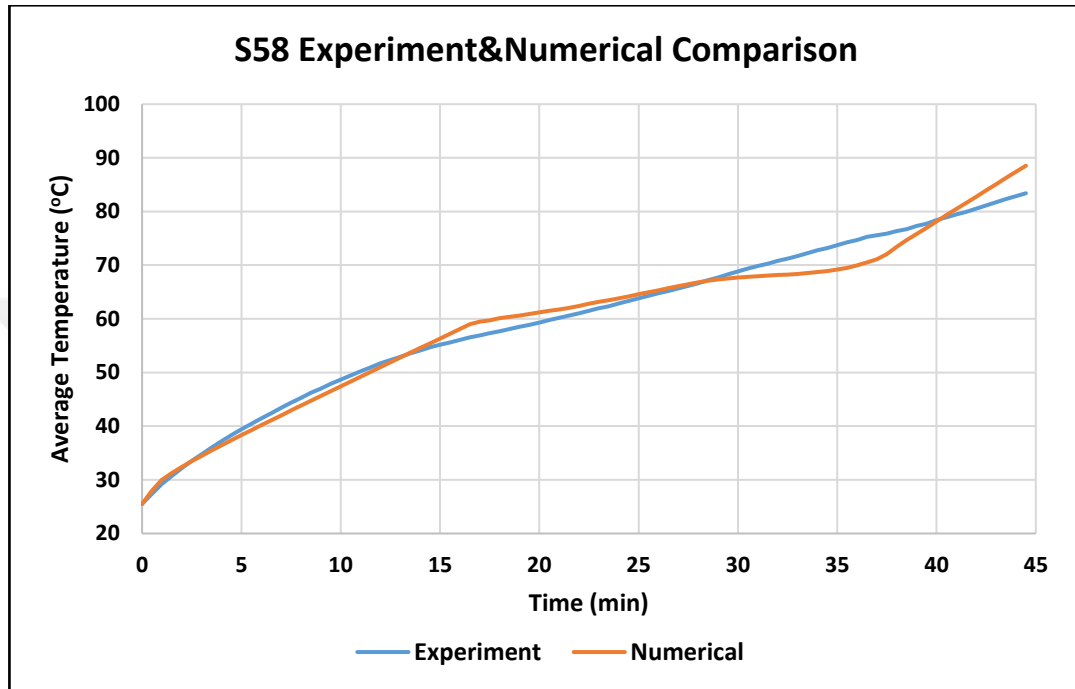


Figure 5.29. Experimental and analysis results of S58 PCM for 4-chambers heatsink at 0° inclination angle.

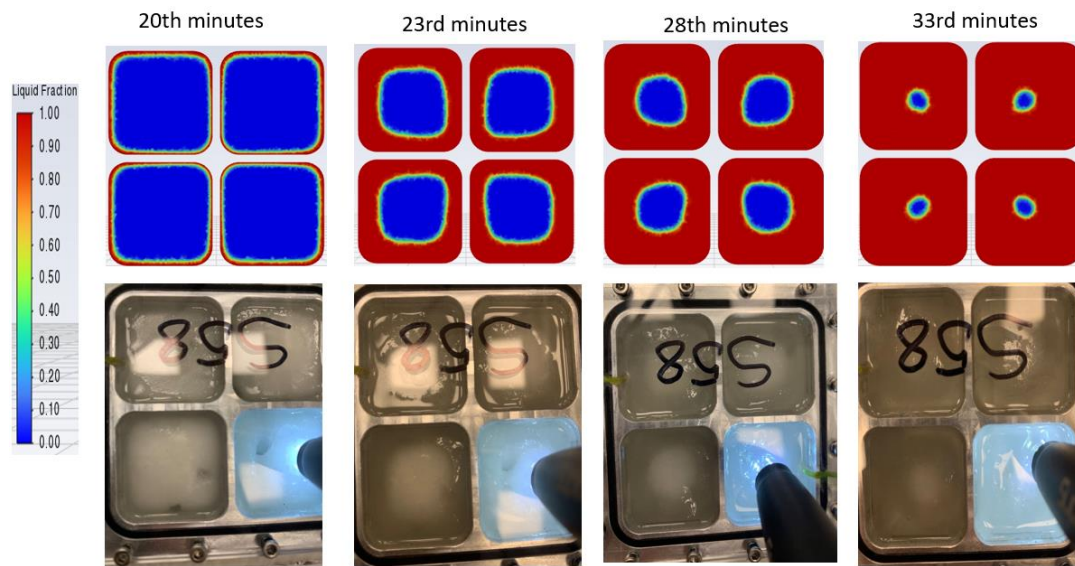


Figure 5.30. Liquid fraction comparison of S58 PCM for 4-chambers heatsink at 0° inclination angle.

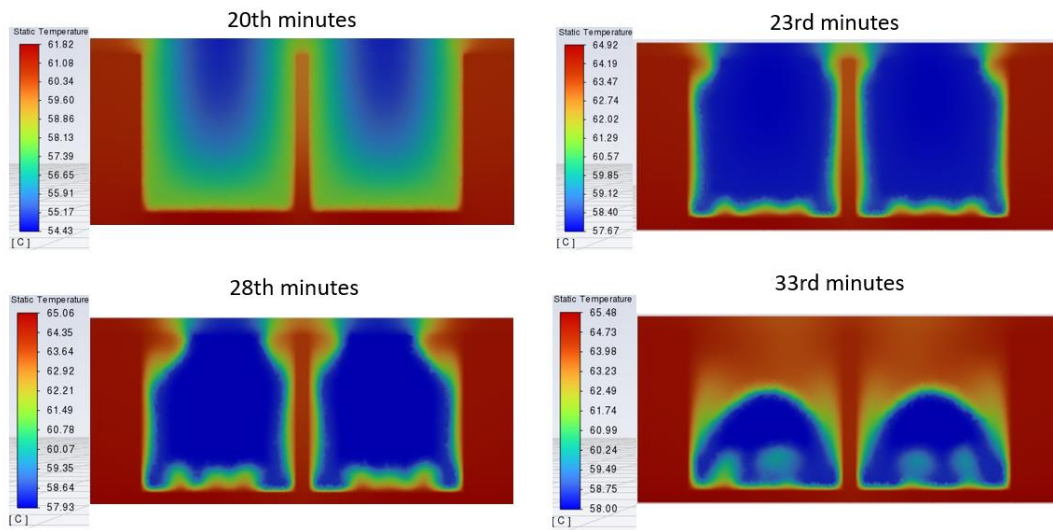


Figure 5.31. Temperature contours obtained from the middle section of 4-chamber S58 PCM heatsink at 0° inclination angle.

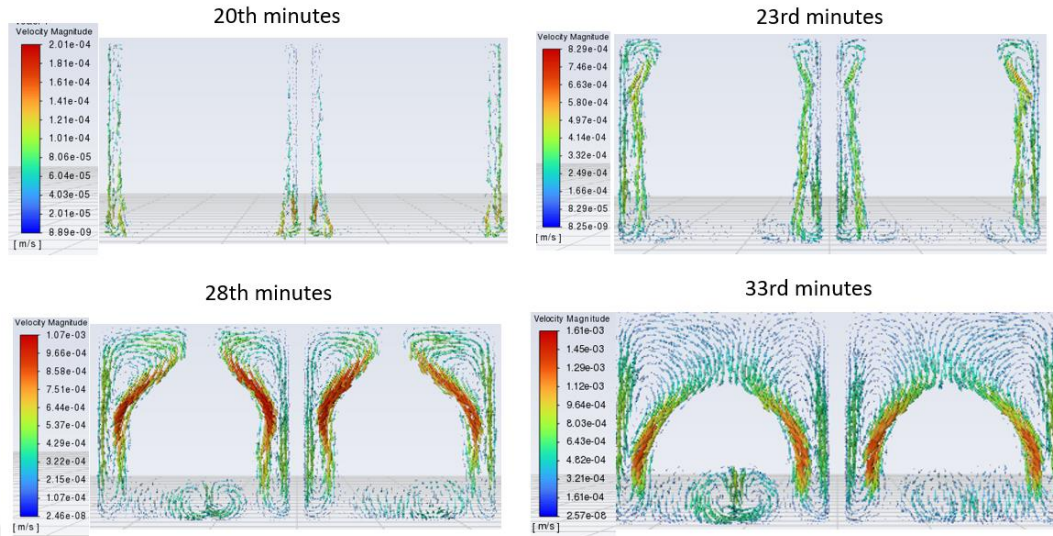


Figure 5.32. Velocity vector contours of S58 PCM for 4 chambers heatsink at 0° inclination angle.

5.3.1.3 RT-62 HC

The experimental and analysis results of base temperature are shown in Figure 5.33. Until 27th minutes, the results are very consistent. However, after that point, slight difference occurs between the results. The effects of natural convection on mushy zone region cause this. Mushy zone constant changes for different periods of melting process and therefore, it affects the modelling. The maximum error of this case is found to be as 7.2%. In the experimental line, distinct slopes and even temperature drops are obtained. This is due to the solid particles detached from PCM in contact with the thermocouple in the chamber and the liquid PCM movements, as can be seen in the velocity contours.

The liquid fraction and temperature contours of experiment and analysis are shown in Figure 5.34 and Figure 5.35. The velocity vectors are shown in Figure 5.36. Varieties of velocity direction and magnitudes of liquid motion cause change in placement and deformation on the shape of PCM. From Figure 5.34, after 30 minutes, shapes of the solid PCMs are deformed due to the liquid PCM motion.

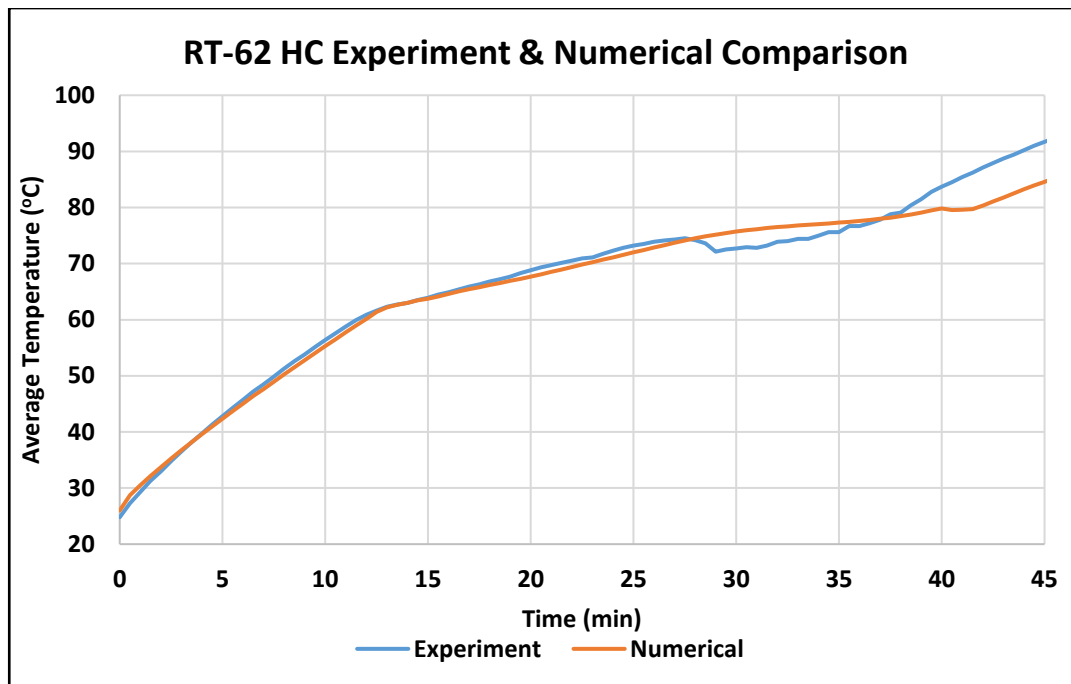


Figure 5.33. Experimental and analysis results of RT-62 HC PCM for 4-chambers heatsink at 0° inclination angle.

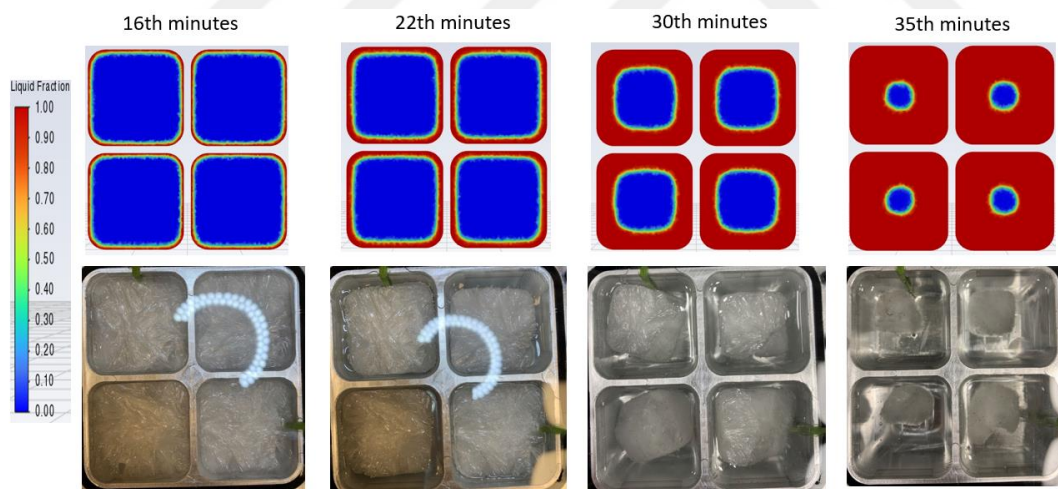


Figure 5.34. Liquid fraction comparison of RT-62 HC PCM for 4-chambers heatsink at 0° inclination angle.

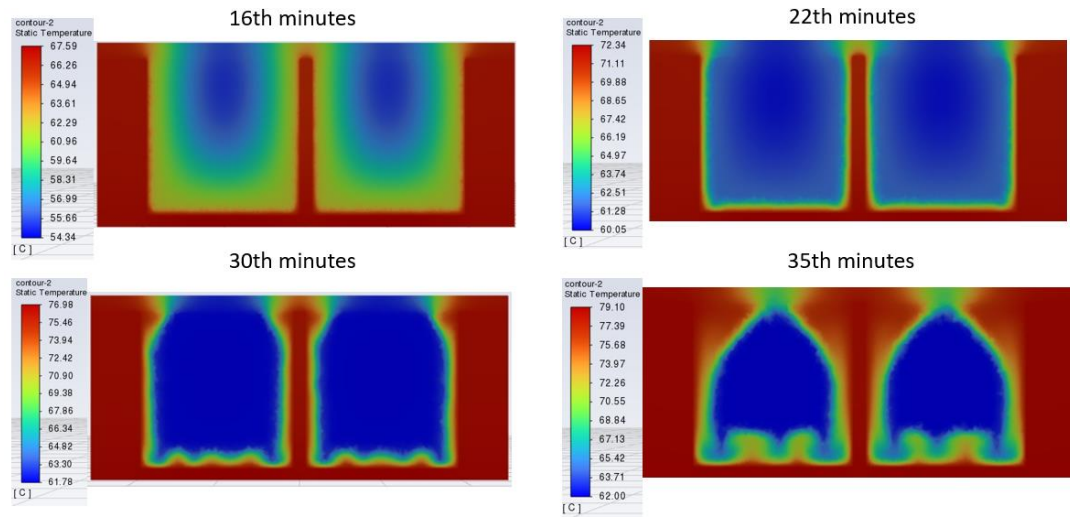


Figure 5.35. Temperature contours obtained from the middle section of 4-chamber RT-62 HC PCM heatsink at 0° inclination angle.

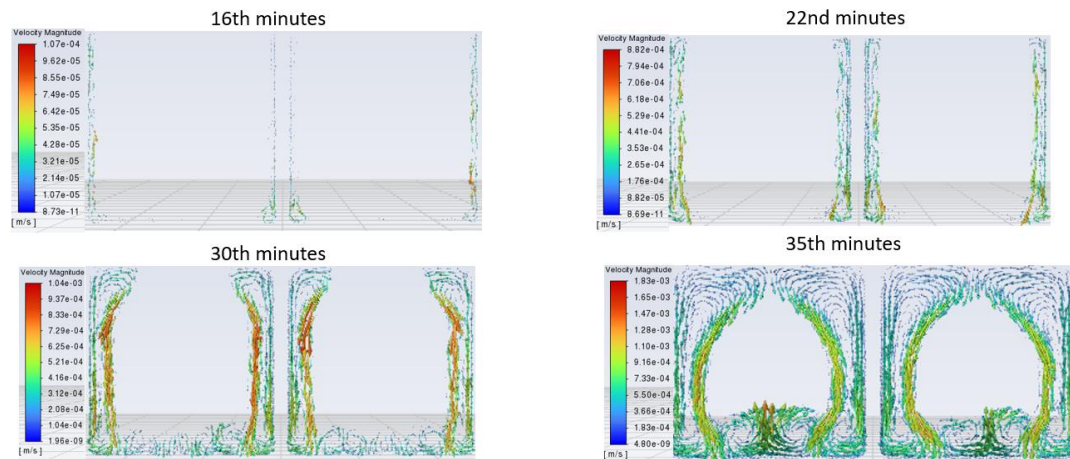


Figure 5.36. Velocity vector contours of RT-62 HC PCM for 4 chambers Heatsink at 0° inclination angle.

5.3.1.4 RT-65

The experimental and analysis results of base temperature are shown in Figure 5.37. The results are similar with S58 PCM case. Difference occurs between experimental and analysis results since conduction effects loses dominance on melting after 20th minutes and natural convection effect (in other words mushy zone constant effect) becomes dominant. The maximum error for this case is found to be as 5.4%.

The liquid fraction and temperature contours of experiment and analysis are shown in Figure 5.38 and Figure 5.39. Due to the motion of the liquid PCM, the solid PCMs change their position in chambers as can be seen in Figure 5.38. The velocity vectors are shown in Figure 5.40.

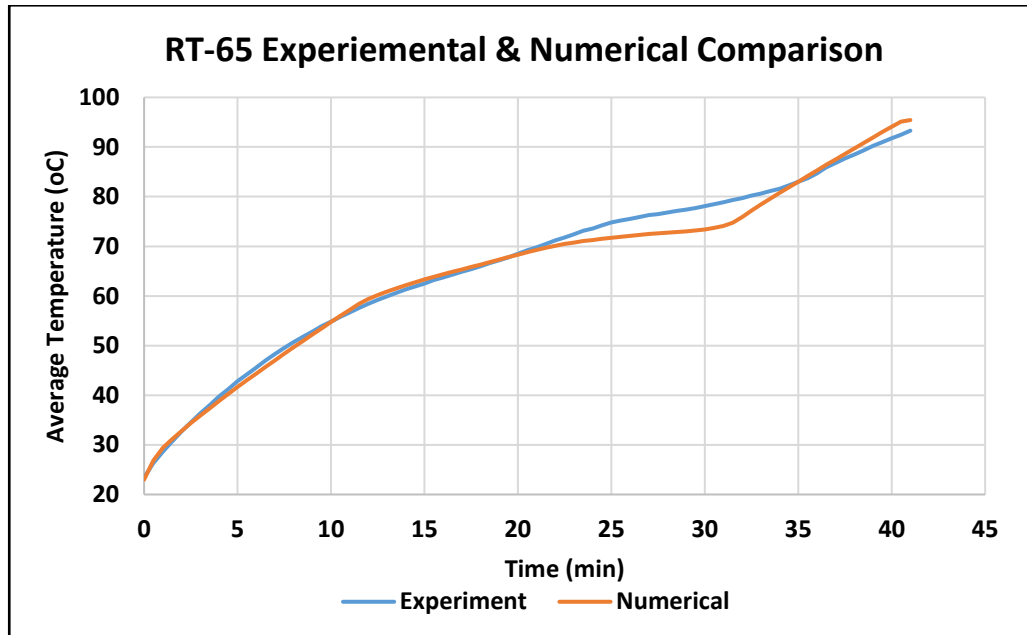


Figure 5.37. Experimental and analysis results of RT-65 PCM for 4-chambers heatsink at 0° inclination angle.

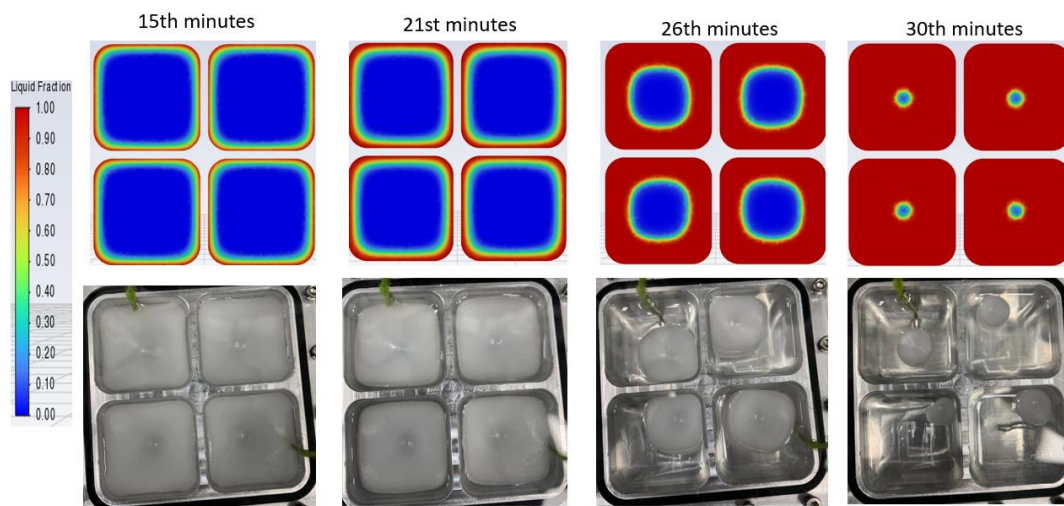


Figure 5.38. Liquid fraction comparison of RT-65 PCM for 4-chambers heatsink at 0° inclination angle.

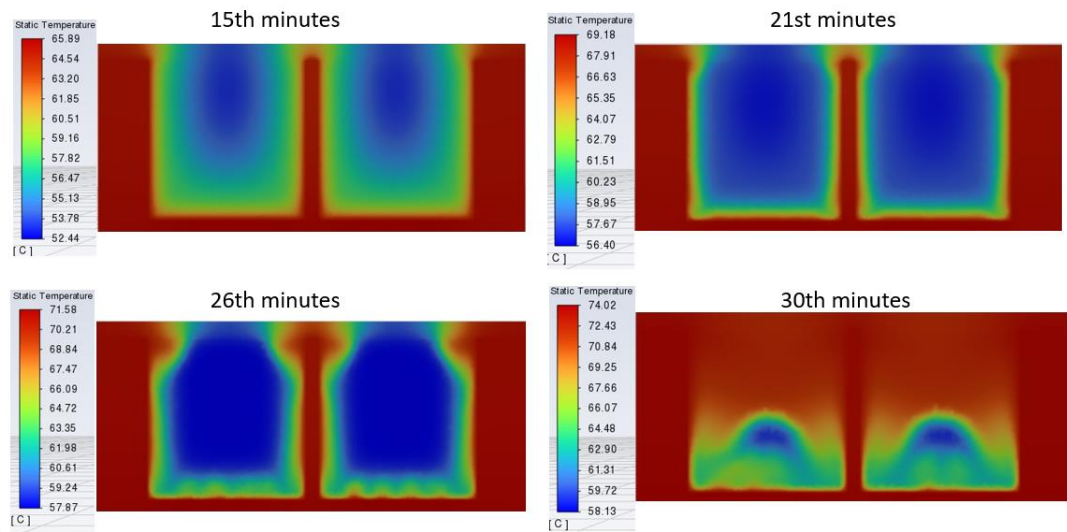


Figure 5.39. Temperature contours obtained from the middle section of 4-chamber RT-65 PCM heatsink at 0° inclination angle.

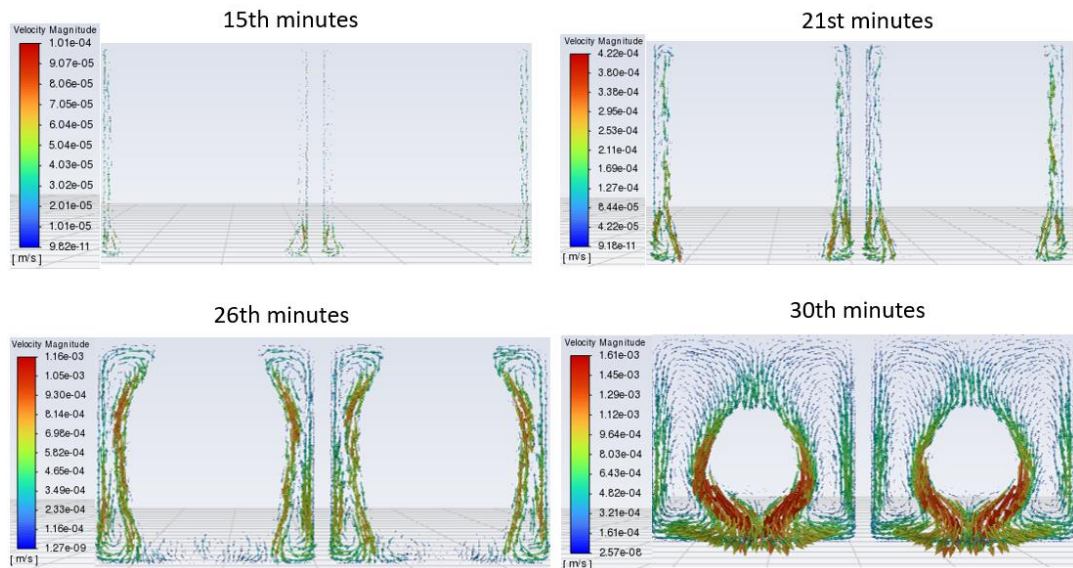


Figure 5.40. Velocity vector contours of RT-65 PCM for 4 chambers heatsink at 0° inclination angle.

5.3.1.5 RT-70 HC

Experimental and analysis results of base temperature are shown in Figure 5.41. The results show consistency, and the maximum error of this case is 3.8%. When the melting temperature increases, melting starts later. Also, RT-70 HC has higher latent heat capacity than other PCMs and therefore melting process took longer like RT-62 HC.

The liquid fraction and temperature contours of experiment and analysis are shown in Figure 5.42 and Figure 5.43, respectively. The velocity vectors of liquid PCM are shown in Figure 5.44. Liquid PCM affects the shape and position of the solid PCM.

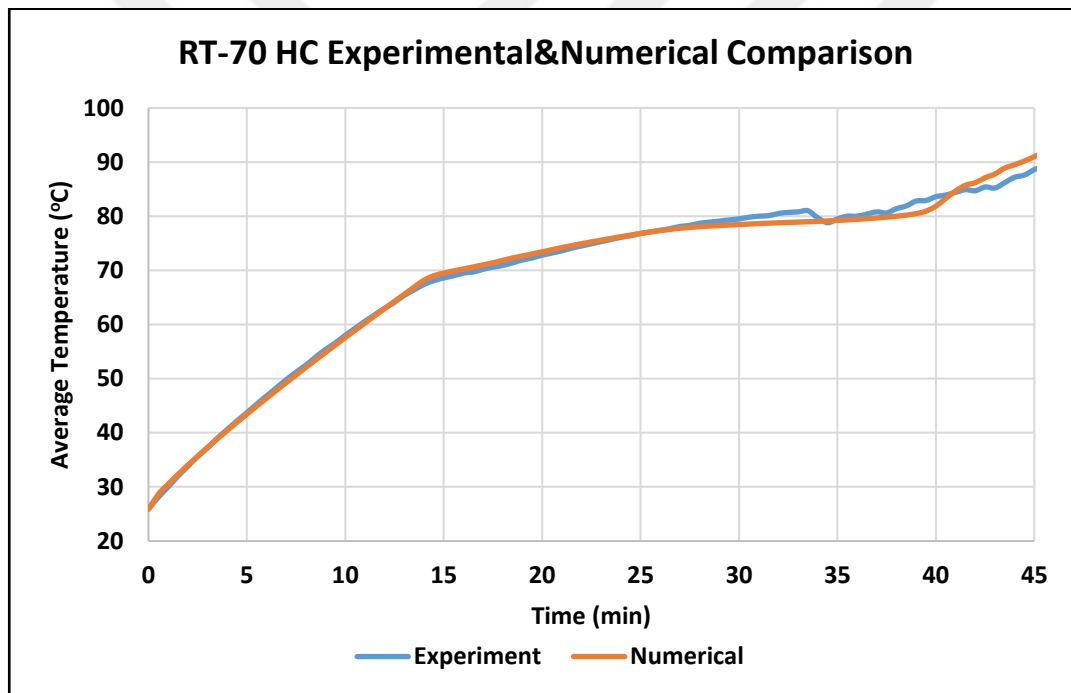


Figure 5.41. Experimental and analysis results of RT-70 HC PCM for 4-chambers heatsink at 0° inclination angle.

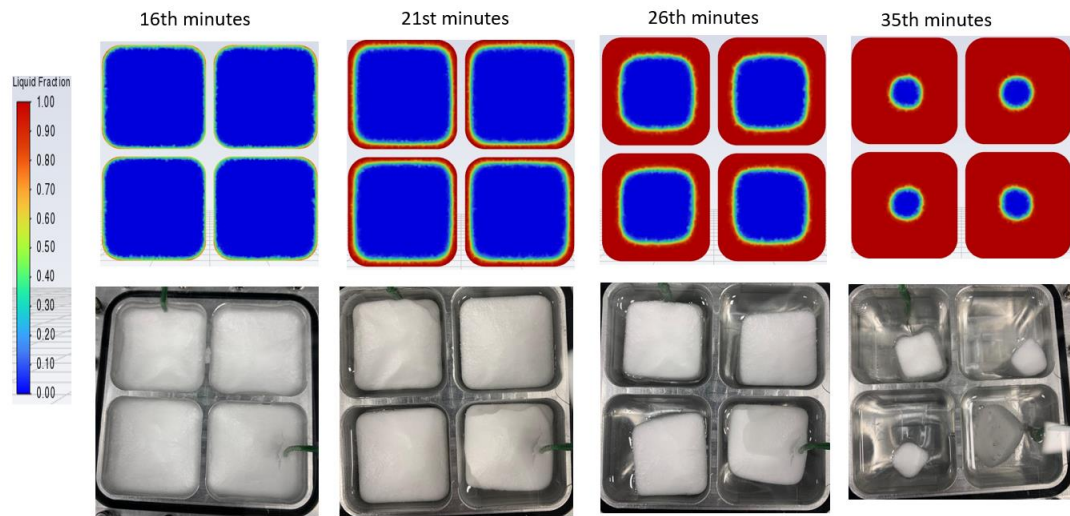


Figure 5.42. Liquid fraction comparison of RT-70 HC PCM for 4-chambers heatsink at 0° inclination angle.

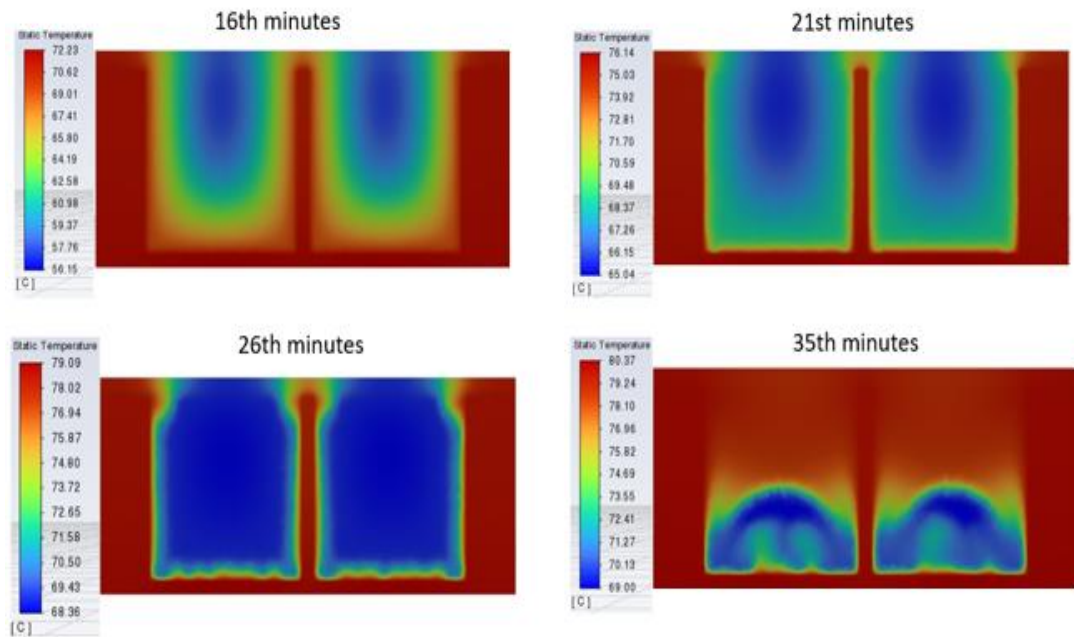


Figure 5.43. Temperature contours obtained from the middle section of 4-chamber RT-70 HC PCM heatsink at 0° inclination angle.

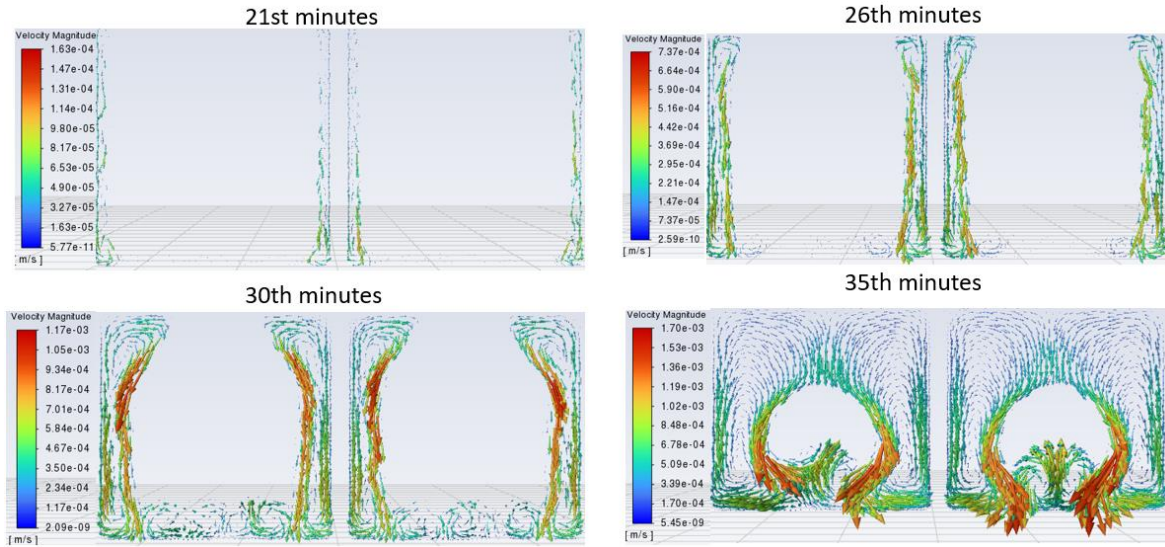


Figure 5.44. Velocity vector contours of RT-70 HC PCM for 4-chambers heatsink at 0° inclination angle.

5.3.1.6 A70

Experimental and analysis results of base temperature are shown in Figure 5.45. The maximum error of this case is found to be as 9.5%. The maximum difference between experimental and numerical results among all cases is obtained in this case.

The liquid fraction and temperature contours of experiment and analysis are shown in Figure 5.45, Figure 5.46 and Figure 5.47, respectively. Velocity vectors are shown in Figure 5.48.

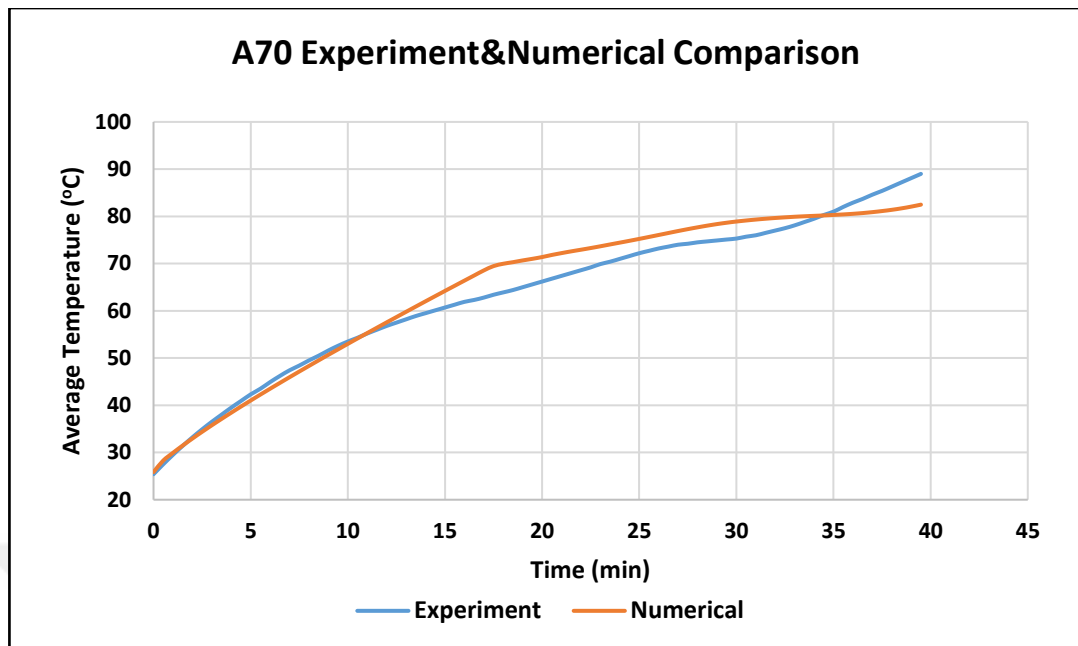


Figure 5.45. Experimental and analysis results of A70 PCM for 4-chambers heatsink at 0° inclination angle.

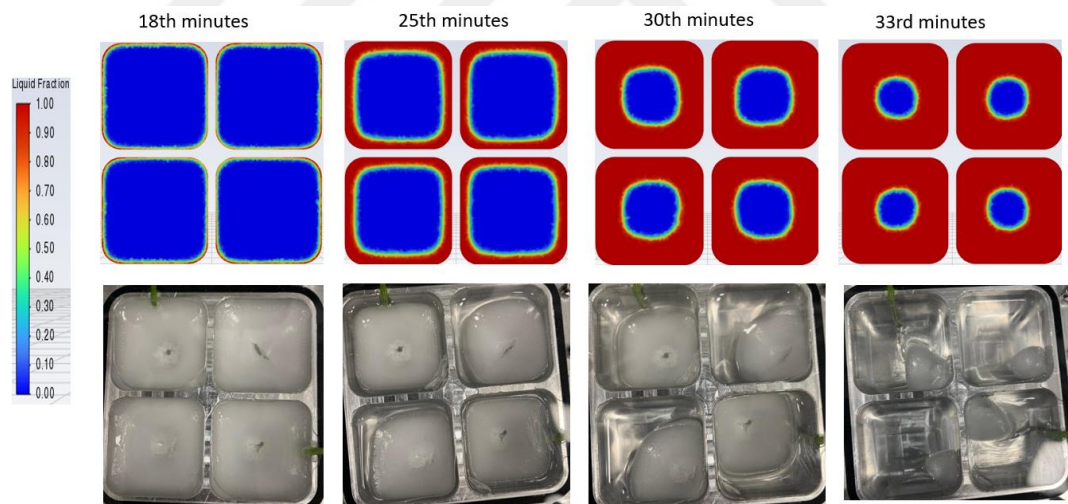


Figure 5.46. Liquid fraction comparison of A70 PCM for 4-chambers heatsink at 0° inclination angle.

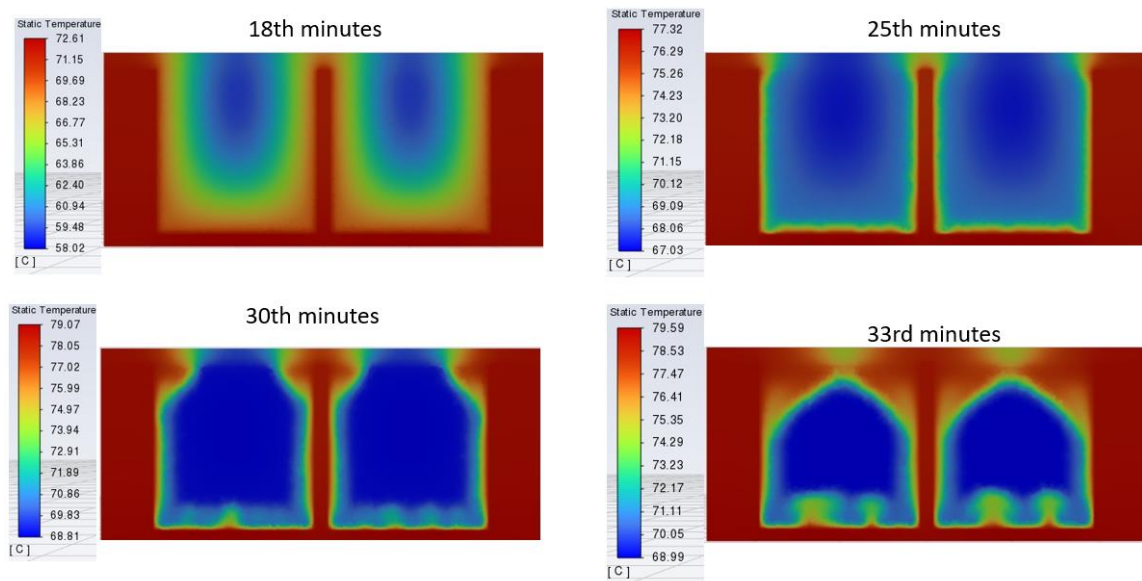


Figure 5.47. Temperature contours obtained from the middle section of 4-chamber A70 PCM heatsink at 0° inclination angle.

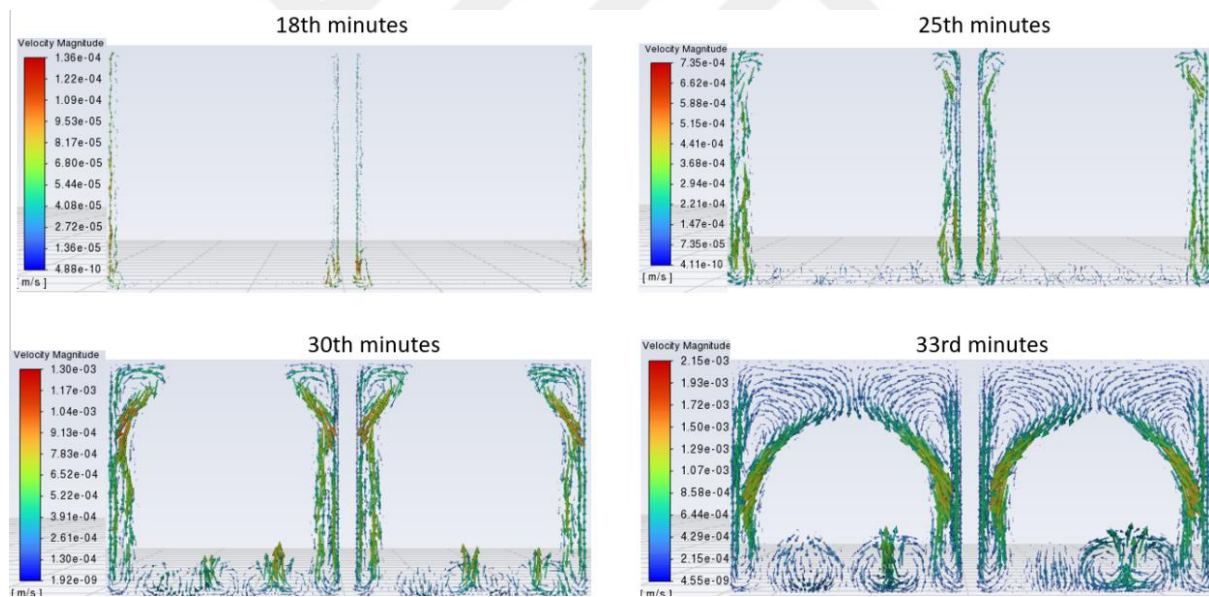


Figure 5.48. Velocity vector contours of A70 PCM for 4-chambers heatsink at 0° inclination angle.

5.3.1.7 S72

Experimental and analysis results of base temperature are shown in Figure 5.49. From Figure 5.49, results show consistency. The maximum error of this case is found to be about 7.2%. The longest melting time is observed in this case because of having the highest melting temperature and latent heat. The liquid fraction comparison, the temperature contours, and the velocity vectors in the liquid phase are shown in Figure 5.50, 5.51, and 5.52, respectively. S72 PCM is an inorganic and ingredients of it is different than organic ones. From Figure 5.50, liquid S72 is observed blurry. When the temperature and velocity vector contours are examined, the secondary flows are observed at the bottom part of S72 solid PCM. These movements cause reverse U shapes that are observed from temperature contours.

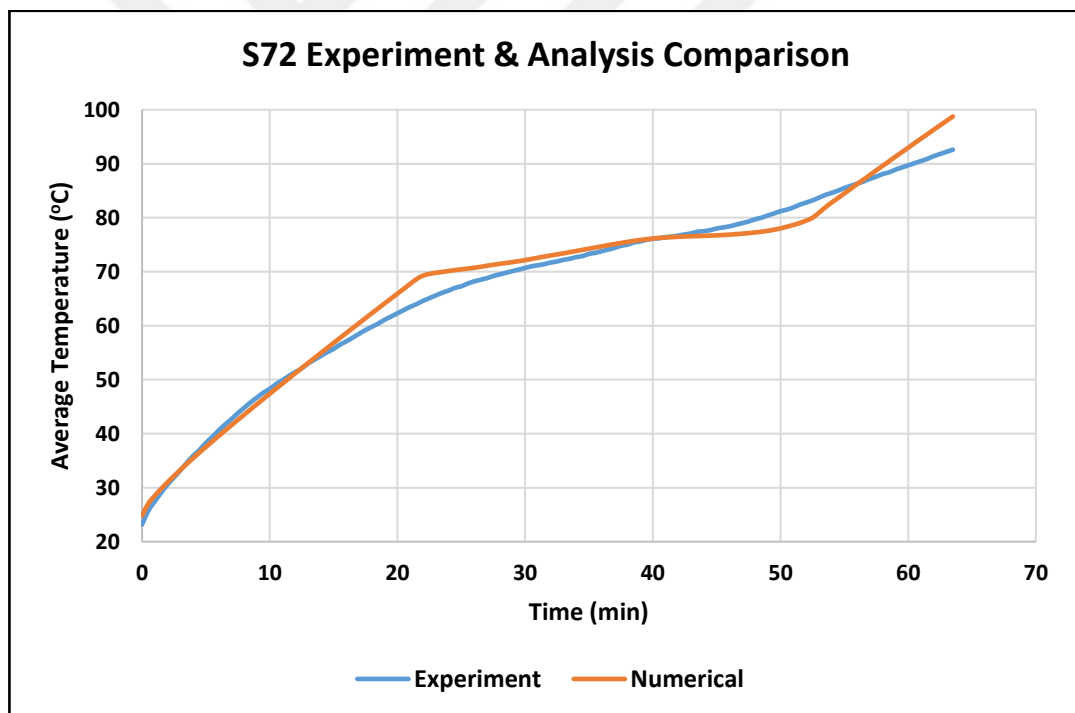


Figure 5.49. Experimental and analysis results of S72 PCM for 4-chambers heatsink at 0° inclination angle.

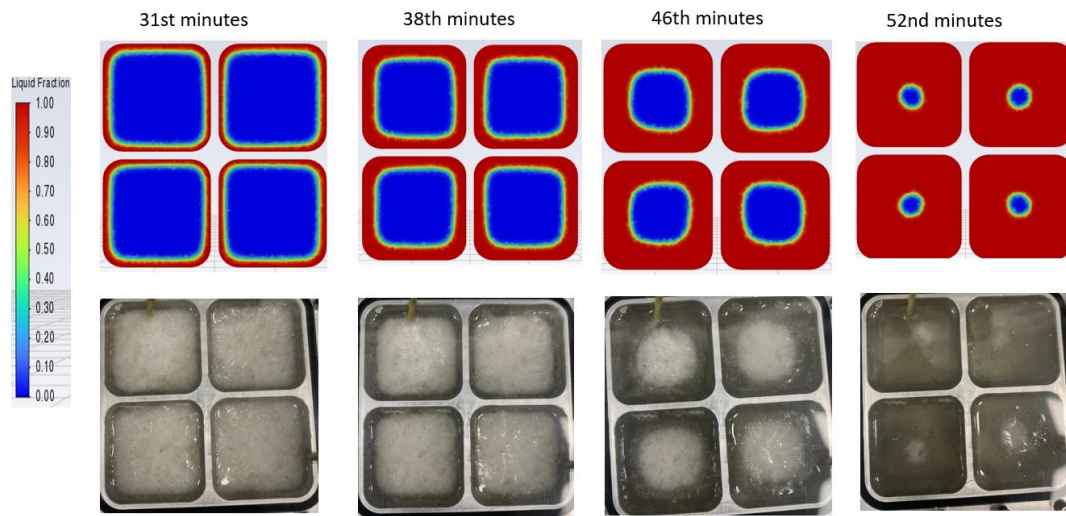


Figure 5.50. Liquid fraction comparison of S72 PCM for 4-chambers heatsink at 0° inclination angle.

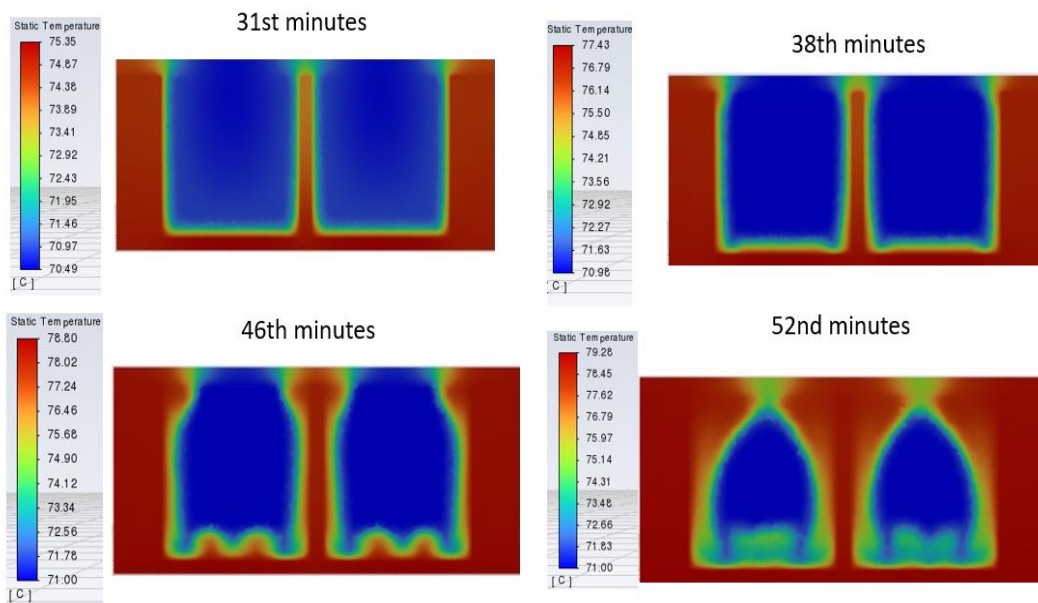


Figure 5.51. Temperature contours obtained from the middle section of 4-chamber S72 PCM heatsink at 0° inclination angle.

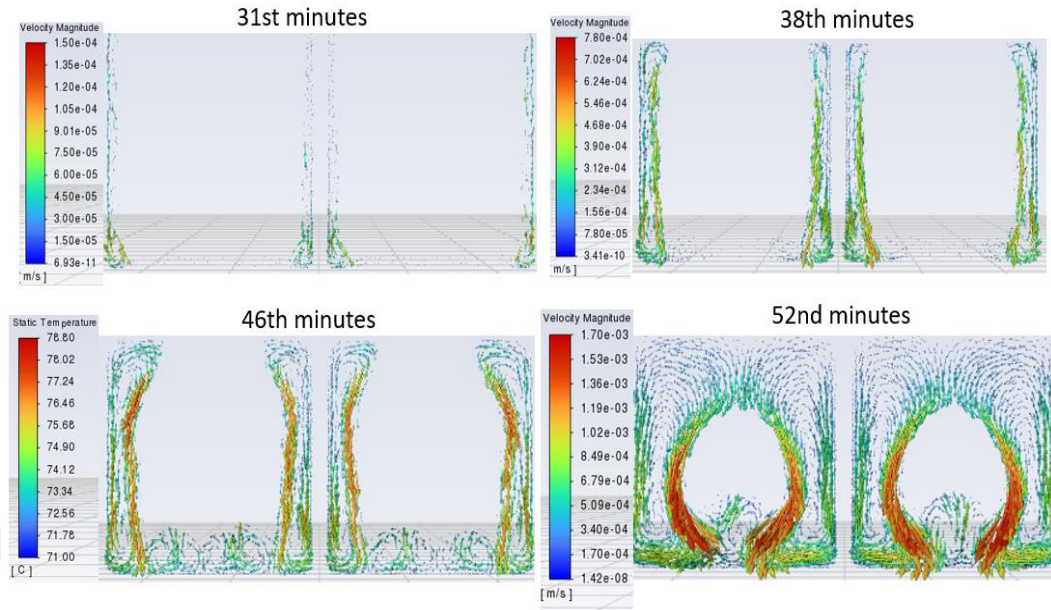


Figure 5.52. Vector contours of S72 PCM for 4-chambers heatsink at 0° inclination angle.

5.3.2 Mushy Zone Constant Investigation

In this section, the mushy zone constant calculations are explained. To calculate this constant, dendrite lengths of PCMs are measured during experiments using Nikon SMZ745T camera. The calculated mushy zone constants are then used in further analysis. The images of RT-55 and S58 PCMs are not suitable to be analysed because of material type and camera resolution, therefore, their mushy zone constant values cannot be calculated. The images of them are shown in Figure 5.53 and Figure 5.54.

Fiji software is used to measure the dendrite lengths of the PCM. For each PCM except RT-55 and S58, calculations are performed on images. 11 different lengths are measured from each image, and average dendrite length is calculated. The mean values and standard deviations of each calculation are given as well.



Figure 5.53. Mushy zone of S58.

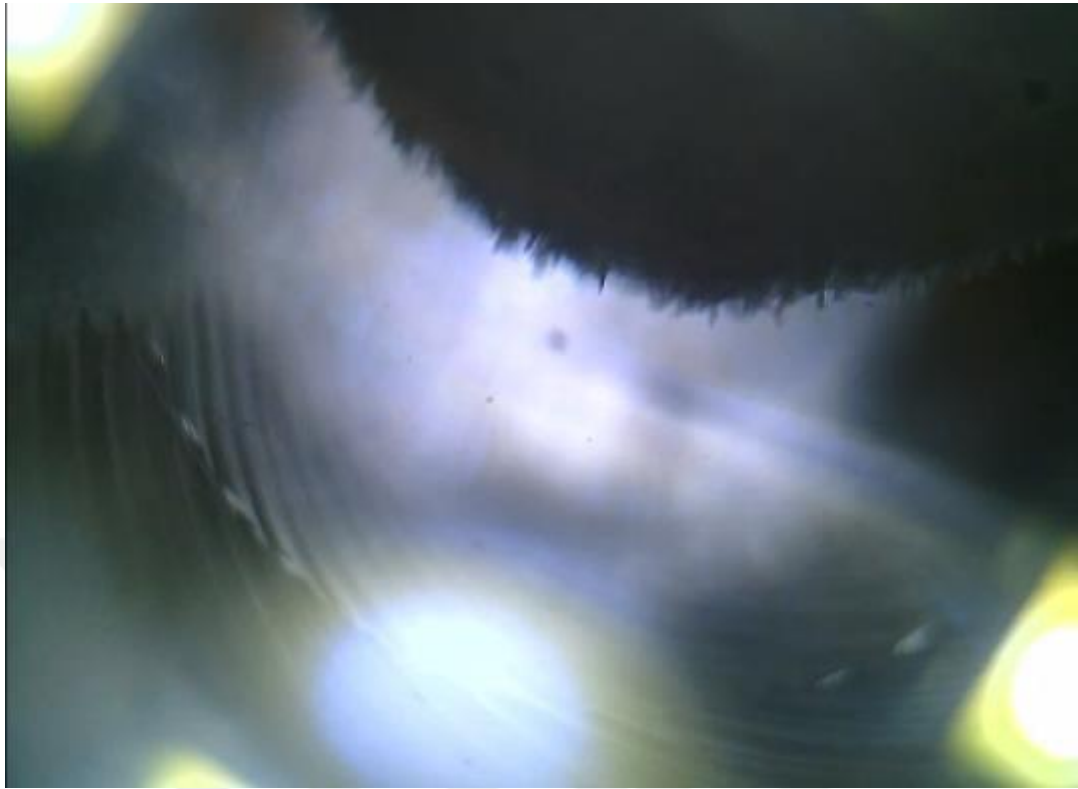


Figure 5.54. Mushy zone of RT-55.

5.3.2.1 Mushy Zone Constant Calculations

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. For the A58H PCM, the dendrites are shown in highlighted circles in Figure 5.55.

The image of A-58H PCM is given in Figure 5.55. Selected dendrite lengths are shown in this figure. The measurement results, mean value and standard deviation of dendrite lengths are given in Table 5.4. As can be seen, the average dendrite length is calculated as 0.25 mm with standard deviation of 3%.



Figure 5.55. Mushy zone and dendrite lengths of A58H PCM.

Table 5.4. Calculation of average dendrite length of A58H PCM.

Samples	Selected Dendrite Lengths (mm)
1	0.212
2	0.182
3	0.225
4	0.295
5	0.243
6	0.235
7	0.273
8	0.278
9	0.288
10	0.265
11	0.246
Mean Value	0.250
Std. Deviation	3%

The image of RT-62 HC PCM is given in Figure 5.56. Selected dendrite lengths are shown in highlighted circles in this figure. The measurement results, mean value and standard deviation of dendrite lengths are given in Table 5.5. As can be seen, the average dendrite length is calculated as 0.28 mm. The standard deviation is calculated as 8% due to the dendrite differences and material characteristic. While a crystalline phase change is observed for A58H PCM, filamentous separation of solid particles is observed during the experiments for RT-62 HC.



Figure 5.56. Mushy zone and dendrite lengths of RT-62 HC PCM.

Table 5.5. Calculation of average dendrite length of RT-62 HC PCM.

Samples	Selected Dendrite Lengths (mm)
1	0.401
2	0.237
3	0.218
4	0.292
5	0.305
6	0.415
7	0.275
8	0.303
9	0.249
10	0.150
11	0.200
Mean Value	0.28
Std. Deviation	8%

The image of RT-65 PCM is given in Figure 5.57. The dendrite lengths are clearly seen from the figure. The measurement results, mean value and standard deviation of dendrite lengths are given in Table 5.6. As can be seen, the average dendrite length is calculated as 0.28 mm with standard deviation of 8.3%. Crystalline phase change is also observed for RT-65.

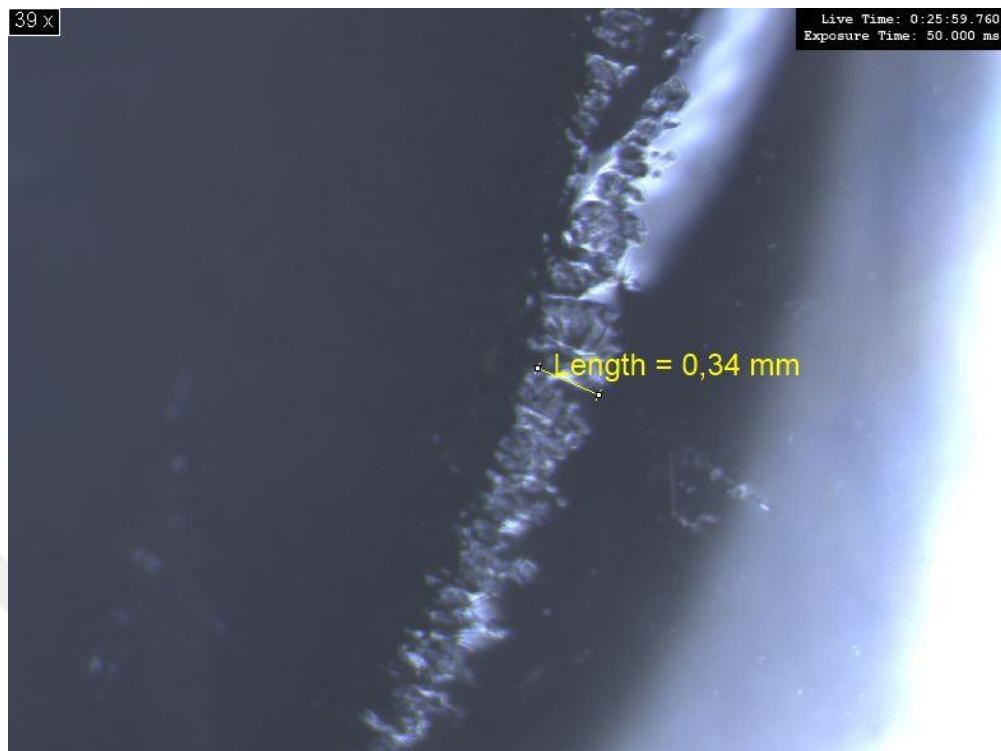


Figure 5.57. Mushy zone and dendrite lengths of RT-65 PCM.

Table 5.6. Calculation of average dendrite length of RT-65 PCM.

Samples	Selected Dendrite Lengths (mm)
1	0.272
2	0.307
3	0.343
4	0.229
5	0.145
6	0.185
7	0.143
8	0.351
9	0.355
10	0.313
11	0.348
Mean Value	0.27
Std. Deviation	8.3%

The image of RT-70 HC PCM is given in Figure 5.58. The measurement results, mean value and standard deviation of dendrite lengths are given in Table 5.7. As can be seen, the average dendrite length is calculated as 0.28 mm. The melting type is similar to the RT-62 HC. As can be seen from Figure 5.58, various dendrite lengths are observed and therefore standard deviation is found as 7.8%.



Figure 5.58. Mushy zone and dendrite lengths of RT-70 HC PCM.

Table 5.7. Calculation of average dendrite length of RT-70 HC PCM.

Samples	Selected Dendrite Lengths (mm)
1	0.237
2	0.250
3	0.150
4	0.136
5	0.410
6	0.275
7	0.178
8	0.298
9	0.224
10	0.200
11	0.185
Mean Value	0.23
Std. Deviation	7.8%

The image of A70 PCM is given in Figure 5.59. The measurement results, mean value and standard deviation of dendrite lengths are given in Table 5.8. As can be seen, the average dendrite length is calculated as 0.42 mm. The melting type is similar to the A58H. The standard deviation is found as 8%.



Figure 5.59. Mushy zone and dendrite lengths of A70 PCM.

Table 5.8. Calculation of average dendrite length of A70 PCM.

Samples	Selected Dendrite Lengths (mm)
1	0.464
2	0.519
3	0.428
4	0.285
5	0.458
6	0.485
7	0.384
8	0.509
9	0.467
10	0.355
11	0.310
Mean Value	0.42
Std. Deviation	8%

The last PCM is S72 which is an inorganic PCM. The images obtained from experiments are blurry however, the dendrites can be measured. This is because of material ingredients. The image of S72 PCM is given in Figure 5.60. The measurement results, mean value and standard deviation of dendrite lengths are given in Table 5.9. The average dendrite length is calculated as 0.42 mm with standard deviation of 2.9%.

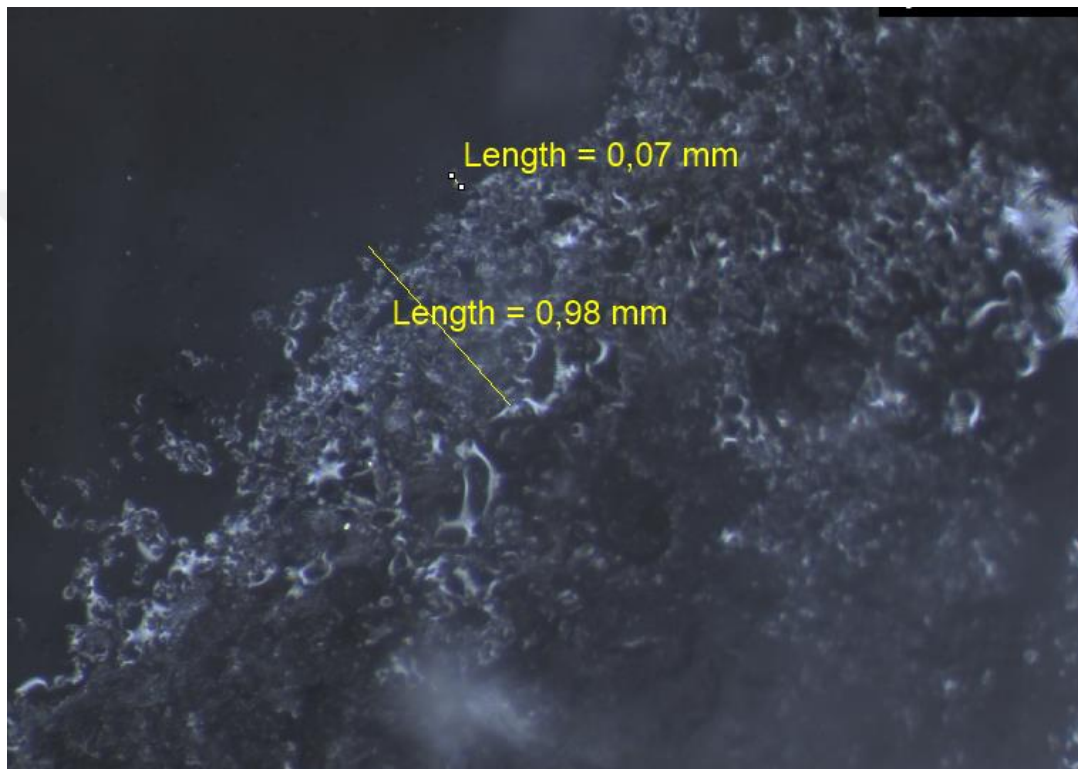


Figure 5.60. Mushy Zone Contour and line position of S72 PCM.

Table 5.9. Calculation of average dendrite length of S72 PCM.

Samples	Selected Dendrite Lengths (mm)
1	0.280
2	0.192
3	0.215
4	0.267
5	0.235
6	0.267
7	0.255
8	0.277
9	0.215
10	0.223
11	0.227
Mean Value	0.24
Std. Deviation	2.9%

5.3.2.2 Mushy Zone Constants and Errors

The calculated mushy zone constants using Equation 3.1 are given in Table 5.10. As can be seen, mushy zone constants for investigated PCMs are found to be between 10^6 and 10^8 . Before the investigations of mushy zone constants, the mushy zone constant of A58H PCM is found to be as 10^7 by trying three different constants in Ansys Fluent and the results are previously given in Section 4.3.3 and in Figure 4.7. As a result, the experimentally found mushy zone constant and numerically found mushy zone constant are almost the same. In addition, Ansys Fluent assumes mushy zone constant of PCMs as 10^5 . However experimental results show that this assumption should be changed for both organic and inorganic PCMs. By using the calculated mushy zone constants, the maximum numerical model error values by comparing experimental results are given in Table 5.11. As can be seen, the maximum error values are below 10%. In addition, operational times of PCMs are

given in Table 5.12. Operational time is the time to reach the critical temperature (85°C for this study). This is important because after this point, the operating performance of IC begins to decrease.

Table 5.10. Calculated mushy zone constants for each PCM.

	A58H	RT62-HC	RT-65	RT-70 HC	A70	S72
Measured Dendrite Length (mm)	0.25	0.28	0.27	0.23	0.42	0.25
Viscosity (kg/ms)	0.007	0.01	0.005	0.007	0.005	0.02
Mushy Zone Constant (kg/m³s)	2.01x10 ⁷	2.29x10 ⁷	1.23x10 ⁷	2.38x10 ⁷	5.10x10 ⁶	5.76x10 ⁷

Table 5.11. The maximum error values of each PCMs between experimental and numerical results.

PCM	The Maximum Error (%)
A58H	4.5
RT-55	6.8
S58	7.2
RT-62 HC	5.4
RT-65	3.8
RT-70 HC	3.8
A70	9.5
S72	7.2

Table 5.12. The operational time of each PCMs.

PCM	Operational Time (minutes)
A58H	45
RT-55	37
S58	44
RT-62 HC	43
RT-65	38
RT-70 HC	46
A70	39
S72	56

5.3.3 Comparison of Different PCM Results

The base temperature results are compared according to the melting temperatures of PCMs. Figure 5.61 shows that for organic PCMs, as the melting temperature decreases the base temperature decreases during the melting phase. However, the melting process of a PCM with a lower melting temperature ends earlier. At that point, the latent heat becomes important in choosing the appropriate PCM. RT-55 has lower latent heat than A58H, after 33 minutes, RT-55 base temperature is higher than A58H because the melting of RT-55 is completed earlier.

For the S-72 and RT-70 HC PCMs, their latent heat values and melting temperatures are close, which can be seen from Table 3.3. However, their density, thermal conductivity, and material types are different. Figure 5.62 shows how these differences affect the base temperature. Due to high thermal conductivity, the base temperature of S72 is lower than RT-70 HC. In addition, S72 reaches critical temperature after 15 minutes from RT-70 HC. This is caused by density and material type differences. S72 gives the best thermal performance among all PCMs.

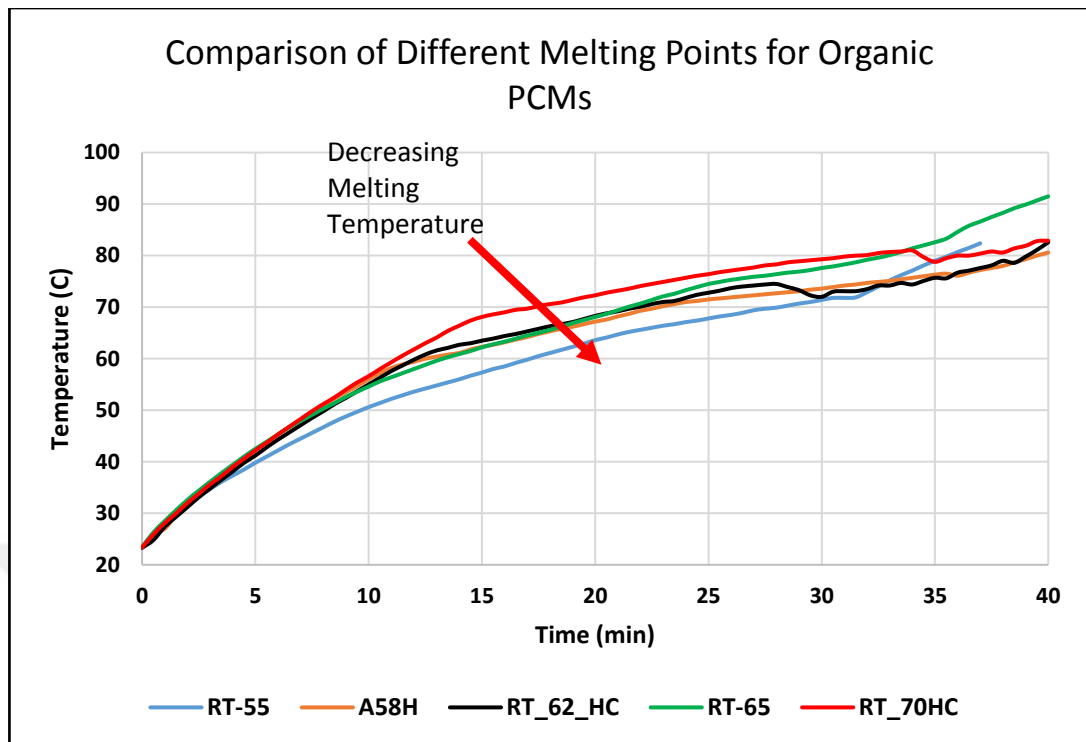


Figure 5.61. Base temperature result comparison of organic PCMs for 4-chamber heatsink at 0° inclination angle.

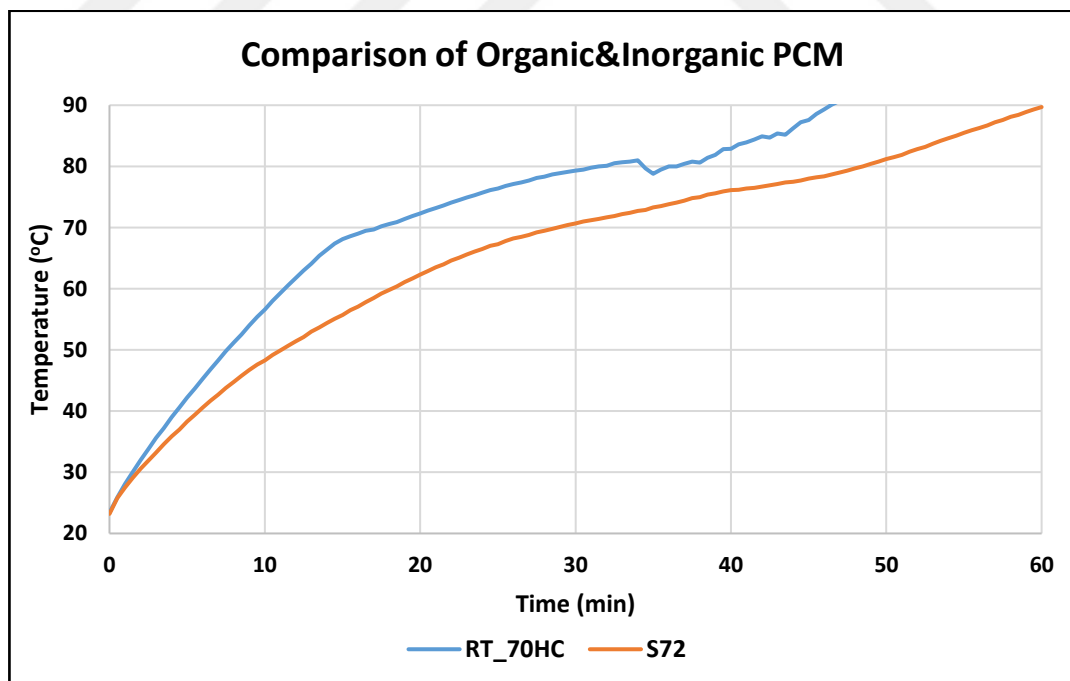


Figure 5.62. Comparison of experimental results of RT-70 HC and S72 PCMs for 4-chamber heatsink at 0° inclination angle.

The latent heat effect is also observed and this effect on base temperature is shown in Figure 5.63. For PCMs having nearly the same melting temperatures, the PCM with a higher latent heat provides longer operational time for PCM heatsinks. Therefore, while choosing a PCM, latent heat is important and should be considered. Another parameter is specific heat value. For this parameter, A58H and RT-62 HC PCMs are compared in Figure 5.64. It is observed that specific heat has no significant effect on thermal performance of PCM heatsinks.

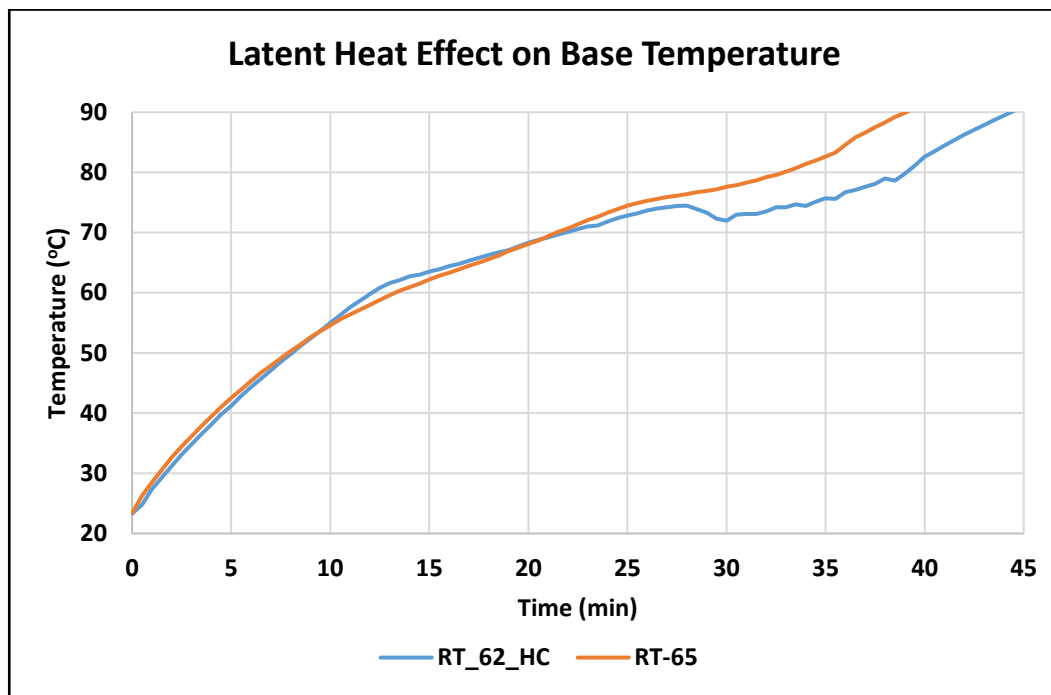


Figure 5.63. Comparison of experimental results of RT-62 HC and RT-65 PCMs for 4-chamber heatsink at 0° inclination angle.

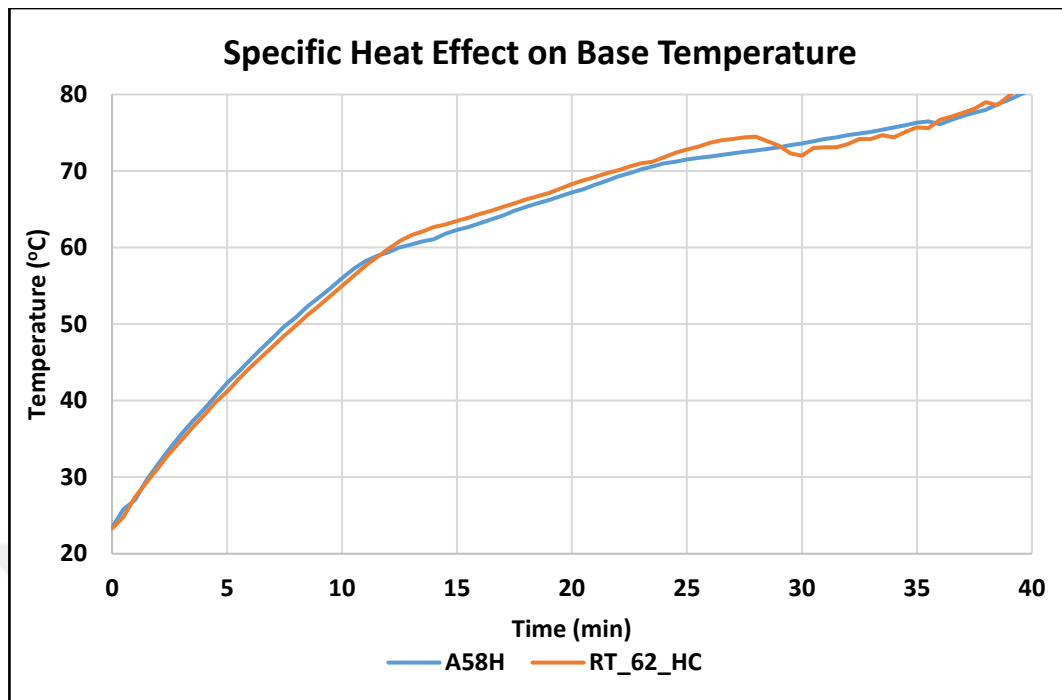


Figure 5.64. Comparison of experimental results of RT-62 HC and A58H PCMs for 4-chamber heatsink at 0° inclination angle.

The contour plot of time to reach critical temperature of 85°C for RT-55, A58H, and S58 having different number of chambers heatsinks is shown in Figure 5.65. The contour regions change according to time to reach critical temperature. For instance, for 9-chamber heatsink, from bottom to top, firstly thermal performance increases. However, as line gets closer to RT-55, thermal performance decreases. Circled regions show the change in contours. The thermal performance effects of A58H and S58 cause this change.

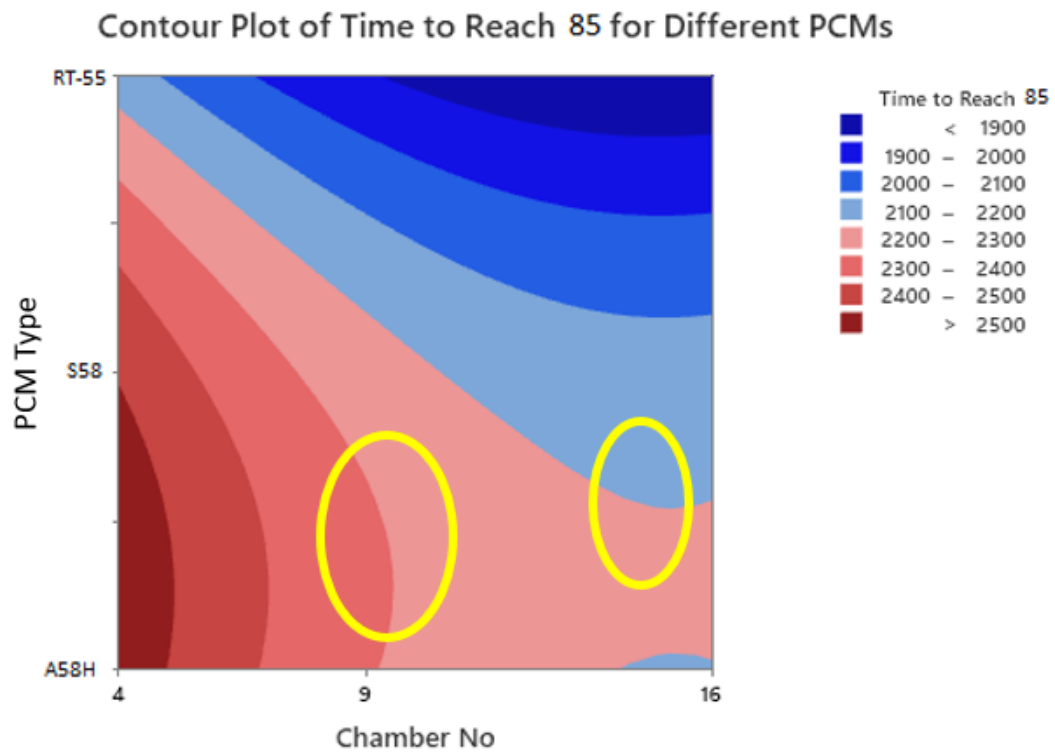


Figure 5.65. Contour plot for number of chamber and different PCM effects for 0° inclination angle.

CHAPTER 6

CONCLUSION & RECOMMENDATIONS

6.1 Conclusion

In this study, three different parameters are examined to keep IC that dissipates 21 W at safe temperatures. Four different types of heatsinks are prepared to examine the number of chamber effect, eight different types of PCMs are filled into the heatsinks to investigate the PCM type effect and system is subjected to seven different inclination angles to observe the effect of inclination angle. Also, mushy zone is investigated, and numerical validation of analyses are completed. The thermal performances of different cases are compared.

Firstly, the number of chamber effect is investigated. Due to latent heat of PCM, PCM heatsinks provide longer operational time for ICs compared to natural convection cooled non-PCM heatsinks. For instance, PCM provides 24 °C lower base temperature of the heat sink at the time when the PCM melting is completed. As the number of chambers increases, the base temperature of heatsink decreases due to increased heat diffusion between heatsink and PCM. However, due to geometrical constraints, as the number of chambers increases, the amount of PCM in the heatsink decreases, which in turn decreases the operational time. 16 chamber PCM heatsink has the highest thermal performance until melting is completed. The numerical analysis using Fluent is also conducted and the maximum error between experimental and numerical results among all cases is found to be as 6%. The natural convection affects the melting process and reverse U shapes are observed in solid PCMs during melting.

Inclination angle studies are conducted for 4-chamber and 16-chamber PCM heatsinks. As the inclination angle increases, the base temperature of heatsink increases, however, after melting is completed, all cases reach the same temperature.

Thus, inclination angle affects the melting and solidification significantly. In addition, for the inclination angles higher than 30° , the T-shape is observed in solid PCMs.

Finally, different PCMs are investigated both experimentally and numerically and the results are compared. As the melting temperature of PCM decreases, the base temperature of heatsink decreases as well. The latent heat is also critical here, because if both the melting temperature and latent heat are lower, than the operational time is shorter. Inorganic PCMs have higher density and thermal conductivity, thus, they can keep the base temperature of heatsink lower and have longer operational time compared to organic ones. Specific heat has no significant effect on the thermal performance of PCM heatsinks.

A microscope and a camera are used to investigate the dendrites and mushy zone constants of PCMs during melting. Using Fiji tool helps to determine the average dendrite length and hence the mushy zone constant. The numerically found mushy zone constant for A58H is consistent with experimentally calculated one. Thus, other PCMs are modelled using experimentally calculated mushy zone constants and the maximum error is found to be 9.5%. Ansys Fluent assumes mushy zone constants as 10^5 . However, calculated mushy zone constants are found to be between 10^6 and 10^8 . CFD analyses conducted in Ansys Fluent show good agreement with experimental results for all cases in this study.

The effects of natural convection during the melting of PCMs are observed in this study. Vortex type flow shapes are observed from velocity vectors, and it causes the change in position and shape of solid PCMs.

Operational times for eight different PCMs are calculated from average base temperature results. S72 shows the best performance with operational time as 56 minutes because of having the highest latent heat and melting temperature.

Before experiments, tests are conducted to check the homogeneous temperature distribution at the base of the heatsinks. It is concluded from these tests, by using

flex heater with Al6061 heatsink, homogeneous temperature distribution can be achieved.

6.2 Recommendations

Beyond the investigated parameters, other important effects can be considered for the future works.

Other thermal conductivity enhancers can be studied. Instead of heatsinks, metal foam structures, topology optimized heatsinks, or nanoparticles can be experimentally and numerically investigated. Although they are economically expensive, they increase the contact surface.

For different heat loads, the PCM heatsink can be examined. PCM can react differently at higher heat loads and sudden increase in temperatures may occur. In addition, forced convection PCM heatsink case can affect the thermal performance and they can be studied.

In addition to melting, solidification process of PCMs can be studied experimentally and numerically. Mushy zone and dendrite length can change during the solidification process of PCMs. which in turn affect the numerical model.



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APPENDICES

A. The Dimensions of the Produced Heatsinks

In this APPENDIX, the dimensions of the produced heatsinks are given.

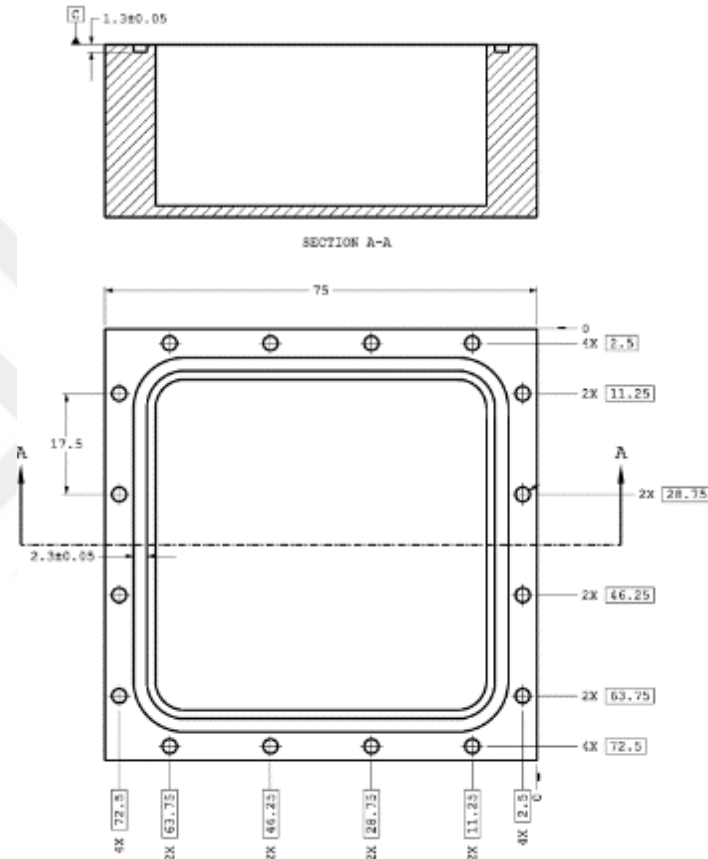


Figure A.1 Technical drawing and dimensions of the 1 chamber heatsink.

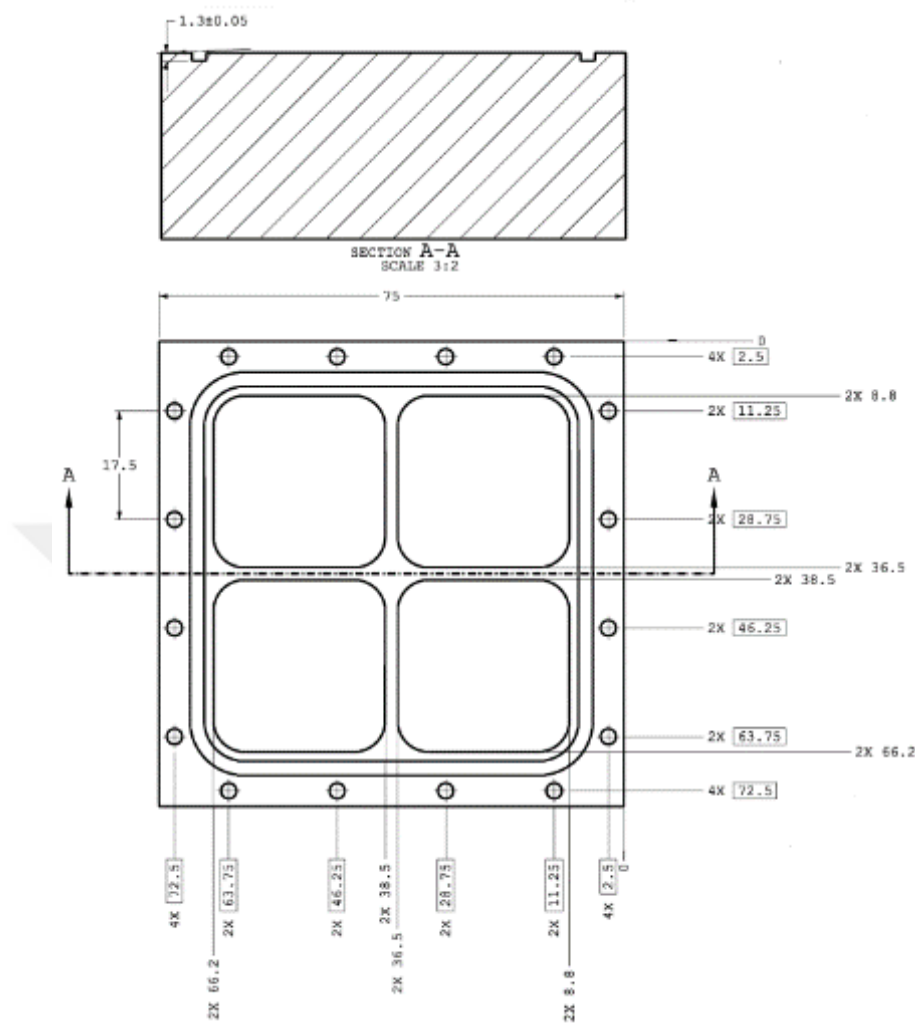


Figure A.2. Technical drawing and dimensions of the 4 chambers heatsink.

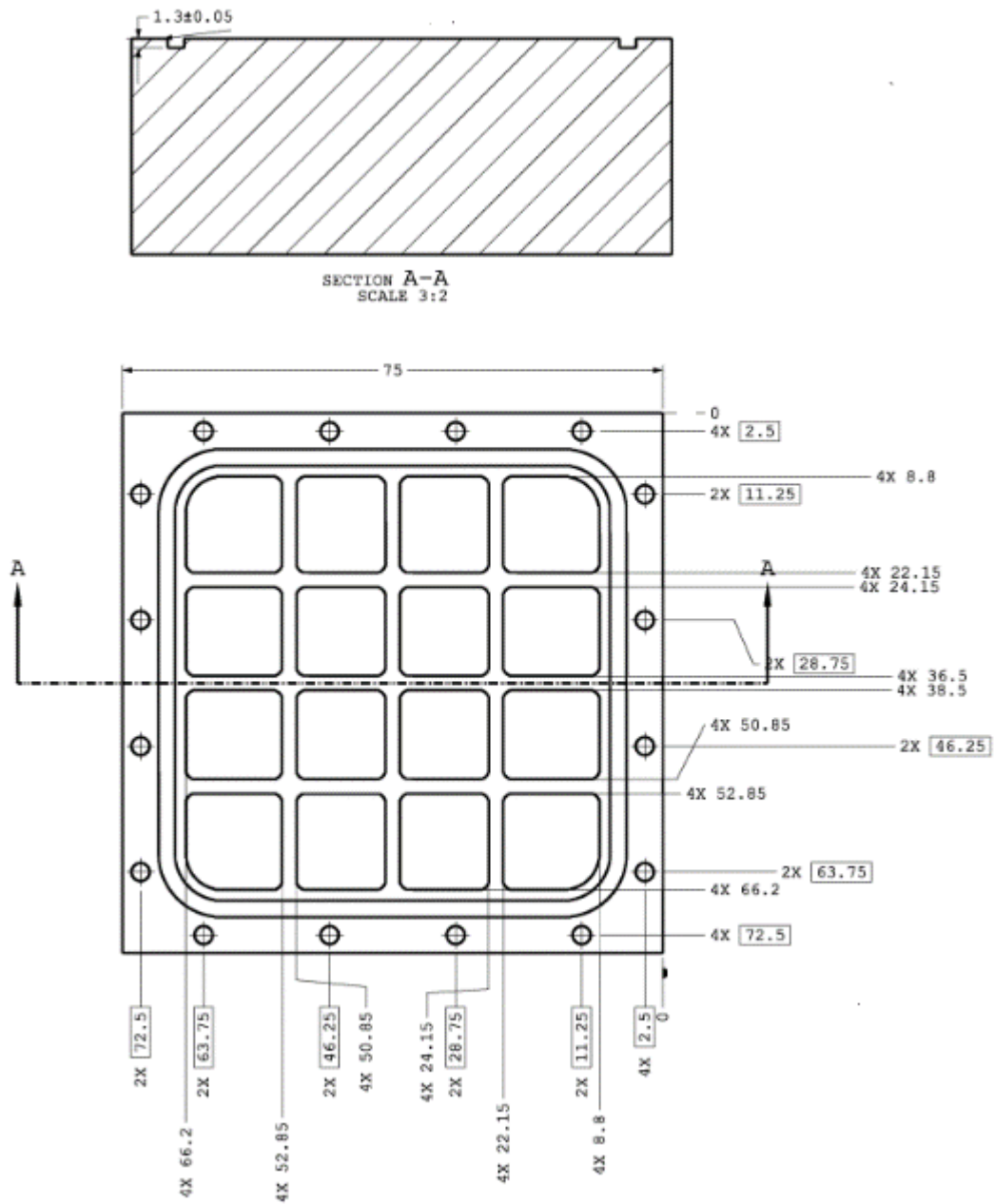


Figure A.4. Technical drawing and dimensions of the 16 chambers heatsink.

B. The Experimental & Numerical Results Comparisons of Number of Chamber Effect for Selected Chamber

In this APPENDIX, the experimental and numerical results of selected chambers in PCM heatsinks are given. The positions of the thermocouple were given in Section 3.2. The T1i T2i etc. represents these positions and they can be found in Section 4.2.

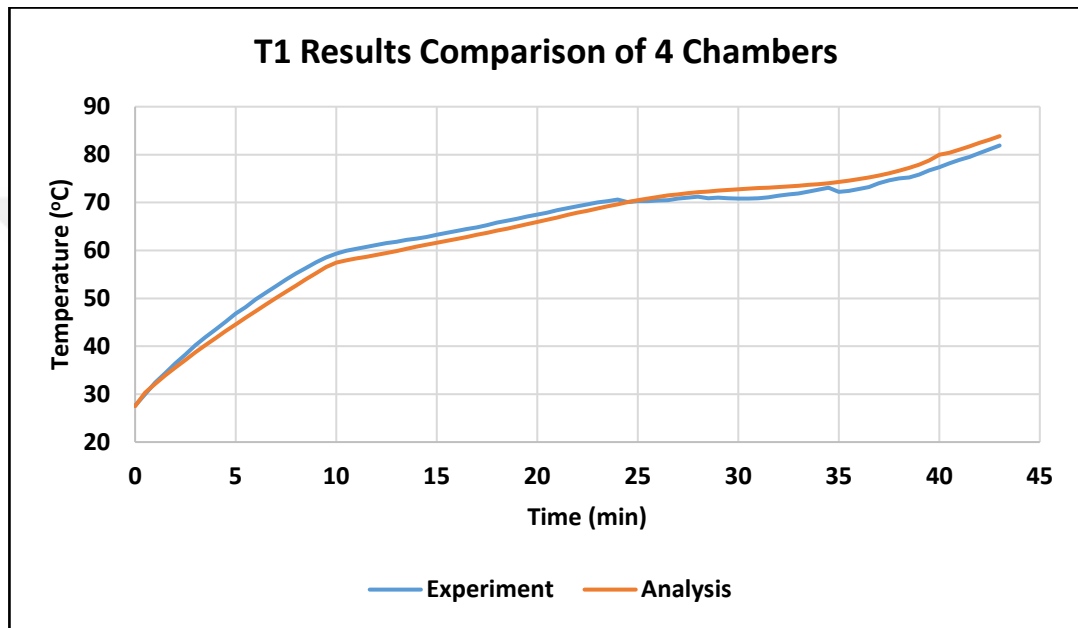


Figure B.1. The T1 results of 4 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

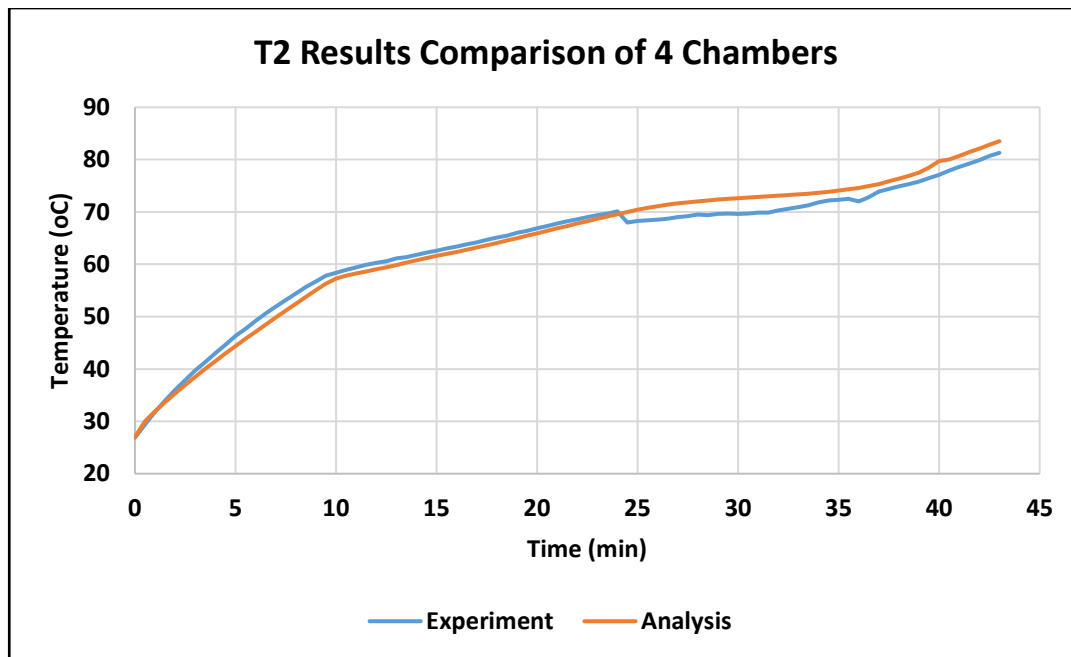


Figure B.2 The T2 results of 4 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

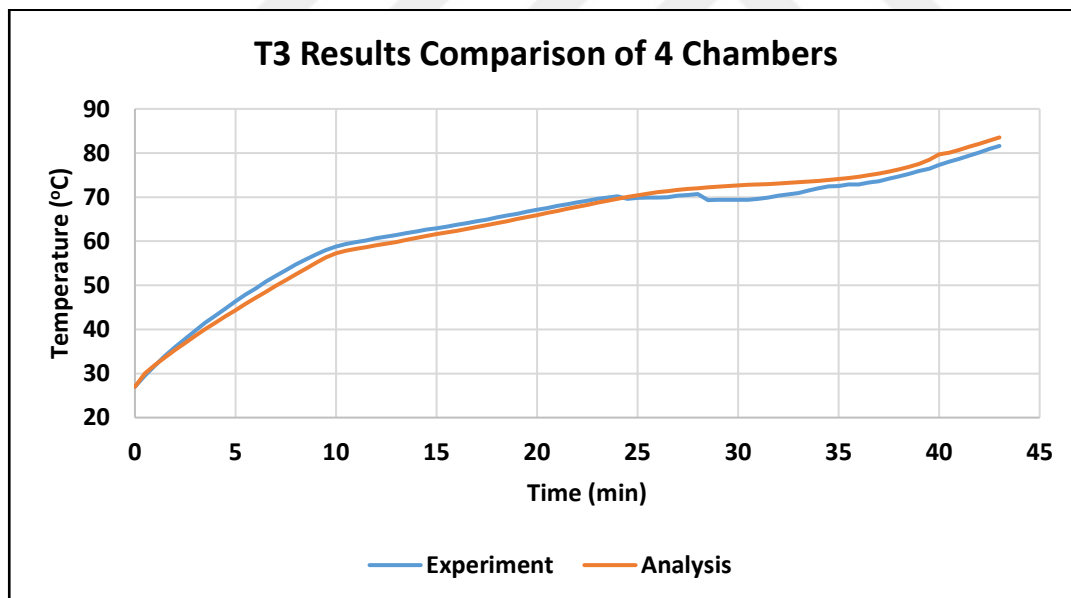


Figure B 3. The T3 results of 4 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

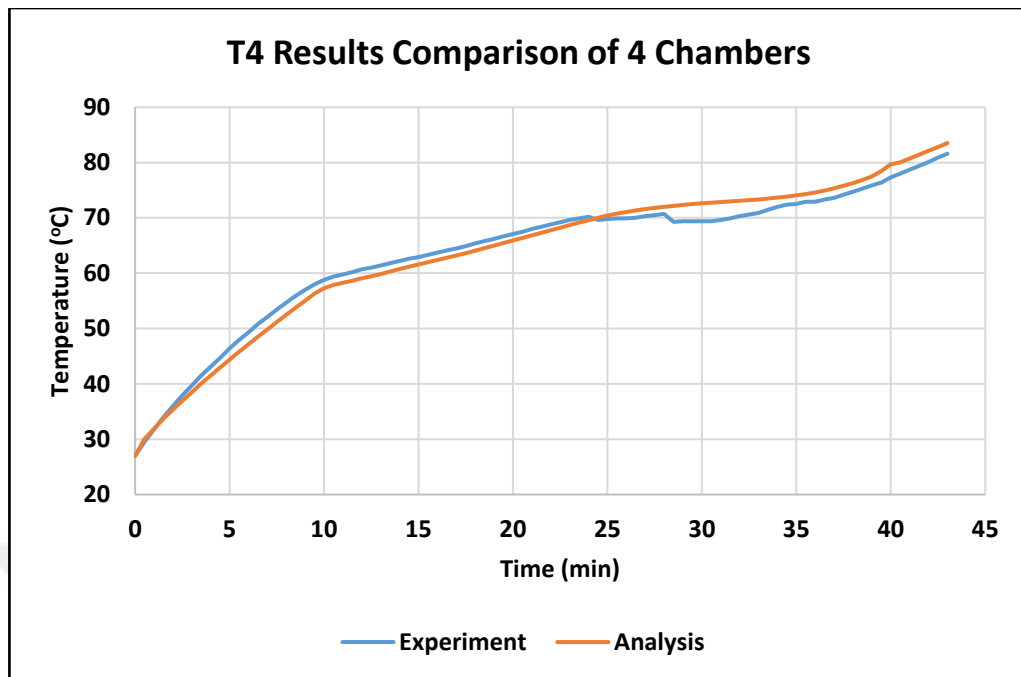


Figure B 4. The T3 results of 4 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

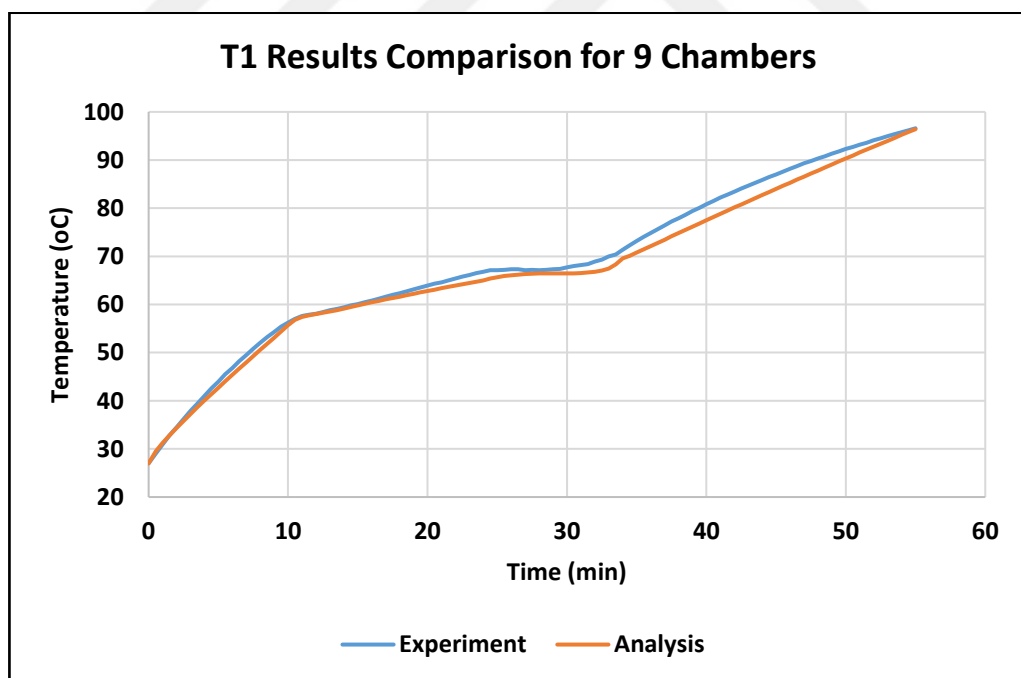


Figure B.5. The T1 results of 9 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

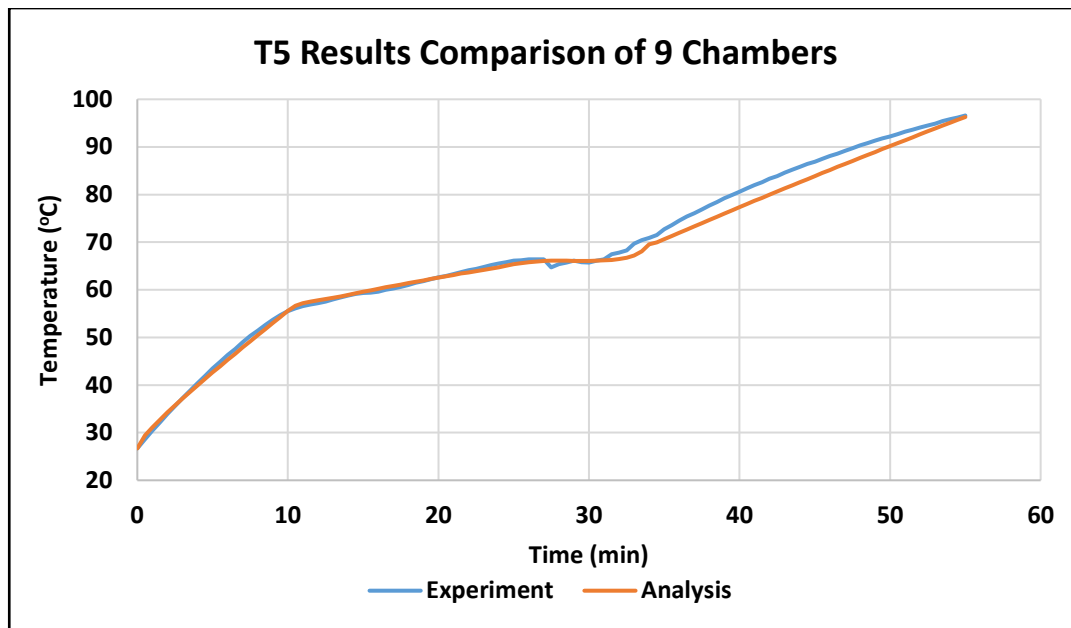


Figure B 6. The T5 results of 9 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

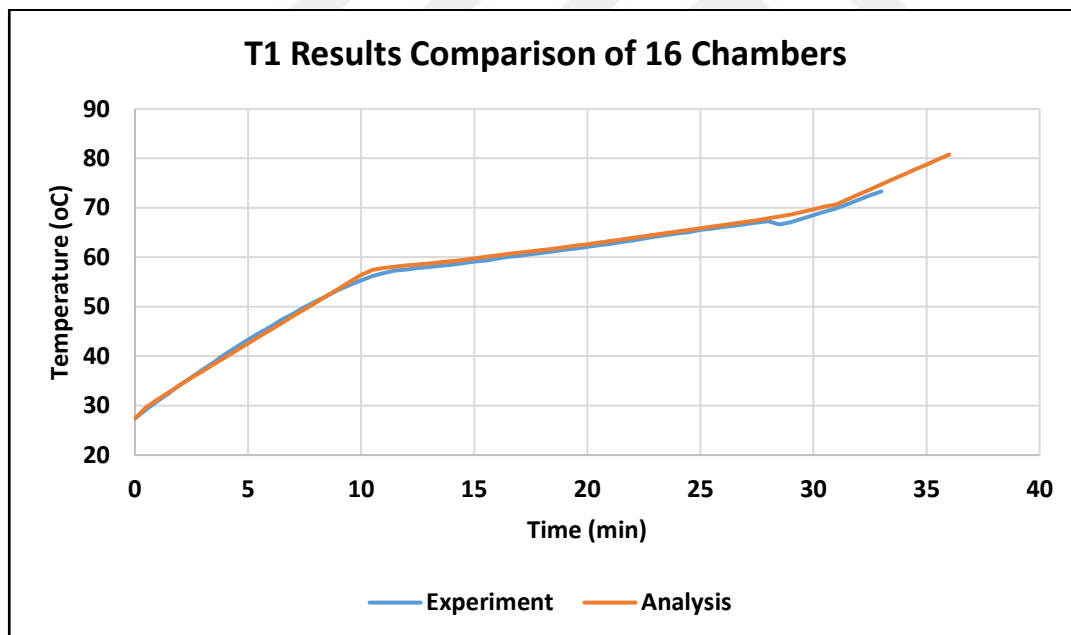


Figure B 7. The T1 results of 16 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

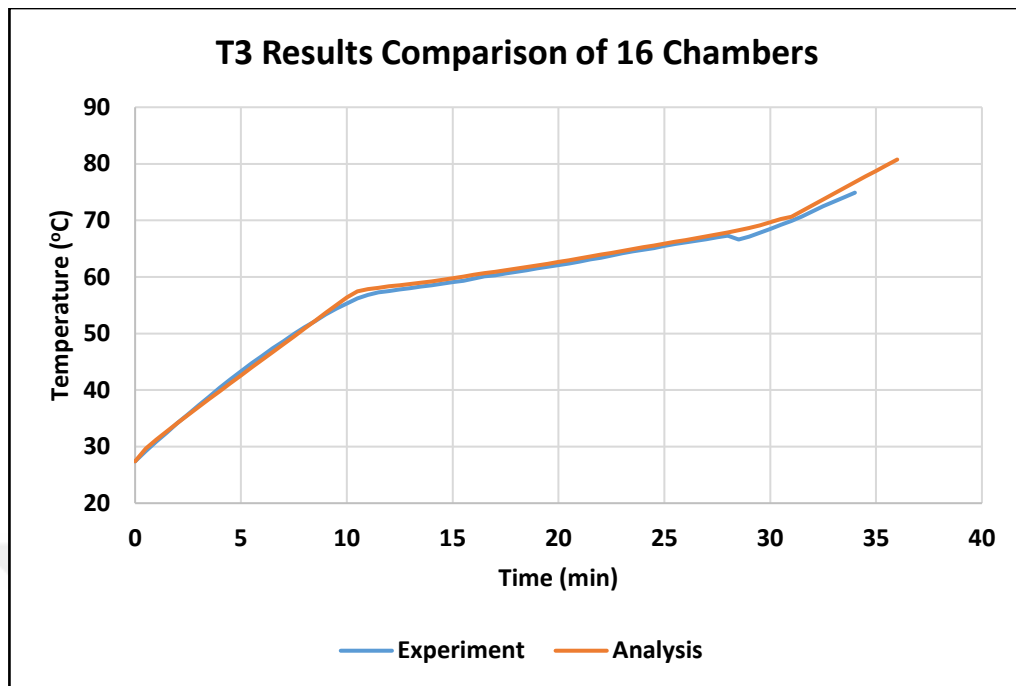


Figure B 8. The T3 results of 16 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

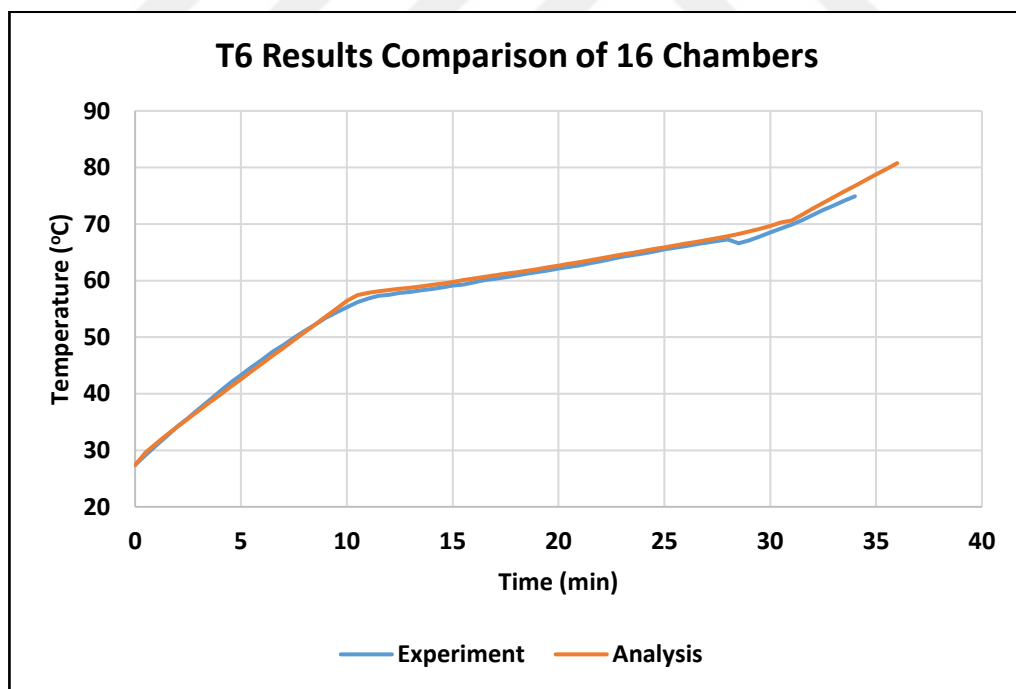


Figure B 9. The T6 results of 16 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

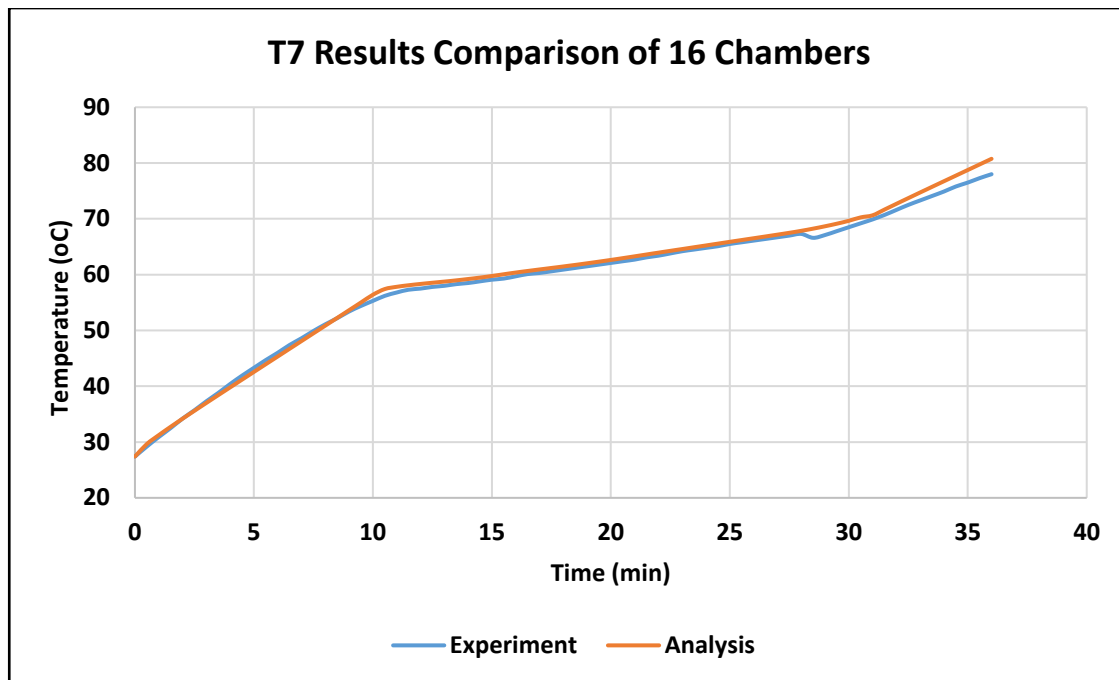


Figure B 10. The T7 results of 16 chamber PCM Heatsink with A58H PCM at 0° inclination angle.

C. The Experimental & Numerical Results Comparisons of PCM Type Effect for Selected Chambers

In APPENDIX C, the experimental and numerical results of selected chambers in 4 chamber PCM heatsinks are given. The positions of the thermocouple were given in Section 3.2. The T1, T2, etc. represents these positions and they can be found in Section 3.2.

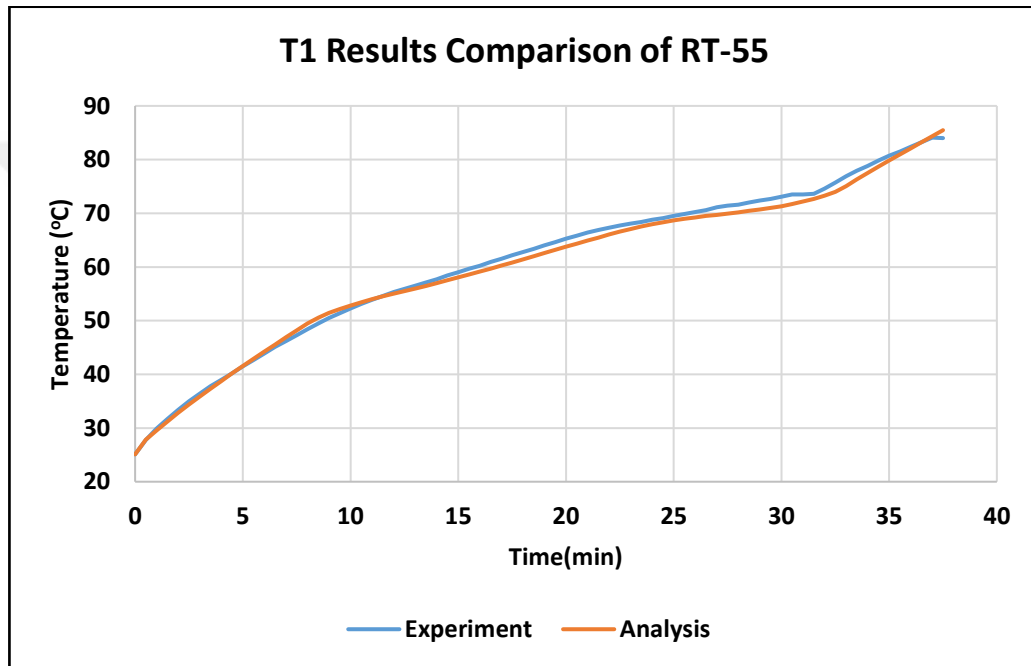


Figure C 1. The T1 results of 4 chamber PCM Heatsink with RT-55 PCM at 0° inclination angle.

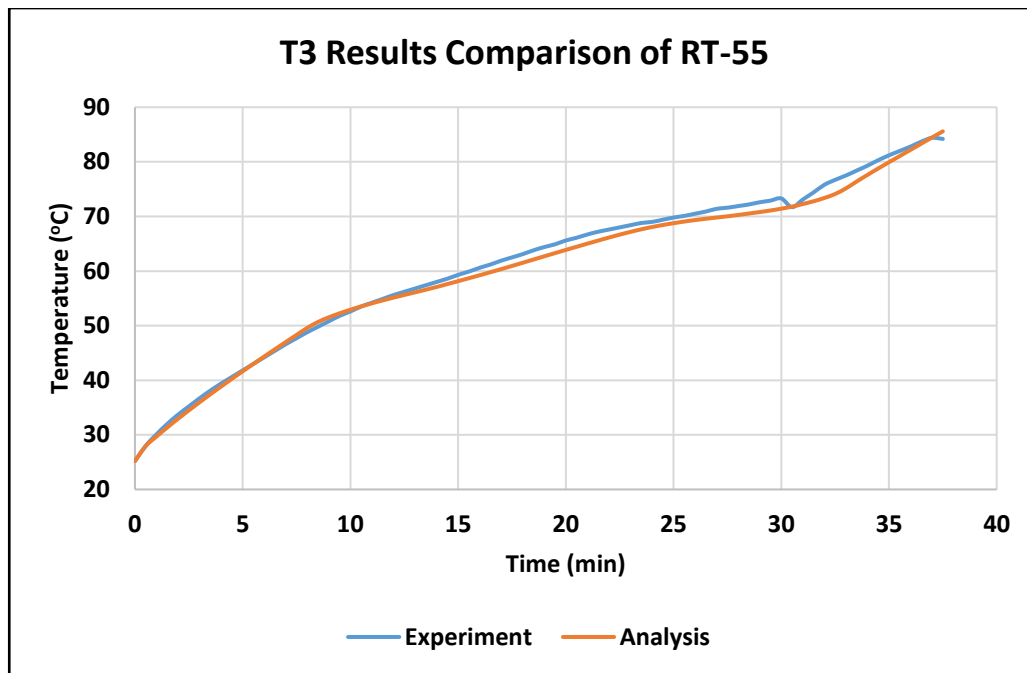


Figure C 2. The T3 results of 4 chamber PCM Heatsink with RT-55 PCM at 0° inclination angle.

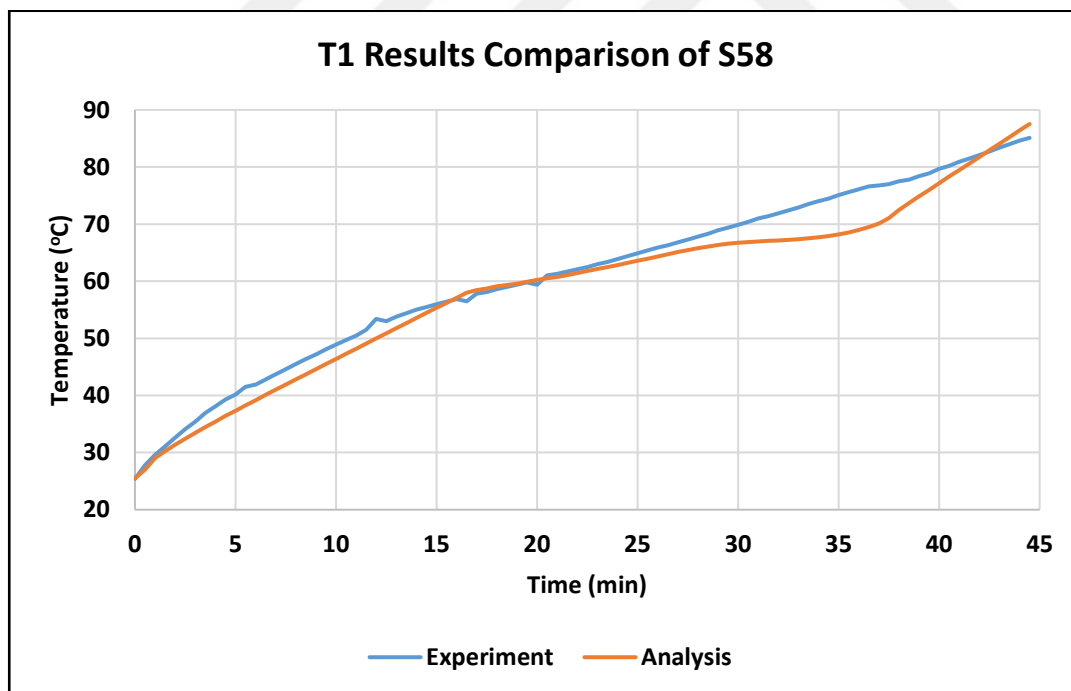


Figure C 3. The T1 results of 4 chamber PCM Heatsink with S58 PCM at 0° inclination angle.

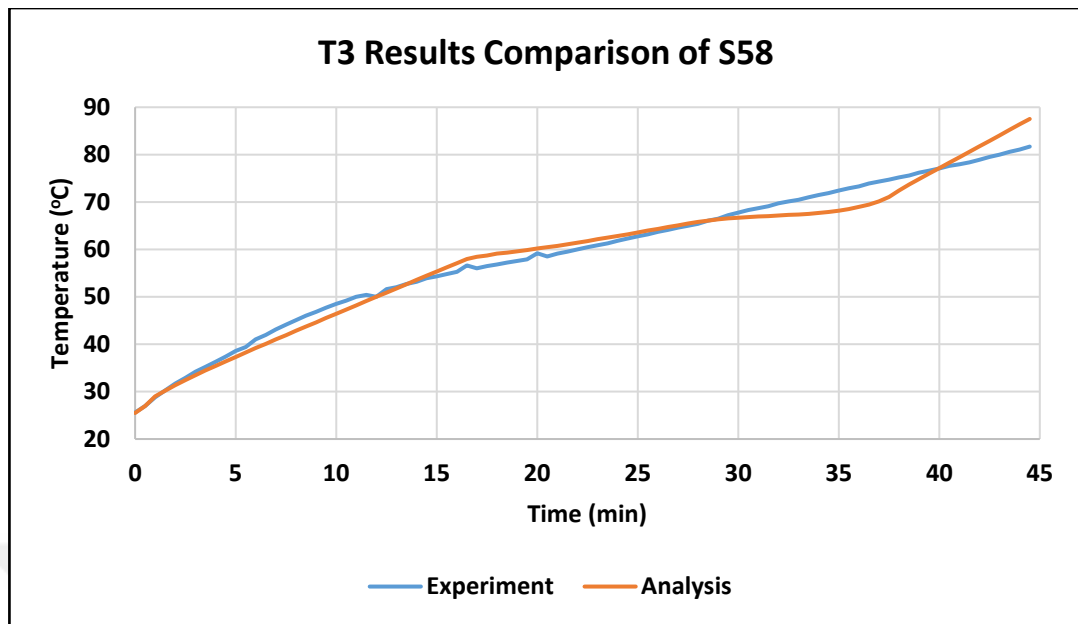


Figure C 4. The T3 results of 4 chamber PCM Heatsink with S58 PCM at 0° inclination angle.

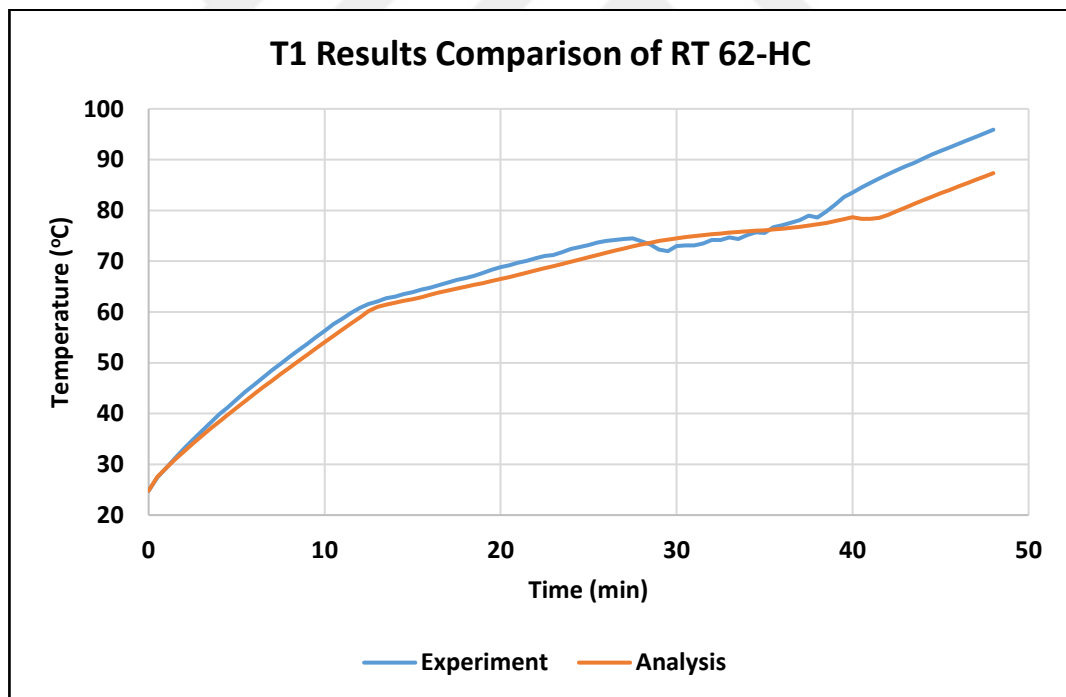


Figure C 5. The T1 results of 4 chamber PCM Heatsink with RT-62 HC PCM at 0° inclination angle.

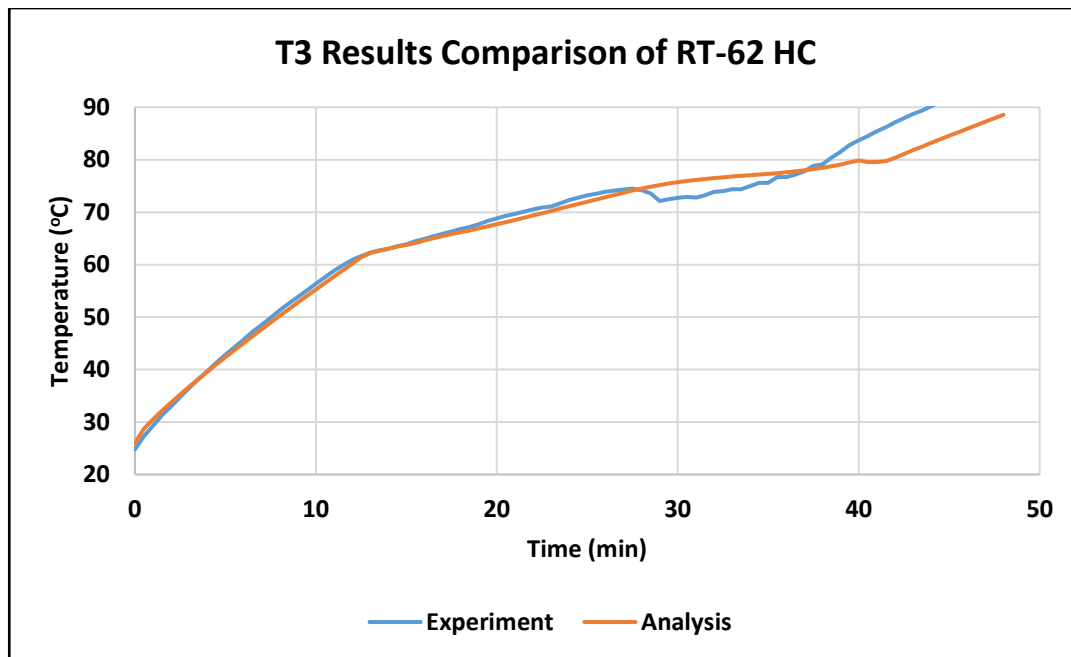


Figure C 6. The T3 results of 4 chamber PCM Heatsink with RT-62 HC PCM at 0° inclination angle.

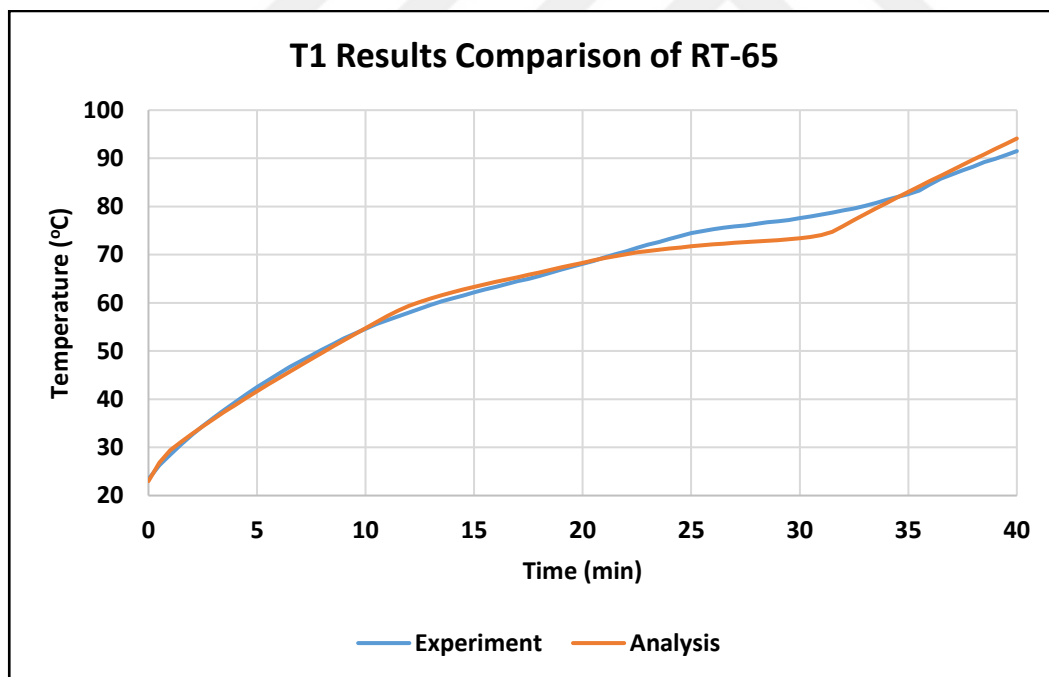


Figure C 7. The T1 results of 4 chamber PCM Heatsink with RT-65 PCM at 0° inclination angle.

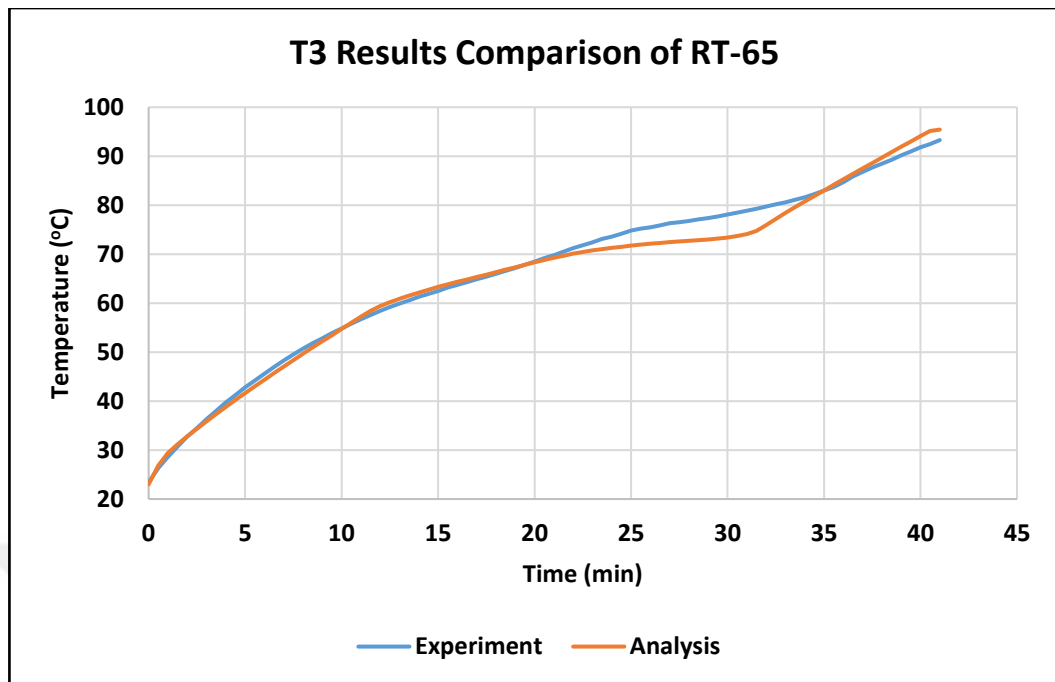


Figure C 8. The T3 results of 4 chamber PCM Heatsink with RT-65 PCM at 0° inclination angle.

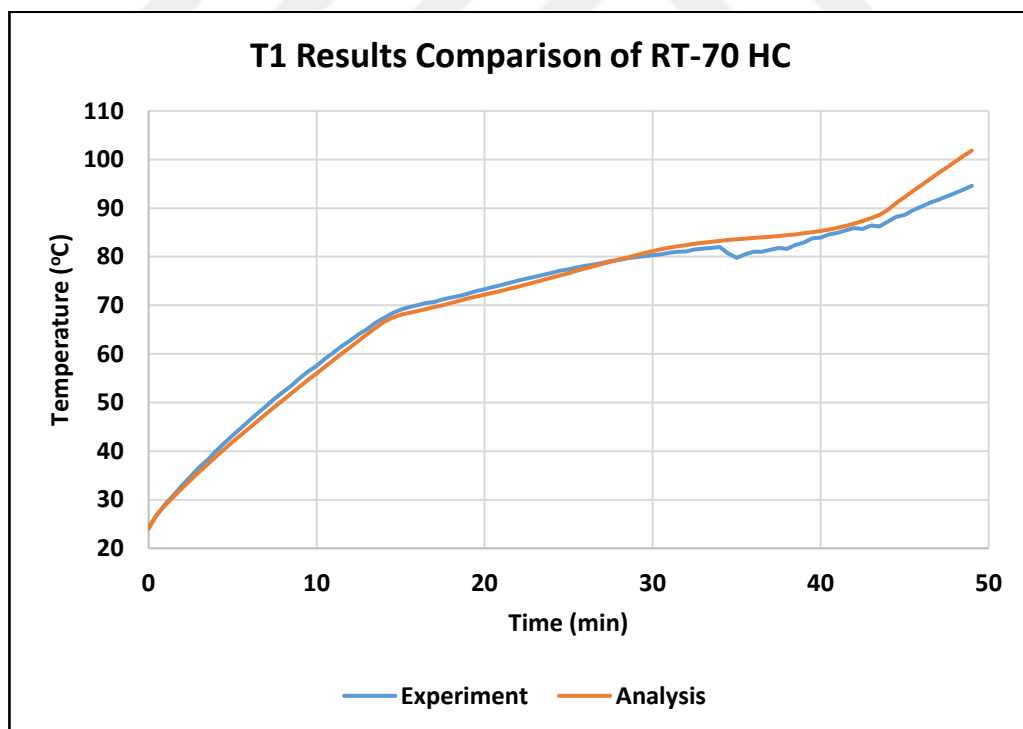


Figure C 9. The T1 results of 4 chamber PCM Heatsink with RT-70 HC PCM at 0° inclination angle.

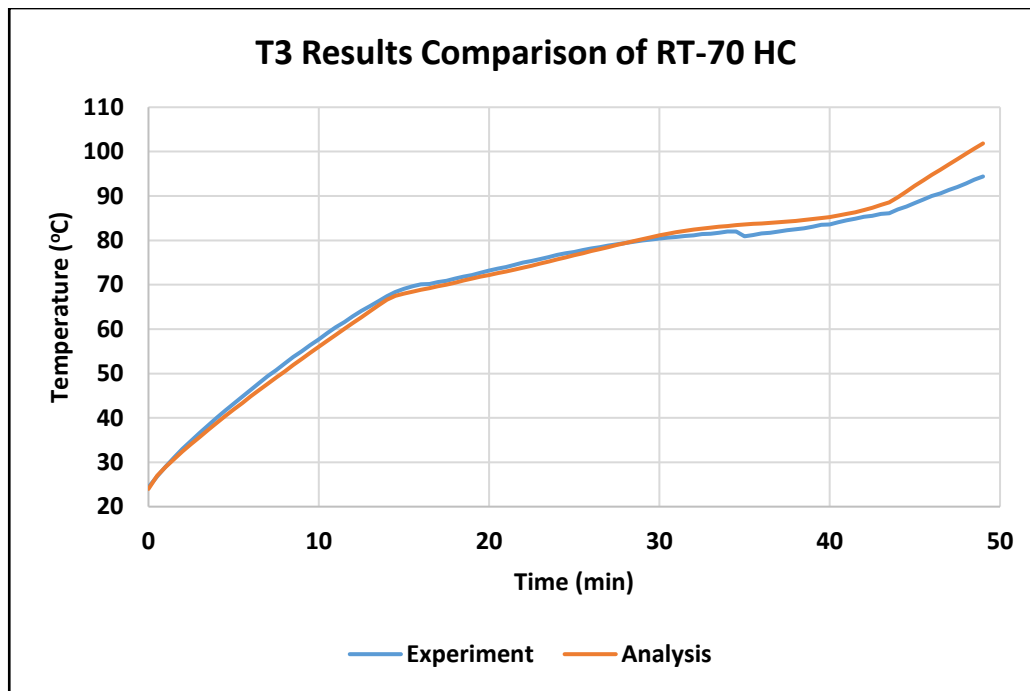


Figure C 10. The T3 results of 4 chamber PCM Heatsink with RT-70 HC PCM at 0° inclination angle.

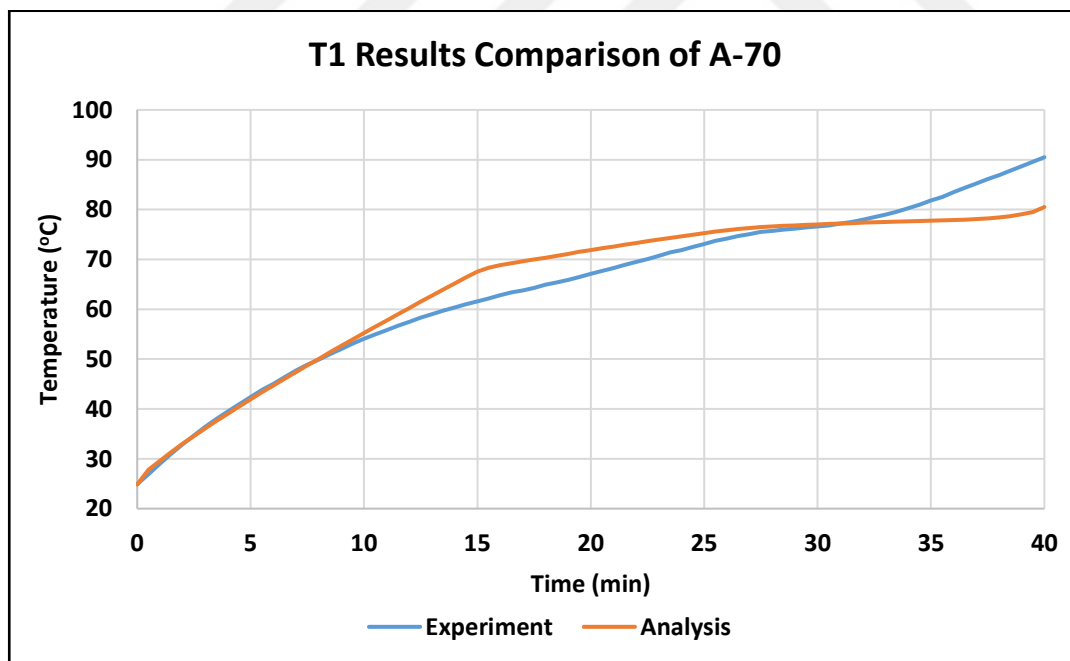


Figure C 11. The T1 results of 4 chamber PCM Heatsink with A70 PCM at 0° inclination angle.

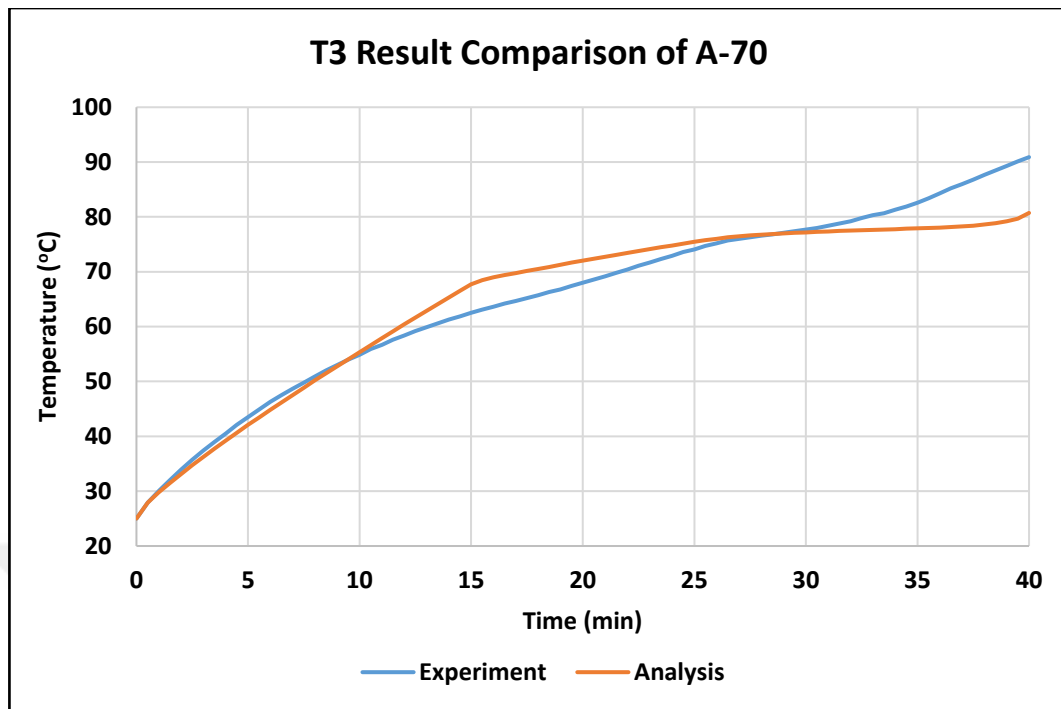


Figure C 12. The T3 results of 4 chamber PCM Heatsink with A70 PCM at 0° inclination angle.

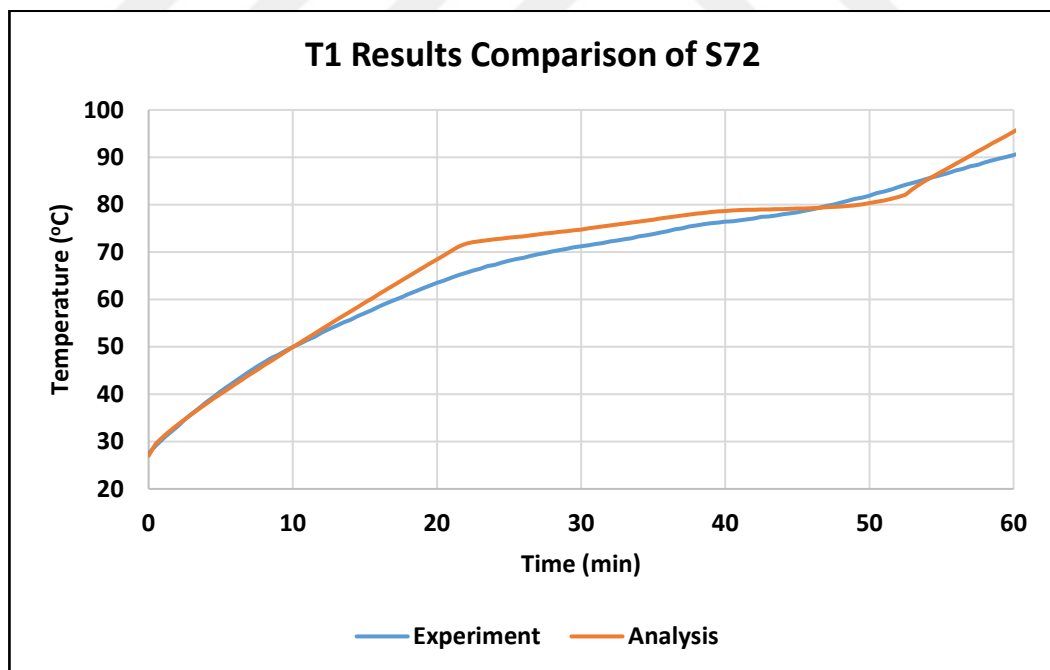


Figure C 13. The T1 results of 4 chamber PCM Heatsink with S72 PCM at 0° inclination angle.

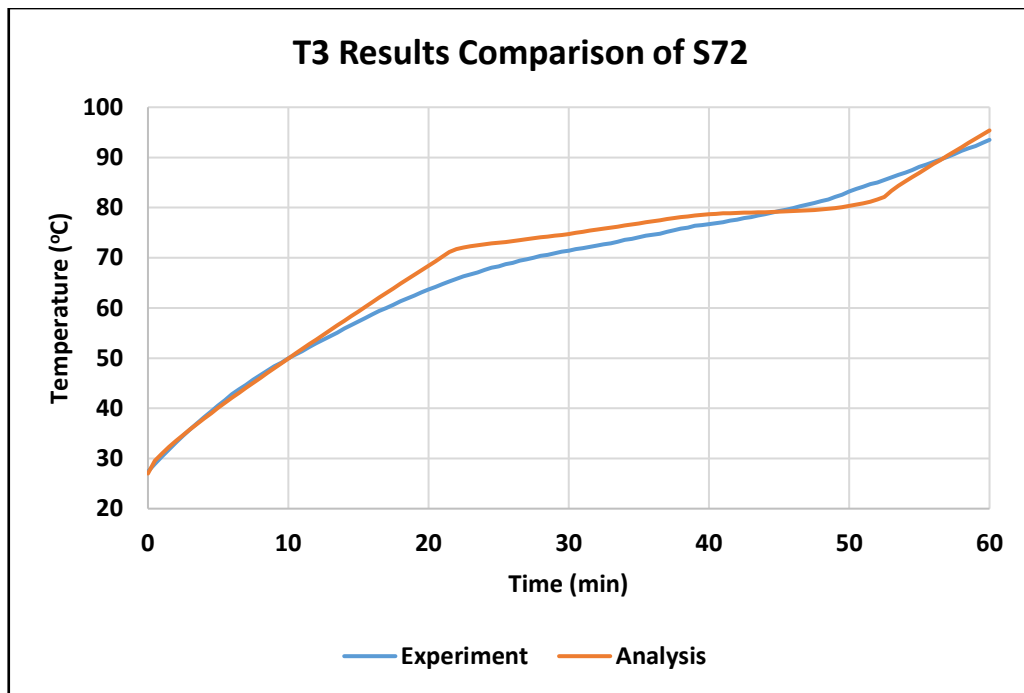


Figure C 14. The T3 results of 4 chamber PCM Heatsink with S72 PCM at 0° inclination angle.