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Investigation of the Effect of Different Fins Configurations on the Thermal Performance of the Radiator

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ABSTRACT

Fins play a crucial role in enhancing heat transfer in various engineering and industrial applications. In this paper, the significance of fins in heat transfer as well as the design of radiators for thermal management are discussed. Fins increase the surface area and improve convective heat transfer. Fins, however, may decrease the surface area available for heat exchange and raise airflow resistance. In order to maximize thermal performance, this study emphasizes the necessity of having a thorough understanding of the relationship between fins and tubes in radiator design. The objectives of the research are to maximize surface area for heat dissipation, assess the impact of fins on heat transfer efficiency, and examine their functions. Thermal performances of radiators with various fin densities that is, radiators with six, eight, and ten fins per inch (FPI) have been investigated using Computational Fluid Dynamics (CFD) Analysis. The ten FPI configurations, in particular, showed remarkable thermal performance, indicating its potential for applications requiring strict thermal control. Further, it is also revealed that the outlet temperature dropped as the FPI rose and proved that the FPI and outlet temperature have an inverse relationship. These findings serve as a foundational framework for future research projects and practical applications, providing essential insights into designing more effective and efficient cooling systems.

1. Introduction

Radiator design plays a pivotal role in diverse fields, from electronic cooling to automotive engineering and HVAC systems. The core components, fins, and tubes are integral for effective heat transfer. Fins, with their expansive surface areas, boost convective heat dissipation by maximizing contact with the surrounding medium, typically air. This enhances thermal exchange, although concerns arise about increased airflow resistance.

Radiator Design Fins have been used in heat exchanger applications for a long time because of their larger surface areas. Fins are an efficient way to increase the surface area exposed to the airflow and aid in convective heat transfer, according to research by Duan *et al.,* [1]. The fin design and placement aid in effective heat dissipation, which greatly enhances cooling efficiency in a variety of

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`thermal systems. However, research conducted by Fawaz *et al.,* [2] revealed several limits with fins, especially concerning airflow resistance and pressure drop. According to their research, fins may improve heat transfer but also obstruct the flow, which would raise energy costs and lower system efficiency.

The effectiveness of fins and tubes in radiators has been the subject of several comparison investigations. This research examines the temperature-dependent thermal conductivity and heat generation in the thermal behaviour of a convective fin. Discussion on the implications of the results for practical applications in mainly reported. Possible insights into optimizing fin design for enhanced heat transfer efficiency under conditions of temperature-dependent properties and heat generation have been reported Ghasemi *et al.,* [3]. Both fins and tubes exhibit unique advantages and limitations in radiator design. Fins offer an enhanced surface area for heat transfer but might induce higher pressure drops, whereas tubes optimize flow but could compromise heat transfer efficiency. A comprehensive comparative analysis considering diverse operational conditions is essential to determine the most suitable design for specific applications.

The paper by Yadav and Singh [4] investigates the performance evaluation of automotive radiators, focusing on aspects related to physical sciences, engineering, and technology. The study presents findings and insights into the performance characteristics of radiators, offering valuable information for the automotive industry. Farooque and Chauhan [5] conducted a comparative study on the use of nano-fluids as coolants in a car radiator, presenting their findings in the IOP Conference Series: Materials Science and Engineering. The research explores the performance and characteristics of nano-fluids for potential applications in improving automotive cooling systems. The performance and thermal analysis of a car radiator are examined by Gurjar *et al.,* [6]. In the context of automotive applications, the research focuses on assessing the radiator's thermal characteristics and efficiency. The design and study of redesigned radiator fins, presented by Mittal *et al.,* [7], aims to improve the overall cooling efficiency of automobile systems.

Another research reported in The SAE Technical Paper provides an overview of the study, which focuses on developing and evaluating radiator fin changes for better thermal performance. Using Python, Shyja [8] compares the optimization of straight fins with varied geometry and presents her findings at ACMS 2022, examining the efficacy of various configurations. According to a study published in the Journal of Physics: Conference Series, Ba *et al.,* [9] experimentally investigate the heat transfer properties of a composite thermosyphon radiator for CPU cooling, offering valuable information on the device's efficacy in thermal management.

Khalid *et al.,* [10] investigated the effect of honeycomb fin design on heat dissipation efficiency by performing a thorough thermal analysis of a car radiator with honeycomb fins. It proved improvement in radiator performance for better vehicle thermal management. Dhaher *et al.,* [11] explores one-dimensional steady-state heat transfer on a star in shape. The study looks into the properties of heat transfer with a particular emphasis on the star fin's distinctive geometry. The authors discuss the structure's thermal performance. The findings provide important new understandings of heat transfer phenomena in non-traditional fin shapes, with possible applications in a range of thermal and engineering systems. A thorough assessment of the state of knowledge regarding flow and heat transfer performance in compact fin-and-tube heat exchangers is reported by Adam *et al.,* [12]. The authors go over several topics, such as heat transfer mechanisms, flow characteristics, and design considerations. The review highlights important factors affecting these heat exchangers' performance and integrates results from various studies. For researchers and engineers working in the field, this information synthesis provides a useful resource that provides insights into the most recent advancements and difficulties related to compact fin-and-tube heat exchanger technology. Ranjbar *et al.,* [13] reported improved heat sink design through the use of porous pin fins arranged in different ways. The study analyses heat transfer and turbulent flow using numerical simulations to examine the improved heat sink's performance. To maximize heat dissipation, the study investigates various porous pin fin configurations. The suggested design has better thermal characteristics, according to the results, which offers important information for the creation of heat sink systems with higher levels of efficiency. By improving heat sink technology, this study helps to improve cooling in a variety of applications. Ibrahim *et al.,* [14] use both experimental and numerical methods to examine the impact of square-shaped perforations on enhanced heat transfer from fins. This study is revealed perforations affect the enhancement of heat transfer. Combining experimental data with numerical simulations, the study provides valuable insights into the thermal performance of fins with square-shaped perforations. The outcomes demonstrate how well this design works to improve heat transfer, and they provide a useful tool for understanding and refining fin configurations for better thermal.

From the above literature, tubes optimize fluid flow conduction, facilitating direct heat exchange with a streamlined design that minimizes pressure loss. Each design has unique advantages and drawbacks, necessitating careful consideration for varied operational contexts. Existing literature has extensively explored specific fin features but lacks comprehensive comparative evaluations across operating circumstances, material factors, and design optimizations.

To address this gap, the study scrutinizes fins distinct functions, evaluating their impact on heat transfer efficiency, optimizing surface area for dissipation, and analysing effects on pressure and airflow dynamics in radiator systems. By individually examining these elements, the research aims to elucidate their roles in enhancing overall thermal performance. This study intends to provide a thorough understanding of the intricate relationship between fins in radiator design. Anticipated findings aim to guide and potentially enhance engineering methodologies across industries, fostering more effective thermal management systems.

To bridge existing gaps in comparative analyses, this study systematically evaluates thermal performance, energy efficiency, and practical implications of fins and tubes in radiator design. Through a comprehensive examination of various operational conditions, material considerations, and design parameters, the research seeks to offer actionable insights for engineers, designers, and researchers looking to optimize radiator systems in diverse applications. The ultimate goal is to contribute to the advancement of radiator technology, leading to more efficient and improved thermal management across industries.

2. Numerical Study-Governing Equations

The current study included a comparison fin for the radiator and analysis using ANSYS 2023 R1 version. The SST-K epsilon turbulence model and pressure-based solver were used to investigate the temperature difference when increasing the number of fins. CFD solver (ANSYS FLUENT User's Guide) is used to solve the governing equation for continuity, momentum, energy, and k – ε as reported in Khan *et al.,* [15].

2.1 Continuity Equation

The generalized 3D continuity equation is given by Eq. (1),

$$\frac{\delta u}{\delta x}+\frac{\delta v}{\delta y}+\frac{\delta w}{\delta z}=0 \quad (1)$$

2.2 Momentum Equations

The momentum equation is given by Eq. (2) to Eq. (4),

$$u\frac{\delta u}{\delta x}+v\frac{\delta u}{\delta y}+w\frac{\delta u}{\delta z}=-\frac{1}{\rho}\frac{\delta p}{\delta x}+\frac{\delta^2 u}{\delta x^2}+\frac{\delta^2 u}{\delta y}+\frac{\delta^2 u}{\delta z^2} \tag{2}$$

$$u\frac{\delta v}{\delta x}+v\frac{\delta v}{\delta y}+w\frac{\delta v}{\delta z}=-\frac{1}{\rho}\frac{\delta p}{\delta y}+\frac{\delta^2 v}{\delta x^2}+\frac{\delta^2 v}{\delta y^2}+\frac{\delta^2 v}{\delta z^2} \tag{3}$$

$$u\frac{\delta w}{\delta x}+v\frac{\delta w}{\delta y}+w\frac{\delta w}{\delta z}=-\frac{1}{\rho}\frac{\delta p}{\delta x}+\frac{\delta^2 w}{\delta x^2}+\frac{\delta^2 w}{\delta y^2}+\frac{\delta^2 w}{\delta z^2} \tag{4}$$

2.3 Energy Equation

The energy equation is given by Eq. (5)

$$u\frac{\delta T}{\delta x}+v\frac{\delta T}{\delta y}+w\frac{\delta T}{\delta z}=-\frac{k}{\rho C_p}\frac{\delta^2 T}{\delta x^2}+\frac{k}{\rho C_p}\frac{\delta^2 T}{\delta y^2}+\frac{k}{\rho C_p}\frac{\delta^2 T}{\delta z^2} \tag{5}$$

2.4 K-Epsilon Model

More equations generally result in a more intricate model that offers greater accuracy but demands higher computational resources during simulations hence k-epsilon model is employed for current study and given by Eq. (6)

$$\frac{\partial}{\partial t}(\rho\kappa)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\left(\frac{\partial k}{\partial x_j}\right)\right]+P_k-\rho\varepsilon+\rho g k \tag{6}$$

Where, ρ is the density of the fluid, k is the turbulent kinetic energy, u_i is the velocity component in the i-th direction, μ is the molecular viscosity, μ_t is the turbulent viscosity, σk is the turbulent Prandtl number for k, P_k is the production of turbulent kinetic energy, ε is the turbulent dissipation rate, gk is the generation of turbulent kinetic energy due to buoyancy.

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\left(\frac{\partial \varepsilon}{\partial x_j}\right)\right]+C_{1\varepsilon}\frac{\varepsilon}{k}P_k-C_{2\varepsilon}\frac{\rho\varepsilon^2}{k}+\rho g\varepsilon \tag{7}$$

Where, ε is the turbulent dissipation rate, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are model constants, σε is the turbulent Prandtl number for ε, P_k is the production of turbulent kinetic energy, gε is the generation of turbulent dissipation rate due to buoyancy.

3. Methodology

The methodology involves systematically evaluating fins in radiator design. This includes analysing their thermal performance, energy efficiency, and practical implications across various conditions, materials, and design parameters to provide actionable insights.

3.1 Geometry of Radiator

A radiator with a fin density of six fins per inch, or six fins every linear inch along the core, is shown in Figure 1. The fins, which have dimensions of 200 mm in length and 75 mm in width, are made to maximise surface area for efficient heat dissipation. Because of the tube's 20 mm diameter, which facilitates easier coolant flow through the radiator, this design improves heat exchange. The radiator's overall length, including the core and the inlet and output tanks, is 480 mm. This distance guarantees effective coolant circulation throughout the system.

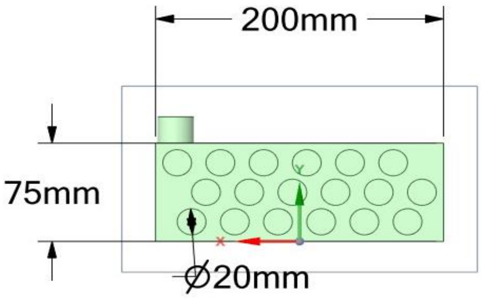

Fig. 1. Cross- section of a 6 FPI radiator

To maintain ideal operating temperatures, the radiator's capacity to control and dissipate engine heat is essential. The design, based on Sakthivel *et al.*, [16], includes the necessary measurements and configuration to increase the radiator's capability for heat control and dissipation. The geometry of 6 FPI radiator is shown Figure 2.

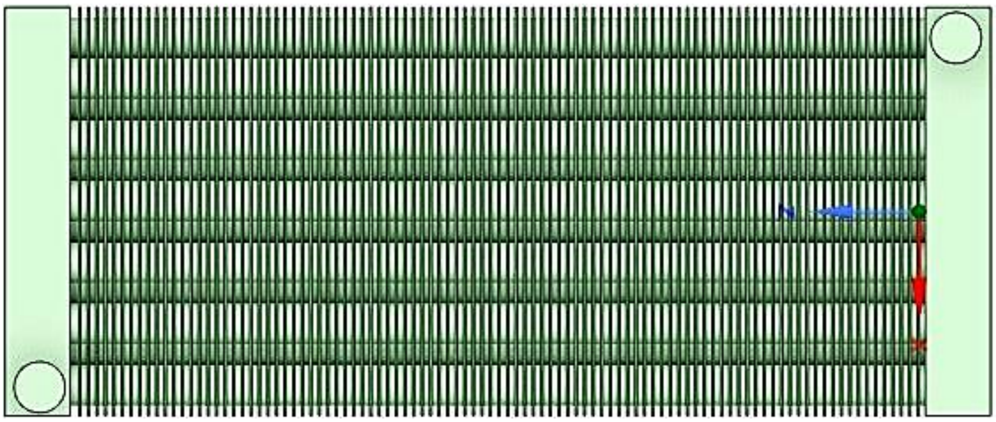
Fig. 2. Geometry of 6 FPI radiator

3.2 Properties of Materials

The properties of aluminium, water and air used in this investigate are tabulated in Table 1, Table 2 and Table 3 respectively.

Table 1
Properties of aluminium

Distance (m)	Velocity (ms^{-1})
Electrical Conductivity	37.7 x 106 S/m
Density	2770 kg/m^3
Thermal Conductivity	190 to 220 W/m-K
Specific Heat Capacity	900 J/kg-K

Table 2
Properties of water

Distance (m)	Velocity (ms^{-1})
Electrical Conductivity	0.08 S/m
Density	998.2 kg/m^3
Thermal Conductivity	0.60 W/m-K
Specific Heat Capacity	4182 J/kg-K

Table 3
Properties of air

Distance (m)	Velocity (ms^{-1})
Electrical Conductivity	10-15 S/m
Density	1.225 kg/m^3
Thermal Conductivity	0.0242 W/m-K
Specific Heat Capacity	1006.43 J/kg-K

3.3 Meshing

Meshing is an important phase in computational fluid dynamics (CFD) simulations, as it affects the accuracy and effectiveness of the analysis. It is critical for describing complex geometries in a numerical form that the CFD solver can manage by breaking down the physical domain into small, interconnected parts. In the context of modelling heat transfer in a finned tube heat exchanger with longitudinal fins with Ansys Fluent, the radiator is divided into smaller parts based on its dimensions and precision requirements. A hierarchical mesh with hexahedral cells is used to increase accuracy and accelerate convergence. To capture the boundary layer near the fins, inflation layers are used, as described by Karthick *et al.*, [17]. A 26.5 mm mesh size is employed to achieve a fin density of 6 fins per inch (FPI). The total number of elements and nodes is found to be 707, 254 and 331, 532, respectively. Figure 3 displays the radiator's meshing

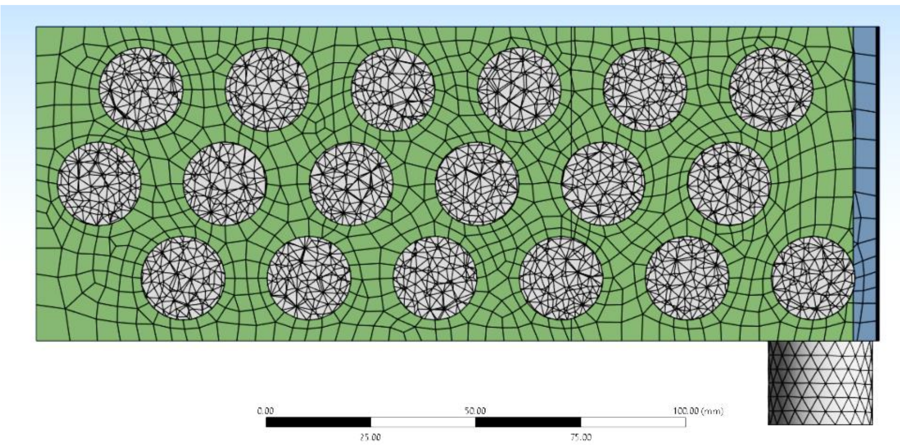

Fig. 3. Meshing of radiator

3.4 Grid Study

The study used advanced Computational Fluid Dynamics (CFD) analysis, specifically ANSYS 2023 R1, to simulate heat transfer dynamics within a finned tube heat exchanger with longitudinal fins. The radiator was methodically separated into manageable components, with a meshing strategy centred on optimising hexahedral cells in a structured mesh to increase accuracy and convergence. The mesh structure was modified, especially near the fins, using complex inflation layers to precisely capture heat transmission nuances and account for boundary layer effects. The study's effectiveness was dependent on carefully established boundary conditions that reflected real-world events. These circumstances included factors such as inlet velocity, outlet pressure, water inlet temperature, and air temperature, which provided a thorough framework for the simulation and ensured an accurate portrayal of the system's thermal behaviour. To improve realism, the study took into account the thermal properties of the radiator's main materials: aluminium, water, and air. Each material was identified by its own thermal properties, which contributed to a more complex and realistic depiction of heat transfer mechanisms within the radiator. This material-centric method advanced the simulation from a theoretical to a practical representation of thermal dynamics. The simulation's convergence time was between 55 and 60 minutes, demonstrating the depth and intricacy of the modelling approach.

3.5 Boundary Conditions

Boundary conditions play a crucial role in modelling the behaviour of heat transfer and fluid flow in radiators. They help define the environment in which the radiator operates and are essential for accurately simulating its performance. Boundary conditions are vital for modelling heat transfer and fluid flow in a radiator system. They define the characteristics of the fluid entering and exiting the radiator, as well as the initial conditions of the surrounding environment. The velocity boundary condition specifies the speed at which the fluid enters the radiator, typically around 0.2 m/s. This velocity is crucial for calculating the fluid's flow rate and its ability to remove heat from the radiator efficiently. The outlet pressure boundary condition determines the pressure at the radiator's outlet relative to atmospheric pressure (gauge pressure). When set to 0 Pa (gauge pressure), the outlet pressure is considered to be at atmospheric pressure. This condition influences the fluid's flow behaviour as it exits the radiator, affecting overall flow patterns and pressure distribution in the system. The temperature boundary condition specifies the initial temperature of the coolant (water) entering the radiator, typically set at 363 K (90°C). This temperature significantly impacts heat transfer within the radiator, as the coolant absorbs heat from the system and its temperature may change as it flows through the radiator. Lastly, the air temperature boundary condition defines the initial temperature of the surrounding air. This parameter is important for understanding the heat exchange between the radiator and its environment. It interacts with the radiator and modifies how quickly heat escapes the radiator and dissipates into the surrounding air as reported in Amrizal [18].

4. Results

This study's main goal is to comprehend the relationship between the FPI and outlet temperature, which is a crucial component in determining a radiator's efficiency. Three distinct radiators with six, eight, and ten FPI, respectively, are the subject of the study. To verify that the results were accurate, the radiators were tested in the same settings. For every radiator, the outlet temperature was carefully measured and noted. The study's conclusions were very illuminating. It was found that the outlet temperature dropped as the FPI rose. In particular, the temperature of the 6 FPI radiator's outlet was 361K, that of the 8 FPI radiators was 360K, and that of the 10 FPI radiators was 359K. This suggests that the FPI and outlet temperature have an inverse relationship. The greater surface area available for heat transfer is what causes the outlet temperature to drop as FPI increases. A greater surface area for heat dissipation is provided by more fins per inch, enabling more effective cooling. This implies that heat-dissipating radiators with a higher FPI might be more efficient.

Table 4
Effect of number of fins and corresponding FPI on outlet temperature

FPI	No. of fins	Outlet Temperature(k)
6	94	361
8	125	360
10	157	359.7

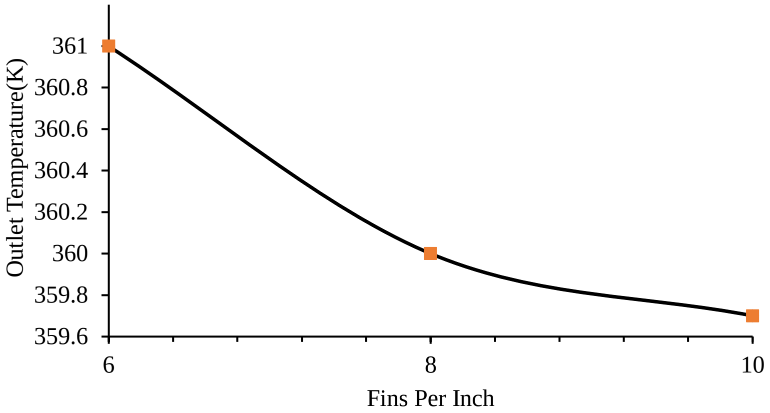

Fig. 4. Fins per inch vs outlet temperature

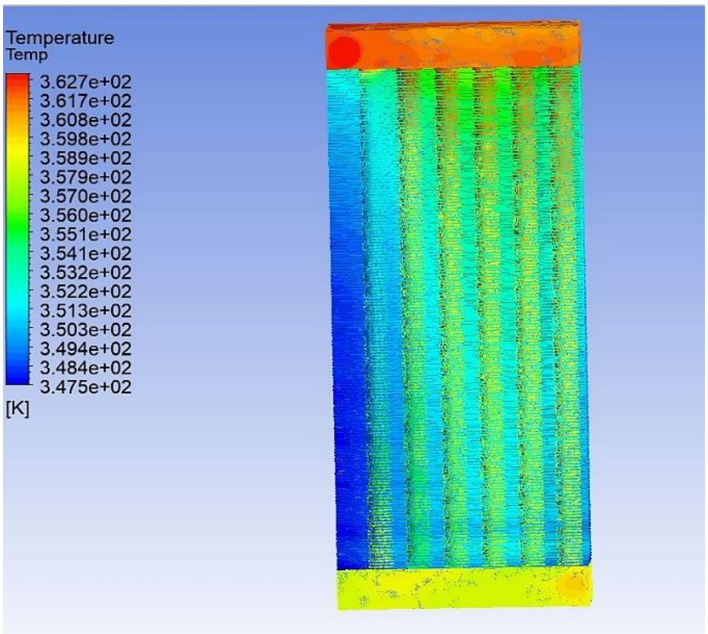

Fig. 5. Temperature contour

Table 5
Shows the variation of temperature with number of elements and sizing

Element Size (mm)	Number of Nodes	Number of Elements	Outlet Temperature (K)
26.5	331532	707254	361.115
27.5	331246	707211	361.109
28.5	331185	706649	361.106
29.5	331163	707822	361.079
30.5	331115	706455	360.869

This study used a thorough Comparative Computational Fluid Dynamics (CFD) Analysis to investigate the thermal performances of radiators with various fin densities—that is, radiators with six, eight, and ten fins per inch (FPI). The goal of the study was to determine the best radiator design to produce the lowest operating temperature possible. Out of all the tested variations, the 10 FPI configurations produced the lowest temperature. The FPI of 6 Radiator showed a somewhat higher operating temperature but a moderate thermal efficiency. Although its reduced fin density allowed for more air to pass through, it also somewhat reduced thermal conductivity, which raised temperatures. Compared to the 6 FPI version, the 8 FPI radiator showed better heat dissipation. In comparison to the 6 FPI radiator, the denser fin structure improved thermal conductivity and decreased temperatures. The 10 FPI Radiator proved to be the best configuration with the best thermal performance. By increasing the surface area for heat exchange, the higher fin density greatly increased heat transfer efficiency and, as a result, the lowest observed temperature of all configurations was reached as reported in Amrizal [18].

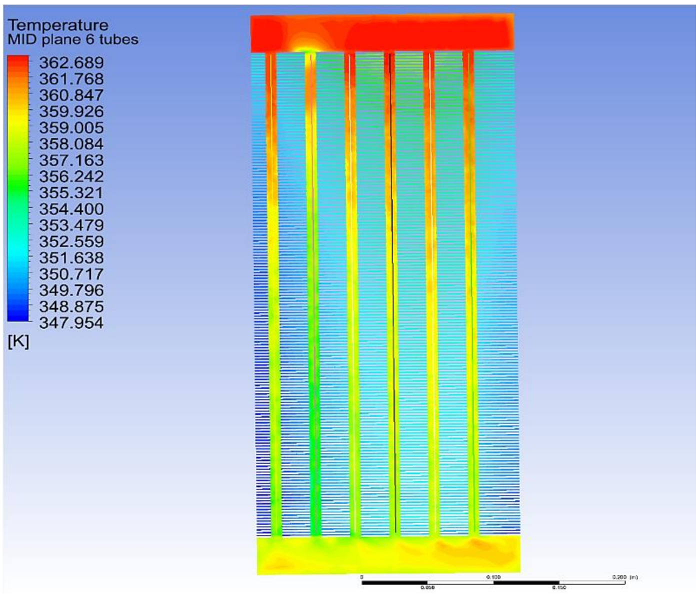

Fig. 6. Temperature distribution along the length of tube

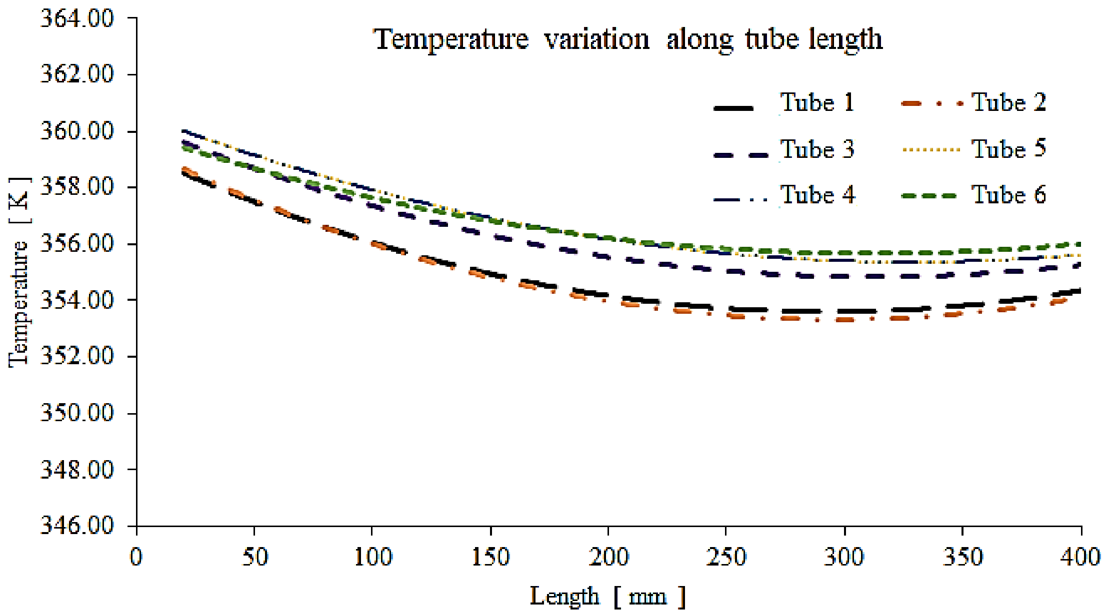

Fig. 7. Temperature variation along tube length

This study looks at the temperature distribution along a 400mm tube's length. The primary focus of the investigation is the tube's centre temperature, which is determined at 20 different points along its length. The temperature contour plots show these measurements as various coloured lines.

Computer simulations were used to model the heat transfer inside the tube. The temperature readings at the tube's centre and 20 evenly spaced locations along its length were used to create a temperature contour plot. The use of different colours to represent different temperature levels allowed for a visual representation of the temperature distribution. Along the entire length of the tube, distinct patterns could be seen in the temperature contour lines. It's interesting to note that the study saw a pattern of temperature decrease along the tube's length, followed by an increase when the hot and cold fluids were mixed. This the decreed pattern seemed to be damped, much like an oscillation graph that has been damped. The temperature gradually dropped over time, signifying a slow loss of thermal energy.

The temperature contour lines, which each represented a distinct location where temperature readings were taken, showed various patterns along the tube. These patterns offered important new information about the properties of heat transfer in the tube and the way thermal energy propagates through the material of the tube or through the medium that is passing through it.

The impact of various materials or fluid properties on variations in temperature gradients and uniformity was also covered in the study. For heat transfer to be optimized in a variety of applications, such as industrial processes, HVAC systems, and heat exchangers, it is essential to comprehend the temperature distribution along the length of channels.

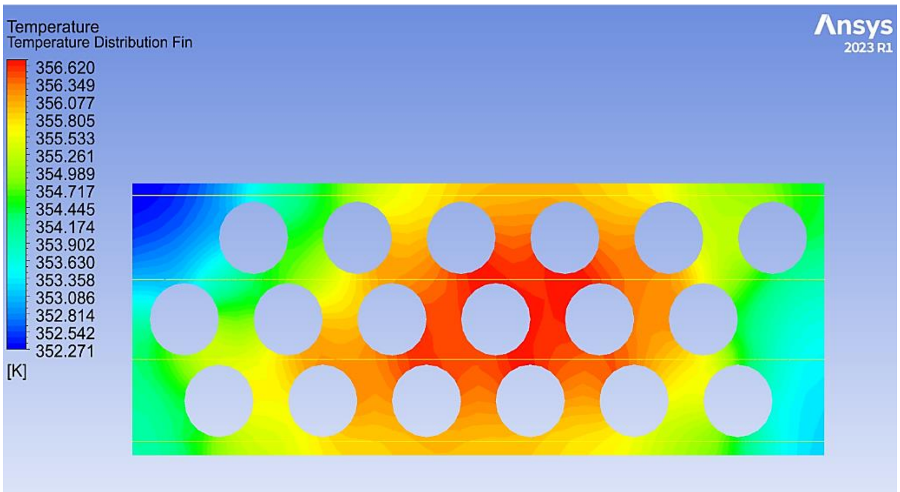

Fig. 8. Temperature distribution along fin

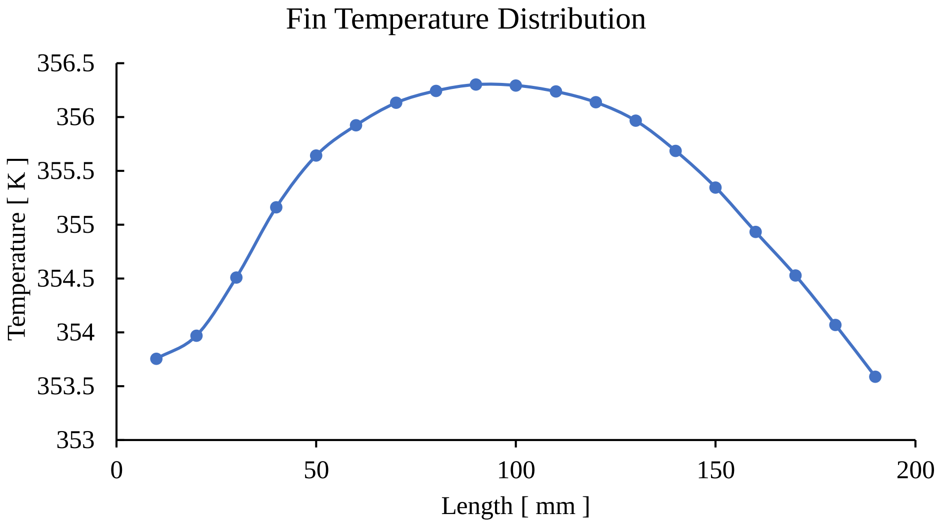

Fig. 9. Fin temperature distribution of 10 FPI radiator

An important understanding of heat dissipation and thermal conductivity can be obtained by measuring the temperature distribution along a 200 mm fin that is operating at 353 K. Knowing how well the fin transfers heat from its base into the surroundings particularly air or a cooling fluid requires knowledge of the temperature distribution along the fin's length. In this case, specific trends in temperature distribution can be expected, assuming a uniform heat transfer coefficient and negligible heat generation along the fin length. Generally, there will be a gradient in temperature along the fin's length. The temperature will peak at the base where it attaches to the heat source [19].

When the temperature reaches its peak, it will be 353 K, the operating temperature. The temperature will progressively drop as we travel away from the base and along the length of the fin. The fin's material, geometry, and the properties of the surrounding medium that affect heat transfer all affect how quickly the temperature drops along the fin. A steeper temperature gradient will be produced by a more effective fin design, such as one with a larger surface area or higher thermal conductivity, which will allow for faster heat dissipation along the fin's length. If sufficient heat dissipation occurs, the temperature at the extremity of the fin (the furthest from the base) will eventually stabilize and approach the temperature of the surrounding air or medium.

The results of this study highlight how important fin density is to radiator performance. Higher fin densities are generally associated with better heat dissipation and lower operating temperatures, as supported by the CFD analysis. The 10 FPI configuration, in particular, showed remarkable thermal performance, indicating its potential for applications requiring strict thermal control. But it's important to think about the possible disadvantages of increased fin densities. Even though 10 FPI radiators have exceptional cooling capabilities, their higher air resistance could cause problems for the system's overall airflow and performance. This emphasizes the necessity of designing radiators with a careful balance between maximizing heat dissipation and minimizing air resistance.

This study has implications for several industries, especially the automotive, aerospace, and electronics sectors. Where the need for effective cooling solutions is paramount. The 10 FPI radiator's exceptional thermal performance indicates that high-performance systems requiring strict heat management are a good fit for it as mentioned in Ahmed *et al.,* [19].

Prospective research endeavours could investigate the optimization of supplementary design parameters, such as varied fin geometries, material compositions, and fluid flow characteristics, in addition to fin density, to augment radiator efficiency and minimize possible airflow constraints. The applicability and dependability of these findings in real-world engineering applications would be enhanced by verifying CFD results through empirical experimentation and looking into the long-term durability and reliability of radiators under varied operating conditions.

5. Conclusion

The design of radiator fins and tubes significantly impacts heat transfer efficiency and overall thermal performance in various applications. Fins, with their larger surface areas, enhance convective heat transfer by increasing contact with the surrounding medium. However, they may also increase airflow resistance. Tubes, on the other hand, optimize fluid flow conduction, facilitating direct heat exchange with minimal pressure loss. The trade-offs between fins and tubes must be carefully considered based on specific operational requirements and design constraints. In a comparative study evaluating the thermal efficiency of different fin densities (6 FPI, 8 FPI, and 10 FPI) in radiator configurations, the 10 FPI configuration exhibited the lowest operating temperature, indicating superior thermal performance. The 8 FPI model showed better heat dissipation, while the 6 FPI model operated at a higher temperature with moderate efficiency. Higher fin densities can improve heat dissipation but may also increase air resistance. Therefore, radiator design should balance optimizing heat dissipation efficiency with controlling airflow restrictions. This research highlights the crucial role of fin density in determining the thermal efficiency of radiator systems. The 10 FPI configuration emerges as the optimal choice for its superior heat dissipation capabilities. However, achieving a balance between airflow restrictions and heat dissipation is critical in radiator design. These findings provide a foundational framework for future research and practical applications, offering essential insights into designing more effective and efficient cooling systems across various industries.

Acknowledgement
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