Comparative Analysis of Phase Change Materials-Based Heat Sinks

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ABSTRACT

In response to the escalating demand for efficient cooling solutions in data centers, this paper explores the integration of Phase Change Materials (PCMs) within heat sinks for passive cooling of electronics, aiming to decrease the load on active cooling systems. Furthermore, PCMs offer the potential to flatten out peak loads, which often leads to the overdesigning of cooling systems. Computational fluid dynamics (CFD) analysis was conducted on various models of HP ProLiant DL160 G6 1U servers created using Ansys Fluent. Each model employed a different PCM within the heat sink, allowing for comparisons with a model containing conventional heat sinks. Commercially available PCMs including RT-44, RT-54, RT-64, RT-69, and RT-80 were used in this study due to their non-toxic nature and higher heat storage capacities. While some models encountered unrealistic results, RT-80 emerged as a promising PCM, demonstrating a noteworthy 24% reduction in maximum processor temperature. RT-80's solid-state stability, coupled with its capability to absorb cyclic peak loads, positions it as a viable solution for steady-state cooling and thermal time-shifting applications.
Keywords : Thermal Management; Phase Change Materials; Electronic Cooling; Heat Sinks; Computational Fluid Dynamics (CFD)

1 INTRODUCTION

THE The Moore's law states that every two years, the number of transistors on a microchip, doubles and the cost of its manufacturing is halved [1]. Once a mere observation made by the Gordon Moore, it became a long-term goal for the computer chip manufacturers and continues to be the driving force behind the modern advancements in the field. This miniaturization has also facilitated the development of more compact and powerful data centers. Data Centers are computer structures with several ICT equipment used for processing, transporting information and storing data [2]. They support daily activities, including online searching, social networking, telecommunications, banking, and shopping. If a data center fails unexpectedly, it might cause widespread disruptions and cost organizations millions. Therefore, they must have low to nil downtime. To ensure this, many state-of-the-art cooling technologies are utilized which often result in high electricity consumption. Overall data centers consume about 2% of the global power and their power consumption has been observed to grow at a rate of 12%. Cooling systems for data centers use about 40% of their total power [3]. Data Centers usually deal with variable loads which fluctuate throughout the day. To prevent any downtime, usually the cooling systems are designed with respect to the peak load borne by the center. This significantly increases the cost of the system that has to be installed. One way to prevent this is to flatten out the peak load by storing the excess heat and releasing at a later time thus preventing the need of an overdesign due to peak loads [4]. This can be accomplished using phase change materials by incorporating them within the pre-existing cooling systems. PCM's are an emerging prospect in cooling technologies due to their high latent heat of fusion and specific heat capabilities [5]. PCM's have the ability to maintain constant temperature by utilizing the incoming heat to break up intermolecular bonds [6]. These properties make them suitable for incorporating into conventional heat sinks. Numerous experimental and numerical studies have been conducted to explore the potential of

PCMs in the field of electronic cooling. Emam et al. investigated the melting of RT25HC, RT35HC, and RT44HC at three distinct heat flux values of 2000, 2950, 3750 W/m2 to simulate the heat from electronic devices. It was revealed that the use of RT25HC, RT35HC, and RT44HC decreased the average wall temperature by about 69.8, 80.44, and 74.44 °C respectively [7]. Kandasamy et al. worked on 3 different aluminum heat sink models and conducted a series of experiments with and without the inclusion of PCMs in the heat sinks at loads ranging from 2W to 6W. The results showed that at loads higher than 2 W, PCM based the heat sinks provided better cooling and a lower maximum temperature was reported. The study was also validated by a numerical investigation whose results were in perfect agreement with the experimental findings [8]. Al Siyab et al. experimentally studied multiple configurations of single and dual PCM heat sinks with RT-46, RT-49, RT-52, RT-55 and RT-58 as PCMs under heating loads of 1W, 1.5W and 2W. The study concluded that using two different PCMs in a heat sink might increase the safe operating time by 18%. Moreover, it was observed that changing the arrangement of the two PCMs inside the heat sink only resulted in a slight difference in maximum temperature [9]. While several experimental studies have been able to showcase the potential of heat sinks, there is a lack of computational studies focusing on the use of PCMs within real server geometries. This study aims to perform a comparative analysis of PCM-based heat sinks to determine the most suitable PCM for the cooling of a micro-processor and explore the effects of such heat sinks on overall cooling of the server.

2 METHODOLOGY

2.1 Overall Framework

To investigate the impacts of a phase change material into a conventional heat sink mounted on a processor contained on an actual server board, a numerical model of the server was created using Ansys Fluent. The model was firstly run with conventional heat sinks. Then, the heat sink of one of the processors was modified to include a compartment filled with a phase change material. Material properties corresponding to different PCMs were entered to create various models each of which was run under the same environmental conditions. The impact of different PCMs on the maximum temperature of the processor was studied at steady state. Moreover, the temperature at different regions of the PCM compartment was also observed to check if it is in solid or liquid state at steady state. The subsequent sections detail the sources of data utilized and the usage of Ansys Fluent to model the system.

2.2 Data Origin and Compilation

The server selected for the purpose of this analysis was HP ProLiant DL160 G6 1U server. The server was composed of 18 DIMM sticks, 2 graphic cards, 2 processors, an IOH chip and an ICH chip along with recommended heat sinks.

The drawings of the server were obtained from the vendor’s datasheets [10]. An online photo-measuring tool [11] was used to identify the distances between different components and their dimensions in the horizontal plane on the technical drawing of the server. To obtain information about the vertical dimension of these components, the datasheets of the components were consulted [12],[13].

The heat sinks for the processors and the chips were selected from their respective thermal and mechanical design guides provided by Intel [14],[15]. The design parameters of the heat sinks are given in the following table.

TABLE I
DESIGN PARAMETERS OF HEAT SINKS

Parameters	Type 1	Type 2
Base Length (mm)	90	50
Base Width (mm)	90	50
Base Height (mm)	2.5	4
Fin Thickness (mm)	0.2	0.7
Fin Height (mm)	61.5	26
Fin Spacing (mm)	1.05	1.55
Number of Fins	72	22

The material library of Cadence Celsius EC Solver was used to obtain thermal data for different components of the server. The thermal design power of the components was acquired from their corresponding thermal and mechanical design guides and other published work regarding the server [16]

TABLE II
PROPERTIES OF SERVER COMPONENTS

Component	Sub-component	Material Name from Cadence Celsius EC Solver Library	Thermal Design Power (W)
Processor	Substrate	Typical Substrate Material	95
	Die	Typical Die Material	
	Integrated Heat Spreader	Aluminum	
	Integrated Loading Mechanism	Aluminum	
PCB	-	Typical Board Material	-
DIMM & Cards	-	Typical Board Material	2.5
Slots	-	Typical Slot Material	-

ICH Chip	Substrate	Typical Substrate Material	4.5
	Die	Typical Die Material	
IOH Chip	Substrate	Typical Substrate Material	27.5
	Die	Typical Die Material	

The PCMs selected for the study were from the RT series manufactured by Rubitherm GmbH. From their catalogue of materials, hydrocarbon-based PCMs were selected due to their non-toxic nature and higher heat storage capacities [17].

TABLE III
PROPERTIES OF PCMS

Material	Density (kg/m^3)	Pure Solvent Melting Heat (kJ/kg)	Solidus Temperature (°C)	Liquidus Temperature (°C)
RT 44	800	250	41	44
RT 54	920	200	53	54
RT 64	830	250	63	65
RT 69	905	230	68	70
RT 70	825	260	69	71
RT 80	850	220	77	80

2.3 Numerical Modeling of Server

The geometrical data collected was used to create the server geometry along with the heat sinks. This model was named as the “Conventional Heat Sink Model” or “CHS Model”. To incorporate the PCMs into the heat sink of first processor, a compartment of 20 mm height was created between the base of the heat sink and its fins. The thickness of compartment was kept as 2.5 mm. A total of five such models were created each of which had a modified heat sink for one of the processors. Each model used a different PCM in the heat sink. All other components and heat sinks were kept the same. These models will be referred to as “RT-XX models” in the paper.

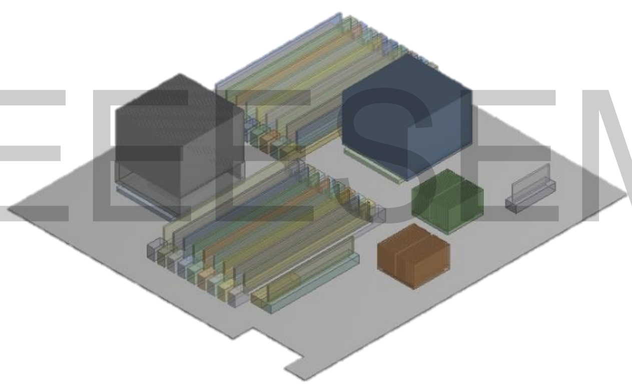

Fig. 1. Geometrical Model of the Server with Heat Sinks

Due to the nature of the model and access to limited computational power, non-uniform meshing was utilized for the purpose of this analysis. The element size for the model was specified as 0.01 m. Mesh sizing objects were then created to specify an element size of 0.001 m to components where heat was being generated. These components included the processors substrates, processor dies, integrated heat spreaders, chip substrates, chip dies, DIMMs, Cards, and the heat sinks.

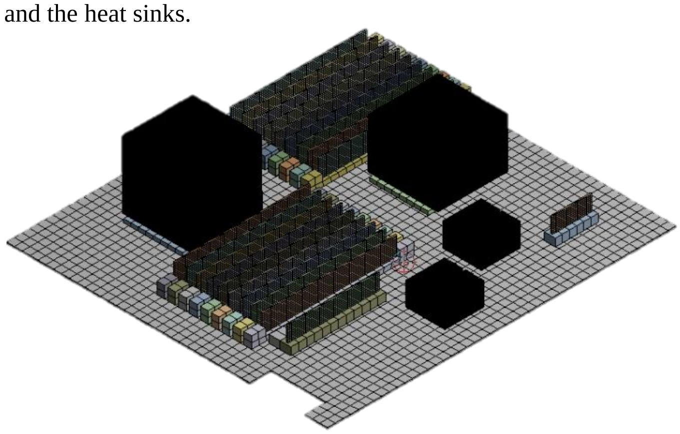

Fig. 2. Non-Uniform Mesh of the Server Model

To calculate the mass flow rate at the inlet and outlet, the fan volume flow data was taken was taken from a similar study [17]. The fans used had a volume flow rate of 26.67 CFM and a total of 12 fans were used making the total volume flow rate equal to 320.04 CFM. The volume flow rate was converted into mass flow rate by using the value of air density as 1.225 kg/m3. The total mass flow rate across the system came out to be 0.1850 kg/s.

On the surfaces exposed to air directly, a convection boundary condition was applied. The surfaces where the convection boundary condition was applied included the outer surfaces of DIMMs, cards and all 4 heat sinks. Moreover, the convection boundary condition was also applied on the upper surface of the PCB. The value of convective heat transfer co-efficient was taken as 91 W/m2K corresponding to fan speed of 11 m/s [18].

3 Results and Discussion

3.1 Conventional Heat Sink Model

Fig. 4 shows that the maximum temperature of 87 °C is present at the IOH chip while the maximum temperature on processor surface is around 71 °C. Although the temperature at the chip is much higher it is in the safer region and its performance is not as adversely affected by higher temperatures as the performance of the microprocessors. Therefore, it is suitable to apply better cooling techniques for the processors. All other components are around ambient temperatures owing to their lesser heat generation rates.

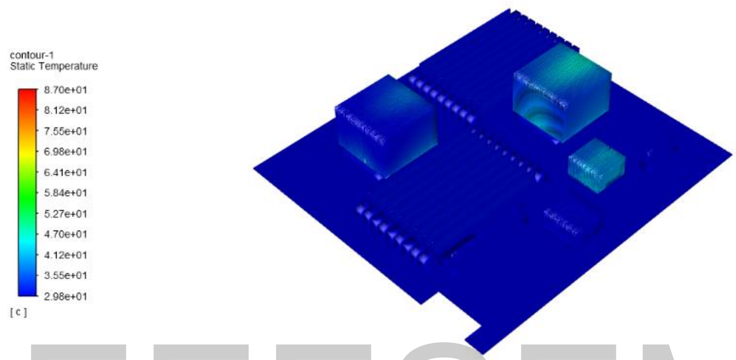

Fig. 3. Temperature Distribution across the CHS Model

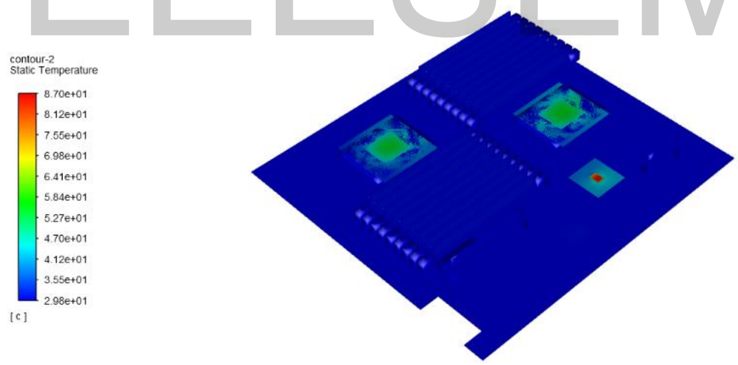

Fig. 4. Temperature Distribution across the CHS Model shown without the Heat Sinks

3.2 RT-44 Model

Fig. 6 shows that the maximum temperature on the first processor surface is around 136 °C while the temperature at the surface of processor 2 is around 71°C. This shows that the inclusion of RT-44 within the heat sink has negatively affected the overall performance of heat sink and heat is being accumulated around the processor rather than being dissipated. This could be due to the fact that the PCM melts too soon and starts to store the energy dissipated by the processor rather than dissipating it via the heat sink fins located above it. This in turn builds up temperature at the processor and results in such higher temperatures which can realistically ruin the processor. The accumulation of heat also affects the DIMMs array behind the heat sink and higher temperatures can be observed at DIMM surfaces. Moreover, the clear difference between the two processor temperatures can also be observed.

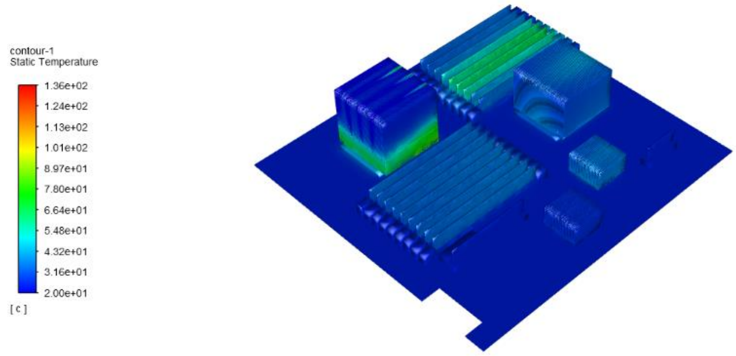

Fig. 5. Temperature Distribution across the RT-44 Model

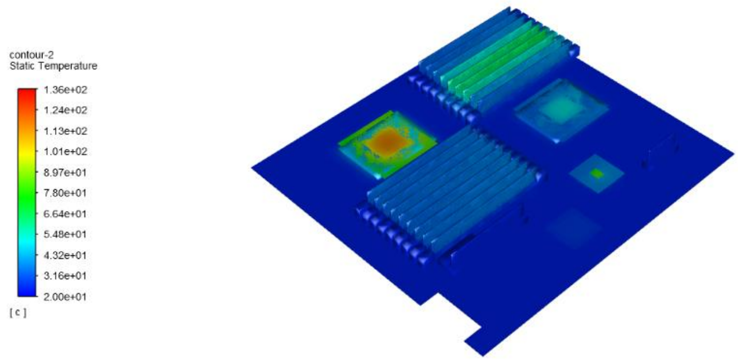

Fig. 6. Temperature Distribution across the RT-44 Model shown without the Heat Sinks

3.3 RT-54 Model

Fig. 8 shows that the maximum temperature on the first processor surface is around 184 °C while the temperature at the surface of processor 2 is around 71°C. This is even worse than RT-44 and shows another case where the PCM with low melting point melts too early and causes accumulation of heat inside the PCM compartment. This ultimately yields a non-realistic result which is not feasible at all. Moreover, it can be seen that PCM temperature has also crossed 100 °C which can also damage the PCM as it is beyond its operating thermal range. Such high temperatures will also create high pressures inside the PCM compartment which might lead to its structural failure.

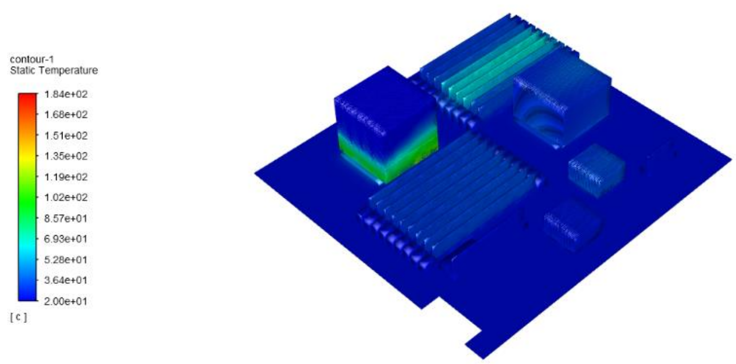

Fig. 7. Temperature Distribution across the RT-54 Model

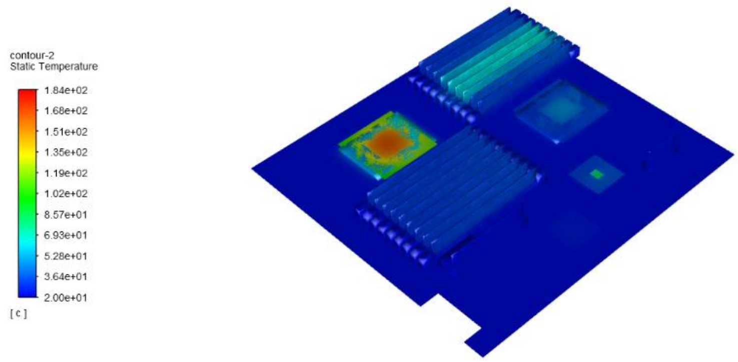

Fig. 8. Temperature Distribution across the RT-64 Model shown without the Heat Sinks

3.4 RT-64 Model

Fig. 10 shows that the maximum temperature on the first processor surface is around 138 °C while the temperature at the surface of processor 2 is around 71°C. The temperature distribution of the model is comparable to that of RT-44 but is better than RT-54. Despite being better than RT-54 it still produces a situation whereby the addition of PCM within the heat sink negatively affects its performance by poor dissipation of heat from the processor.

The DIMMs of RT-64 Model are at lower temperature as compared RT-44 Model. At the same time however, RT-44 Model has better distribution of heat along the vertical fins of the heat sink. This behavior is not present in the model under discussion.

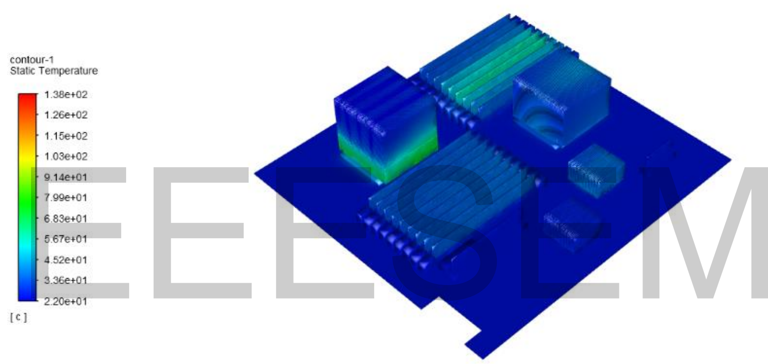

Fig. 9. Temperature Distribution across the RT-64 Model

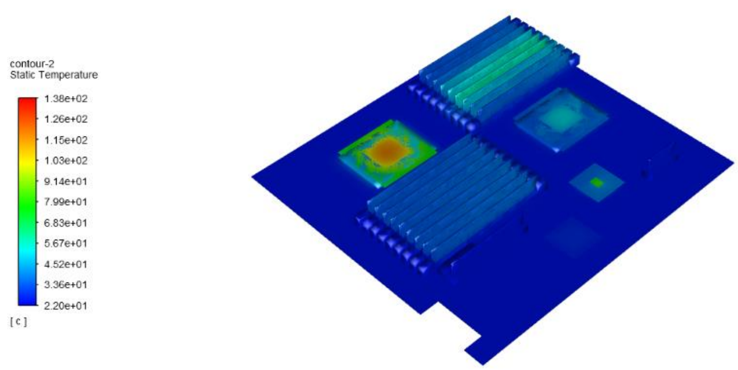

Fig. 10. Temperature Distribution across the RT-64 Model shown without the Heat Sinks

3.5 RT-69 Model

The temperature contours obtained for RT-69 Model are comparable to those of the CHS Model as shown by Fig. 12. However, the temperature of the processor does not show any improvement rather its temperature is a little above the maximum processor temperature obtained for the Conventional Heat Sink Model. It can be observed that the PCM is in partially solid state and has not fully melted yet. The PCM has attained a state of partial solidity at steady state. About half of the PCM appears to have melted while the rest appears solid. The limitations of the analysis can also be observed from these figures as realistically it is not possible for the solid PCM to sit above the melted portion of the PCM and natural convection comes into play to create very complex scenarios which are out of the scope of this study.

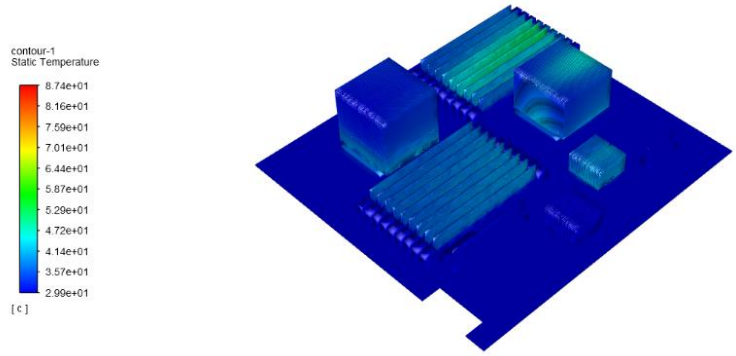

Fig. 11. Temperature Distribution across the RT-69 Model

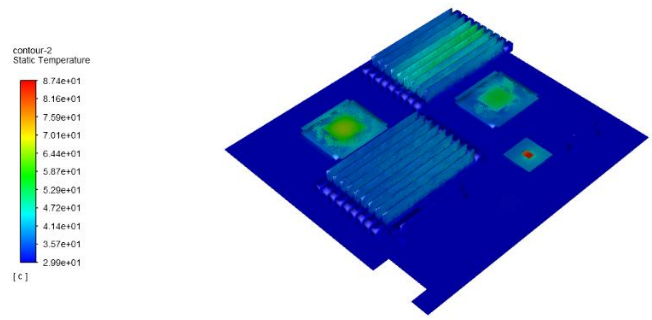

Fig. 12. Temperature Distribution across the RT-69 Model shown without the Heat Sinks

3.6 RT-80 Model

Fig. 13 and Fig. 14 both show that the temperature at Processor 1 and Heat Sink 1 is below that of Processor 2 and Heat Sink 2. To be exact, the maximum temperature at Processor 1 surface is 54°C while at the surface of Processor 2 it comes out to be around 71°C. This shows a 24% decrease in temperature achieved by the PCM based heat sink. The maximum overall temperature is 87°C which corresponds to that of IOH chip. The PCM at steady state is in full solid form and has not melted except at the interface between the processor and the heat sink. The PCM being in solid form at steady state means that the heat sink is able to withstand any cyclic peak load that might occur on the processor. In case of a peak load the PCM would start melting and limit the temperature to 80 °C (average melting temperature of RT-80) which is around the threshold of maximum allowable temperature of processors.

Moreover, due to no accumulation of heat, the temperature of the air flowing over the heat sink does not rise as drastically as it is rising for Processor 2. Consequently, the DIMM array placed behind Heat Sink 1 is at a higher temperature than ambient but this temperature is acceptable as it is around 40°C.

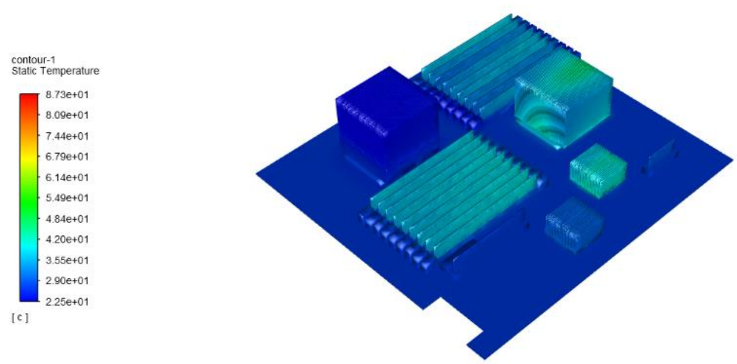

Fig. 13. Temperature Distribution across the RT-80 Model

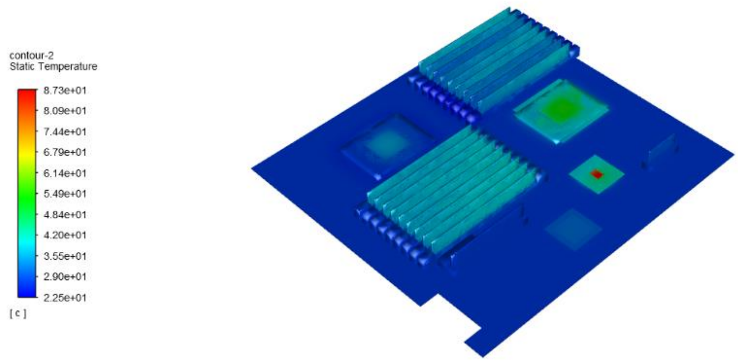

Fig. 14. Temperature Distribution across the RT-80 Model shown without the Heat Sinks

3.7 Comparison Summary

All the discussion regarding the different models is summarized graphically by Fig. 15. From the trend observed, it seems that PCMs melting at temperatures higher than 80 °C might yield even better results but the hydrocarbon based PCM closest to RT-80 is RT-90 which has the melting point right at the end of the safe operating range of the processor.

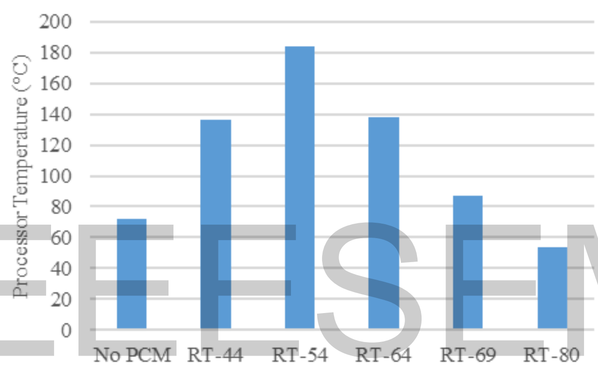

Fig. 15. Comparison between Maximum Processor Temperatures of various Models

4 Conclusion

CFD analyses were carried out for various models of the same server whereby each model used a different PCM within the heat sink. Moreover, a model with simple heat sinks was also created for comparison. RT-44 Model, RT-54 Model and RT-64 Model showed unrealistic results with maximum temperatures going well above 100 °C which is damaging to both the processor and the PCM. RT-69 Model showed results which were comparable to the Conventional Heat Sink Model but it did not justify the inclusion of PCM within the heat sink. RT-80 Model showed the most promising results with a 24% decrease in maximum processor temperature. Furthermore, it could also be used to absorb cyclic peak loads at constant temperature as it does not melt at steady state. The aspect of incorporating internal fins within the PCM compartment can be explored in future work to see how enhancement of thermal conductivity affects the overall performance of PCM based heat sinks. Moreover, similar investigations can be carried out by using PCM based heat sinks for other components within the server to explore the potential effects it can have on the flow of air over the entire server.

5 Acknowledgement

The authors extend their heartfelt thanks to Mr. Muhammad Kashif Tariq m.kashif@uet.edu.pk for his invaluable guidance and insightful contributions throughout the course of this study. His expertise and support were crucial in shaping the direction of this research and enhancing its quality. We deeply appreciate his dedication and commitment to our work.

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