

# Numerical And Experimental Study of PCM- Enhanced Finned Heat Pipe Radiator

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## Abstract

Efficient thermal management is a critical requirement in modern engineering applications, particularly in systems subjected to high heat flux. This study presents a combined numerical and experimental investigation of a Phase Change Material (PCM)-enhanced finned heat pipe radiator, aimed at improving heat dissipation performance and thermal stability. In the experimental phase, radiator prototypes were fabricated using identical geometrical configurations with different materials to examine the influence of material properties on thermal performance. A controlled setup consisting of a heat source, coolant circulation loop, and forced convection system was developed to replicate realistic operating conditions. Key parameters such as temperature variation, flow characteristics, and thermal response were monitored to evaluate system performance. The experimental observations indicate that material selection plays a significant role in determining heat transfer effectiveness, with high-conductivity materials demonstrating superior cooling behaviour. To support the experimental work, a detailed Computational Fluid Dynamics (CFD) analysis was carried out using ANSYS Fluent. A three-dimensional model of the radiator was developed and analysed under consistent boundary conditions to study temperature distribution, velocity profiles, and heat flux characteristics. The numerical results show good agreement with experimental trends, providing deeper insight into the thermal behaviour of the system. The incorporation of PCM enhances thermal energy storage through latent heat absorption, thereby reducing temperature fluctuations and improving overall system stability. The combined use of fins, heat pipe configuration, and PCM integration significantly enhances heat transfer performance. Overall, the study demonstrates that hybrid thermal enhancement techniques, along with appropriate material selection, can effectively improve radiator efficiency and offer promising solutions for advanced cooling applications in automotive, electronic, and energy systems.

## Index Terms

*Wind Energy, 3D Printing, Renewable Energy, Electricity Generation, Water Pumping, Horizontal Axis Wind-mill, Decentralized Energy.*

## 1. INTRODUCTION

The rapid advancement of modern engineering systems, particularly in automotive, electronics, and energy applications, has significantly increased the demand for efficient thermal management solutions. High heat generation in compact systems leads to performance degradation, reduced reliability, and potential component failure if not effectively dissipated. Therefore, the development of advanced cooling techniques has become a critical area of research in thermal engineering. Radiators are widely used heat exchangers designed to transfer heat from a working fluid to the surrounding environment. Their performance is primarily governed by material properties, surface geometry, airflow conditions, and coolant characteristics. Conventional radiators rely on extended surfaces such as fins to enhance convective heat transfer by increasing the effective surface area. However, with increasing thermal loads, traditional cooling methods often face limitations in maintaining temperature stability.

To overcome these limitations, the integration of **heat pipes and Phase Change Materials (PCM)** has emerged

as a promising approach. Heat pipes are highly efficient thermal devices that transfer heat through phase change mechanisms, enabling rapid heat distribution with minimal temperature gradients. On the other hand, PCM absorbs and stores thermal energy during phase transition, thereby reducing temperature fluctuations and enhancing thermal stability.

The combination of these technologies with finned structures leads to improved heat dissipation performance. Material selection plays a vital role in determining the overall efficiency of radiator systems. Materials with high thermal conductivity, such as copper, facilitate faster heat transfer, while alternatives like aluminium offer advantages in terms of weight and cost. Titanium, although mechanically strong and corrosion-resistant, presents different thermal characteristics that require evaluation. A comparative analysis of these materials is essential to identify optimal performance under varying conditions.

In this study, a **PCM-enhanced finned heat pipe radiator** is investigated using both experimental and numerical approaches. The experimental work involves the fabrication of radiator prototypes and evaluation under controlled conditions, while the numerical analysis is carried out using Computational Fluid Dynamics (CFD) to study temperature distribution, flow behaviour, and heat transfer characteristics. This integrated approach provides a comprehensive understanding of the system and enables validation of results.

The primary objective of this research is to analyse the influence of material properties and hybrid thermal enhancement techniques on radiator performance.

## 2. LITERATURE REVIEW

The performance of radiator systems and heat exchangers has been extensively studied with a focus on enhancing heat transfer through design optimization, material selection, and advanced cooling techniques.

- **Hussaini Syed Mujtaba et al. (2023)** investigated the influence of design parameters on finned-tube heat exchangers using CFD analysis. Their study highlighted that material selection significantly affects heat transfer performance, with higher conductivity materials providing improved thermal efficiency.
- **Máté Petrik et al. (2019)** conducted a parametric study on finned tube heat exchangers and concluded that fin geometry, spacing, and thickness play a crucial role in determining heat transfer characteristics and overall cooling efficiency.
- **S.S.P. and C.K.K. (2020)** explored nano-coated radiator tubes and demonstrated that surface modification techniques can significantly enhance thermal conductivity and improve heat transfer rates, especially when combining different material advantages.
- **Applied Thermal Engineering (2005)** presented an analysis of aluminium radiators, emphasizing their advantages in terms of lightweight and cost-effectiveness, while also noting limitations in thermal performance compared to copper-based systems.
- **Aandhavelu et al. (2023)** carried out experimental investigations using composite materials in radiator systems. Their findings showed that material modification and hybrid configurations can effectively enhance heat transfer performance.
- **Jefferson Raja Bose et al. (2023)** studied nanofluid-based heat transfer systems and reported improved thermal conductivity and enhanced heat transfer characteristics compared to conventional fluids, indicating the potential for advanced cooling applications.
- **Journal of the Taiwan Institute of Chemical Engineers (2021)** examined the use of hybrid nanofluids in aluminium radiators and concluded that convective heat transfer can be significantly improved without altering the base material.
- **Materials Today Proceedings (2022)** focused on optimizing radiator surface geometry through CFD analysis. The study revealed that fin design parameters such as spacing, angle, and configuration have a strong influence on heat transfer efficiency.
- **Ya Liu et al. (2020)** investigated advanced heat pipe materials and demonstrated that innovative materials

findings of this study are expected to contribute to the design and development of efficient and reliable cooling systems for advanced engineering applications. can significantly enhance heat dissipation performance, suggesting future potential for high- efficiency thermal systems.

- **Yijin Mao et al. (2016)** analysed heat transfer between fluid flow and metallic surfaces, confirming that materials with higher thermal conductivity exhibit superior convective heat transfer behaviour.
- **Mustafa Tutar et al. (2025)** emphasized the importance of accurate CFD modelling in predicting thermal performance. Their study validated that numerical simulations can effectively capture temperature distribution and heat flux characteristics in heat transfer systems

### 3. METHODOLOGY

This study adopts a combined experimental and numerical approach to evaluate the thermal performance of a PCM-enhanced finned heat pipe radiator. The methodology is structured to ensure accurate analysis, material comparison, and validation of results under controlled conditions.

#### 3.1 System Design and Modelling

A three-dimensional model of the finned heat pipe radiator was developed based on practical thermal management requirements. The design consists of a heat pipe structure integrated with extended fin surfaces and a PCM storage region to enhance heat transfer and thermal stability. The geometry was created with careful consideration of surface area, flow passage, and compactness to ensure efficient heat dissipation.

The same geometric configuration was maintained for all material cases to enable a consistent and fair comparison of thermal performance.

#### 3.2 Fabrication and Experimental Setup

An experimental prototype of the radiator system was fabricated to validate the proposed design. The setup includes a heat source, coolant circulation system, finned heat dissipation unit, and a forced convection mechanism using a fan.

A working fluid was circulated through the system while heat was supplied to simulate real operating conditions. Temperature measurements at different locations, along with flow conditions and ambient parameters, were recorded to evaluate the heat transfer characteristics. The experimental setup was designed to ensure steady operation and repeatability of results.

#### 3.3 Numerical Simulation (CFD Analysis)

To complement the experimental investigation, Computational Fluid Dynamics (CFD) analysis was performed using ANSYS Fluent. The developed 3D model was imported into the simulation environment, where discretization was carried out using a refined mesh to capture heat transfer behaviour accurately. The

simulation considered fluid flow and heat transfer phenomena by solving the governing equations of mass, momentum, and energy. Appropriate physical models were applied to represent convective heat transfer and flow characteristics within the system.

**3.4 Boundary Conditions and Material Selection** Consistent boundary conditions were applied across all simulations to ensure comparability. These include specified inlet flow conditions, outlet pressure conditions, and thermal boundary conditions representing the heat source and ambient environment. Three different materials—aluminium, copper, and titanium—were assigned to the radiator model to evaluate the effect of thermal conductivity and material properties on performance. All other parameters were kept constant to isolate the influence of material selection.

### 3.5 *Data Analysis and Performance Evaluation*

The performance of the radiator system was evaluated based on temperature distribution, heat transfer characteristics, and overall thermal behaviour. Both experimental observations and numerical results were analysed to identify trends and compare material performance. The results obtained from CFD simulations were correlated with experimental findings to ensure validation and reliability of the analysis. This integrated approach provides a comprehensive understanding of the thermal performance of the proposed system.

## 4. THEORETICAL INFORMATION

## 5. GEOMETRY AND 3D MODEL DESIGN

### 5.1 *Design Overview*

The three-dimensional model of the PCM-enhanced finned heat pipe radiator was developed to represent the physical system used for thermal analysis. The design integrates a heat pipe structure, extended fin surfaces, and a PCM storage region to enhance heat transfer and thermal stability. The geometry was created with the objective of maximizing heat dissipation while maintaining a compact and practical configuration.

The model ensures effective heat transfer from the source region to the finned section, where heat is dissipated to the surrounding environment through convective mechanisms.

### 5.2 *Geometrical Configuration*

The radiator model consists of three primary sections:

- **Heat Pipe Section:**

The heat pipe is modelled as a tubular structure responsible for transferring heat from the source to the fin region. It enables efficient heat conduction along its length.

- **Finned Heat Sink Region:**

Multiple thin fins are attached to the heat pipe to increase the effective surface area. The fins are arranged uniformly to enhance airflow interaction and improve convective heat transfer.

- **PCM Storage Region:**

A designated region is incorporated to accommodate the phase change material. This region is positioned near the heat source to absorb and store thermal energy during operation. An external airflow domain is also included around the fin region to simulate forced convection conditions.

### 5.3 *Design Considerations*

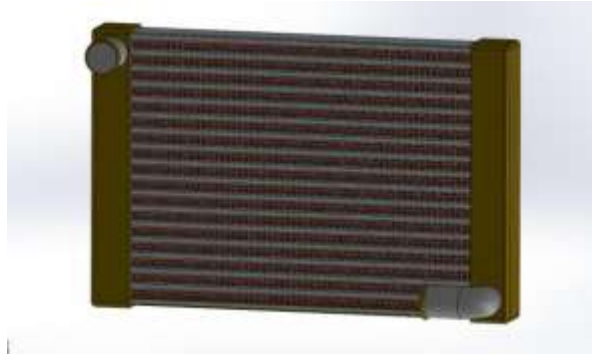
The design of the radiator model is based on the following key considerations:

- Maximization of heat transfer surface area through fin arrangement
- Uniform heat distribution using heat pipe configuration
- Compact and application-oriented design
- Simplification of geometry for efficient numerical simulation

### 5.4 *CAD Modelling*

The geometry was developed using CAD software and imported into ANSYS Workbench for further analysis. The model includes all essential components such as tubes, fins, and flow domains, ensuring an accurate representation of the physical system.

Proper alignment and connectivity between components were maintained to avoid errors during meshing and simulation processes.



### 5.5 *Material Assignment for Simulation*

The same geometric model was used for all simulations while varying only the material properties. This ensures a consistent basis for comparison of thermal performance.

The materials considered include:

- Aluminium
- Copper
- Titanium

Each material was assigned appropriate thermal properties to evaluate its influence on heat transfer characteristics.

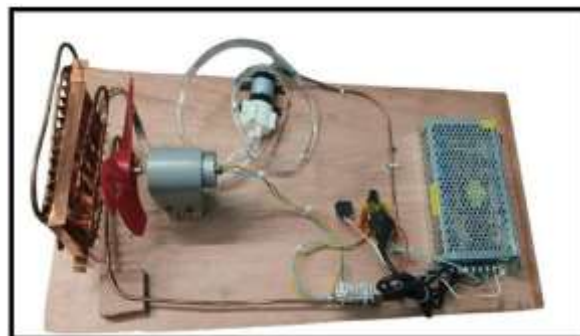
### 5.6 *Significance of the 3D Model*

The 3D model forms the foundation for numerical analysis and plays a critical role in understanding the thermal behaviour of the system. It enables visualization of temperature distribution, heat flow paths, and airflow patterns within the radiator. A well-defined geometry ensures accurate simulation results and reliable performance evaluation, making it an essential component of the study.

## 6. FABRICATION AND EXPERIMENTAL SETUP

### 6.1 *Overview*

The fabrication of the PCM-enhanced finned heat pipe radiator was carried out to validate the proposed design under practical conditions. The objective was to develop a functional prototype that demonstrates heat absorption, transfer, and dissipation using a combination of heat pipe configuration, finned surfaces, and phase change material. The fabricated model represents a physical realization of the designed geometry and enables experimental evaluation of thermal performance.



## 6.2 Components Used

The experimental setup consists of the following major components:

- **Heat Pipe Structure:**  
Copper tubes were used to simulate the heat pipe due to their high thermal conductivity and effective heat transfer capability.
- **Finned Heat Dissipation Unit:**  
Metallic fins were attached to the heat pipe to increase surface area and enhance convective heat transfer.
- **Phase Change Material (PCM) Chamber:** A dedicated section was provided for PCM to absorb and store thermal energy during operation.
- **Cooling Fan:**  
A DC fan was used to provide forced convection, improving airflow across the fin surfaces.
- **Coolant Circulation System:**  
A pump was incorporated to maintain continuous flow within the system, ensuring uniform heat distribution.
- **Power Supply Unit:**  
A regulated power source was used to operate the fan and pump.
- **Base Structure:**  
A rigid base platform was used to support and stabilize all components.

## 6.3 Fabrication Procedure

The fabrication process was carried out in a systematic manner to ensure proper assembly and functionality of the system.

Initially, the copper tubes were shaped into the required configuration to form the heat transfer path. The fins were then attached to the tube structure to enhance the heat dissipation area. Care was taken to ensure proper thermal contact between the fins and the tubes.

The cooling fan was mounted in alignment with the finned region to direct airflow effectively. The coolant circulation system was assembled using flexible connections to ensure continuous flow throughout the system.

All electrical components were connected to the power supply using insulated wiring. The complete setup was then fixed onto a base structure to maintain stability during operation.

## 6.4 Experimental Setup

A controlled experimental setup was developed to simulate realistic operating conditions. A heat source was used to generate thermal energy, which was transferred through the system. The coolant circulated through the heat pipe structure, while airflow was maintained across the fins using the fan.

Temperature measurements were taken at different locations to analyse heat transfer behaviour. The setup was designed to ensure steady-state operation and consistent performance during testing.

## 6.5 Working Principle

The fabricated system operates based on combined heat transfer mechanisms. Heat generated at the source is absorbed and transferred through the heat pipe structure to the finned region. The fins facilitate heat dissipation to the surrounding air through convection, which is enhanced by forced airflow.

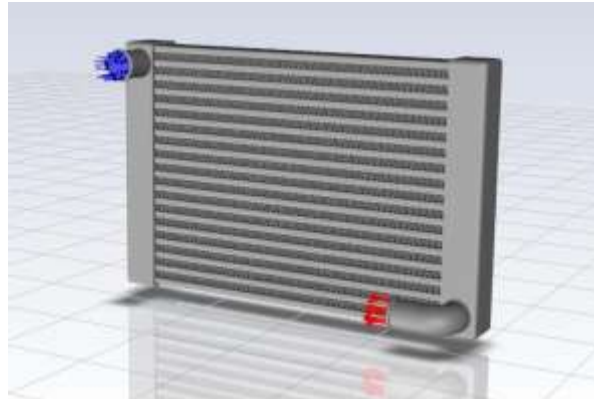
The PCM absorbs excess thermal energy during phase change, reducing temperature fluctuations and improving thermal stability. The continuous circulation of fluid ensures uniform heat distribution and prevents localized overheating.

## 6.6 Significance of Fabrication

The fabrication of the prototype plays a crucial role in validating the numerical analysis and demonstrating the practical feasibility of the proposed design. It provides real-time insights into system performance and supports the reliability of the simulation results. The experimental setup confirms the effectiveness of combining PCM, fins, and heat pipe configuration in enhancing thermal management.

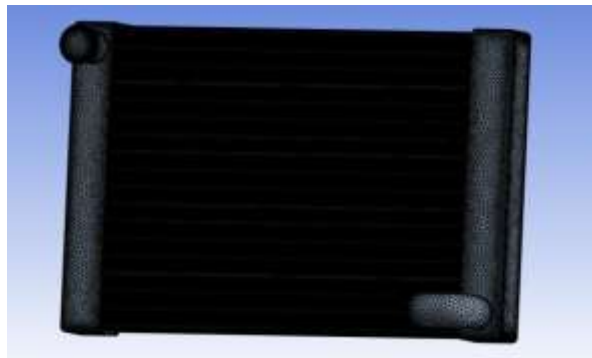
## 7. CFD ANALYSIS

### 7.1 Overview



Computational Fluid Dynamics (CFD) analysis was performed to investigate the thermal and flow behaviour of the PCM-enhanced finned heat pipe radiator. The objective of the analysis is to evaluate temperature distribution, airflow characteristics, and overall heat transfer performance under controlled conditions. The numerical study provides detailed insight into internal thermal phenomena that are difficult to measure experimentally.

### 7.2 Geometry and Mesh Generation



The three-dimensional CAD model of the radiator was imported into ANSYS Workbench for simulation. The computational domain includes the heat pipe structure, finned region, and surrounding airflow domain.

The geometry was discretized into finite elements using a refined mesh. Tetrahedral elements were predominantly used due to the complexity of the geometry. Additional mesh refinement was applied near the fin surfaces and heat transfer regions to accurately capture temperature gradients and flow behaviour.

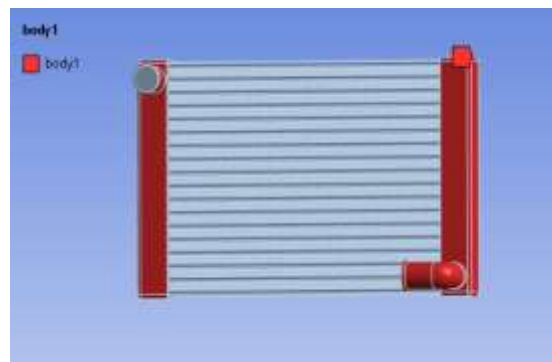
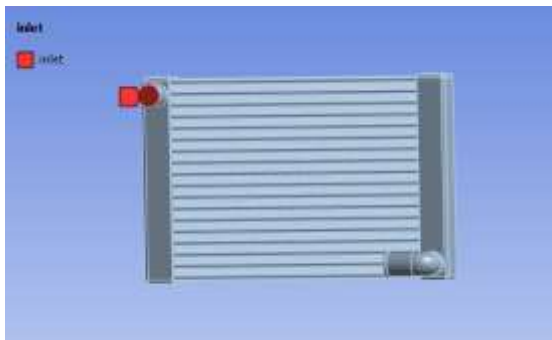
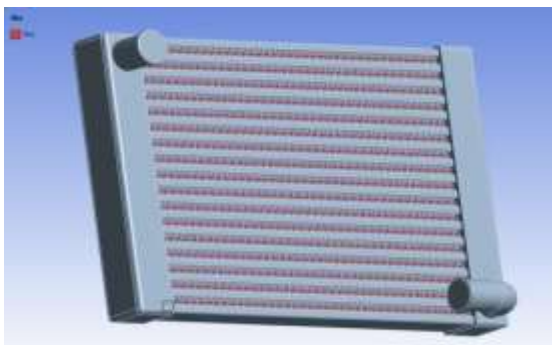
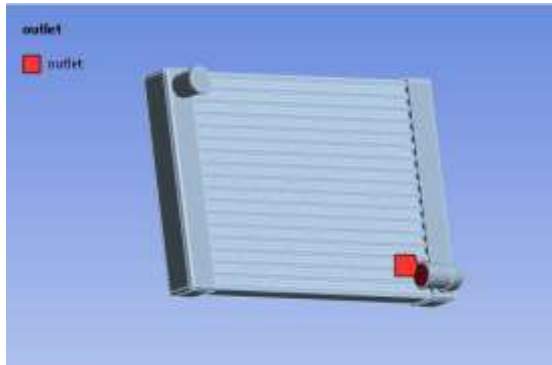
Mesh quality was verified based on parameters such as element skewness and smoothness to ensure numerical stability and accuracy.

### 7.3 Physical Models and Governing Equations

The CFD analysis was conducted by solving the fundamental governing equations of fluid flow and heat transfer, including:

- Continuity equation (mass conservation)
- Momentum equations (fluid flow behaviour)
- Energy equation (heat transfer analysis) The energy equation was enabled to account for heat transfer within the system. A suitable turbulence model was applied to represent airflow behaviour under forced convection conditions.

### 7.4 Boundary Conditions



Appropriate boundary conditions were applied to simulate realistic operating conditions:

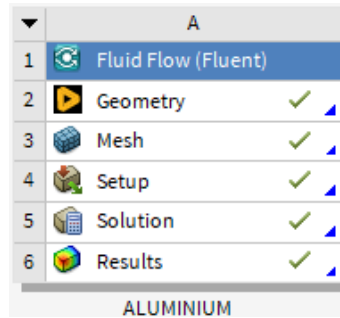
- **Inlet:** Specified velocity and temperature of the working fluid
- **Outlet:** Pressure outlet condition
- **Walls:** No-slip condition applied to all solid surfaces
- **Heat Source Region:** Thermal boundary condition representing heat input
- **Airflow Domain:** Simulated to represent forced convection across fins

All boundary conditions were maintained consistently across simulations to ensure accurate comparison.

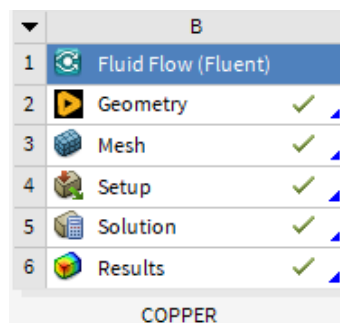
### 7.5 Material Properties

The same geometry was analysed using different materials to evaluate their influence on thermal performance. The materials considered include:

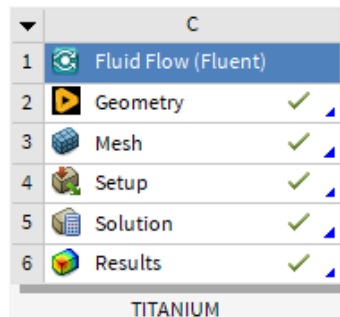
- Aluminium



- Copper



- Titanium



Each material was assigned its respective thermal properties, particularly thermal conductivity, which plays a key role in heat transfer efficiency.

### 7.6 Phase Change Material

In the present study, **Phase Change Material (PCM)** is incorporated into the finned heat pipe radiator to enhance thermal energy storage and improve temperature regulation. The PCM is integrated within the radiator system near the heat source region to effectively absorb excess thermal energy during operation.

A suitable PCM selected for this study is **Paraffin Wax (RT-series PCM)**, which is widely used in thermal management applications due to its favourable thermal properties. Paraffin-based PCM exhibits high latent heat capacity, chemical stability, non-corrosive behaviour, and compatibility with metallic components such as copper and aluminium. The PCM functions as a thermal energy storage medium by absorbing heat during its phase transition from solid to liquid. This process allows the system to store a significant amount of heat without a substantial rise in temperature.

When the temperature decreases, the PCM releases the stored heat, thereby maintaining thermal balance within the radiator system. This cyclic process improves overall thermal stability and prevents rapid temperature fluctuations.

In this project, the PCM is incorporated in proximity to the heat pipe region and finned section, where maximum heat is generated and transferred. This strategic placement ensures efficient heat absorption and improves the overall performance of the radiator. The integration of PCM works in combination with:

- Heat pipe (for rapid heat transfer)
- Fins (for enhanced convection)

### 7.7 Solver Settings

The simulation was performed under steady-state conditions using a pressure-based solver. The solution was obtained by iterating until convergence was achieved. Residual monitoring was used to ensure the accuracy of the solution, and appropriate discretization schemes were applied for stability and precision.

### 7.8 Post-Processing and Parameters Evaluated

After completion of the simulation, results were analysed using post-processing tools. The following parameters were evaluated:

- Temperature distribution across the radiator
- Velocity contours of airflow
- Heat flux variation
- Thermal gradients within the structure

These results provide a detailed understanding of heat transfer mechanisms and system performance.

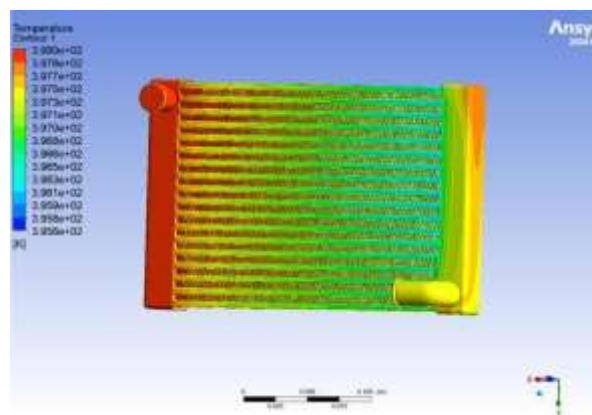
### 7.9 Significance of CFD Analysis

CFD analysis plays a crucial role in predicting the thermal behaviour of the radiator system. It allows visualization of temperature and flow fields, enabling identification of critical regions and performance limitations. The numerical results complement the experimental findings and provide a deeper understanding of the influence of material properties and design configuration on overall performance.

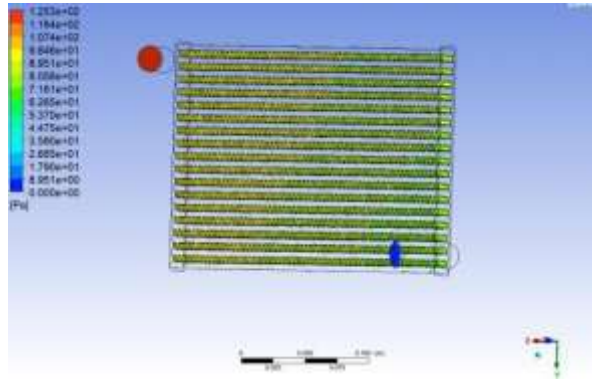
## 8. RESULTS AND DISCUSSION

### 8.1 CFD ANALYSIS RESULT OF ALUMINIUM RADIATOR

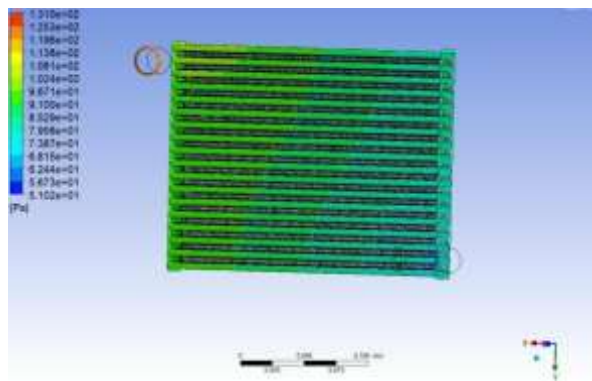
#### *Temperature Distribution*



TOTAL RADIATOR FLOW



FINS FLOW

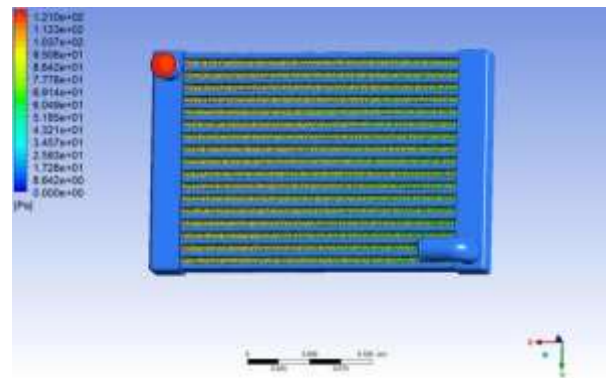
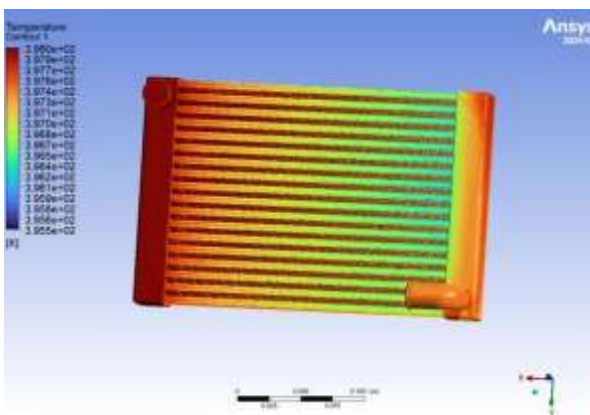


FINS PLATE FLOW

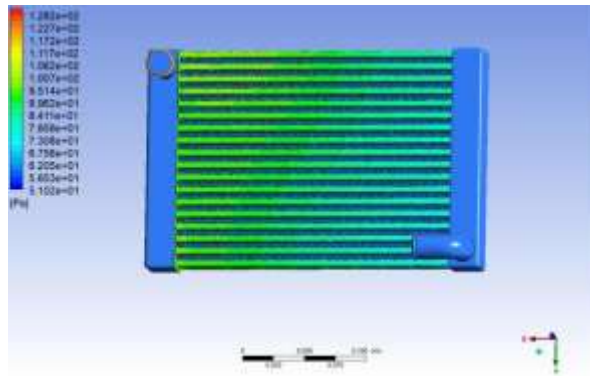
## 8.2 CFD ANALYSIS RESULT OF COPPER RADIATOR

### Temperature Distribution

#### TOTAL RADIATOR FLOW



## FINS FLOW



The thermal performance of the PCM-enhanced finned heat pipe radiator was analysed through both experimental investigation and CFD simulation. The results demonstrate that the proposed configuration effectively improves heat dissipation and overall thermal management. The temperature distribution obtained from numerical analysis shows a smooth and gradual reduction from the heat source to the finned region, indicating efficient heat transfer throughout the system. Materials with higher thermal conductivity exhibit more uniform temperature profiles, resulting in improved cooling performance and reduced thermal gradients. The presence of PCM contributes to enhanced thermal stability by absorbing heat and minimizing

temperature fluctuations. Flow analysis confirms that the airflow across the finned surfaces is well distributed, supporting effective convective heat transfer. The use of fins increases the available surface area, while forced convection further enhances heat removal from the system. The comparative evaluation of materials highlights that copper provides superior thermal performance due to its high conductivity, whereas aluminium offers a balanced combination of thermal efficiency and structural advantages. Titanium, although mechanically strong, shows comparatively lower heat transfer capability. A strong agreement between experimental observations and CFD results validates the reliability of the numerical model. Overall, the integration of PCM, fins, and heat pipe configuration significantly enhances radiator performance, making the system suitable for advanced cooling applications.

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