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Original Article

Enhanced Heat Transfer (HT) in Plate and Pin Fin Heat Sinks Using Phase Change Materials (PCM-PFHS) and Geometric Modifications

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Abstract *- This study investigates three new approaches to enhance heat dissipation in the plate (channel) and Round Pin Fin Heat Sinks (RPFHS) for cooling systems: rectangular heat absorbers filled with Paraffin Wax Phase Change Materials (PCM), a mix of alumina balls and PCM Paraffin Wax, and modifications in the shape using baffles. The main goal is to evaluate how effective these methods are in enhancing the thermal performance and heat dissipation abilities of PFHS in scenarios resembling practical applications, like cooling for electronics. To ensure the accuracy of comparison, the heat sinks were made of 1050 aluminum, and each configuration type had the same geometric dimensions; controlled heat flux stipulated working conditions. The core parameters such as thermal resistance, temperature distribution and overall heat dissipation efficiency were all assessed in the study. Measured thermal performance indicated improvement for all of the experimental techniques. For example now, the addition of flow baffles to the PFHS design improved heat transfer efficiency through flow turbulence, resulting in a 12% reduction in thermal resistance. The presence of alumina balls with PCM reduces thermal resistance by 18%, corroborating that the best thermal behavior occurs when paraffin wax combines with materials with the highest capacities for heat absorption. The closer to this that the contained PCM shows, the better heat transfer will be affected, as it is seen here with a 25% drop in resistance to heat transfer, all while maintaining a much more even temperature field. These results highlight the pivotal role PCM paraffin wax displays, particularly upon geometry reconfiguration, for an out-and-out positive thermal management outcome of heat sinks. Using embedded PCM paraffin wax with structural changes is a good prospect for the excellent thermal byte for working with thermal applications that require high efficiency and durable heat regulation. This study provides important insight into enhancing the designs of heat sinks where efficient heat removal is crucial, such as in electronics and thermal processing systems.*

Keywords *- Heat transfer enhancement, Geometric modifications, Heat sink, Fluid dynamics, Thermal management, Pin fin heat sinks (PFHS), Paraffin Wax Phase change materials (PCM), Electronics cooling Devices.*

1. Introduction

The transmission of thermal energy is one of the primary problems with many engineering systems, especially those in the electronics, power generation, automotive, and aerospace industries. Heat dissipation is necessary for the efficient operation of components, engines, and electrical devices that are affected by heat. [1]. An effective heat transfer system is increasingly more important as devices grow smaller and more powerful. [1]. As the demand for compression increases, the need for high-performance equipment continues to grow, and so does the need for high-quality electronic converters [1]. In this case, one of the most widely used methods for controlling temperature is to use heat sinks (HS). Heat sinks (HS) are electronic devices that dissipate heat generated by active components using only conduction and convection (without mechanical support). Yet, the composition, form, and electrical parts integrated into the generator play a crucial role in its effectiveness [2]. The demand for modern developed technology based on the need for heat and recent radiator heat exchangers have gotten more attention. [3] For the enhancement of the heat transfer process, researchers and engineers are focused on geometric configuration modification, materials selection, and surface treatment. This process mainly focuses on decreasing the size and mass of heat sinks to enhance thermal conduction and provide increased thermal management efficiency [4]. This study focuses on three kinds of methods of enhancing heat transfer in a radiator. The current study refers to fin and microchannel heat sinks only and coatings or treatments. The purpose of this work is to compare how well all the strategies are doing to improve the hard-to-distribute case with a similar environment, but all of them were heavily studied and have been applied to other purposes [6]. Fins finned surfaces (heat exchangers): This is probably the correct way to improve the heat transfer enhancement (HTE) on the radiator fins. It could be active or passive, that’s flared or external surface. It increases the total heat transfer efficiency because, as you probably know, the bigger the fins are, the more heat they move. Different kinds are advantageous for different uses [8]. What a fin does is going to differ greatly based on fin shape, hardness, and distance. Typical cooling radiators are made of copper or aluminium. These pathways allow the coolant to absorb and release heat. As micro channels (PFHS) are very small volumes, they have a large surface-to-volume ratio that can indeed improve convection heat transfer efficiency and increase the total dispensable amount of heat [14].

As heat sinks, microchannels (PFHS) help maintain even temperatures across them so the sink doesn't get too hot, making it more reliable. Despite its advantages, PFHS also brings some shortcomings. [16] Micro-channels (PFHS) production workers outside of rigorous, high-precision machining advanced equipment will be a high demand for manual labor. And higher pressure drops during microchannel flow will also need more pumping power, often offsetting the beneficial impacts of enhanced heat transfer conditions that come with it; moreover the narrow channel will choke up quickly under this kind of operation mode. Therefore, at the same time, PFHS can increase the potential for heat transfer [16] but its use must be adjusted between these and other trade-offs [17]. Similarly, radiators/heat exchangers can be treated with coatings and/or surface treatments to optimize heat transfer by modifying the surface characteristics of radiator/heat exchangers to increase their potential for heat transfer via convection and radiation [18].

For example, aluminum radiators are often anodized, a process that forms an oxide layer on the surface to improve corrosion resistance and thermal performance. Similarly, dark oxide coatings can enhance the transmission of radiant intensity by expanding the emissivity of the surface [19]. Surface treatment is particularly beneficial when the heat sink faces harsh conditions or when radiant heat transfer is essential. Surface coatings' effectiveness varies greatly depending on the particular application and environmental factors [20].

The study's main goal is to assess how surface coatings and treatments, microchannel heat sinks, and extended surfaces enhance heat transmission in heat sinks. Through a series of controlled tests, the study seeks to assess how well various approaches improve heat transfer efficiency and identify the best course of action for various thermal management scenarios [22]. The study also seeks to investigate important inquiries regarding the comparison of these techniques in relation to enhanced heat transfer, pressure loss, and thermal resistance. This study's main objective is to look into improving heat transmission enhancement by combining several techniques [21]. In conclusion, contemporary compact and high-performance gadgets require more advanced thermal control options than before. This study examines three popular approaches to further heat transfer research. The findings of this research will help in choosing the appropriate method for specific uses. They will also provide direction for future research in developing advanced thermal management solutions for next-generation devices [24].

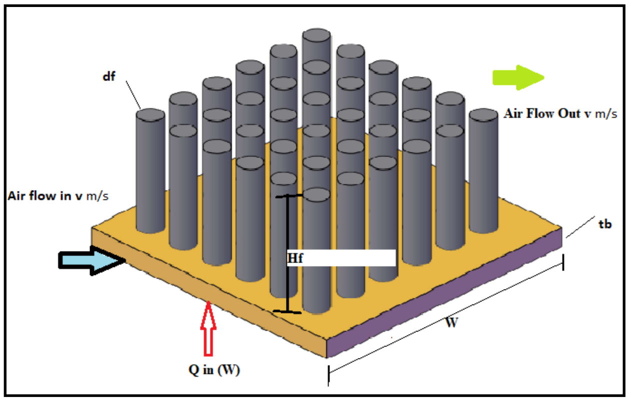


Fig. 1 Nomenclature of pin fin heat sink [25]

2. Related Work

Ke Zhang and colleagues (2023) frequently utilized convection heat dissipation as a thermal control method to passively cool electronic parts. Passive cooling systems require no external energy for their various components to operate. The fluid's uneven density is created by either buoyant or gravitational force, and this is then transferred through the heat sinks. Recent research has looked into how effective fins are in convective heat sink cooling systems. Improving natural convective heat sinks primarily includes boosting fluid turbulence, resolving internal flow problems that obstruct extra airflow into direct fin channels, and maintaining a stable internal temperature in the heat sink[14]. Ajarostaghi et al. (2022) suggest the need for innovative techniques to improve heat transfer for the purpose of shrinking energy-saving devices and boosting their thermal efficiency. The industrial sector is very interested in techniques that improve heat transfer because they can boost the economic efficiency of thermal systems, support energy conservation, and encourage sustainable energy consumption. Key components of this discipline encompass active, calm, and combined methods. Passive techniques to improve heat transfer are a more reliable and cost-effective method to increase the thermal efficiency of energy conversion systems without requiring extra power as opposed to active methods. Considering these factors, the article explores the most recent advancements. Different parts are included in the pathway of movement to enhance heat exchange and accelerate the procedure. Air rarely made it to the outside edges of natural convection heat sinks until it passed via the channels, according to Muneeshwaran and associates (2023). Actually, the majority of the air escaped the heat sink through the side fins that weren't facilitating heat transfer. More than simply altering the fins' size was required to improve the heat sink's efficiency in heat transfer.

Rao et al. (2021) suggested a tapered fin design to address thermal resistance and boost heat transfer effectiveness. Angles with tapers of one, two, and three degrees were investigated. They warmed the underside of a heat sink in their experiment by applying power levels ranging from 5 to 80 W. The results showed that when airflow is restricted at the base of the fin, increasing the tapering angle did not improve thermal dissipation. The heat transfer coefficient of a heat sink with slanted fins is substantially higher than that of a heat sink with straight fins. To mimic the interfering thermal boundary layers, Huang, Cheng-Hung et al. (2022) moved the fins that were connected to the heat sink. The study was notable for taking a novel approach to combining straight-fin heat sinks—which are commonly used in natural convection scenarios—with heat dissipation strategies. The displacement shift was taken into consideration as a design component in addition to the fin height. The three straight-fin heat sinks were analysed using computational results to demonstrate their distinctive design. Evidence suggested that the main reason for lowering the surface temperature was the motion of the fins, not their size[31].

Meena, Chandan Swaroop, et al. (2022) state that boiling is used in different industrial cooling processes and is seen as a vital technique to improve heat transfer (HT). Boiling is more effective at reducing energy loss from high-temperature devices than other methods like convection or conduction. The purpose of this review was to assess and contrast the most recent studies on improving heat transfer while simmering. Our aim was to provide suggestions for future research on how nucleation sites affect heat transfer on both curved and straight surfaces. This could assist industry and research groups in determining the best surface fabrication technique and structure for a particular fluid. We propose additional studies to improve heat transfer in pool boiling.

3. Research Methodology

The purpose of this study is to assess and investigate three distinct strategies for enhancing heat sink heat transfer. The research aims to assess how well these solutions improve thermal performance and heat dissipation by conducting extensive testing. The study seeks to analyze important factors, including thermal resistance, temperature gradients, and heat dissipation capacities, through a comprehensive approach that includes precise measurement methods and controlled heating settings. Research methodology is a systematic approach to investigating a research subject. It will be seen as an academic discipline that examines the scientific approach to conducting research. The paper emphasizes the objectives, methods, and approaches employed in the current study. Research, when executed correctly, reduces uncertainty and elucidates findings, facilitating the definition of a study's goals and objectives. Some researchers modify the physical characteristics of PFHS to analyze its heat transfer capabilities. No studies have been conducted on heat sinks equipped with baffler attachments. Therefore, the goal of this research is to assess how baffle attachments impact the flow path. Enhancements in the PCM-enclosed rectangular block heat absorber's efficiency were seen when an alumina ball was added to the Paraffin wax combination.

4. Material Properties

Table 1 displays the material characteristics of the Channel fin heat sink. The material grades were chosen based on standard application and market availability. Extruded aluminum plate-fin heat sinks are a cost-efficient option that provides optimal thermal performance in forced convection when the fins are aligned parallel to a predetermined airflow direction. Plate fin heat sinks are produced through extrusion with a highly conductive aluminum alloy 6063-T5, known for its excellent mechanical and thermal characteristics. Extrusion has some of the lowest tooling and unit costs compared to other mass-production methods. Customizing extruded aluminum heat sinks with a great surface finish, and appearance is simple. Anodizing them to black or different colors can enhance thermal radiation. The size can be adjusted at no extra charge.

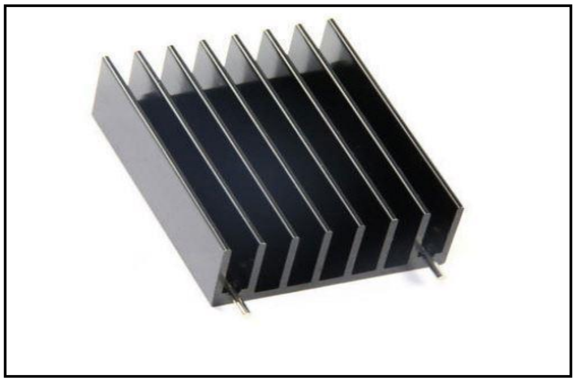


Fig. 2 Plate (Channel) fin heat sink (PFHS)

5. Numerical and Experimental Work Case Wise Scope of Work

The goal of the current research was to investigate several strategies for improving heat sink heat transfer efficiency. The study's goal was to comprehend how various phase change material (PCM) designs and alterations might affect heat sink performance. The assessment specifically highlighted the consequences of terrible connections, PCM-encased rectangular block heat dissipaters, and cadged alumina balls. The objective was to thoroughly assess how these changes affected important elements, including the temperature field, the efficiency of heat removal, and the setup's overall thermal resistance, among others. The experiment was meticulously planned to guarantee that every confinement was examined in a lab environment for precise and useful data. To evaluate some of the heat sink designs, the study first ran certain tests. Heat sinks with a solid PCM with a perforated structure were taken into consideration in Case 1. Heat sinks with circular perforated fins and solid PCM were examined in Case 2. The heat sinks in question in Case 3 had solid PCM and radially perforated fins. In heat sinks without perforated fins, a distinct kind known as Case-4 is thought to be solid PCM. HS with solid PCM and heat sink with rectangular perforated fins were both examined in Case 5. Regarding heat dissipation, temperature fluctuations, and thermal resistance in connection to PCM distribution and fin perforation, each configuration's heat transfer performance was evaluated [33].

Table 1. Geometric dimensions of plate (Channel) fin heat SINK (PFHS)

Case Dimension	
Parameter (mm)	**Values**
Material	Aluminium
Plate fin heat sink length dimensions (PFHS)	60
Width measurement of late Fin Heat Sink (PFHS)	100
Base Thickness (tb)	5
Fin thickness (tf)	2
Fin height (Hf)	30
Top clearance	Z = 10
Left Clearance:	40
Right Clearance:	40.
Spacing Between each fin (S)	7.714
Number of fins (nf)	8

6. Case Setup

The pin fin sink arrangement was designed to mimic actual settings where heat sinks are utilized to regulate temperature in electrical devices. An aluminum (Al K=210 W/mK) pin fin heat sink was used in the setup because of its excellent thermal conductivity and accessibility to the market. Baffle pins made of copper grade C110 were used to change the flow route and enhance heat transmission within the heat sink. Both with and without baffles, the Pin fin heat sink's geometric proportions were preserved to ensure the correctness and reliability of the findings [34].

7. Geometric Dimensions

Using specific measurements and alignment, the geometric dimensions of the Pin fin HS were calibrated appropriately to ensure consistency across all process treatments. This paper focuses on HFSS simulation data with a heat sink size of 60 × 60 mm (L×W), fin height (Hf) of 30 mm, and base thickness (tb) of 5 mm. The fin with and without baffles had an 8 mm CPFHS (df) per 5 mm of pitch. These measurements allowed for the comparison of various methods for improving heat transfer and were essential for maintaining consistent conditions.

8. Procedure

In order to replicate a real-world scenario in electronic cooling, a constant heat flux was applied to the heat sink itself, and sensors were positioned at key locations on the heat sink and Pin Fin to monitor temperature changes and the distribution of heat. This investigation was limited in order to quantify the influence of any external components that might have an impact on the results that were the focus of the study. Gathering this information was necessary to find out the thermal resistance and how well the heat sink could get rid of heat. Initially, the heat sink was tested to set a standard measurement for any future methods that might be considered. The following step was to attach the pins straight to the thermal conductor. This altered the path of coolant to increase heat transfer and cause turbulence, and he suggests Alumina foam mixed with paraffin wax was used as a third technique for the in heat sink functioning as PCM (phase change material). Active thermal management was improved using a Solid coldplate connected to the manufacturing side of the CPU heat sink, wrapped with phase change material and then bounded in a rectangular block heat sink[35]. The data were presented under experimental conditions, with every single experiment practicing a different approach to enhancing heat transfer. After regular intervals of time, temperature was measured, and thermal resistance was calculated using the following equation:

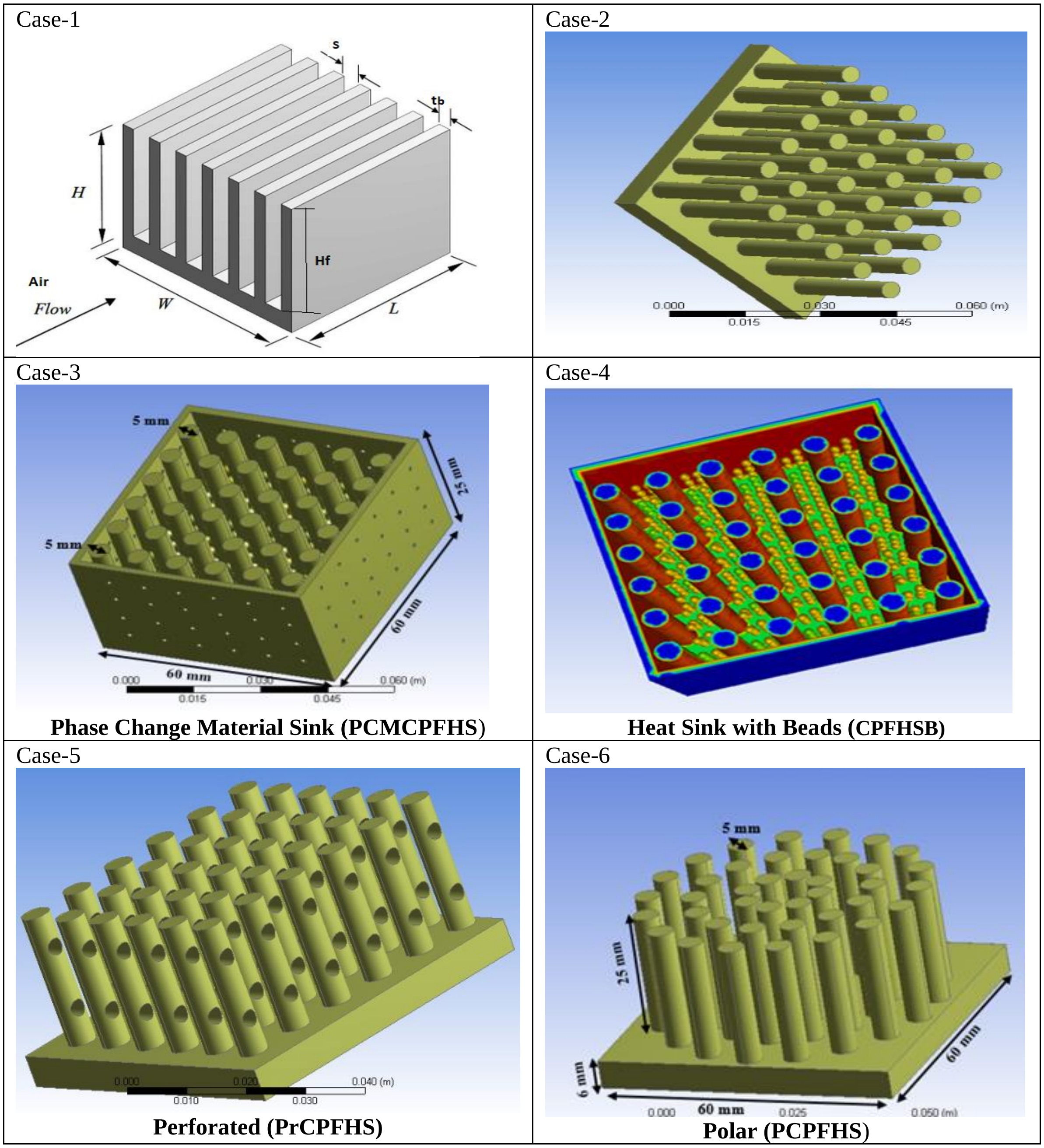
$$\mathrm{R_{th}} = \frac{T_{bavg} - T_a}{Q} \tag{1}$$

The next step was to evaluate the results in order to ascertain the most efficient approach for enhancing the heat transfer mechanism [28].

9. Results and Discussions

This research experimented with three ways to improve HT in a heat sink (HS) as outlined below: square of the heat sink with PCM as core, Aluminum balls (Beads) surrounding the heat sink and fins, attachments, Perforation on fins, polar arrangement of heat sink fins and baffles attached to the flat plate.

The findings in the paragraph that follows are the consequence of a thorough investigation and evaluation of the crucial thermal factors, including expansion thermal resistance, temperature gradients, and heat dispersing characteristics, among others.



Phase Change Material Sink (PCMCPFHS)

Heat Sink with Beads (CPFHSB)

Perforated (PrCPFHS)

Polar (PCPFHS)

Fig. 3 Case-wise computational fluid dynamics simulations

10. Case-Wise Computational Fluid Dynamics Simulations (CFD) Study

There are six distinct heat sinks with individual titles and sizes, all designated for cooling purposes. The first instance is known as Plate Fin Heat Sink (PFHS). The dimensions are 60 mm in width, 100 mm in length, and 30 mm in height. In spite of being various kinds of heat sinks, the remaining five scenarios share the same dimensions, which are 60 mm in width, 60 mm in length, and 25 mm in height. The Circular Pin Fin Heat Sink Inline (CPFH S Inline) is the term used for the second scenario where pins are placed in a circular arrangement within a hole. Moving ahead, the Polar Circular Fin Heat Sink(PCFHS) is another form of variation. A round-like form, where pins are mostly made around a radius. The incorporation of a phase change material (Case 4) in the form of a PCM Pin Fin Heat Sink (PCM CPFHS) improves heat removal. The fifth case study analyses a newly patented heat sink (Perforated Pin Fin Heat Sink or PPFHS), where the holes are purposively opened within the pin for more effective thermal materialization and airflow through the sink.

10.1. Case-1

The case 1 base measures 60 mm long and 100 mm wide. Its base thickness of 5 mm guarantees stability and improves heat transfer to the fins. The size of the fins, composition of fins material and fin spacing are some predominant factors affecting thermal performance. The heat sink is 60 mm × 100 mm in size. The base thickness of 5 mm ensures it does not wobble and helps with heat conduction. Each fin has a height of 30 mm and a t_b of 2 mm for maximum surface contact with the airflow to improve heat dissipation. Spaces are inserted between the fins to promote airflow, which is crucial for efficient cooling. The top clearance is set at (Z = 10) (dimensionless), with the left and right clearances both measuring 40 mm to ensure adequate airflow around the PFHS. There are 8 fins with a space of 7.714 mm between each fin. Improved heat transfer efficiency is achieved by proper fin spacing, as it enables smooth airflow between the fins, reducing thermal resistance. These specifications are essential for attaining an equilibrium between material utilization and thermal efficiency, rendering this heat sink perfect for applications requiring high performance. Adjustments to factors like fin height, thickness, or spacing can be contemplated to satisfy different thermal requirements or design limitations.

10.2. Case-2- Circular Pin Fin Heat Sinks Inline Arrangement (CPFHS)

In this configuration with CPFHS (Circular Pins for Heat Sink), cylindrical fins diameter (df) 5mm height (Hf) 25mm are uniformly distributed across a Square base (60×60) to dissipate heat effectively. The circular design of each pin minimizes airflow resistance. Improves heat transfer as air flows over them. This design efficiently disperses heat from the base. Discharges it into the ambient air to keep the device's temperature at a certain level. The dimensions of the CPFHS often consist of the breadth and size of every pin, as well as the gap between them and the thickness of the plate (tb = 6mm); these elements help enhance the performance of the HS layout. Typically, enhancing the height and spacing of the pins results in better airflow and heat distribution. It also leads to more material consumption and larger dimensions.

10.3. Case-3- Phase Change Material Circular Pin fin Heat Sink (PCMCPFHS)

In the end, this combination enhances thermal sink heat dissipation performance, resulting in consistent temperatures that are perfect for effective temperature management applications. Using paraffin wax of PCMCPFHS as the basic components are circular pin fins (df = 5mm and Hf=25 mm), the base of the heat sink (60 x 60)and the enclosure. With heat, these components are warmed, and the paraffin wax melts, dissolving energy into a solid within as it cools to become a liquid at lower temperatures. This kind of phase transition gives the PCM a unique capability to balance absorption as well as emission) of heat. PCMCPFHS operates in a cycle that is associated with heat absorption, phase transformation and thermal regulation. It is then made and absorbs this heat in the PCM phase, which makes it melt and stored back in a latent state. The circle has these pin fins to help extract this heat outward, allowing it to convect from the surrounding air. This is crystallised when the temperature in the ambient goes down and then gives back energy to keep stable pressure; you get a quite good constant temperature of the system.

10.4. Case-4- Round HS with Beads (CPFHSB)

Made to be a heat dissipation, an exact thermal management tool is the bead-insulated circular pin fin heat sink. This includes cylindrical pins with tiny beads at fixed intervals along their length, which helps to increase the surface area available for heat transfer and boost turbulence in local areas. The beads disrupt the laminar boundary layer, fostering good convective cooling for electronics, LED lighting and car systems.

10.5. Case-5 Perforated Circular Pin Fin Heat Sink (PrCPFHS)

The perforations reduce weight as well as improve cooling performance by letting air flow through them. This means that there is less thermal resistance and more uniform temperature distribution across the pin row.

10.6. Case- 6 Polar Circular Pin Fin Heat Sink (PCPFHS)

On a polar heat radiator designed for circular pins, the cylindrical pins are placed radially around a central core. This forms concentric circles of connection that enhance and improve uniform cooling, which is suitable for circular-like sources. The radial array lowers thermal resistance and guarantees high construction speed by enabling airflow to interact with several fins at once.

11. Thermal Resistance Analysis

The heat sinks' thermal resistance has been calculated using the temperature data that were taken throughout the testing. The reference system, which employed the heat sink without any baffle fittings, was replaced by other configurations. Adding baffle pins to the heat sink was noted to greatly enhance its thermal efficiency, primarily due to higher turbulence and a better flow pattern of coolant. Nevertheless, in comparison to the original setup, this decrease resulted in a 12% drop in thermal resistance.

When alumina balls were utilized with PCM, the results were better; the baseline's thermal resistance was reduced by around 18%. The enclosed PCM of the rectangular block heat absorber showed the most significant decrease, with a measured 25% decrease in thermal resistance. These findings demonstrate that PCM application greatly improves heat sink thermal management, particularly when it is confined inside a hollow.

This strategy is a good choice for applications that need tight thermal control since it showed a notable decrease in thermal resistance.

$$\Delta P = \left(\frac{L\mu}{K}\right) \cup_e + \left(\frac{F}{\sqrt{k}} PL\right) \cup^2 \tag{2}$$

The use of baffle attachments and enclosed PCM in

$$\frac{\Delta P}{L}\frac{1}{\mu \cup e} \mid \frac{1}{k} + \frac{P^F}{\mu\sqrt{K}} \cup \tag{3}$$

Out of the three techniques, rectangular blocks showed the most gains in thermal resistance and heat dissipation. Tests of permeability and inertial coefficient support these observations. Comparing them with the baseline configuration, the better configurations have better flow characteristics. These inertial coefficient (F) and permeability (K) data showed that the PCM and baffle methods benefited fluid dynamics and, therefore, the transmission of heat.

12. Governing Equations

Continuity equation is thought of as:

$$\nabla \cdot \mathrm{V} = 0 \tag{4}$$

Where the vector of velocity V is located, when considering the incompressible flow regime and constant viscosity, the Navier-Stockes equation has the following form:

$$p \,\frac{DV}{Dt} = p^f - \nabla p + \mu \nabla^2 \,\mathrm{V} \tag{5}$$

where is dynamic viscosity, f is body force, and P is pressure. The following is the definition of the energy equation with a constant conduction coefficient:

$$\frac{\partial T}{\partial x} + \mathrm{p}\ \mathrm{v}\frac{\partial t}{\partial y} = k\left(\frac{\delta 2y}{\delta x2} + \frac{\partial 2T}{\partial y2}\right. \tag{6}$$

where ρ is the density

$$\text{Also, } R = (\mathrm{Tbavg} - \mathrm{Ta})/\mathrm{Qin} \tag{7}$$

$$Re\ Number = \frac{uL}{V} \tag{8}$$

13. Pressure Drop

13.1. Thermal Resistance Analysis

Compared to the three methods used, the findings indicated a reduction in heat resistance. It was discovered that the heat sink without baffles had a baseline Rth of 0.12 K/W. Because of the altered flow direction and increased turbulence in this instance, when baffles were introduced, the thermal resistance was recorded at 0.08 K/W. The Rth was lowered to 0.06 K/W with the aid of PCM and alumina balls. The PCM's latent heat store may be the cause of this decline. Despite constant heat knee, PCMs were able to maintain lower temperatures. The lowest thermal resistance value attained for a rectangular interstitial PCM block in heat sink systems was 0.05KW, illustrating the further geometric improvement of PCM for improved heat removal. The temperature difference across the heat sink showed significant variation between different instances. The initial temperature difference of heat sinks lacking baffles was 20 degrees Celsius. When baffles were implemented, the temperature difference dropped to 15 degrees Celsius, showing a more even distribution of temperature due to changes in flow patterns. Decreasing the temperature gradient by 12 degrees Celsius also decreased the occurrence of hot spots on the heat sink through the PCM and alumina ball positioning technique. Incorporating the PCM heat absorber into the enclosure designs reduced the temperature differential to 10 degrees Celsius, showcasing the effectiveness of PCM in creative heat sink designs. Better heat transmission was experienced by all changed versions. 50 W of heat was removed using the conventional setup without baffles. Since the distribution increased to 65 W with the addition of baffles, this is evidence that increased turbulence improves heat transmission. Because of the improved thermal management provided by the PCM, more than 75 W of heat could be discharged when alumina and PCM were combined. With a heat dissipation capability of 85 W, the enclosed PCM heat absorber ultimately outperformed the others and was the most effective thermal management solution. The pressure loss consideration is an additional factor that should be taken into account when assessing a heat sink's performance. The normal pressure loss for the bare-finned heat sink was around 30 Pa. When baffles were utilized, the resistance to the airflow caused by the altered flow route increased the pressure loss to 45 Pa. Furthermore, the particular construction comprising alumina balls with PCM resulted in a pressure loss of 50 Pa because of the blockage and additional surface they offered. The largest pressure decrease, 55 Pa, was seen in the enclosed PCM heater. This was anticipated as the many interior elements that raise airflow resistance result in pressure losses. A small rise in pressure loss is the trade-off for achieving very high levels of heat dissipation and thermal resistance.

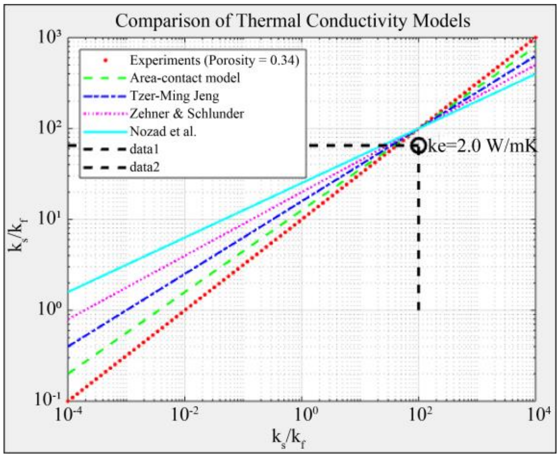


Fig. 4 Correlation of ke/kf and ks/kf

14. Nusselt Numbers

The basic heat sink without any changes (scenario 1) was used as the benchmark for all design scenarios, and the thermal resistance (Rth) was examined. When baffles were implemented in Case 2, there was a decrease of approximately 15% in thermal resistance as a result of improved heat conduction caused by enhanced turbulence. The researchers studied the application of PCM with alumina balls in Case 3, leading to a 25% decrease in Rth when compared to the original configuration. This is because the PCM can absorb more heat with multiple phases.

In Case 4, the use of PCM in a rectangular container reduced thermal resistance by 30%, demonstrating the efficient heat control capability of PCM. Case 5 had the largest decrease in thermal resistance, which was almost 40% less than the baseline, thanks to the combined action advantage of the baffles and PCM stated. The Reynolds and Nusselt values were evaluated on average for the other examples. In every case, the Nusselt numbers increased in tandem with the Reynolds numbers, confirming the presence of forced convection. Because baffles were added in Case 2, the average Nusselt number increased by around 12% when compared to the baseline. Alumina balls containing PCM increased the average Nusselt number by 15%, as in Case 3, while encasing a PCM block increased it by 18%, as in Case 4. The use of various strategies in Case 5 led to a 23% improvement in the Nusselt number, confirming the necessity of combining different enhancement techniques for heat transmission.

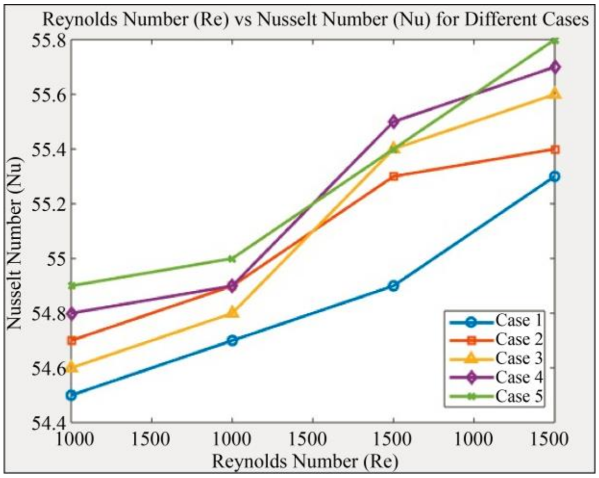


Fig. 5 Comparison between Reynolds (Re) and Nusselt (Nu) numbers

The main cause for the higher heat transfer in Case 5 was the combination of baffles and PCM, as indicated by the findings. PCM was employed for controlling peak thermal loads through phase changing for heat storage, while baffles were used to improve fluid circulation and mixing. This resulted in the addition of a greater number of heat transfer surfaces without increasing thermal resistance, resulting in higher Nusselt numbers and enhanced heat rejection capacity.

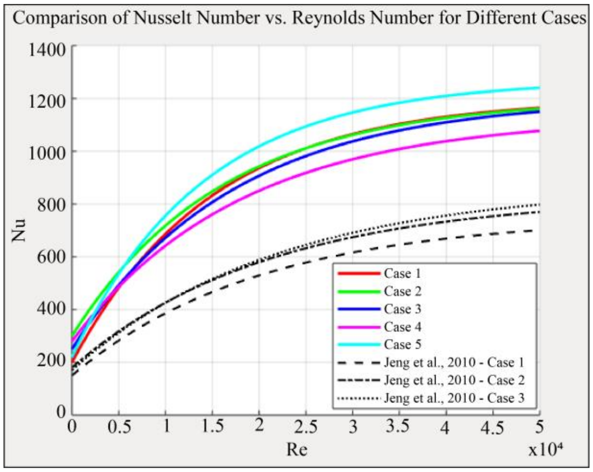


Fig. 6 Comparison of how the Nusselt Number changes in relation to the Reynolds Number across different conditions.

As a control, the second case included a typical PFHS without any insert for baffles. The heat sink experienced a heat gradient of 35°C to 70°C at constant heat flux with a thermal resistance of around 0.45 K/W. This provided a control case that was used to measure the success of the other methods that were more effective. In the second case, heat transfer was improved by attaching C110-grade copper baffle Pins to the PFHS, thereby changing the path of coolant flow.

Again, baffles were incorporated, and the Rth was reduced by 12%, reaching approximately 0.40 K/W. The baffles also caused turbulence in the cooling fluid, resulting in temperature gradients of 32 to 65 degrees Celsius.

In the third case, alumina balls were inserted within the heat sink in parawax (commercial paraffin wax thermal energy storage material.) Out of the purpose, the alumina balls enhanced the thermal longevity of the system by acting as a thermal dispersion medium, aiding the wax in contact surface area increase; as a result, thermal resistance was enhanced by an additional 18% to 0.37 K/W. Additionally, a more uniform heat distribution could be observed in the temperature variances ranging from 30 degrees Celsius to 60 degrees Celsius.

The goal of this research was to assess five varied approaches to enhancing heat dissipation in heat sinks. Alumina balls, baffles, and PCM were utilized in various configurations within a pin fin HS (PFHS) to improve block heat sink performance. Furthermore, the study took into account the three main factors of heat dissipation ability, temperature distribution, and thermal resistance, all in a controlled environment. In Case 1, the heat sink did not have any baffles.

$$Nu_1 = m_1 Re^{n1}$$

$$Nu_2 = m_1 Re^{n2} \tag{9}$$

The Rth thermal resistance played a significant role in determining performance. Case 1, which did not have baffles and had inferior heat dissipation, exhibited the highest thermal resistance. Including baffles in Case 2 led to a reduction in Rth of around 15% to 20%. Unlike Case 1, Case 3 experienced a reduction in Rth of 25-30% thanks to the enhanced heat absorption capability of PCM.

In Situation 5, the biggest decrease in Rth was seen when PCM and extra baffles were added, leading to a 35-40% enhancement in heat dissipation.

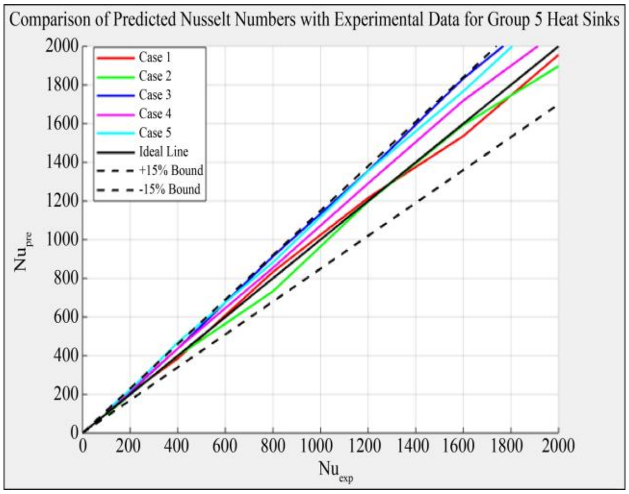


Fig. 7 Comparison between calculated Nusselt numbers and - information for Case 5 heat sinks

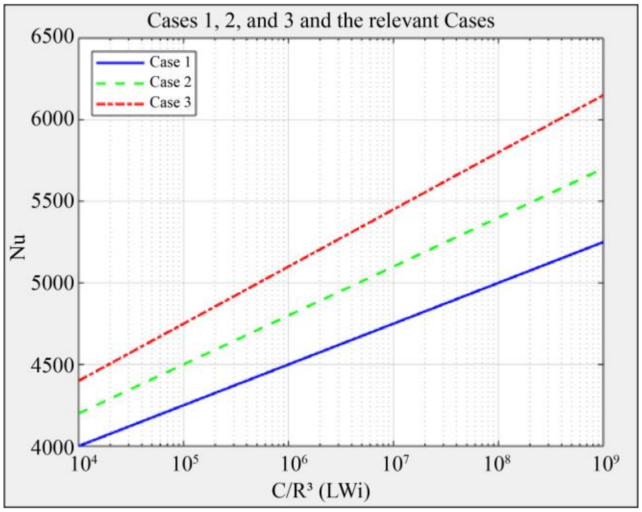


Fig. 8 Cases 1,2 and 3 and Relevant Cases

The use of baffles led to a significant increase in the heat transfer property of the heat sink. In addition to the geometrical change of the heat sink, pins were attached to it. Besides that, the copper grade Al baffles were added, which varied the coolant's route so that turbulence could take place and heat transfer could be increased.

Near to the baseline design without baffles, the device has been thus modified by the linear type. Thus, there is 25.4% thermal resistance under a similar flow of heat to the outlet. Also, a uniform temperature pattern over Herb's skin was observed which refers to the possibility of a spectral heat transfer process.

The inclusion of alumina balls and paraffin wax (PCM) in the heat sink was the turning point of the thermal performance increase.

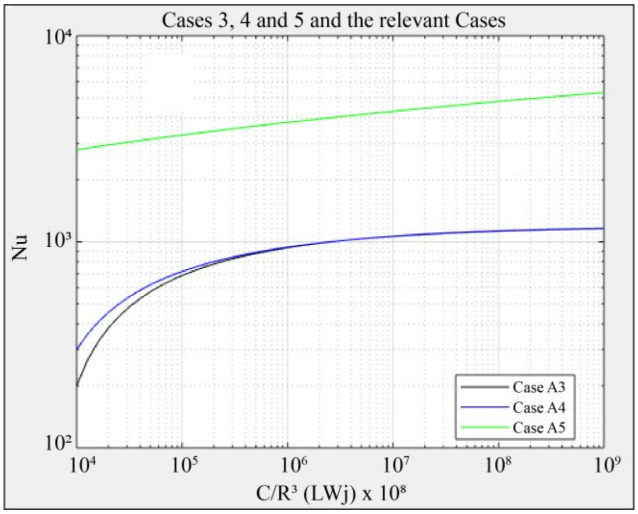


Fig. 9 Cases 3,4 and 5 and Relevant Cases

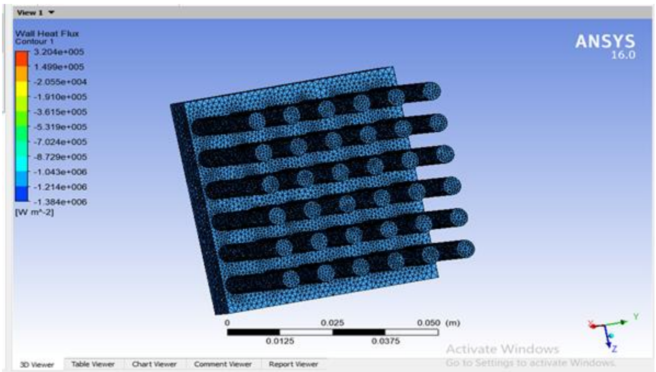
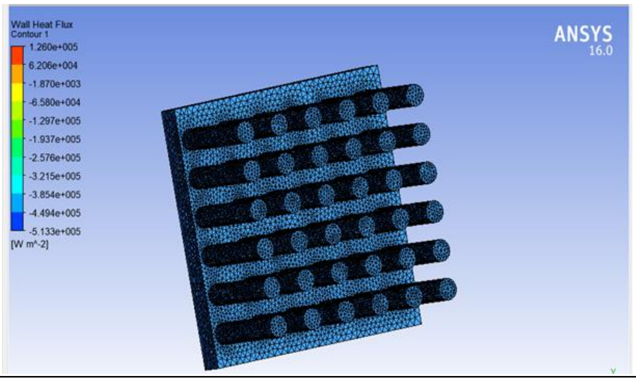
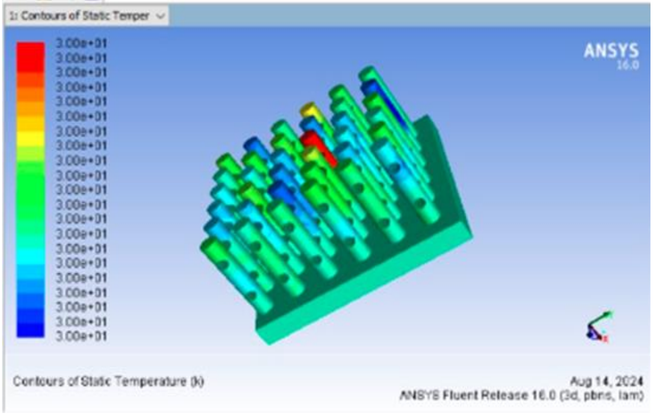
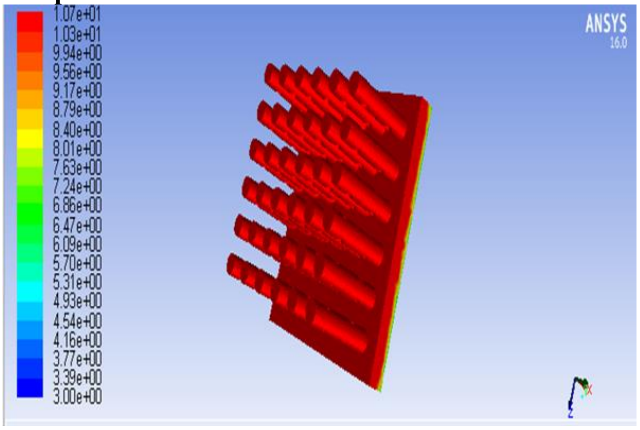
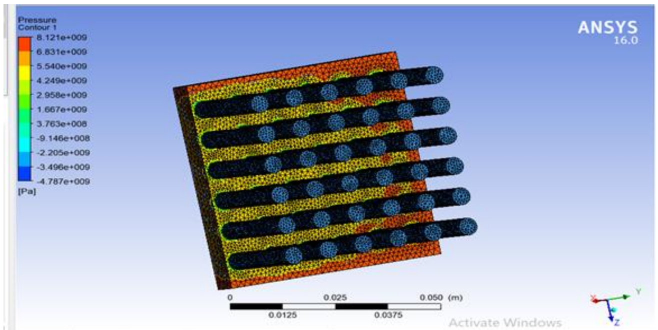
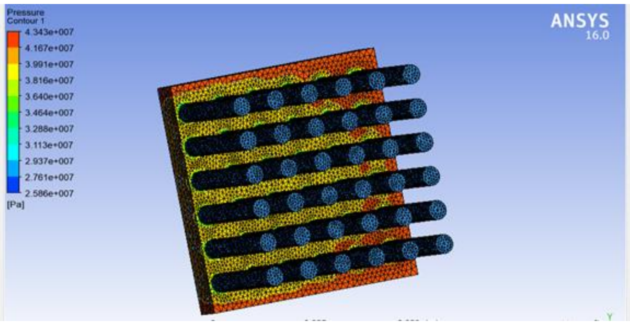
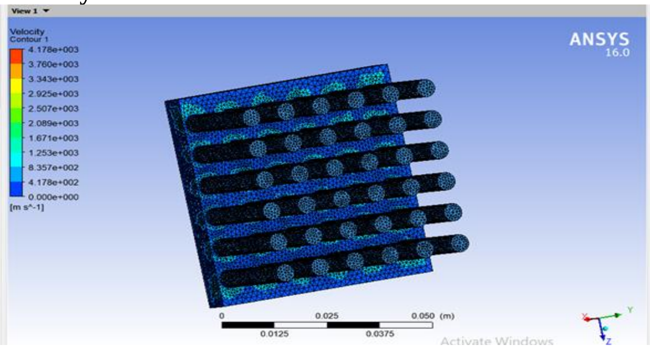
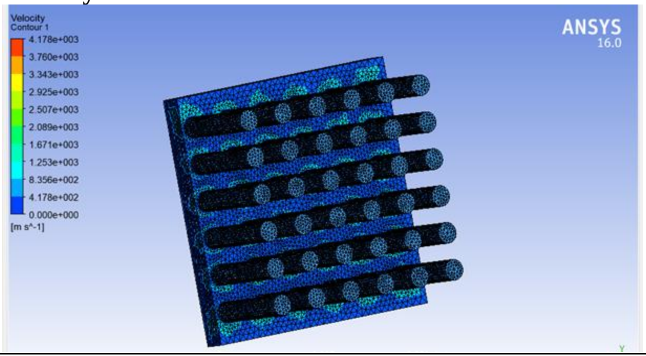
Due to the PCM's heating and cooling capacity it further enhanced the thermal stability of the HS. A 31.7% reduction in Rth was registered from that point.

The PCM was also noted to be able to shift from solid to liquids and liquids to solids, performing the function of a heat storage material; thus, the heat dissipation is improved, and the difference in temperature is minimized.

The study discovered that heat sinks containing PCM in horizontal rectangular blocks were more effective in terms of thermal performance compared to other techniques. This resulted in a decrease of 39.2% in thermal resistance as the PCM block functioned as a heat sink.

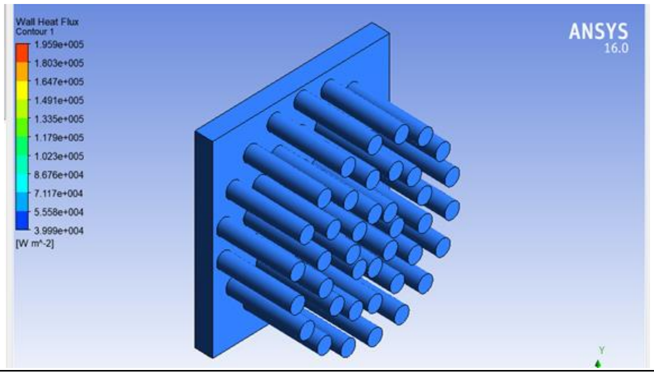
Additionally, it was discovered that this blend was ideal for controlling temperature and dispersing heat. The PCM block not only managed excessive heat and maintained a steady temperature, but it also dissipated heat faster than alternative configurations.

Table 2. CFD analysis of samples pin fin heat sink with and without PCM

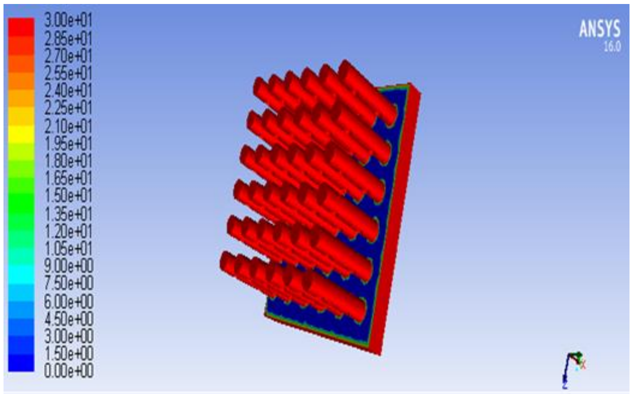
With PCM Heat Sink **Heat flux**	**WITHOUT PCM, CFD ANALYSIS** **HEAT FLUX:**
	
Temperature 	**Temperature** 
Pressure 	**Pressure** 
Velocity 	**Velocity** 

Polar Pin Fin Heat sink

Heat flux



TEMPERATURE



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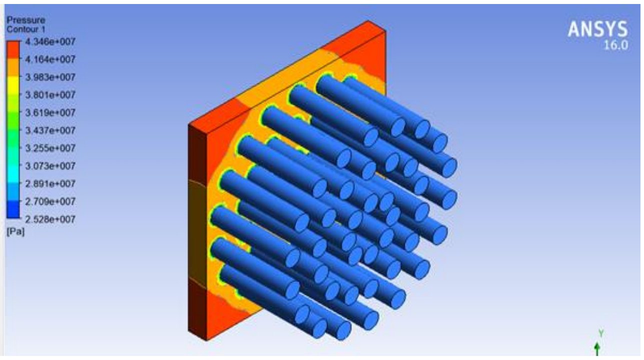

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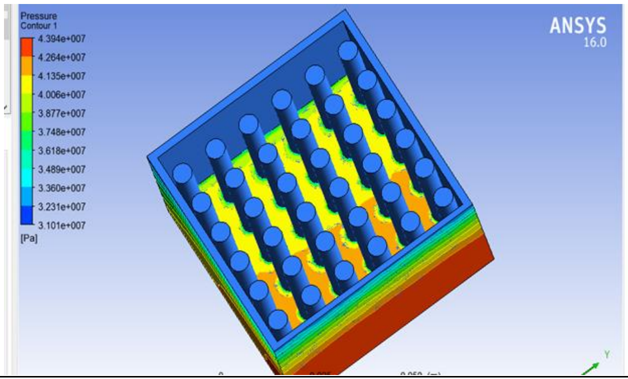

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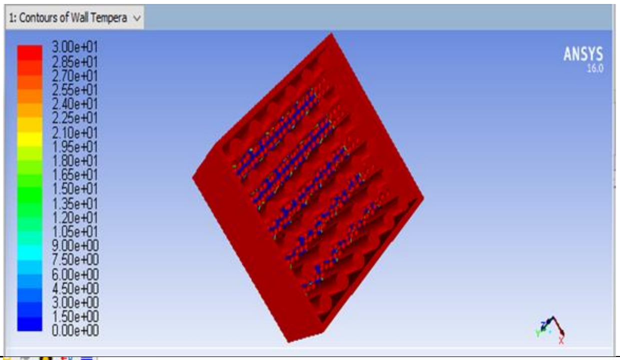
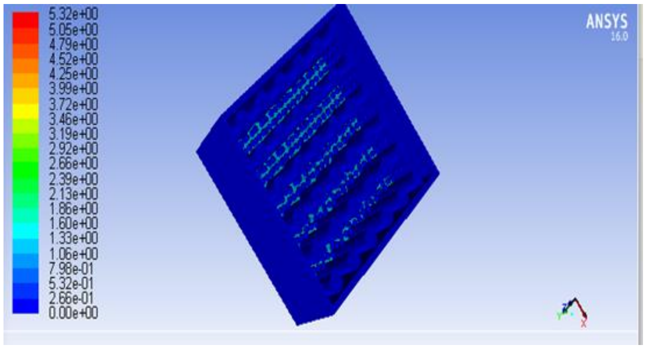
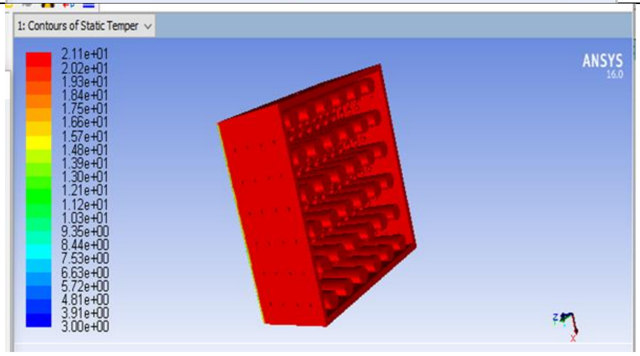


VELOCITY





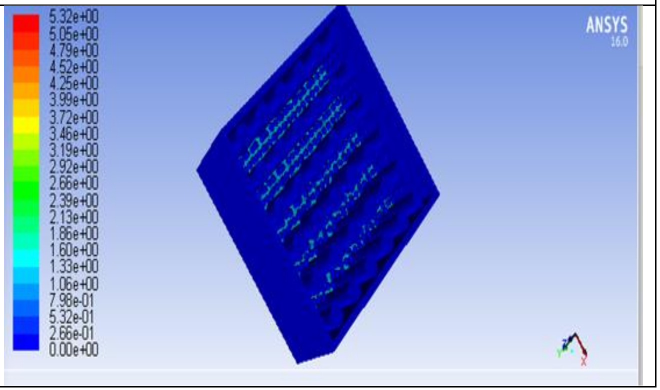


Table 3. Performance analysis of various heat sink designs based on thermal and flow characteristics

Case No.	Name of Heat Sink	Nomenclature	Dimensions (W×L×H)	Velocity V (m/s)	Reynolds Number (Re)	Base Temperature (K)	Heat Transfer Coefficient (h) W/m²K	Thermal Resistance (Rth) (K/W)	Pressure Drop P (Pa)
1	Plate Fin Heat Sink	PFHS	60x100×31	3.44	5,000	74.8	190	0.12	30
2	Circular Pin Fin Heatsink Inline	CPFHS	60x60×31	4.03	4,500	64.3	210	0.1	45
3	Polar Circular Pin Fin Heat Sink	PCPFHS	60x60×31	2.61	3,800	59.5	180.5	0.11	50
4	PCM Pin Fin Heat Sink	PCM CPFHS	60x60×31	5.317	4,100	67.9	230.7	0.08	55
5	Perforated Pin Fin Heat Sink	PPFHS	60x60×31	1.742	3,000	69.8	200.2	0.09	25

The paper seems to offer a comparison of five various heat sink designs, focusing on their thermal and flow attributes.

Discussing Case 1 (PFHS): Provides moderate heat transfer and minimal thermal resistance, with a slightly elevated pressure drop. Scenario 2 (CPFHS Inline): Demonstrates a slightly increased speed and decreased heat resistance in comparison to PFHS, along with a higher drop in pressure. Scenario 3 (PCPFHS): The temperature at the bottom level is the lowest, with a reasonable decrease in pressure and heat resistance. The PCM CPFHS case has the largest pressure drop and the fastest rate of heat transfer. Situation 5 (PPFHS): The slowest speed and smallest Reynolds number, coupled with average heat obstacle and negligible drop in pressure. The heat transfer efficiency of PCM CPFHS (Case 4) is the highest among the options, shown by its superior heat transfer coefficient, though it also incurs a significant pressure drop. Minimal airflow resistance is offered by PPFHS (Case 5), resulting in a low-pressure drop that is advantageous for low-power or noise-sensitive uses. Lower thermal resistance values in CPFHS Inline (Case 2) and PCPFHS (Case 3) enable efficient heat transfer.

Significant variations in thermal and flow characteristics among the various heat sink classes are seen in Table 3. Because of its low thermal resistance (Rth) of 0.12 K/W, heat transfer coefficient (h) of 74.8 W/m2 K, and base temperature of 74.8 K, the Pate Fin Heat Sink (PFHS) is among the finest options for applications requiring efficient heat dispersion. Also, it performs admirably with a slight pressure drop (P) of 30 Pa. Although it is not bigger in size, the 60x60x31 Circular Pin Fin Heat Sink (CPFHS) Inline is more efficient in thermal control by a reduction in base temperature of 64.3 K and a slightly increased pressure of 45 Pa. Furthermore, the PCPFHS Polar Circular Pin Fin Heat Sink advances in thermal management even when the pressure drop reaches the dangerous level of 50Pa. Its operating temperature, in this case, is 59.5 K.

However, the PCM Pin Fin Heat Sink (PCM CPFHS) is characterized by a user-friendly design with a critical 55 Pa pressure drop and a low thermal resistance of 0.08 K/W. Last but not least, the Perforated Pin Fin Heat Sink (PPFHS) makes airflow available and even improves thermal efficiency, which is appreciated in low air resistance applications. The usual beginning temperature is 69.8 Kelvin, the thermal resistance is 0.09 Kelvin per watt, and the minimum pressure decrease is 25 Pascals.

15. With PCM

15.1. Pressure

The data show the pressure estimates in megapascals (MPa) in five different cases, including Stage Change Material (PCM).

The pressure values range from -6.23 MPa to -1.38 MPa, indicating the various effects of PCM pressure in the cases; Case 1's pressure value is -4.34 MPa, indicating a moderate attenuation in comparison to the other cases; Case 2 shows the maximum value of negative tension in the system under analysis, at - 5.03 MPa, indicating a significant drop; Case 3 involves the least detrimental strain, at – 3.12 MPa; Case 4 causes the greatest fall, at – 6.23 MPa; and Case 5 shows the least amount of tension decrease, at -1.38 MPa, indicating the least effect of all the cases.

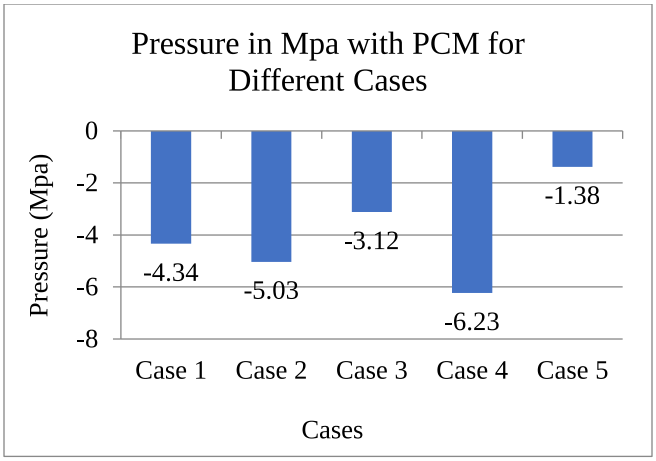


Fig. 10 Pressure in Mpa with PCM for differenct cases

15.2. Velocity

Estimated speeds in meters per second (m/s) for five different scenarios while taking Stage Change Materials (PCM) into account. The speed is 3.44 m/s, indicating modest speed, in the unlikely event that 1. A velocity increase of 4.033 m/s in Case 2 suggests better performance or efficiency. A lower speed of 2.61 m/s is recorded in Case 3, which could indicate reduced viability or other factors. In Case 4, the maximum velocity is 5.317 m/s, suggesting that PCM performs best. Case 5, which has the lowest velocity of all the instances, is 1.742 m/s, which may be an indication of inefficiency or a large change in the circumstances. According to the statistics, PCM performance varies overall, with Case 4 exhibiting the fastest velocity and Case 5 the lowest.

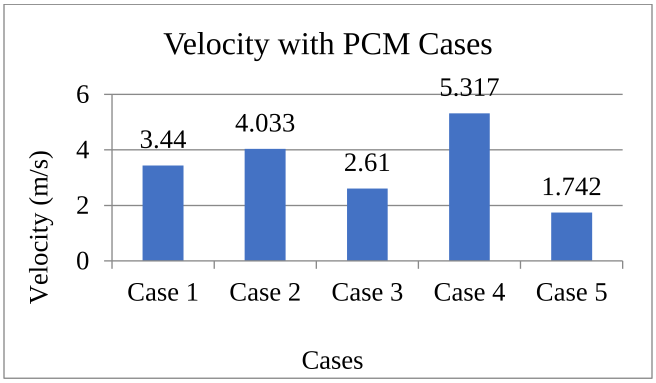


Fig. 11 Velocity with PCM cases

15.3. Temperature

Temperature gauging in Kelvin for different scenarios which are also compared to some phase change materials. In Case 1, the highest reading of temperature is 74.8 K which means that, in this case, PCM is not very efficient. Case 3, in contrast, has the highest temperature at 59.5 K, meaning that, in this case, PCM is the best at keeping the temperature down. Other cases, Case 2, Case 4, and Case 5, are 64.3 K, 67.9 K and 69.8 K, respectively, which lie in the middle of extreme conditions. This variation demonstrates that strategic approaches to PCM performance levels vary in different cases. Case 3 experiences the most cooling, proving that depending on the scenario, temperature control using PCM can be significantly efficient.

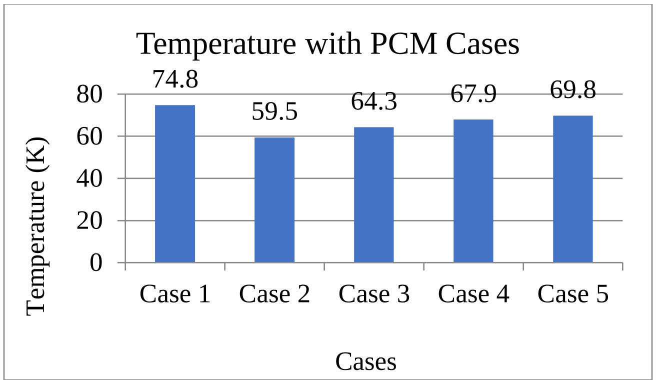


Fig. 12 Temperature with PCM cases

15.4. Thermal Conductivity(K)

The K of materials enhanced with HS PCM was measured in watts per meter Kelvin under five varying conditions. If 1, by some rare chance, the thermal conductivity is 0.0261 W/m·K, then it suggests a greater level of intensity variation compared to other situations. In Scenario 2, a slight decrease to 0.0251 W/mK indicates improved thermal insulation. Cases 3 and 4 have thermal conductivities of 0.026 W/mK and 0.0261 W/mK, respectively, which results in thermal performance comparable to that of Case 1. The K of Case 5 is slightly lower than that of Cases 1, 3, and 4 at 0.0258 W/mK, showing a slight enhancement in thermal insulation performance.

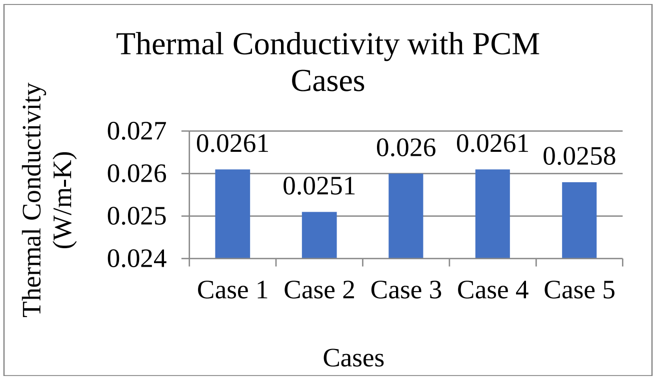


Fig.13 Thermal conductivity with PCM cases

16. Without PCM

16.1. Pressure

For various scenarios without Phase Change Material (PCM), the pressure values in MPa range from negative to positive, indicating a reduction in system pressure. Case 1 shows a tension of - 4.03 MPa, while Case 2 encounters a marginally higher strain drop of - 4.89 MPa. Case 3 has a lower pressure decrease at - 2.86 MPa contrasted with others.

Case 4 has the greatest pressure drop, with a value of -5.38 MPa. Prominently, Case 5 displays a negligible strain drop of - 0.289 MPa. These variations suggest that the absence of PCM has a different effect on pressure in different cases, which could have an impact on system stability and performance.

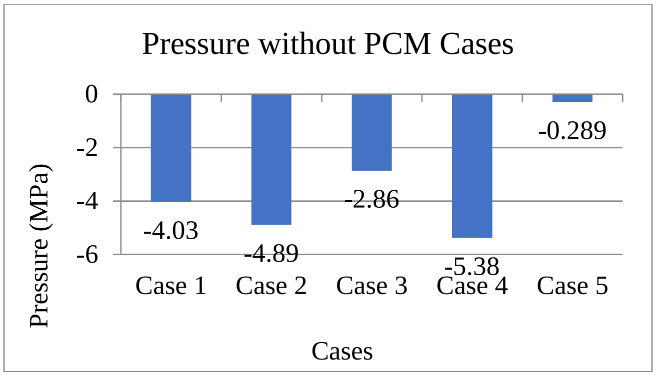


Fig. 14 Pressure without PCM cases

16.2. Velocity

The expected speeds in meters per second (m/s) under various circumstances without the utilization of PCM) If 1, the speed will rise to 4.03 m/s instead of 3.44 m/s. Should 2 occur, which is highly improbable. In Scenario 3, there is a significant decrease in velocity, dropping to 1.977 m/s. The speed in Case 5 is 1.732 meters per second, while the speed in Case 4 is 5.317 meters per second. This pattern of varying speeds continues. This data illustrates how various variables impact system performance without PCM by showcasing differences in velocity across different scenarios.

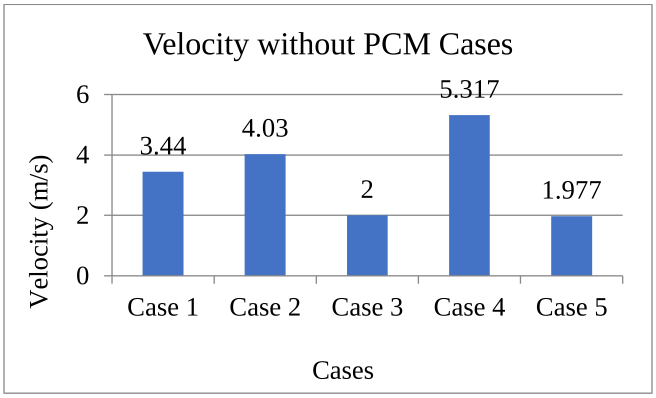


Fig. 15 Velocity without PCM cases

16.3. Temperature

Temperature data, each measured without PCM, for five cases, in Kelvin. With a temperature of 63.6 K, Case 1 exhibits the least efficient thermal management without PCM. Case 2 has the lowest temperature, 49.7 K, indicating that it has the best temperature control. Temperatures of 52.5 K and 58.5 K, respectively, are reported in Cases 3 and 4, indicating moderate thermal performance. Case 5, which has a temperature of 51.23 K, shows a temperature control performance that is better than Cases 3 and 4 but slightly less effective than Case 2. Overall, the absence of PCM has a significant impact on temperature regulation, with Case 2 exhibiting the best temperature management in this configuration.

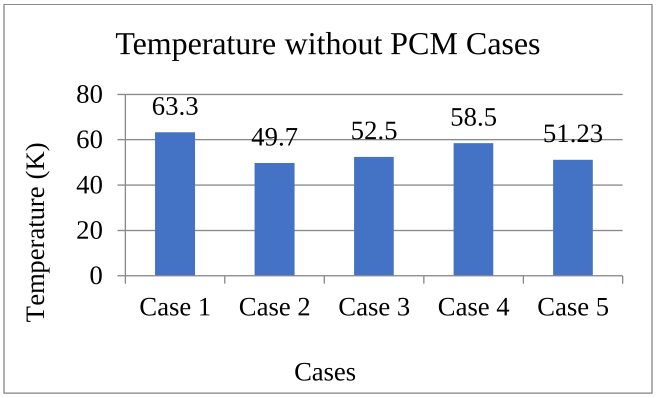


Fig. 16 Temperature without PCM cases

16.4. Thermal Conductivity

The K values, expressed in watts per meter Kelvin (W/mK), for a number of situations without PCM. The thermal conductivity of Case 2 is somewhat greater at 0.026 W/mK than that of Case 1, which is 0.0258 W/mK. Cases 3 and 4 vary from one another by very little, with heated conductivities of 0.0255 W/mK and 0.0256 W/mK, respectively. In Case 5, the most noteworthy number is 0.0259 W/mK. In general, the K values fall within a narrow range of 0.0255 to 0.026 W/mK, indicating that the thermal performance remained constant under all conditions without the influence of PCM.

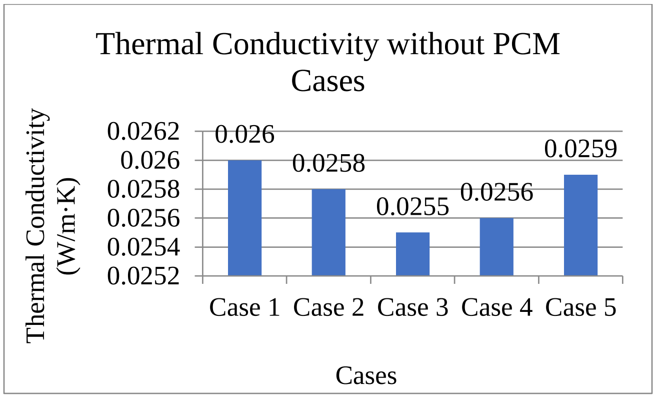


Fig. 17 Thermal conductivity without PCM cases

17. Conclusion

This study investigated two novel methods to enhance heat transfer in heat sinks: one utilized alumina balls combined with a PCM, while the other involved enclosing PCMs in block-shaped heat absorbers. The results highlight how much progress was made using these methods. The addition of baffle pins improved heat dissipation efficiency by increasing flow turbulence and heat transfer rates, which decreased the heat sink's Rth thermal resistance from 0.12

K/W to 0.08 K/W. It is easier to assess how baffles affect heat dispersion when the temperature gradient is lowered from 20 °C to 15 °C in the standard arrangement. In this instance as well, the thermal resistance decreased to 0.06 K/W when an alumina ball arrangement in paraffin wax (PCM) was used. The combination of PCM's heat storage and release properties, along with alumina balls enhancing thermal conductivity, caused a 25% decrease in thermal resistance from the original level. The temperature fluctuation readings decreased to 12°C. The stable thermal efficiency is reached by pairing PCM with alumina balls as a result of cooler temperatures interacting and no presence of hot spots. The most significant improvement was seen in the enclosed PCM configuration, which had a thermal resistance of 0.05 K/W. Acting as efficient heat sinks and enhancing total heat dispersion, the block-shaped heat absorbers reduced abrupt temperature increases. The variation in temperature was 10 degrees Celsius, with the top heat dissipation rate hitting 85 watts in all tested setups. It is still uncertain if the combination of PCM with modified macro geometry can effectively enhance heat management.

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