A Numerical Investigation on Heat Transfer Characteristics for Different Radiator Designs with Nanofluid Coolants

Submitted by:
Saraban Salsabila
190011133
MD Yousuf Julfikar
210032101

Supervised by:
Dr. Mohammad Ahsan Habib
Professor, Department of Mechanical & Production Engineering
Islamic University of Technology

Department of Mechanical and Production Engineering (MPE)

Islamic University of Technology (IUT)

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, "**A Numerical Investigation on Heat Transfer Characteristics for Different Radiator Designs with Nanofluid Coolants**", is the outcome of the investigation and research carried out by me under the supervision of **Dr. Mohammad Ahsan Habib**, Professor, Department of Mechanical & Production Engineering, Islamic University of Technology.

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Name of the Student
Student No: 190011133

Name of the Student
Student No: 210032101

Recommendation of the Thesis Supervisors

The thesis titled "**A Numerical Investigation on Heat Transfer Characteristics for Different Radiator Designs with Nanofluid Coolants**" submitted by **Saraban Salsabila**, Student No: 190011133 and **MD Yousuf Julfikar** Student No: 210032101 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of B Sc. in Mechanical Engineering on **3rd June, 2024**.

1. **-------------------------------------**
   Dr. Mohammad Ahsan Habib (Supervisor)
   Professor,
   Department of Mechanical & Production Engineering,
   Islamic University of Technology.

CO-PO Mapping of ME 4800 -Thesis and Project

COs	Course Outcomes (CO) Statement	(PO)	Addressed by	
CO1	Discover and Locate research problems and illustrate them via figures/tables or projections/ideas through field visit and literature review and determine/Setting aim and objectives of the project/work/research in specific, measurable, achievable, realistic and timeframe manner.	**PO2**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO2	Design research solutions of the problems towards achieving the objectives and its application. Design systems, components or processes that meets related needs in the field of mechanical engineering	**PO3**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO3	Review, debate, compare and contrast the relevant literature contents. Relevance of this research/study. Methods, tools, and techniques used by past researchers and justification of use of them in this work.	**PO4**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO4	Analyse data and exhibit results using tables, diagrams, graphs with their interpretation. Investigate the designed solutions to solve the problems through case study/survey study/experimentation/simulation using modern tools and techniques.	**PO5**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO5	Apply outcome of the study to assess societal, health, safety, legal and cultural issue and consequent possibilities relevant to mechanical engineering practice.	**PO6**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO6	Relate the solution/s to objectives of the research/work for improving desired performances including economic, social and environmental benefits.	**PO7**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO7	Apply moral values and research/professional ethics throughout the work, and justify to genuine referencing on sources, and demonstration of own contribution.	**PO8**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO8	Perform own self and manage group activities from the beginning to the end of the research/work as a quality work.	**PO9**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO9	Compile and arrange the work outputs, write the report/thesis, a sample journal paper, and present the work to wider audience using modern communication tools and techniques.	**PO10**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO10	Organize and control cost and time of the work/project/research and coordinate them until the end of it.	**PO11**	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO11	Recognize the necessity of life-long learning in career development in dynamic real-world situations from the experience of completing this project.	**PO12**	Thesis Book	
			Performance by research	
			Presentation and soft skill	

Student Name /ID:

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Signature of the Supervisor: …………………………

Name of the Supervisor: ……………………………..

K-P-A Mapping of ME 4800 -Theis and Project

COs	POs	Related Ks								Related Ps							Related As				
		K1	K2	K3	K4	K5	K6	K7	K8	P1	P2	P3	P4	P5	P6	P7	A1	A2	A3	A4	A5
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Acknowledgment

"In the name of Allah, Most Gracious, Most Merciful"

Our gratitude is to Almighty Allah for blessing us with the chance to complete this thesis and for enabling us to resolve the challenges that emerged throughout our research work.

We would like to express our sincere appreciation to our supervisor, Dr. Mohammad Ahsan Habib, for his kind supervision, helpful advice, and continuous support. His creative and technical guidance was essential to the success of this research project. This thesis would not have been completed without his invaluable help and direction.

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Abstract

This thesis presents a comprehensive numerical investigation into the heat transfer characteristics of different radiator designs using nanofluid coolants. The study focuses on evaluating and comparing the thermal performance of radiators equipped with various fin configurations, including triangular, rectangular, and cone pin fins. Additionally, the influence of nanofluid additives, specifically Al_2O_3 and CuO nanoparticles at concentrations of 0.05%, 0.15%, and 0.30%, is analyzed to assess their impact on heat dissipation efficiency. Numerical simulations are conducted using ANSYS Fluent to simulate fluid flow and heat transfer processes within the radiators. Key parameters such as outlet temperature, temperature difference, and heat transfer rate are analyzed to understand the effectiveness of each radiator design in enhancing thermal performance. The results highlight significant variations in heat transfer rates among different fin designs and nanofluid concentrations, providing valuable insights into optimizing radiator configurations for improved heat dissipation in various engineering applications.

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Nomenclature

Nu	*Nusselt number*
Re	*Reynold's number*
h	*Heat transfer coefficient*
Pr	*Prandtl number*
d	*Hydraulic diameter*
Q	*Rate of heat transfer*
$\dot{m}$	*Mass flow rate*
T	*Temperature*
ρ	*Density*
φ	*Particle sphericity*
Cp	*Specific heat capacity*
Φ	*Thermal conductivity*
μ	*Viscosity*

Chapter 1 Introduction

1.1 Objectives

- To analyze the effect of different radiator designs on heat transfer efficiency by employing nanofluid coolants in simulated setups.
- To explore the varying heat transfer efficiencies resulting from different nanofluid compositions in the simulations.

1.2 Background

Thermal management stands as a foundational element in the quest for efficiency and longevity across diverse applications, ranging from the automotive industry and electronic devices to industrial machinery. Effective heat dissipation is not merely a desirable attribute but a critical necessity for maintaining optimal operational conditions. This ensures that systems operate within their designed thermal limits, enhancing their reliability and performance. Among the various components involved in thermal management systems, radiators hold a pivotal role. They are instrumental in facilitating heat transfer, thereby substantially contributing to the overall performance and dependability of the systems they support.

Radiators are integral to the thermal regulation of engines, electronics, and industrial equipment. They function by dispersing the heat generated during operation, which is essential for preventing overheating and ensuring the longevity of these systems. The importance of radiators extends beyond their basic functionality; they are active participants in maintaining the delicate balance of temperatures within safe operational ranges. Mastering the regulation and management of temperature variations is crucial for the smooth operation of any system, underscoring the significance of radiators in thermal management.

In the context of today’s rapidly evolving technical landscape, the drive to enhance radiator efficiency is more pressing than ever. Technological advancements continually push the boundaries of what is possible, demanding superior thermal performance from all components involved. As we strive for better fuel economy, reduced energy consumption, and overall increased efficiency, a comprehensive reassessment of radiator performance becomes imperative. Enhanced radiator efficiency leads to improved heat dissipation, which in turn boosts the performance and durability of engines, electronics, and industrial operations. This relentless pursuit of optimization underscores the need for innovative approaches to radiator design and functionality.

One of the most promising areas of innovation in thermal management is the exploration of radiator design coupled with the application of nanofluid coolants. Nanofluids, which are fluids engineered with nanoparticles to enhance their thermal properties, offer significant potential for improving heat transfer capabilities. By incorporating nanofluids, radiators can achieve superior thermal conductivity, resulting in more efficient heat dissipation. However, understanding the full impact of nanofluid coolants on radiator performance requires a detailed analysis, which is where Computational Fluid Dynamics (CFD) simulations come into play.

CFD simulations, particularly those conducted using ANSYS software, provide a powerful tool for exploring the effects of nanofluids on radiator outlet temperatures. This shift from traditional experimental methods to digital simulations represents a significant advancement in precision and comprehensiveness. CFD simulations allow for a thorough examination of various radiator designs under different operating conditions, providing insights that are difficult to achieve through conventional experimentation alone.

By delving into the complex interactions between radiator designs and nanofluid coolants through CFD simulations, we can uncover the nuanced mechanisms that drive thermal performance. This approach not only enhances the accuracy of our findings but also enables a more detailed analysis of the variables at play. The insights gained from these simulations can inform the design and development of more efficient radiators, tailored to meet the demands of modern technology.

Ultimately, the goal is to leverage these advanced simulation techniques to optimize radiator performance across a range of applications. By achieving a deeper understanding of how to enhance heat dissipation through innovative designs and materials, we can pave the way for future advancements in thermal management. This will not only meet the current demands for efficiency and sustainability but also drive progress in various fields, ensuring that systems operate at their peak performance while maintaining durability and reliability.

1.3 Chapter Conclusion

In this introductory chapter, we have established the critical role of thermal management in ensuring the efficiency and longevity of systems across various applications. Radiators have been highlighted as key components in this process, essential for effective heat dissipation in engines, electronics, and industrial machinery. As technology advances, the demand for enhanced thermal performance becomes increasingly pressing, necessitating innovative approaches to radiator design and functionality.

We have outlined the objectives of this study, which focus on analyzing the impact of different radiator designs and nanofluid coolant compositions on heat transfer efficiency using CFD simulations. This approach promises to offer a comprehensive and precise understanding of the variables influencing radiator performance, moving beyond traditional experimental methods.

The background provided underscores the importance of optimizing radiator efficiency to achieve better fuel economy, reduced energy consumption, and overall enhanced system performance. The integration of nanofluid coolants, with their superior thermal properties, presents a promising avenue for improving heat transfer capabilities. CFD simulations, particularly through the use of ANSYS software, emerge as a powerful tool for exploring these advancements in a simulated environment.

In conclusion, this chapter sets the stage for a detailed investigation into the interplay between radiator design and nanofluid coolants. By leveraging advanced simulation techniques, we aim to uncover the mechanisms driving thermal performance and pave the way for future innovations in thermal management. The insights gained from this study will be crucial in meeting the modern demands for efficiency and sustainability, ensuring that systems continue to operate at their peak performance while maintaining durability and reliability.

Chapter 2 Literature Review

This chapter is structured to provide a detailed exploration of the various aspects of radiator technologies and thermal management, starting with an introduction to radiators and their components, followed by an examination of the heat dissipation process and the different types of radiator designs and fins. It also covers the materials used in radiators and the considerations involved in design selection, along with the factors affecting radiator efficiency. The chapter then delves into the properties and composition of coolants, focusing on the role of nanofluids in enhancing heat transfer. Finally, it discusses the advantages and disadvantages of using nanofluids and the application of ANSYS simulations in optimizing radiator designs.

The pursuit of effective heat dissipation in radiator systems has led to significant research into the use of nanofluid coolants and radiator design optimization. This literature review seeks to provide a comprehensive understanding of the current state of knowledge in this field by integrating key findings from studies on heat transfer characteristics, focusing on various radiator designs and the use of nanofluid coolants. By exploring the latest advancements in radiator technologies, coolant properties, and simulation techniques, this review aims to elucidate the critical factors that influence the thermal performance of radiator systems.

Radiators are essential components in thermal management systems, ensuring that engines, electronic devices, and industrial machinery operate within safe temperature ranges. Effective radiator design and the selection of appropriate coolants are crucial for enhancing heat transfer efficiency, thereby improving the overall performance and longevity of the systems they support. The evolution of radiator technologies has seen significant advancements in materials, geometric configurations, and manufacturing techniques, all aimed at optimizing heat dissipation.

Nanofluids, which are engineered colloidal suspensions of nanoparticles in base fluids, have emerged as promising coolants due to their enhanced thermal properties. Studies have shown that nanofluids can significantly improve the thermal conductivity and convective heat transfer coefficients of coolants, making them highly effective for use in radiator systems. However, understanding the precise mechanisms by which nanofluids enhance or sometimes decrease heat transfer rates remains a critical area of research.

Simulation techniques, particularly those utilizing advanced software like ANSYS, have proven invaluable in assessing and predicting the heat transfer properties of different radiator designs with nanofluid coolants. Numerical simulations allow researchers to explore a wide range of design variations and operating conditions, providing detailed insights that are often challenging to obtain through experimental methods alone.

By reviewing the literature on these topics, this chapter aims to provide a solid foundation for understanding the complex interplay of factors that determine the heat transfer performance of radiator systems, guiding future research and development efforts in this critical area of thermal management.

2.1 Radiator Technologies and Thermal Management

The field of thermal management has experienced significant advancements over the years, driven by the increasing complexity and performance demands of modern systems. At the heart of thermal management strategies lies the radiator—a component crucial for dissipating heat and maintaining optimal operating temperatures in a variety of applications, including automotive engines, electronic devices, and industrial machinery. Understanding the evolution and technologies behind radiators is essential for appreciating their role in contemporary thermal management solutions.

Radiator technologies have evolved considerably since their inception, with continuous improvements aimed at enhancing heat transfer efficiency and overall performance. Traditional radiators, primarily constructed from copper and brass, have given way to more advanced designs utilizing aluminum and other high-performance materials. These modern materials not only offer superior thermal conductivity but also contribute to lighter and more durable radiator structures.

One of the most significant advancements in radiator technology is the development of enhanced fin and tube designs. These designs increase the surface area available for heat exchange, thereby improving the efficiency of heat dissipation. Additionally, the integration of advanced manufacturing techniques, such as brazing and precision welding, has enabled the production of radiators with intricate geometries that further optimize thermal performance.

In parallel with material and design innovations, the application of Computational Fluid Dynamics (CFD) simulations has revolutionized radiator development. CFD allows for detailed analysis and optimization of radiator designs in a virtual environment, enabling engineers to test various configurations and predict their performance under different operating conditions. This digital approach not only accelerates the development process but also provides insights that are difficult to obtain through conventional experimental methods.

Another groundbreaking development in thermal management is the use of nanofluid coolants. Nanofluids, which are fluids containing nanoparticles, exhibit superior thermal properties compared to conventional coolants. The addition of nanoparticles enhances thermal conductivity, heat capacity, and viscosity, resulting in more efficient heat transfer. When used in radiators, nanofluids can significantly improve cooling performance, making them a promising area of research and application in thermal management systems.

The combination of advanced radiator designs, high-performance materials, and innovative coolants forms the foundation of modern thermal management strategies. As the demand for more efficient and sustainable systems continues to grow, the role of radiators becomes increasingly critical. This chapter delves into the technologies and advancements that have shaped contemporary radiator designs, examining their impact on thermal management across various applications.

We will explore the historical progression of radiator technologies, highlighting key milestones and innovations. Additionally, we will discuss the principles of thermal management and the specific challenges associated with heat dissipation in different contexts. By understanding the current state of radiator technologies and their applications, we can better appreciate the ongoing efforts to enhance thermal performance and develop next-generation cooling solutions.

In summary, this sub-chapter provides a comprehensive overview of radiator technologies and their integral role in thermal management. Through a detailed examination of materials, designs, and simulation techniques, we aim to shed light on the advancements that have transformed radiators into sophisticated components capable of meeting the demands of modern systems. This understanding sets the stage for further exploration of cutting-edge innovations in radiator design and their implications for future thermal management solutions.

2.1.1 Introduction to Radiators

Radiators are indispensable components in thermal management systems, playing a crucial role in dissipating heat and maintaining optimal operating temperatures in various applications. From automotive engines and electronic devices to industrial machinery, radiators ensure that systems operate within safe thermal limits, thereby enhancing their reliability, efficiency, and longevity. This chapter provides a comprehensive introduction to radiators, examining their fundamental principles, historical development, and the technological advancements that have shaped their evolution.

Radiators function on the basic principle of heat transfer, where heat is transferred from a hot fluid (coolant) circulating within the radiator to the surrounding air. This process involves three primary mechanisms: conduction, convection, and radiation. The efficiency of a radiator depends on its ability to maximize these heat transfer processes, ensuring effective cooling of the system it serves.

Historical Development:

The development of radiators dates back to the late 19th and early 20th centuries, coinciding with the advent of internal combustion engines and the need for effective cooling solutions. Early radiators were typically constructed from copper and brass due to their excellent thermal conductivity. These materials, combined with simple fin-and-tube designs, provided the necessary cooling performance for early automotive and industrial applications.

As technology progressed, the demand for more efficient and compact cooling solutions led to significant advancements in radiator design and materials. The introduction of aluminum as a primary material marked a significant milestone in radiator technology. Aluminum radiators offered several advantages, including lighter weight, superior thermal conductivity, and enhanced corrosion resistance. These benefits made aluminum radiators the preferred choice for modern automotive and industrial applications.

Technological Advancements:

Modern radiators have evolved far beyond their early counterparts, incorporating advanced materials, intricate designs, and innovative manufacturing techniques.[1] Key advancements include:

1. **Enhanced Fin and Tube Designs:** Modern radiators feature highly engineered fin and tube configurations that increase the surface area available for heat exchange. This design improvement significantly boosts the efficiency of heat dissipation.
2. **High-Performance Materials:** The use of materials such as aluminum alloys and composite materials has improved the thermal conductivity and durability of radiators. These materials enable the production of lightweight and robust radiator structures capable of withstanding harsh operating conditions.
3. **Advanced Manufacturing Techniques:** Precision manufacturing methods, such as brazing, welding, and extrusion, have enabled the creation of complex radiator geometries that optimize airflow and heat transfer. These techniques ensure that radiators can meet the stringent performance requirements of modern systems.
4. **Integration of CFD Simulations:** Computational Fluid Dynamics (CFD) simulations have revolutionized radiator design by allowing engineers to model and analyze the performance of various radiator configurations in a virtual

environment. This approach facilitates the optimization of radiator designs, ensuring maximum thermal efficiency and performance.

5. **Nanofluid Coolants:** The development of nanofluid coolants, which contain nanoparticles to enhance thermal properties, represents a significant innovation in thermal management. Nanofluids offer superior thermal conductivity, heat capacity, and viscosity compared to traditional coolants, leading to more efficient heat transfer when used in radiators.

Applications and Importance:

Radiators are integral to the thermal regulation of numerous systems, including:

- **Automotive Engines:** Radiators prevent engine overheating by dissipating heat generated during combustion. Efficient radiator performance is crucial for maintaining engine reliability and fuel efficiency.

- **Electronic Devices:** In electronics, radiators (or heat sinks) ensure that components such as CPUs and GPUs operate within safe temperature ranges, preventing thermal damage and ensuring optimal performance.

- **Industrial Machinery:** Radiators in industrial equipment manage the heat generated by heavy machinery, preventing overheating and ensuring continuous operation.

2.1.2 Components of a Radiator

- **Tubes:** Radiators feature a network of tubes responsible for circulating coolant throughout the cooling system. These tubes play a critical role in transporting heated coolant from the engine to the radiator to initiate the cooling process.
- **Fins:** Radiators are equipped with fins strategically placed to maximize surface area for efficient heat dissipation. These fins optimize the transfer of heat from the coolant to the surrounding air through convection. As the hot coolant passes through the tubes, the fins facilitate the cooling process by enhancing heat exchange.
- **Coolant:** Radiators use a coolant mixture typically consisting of water and antifreeze like ethylene glycol or other additives. This coolant absorbs heat generated by the engine and transports it to the radiator for dissipation. Selecting the right coolant mixture is essential to ensure optimal thermal conductivity and maintain the engine at a stable operating temperature.
- **Other Essential Elements:** Several components, including headers, tanks, and pressure caps are necessary to provide proper fluid circulation, pressure regulation, and structural integrity.

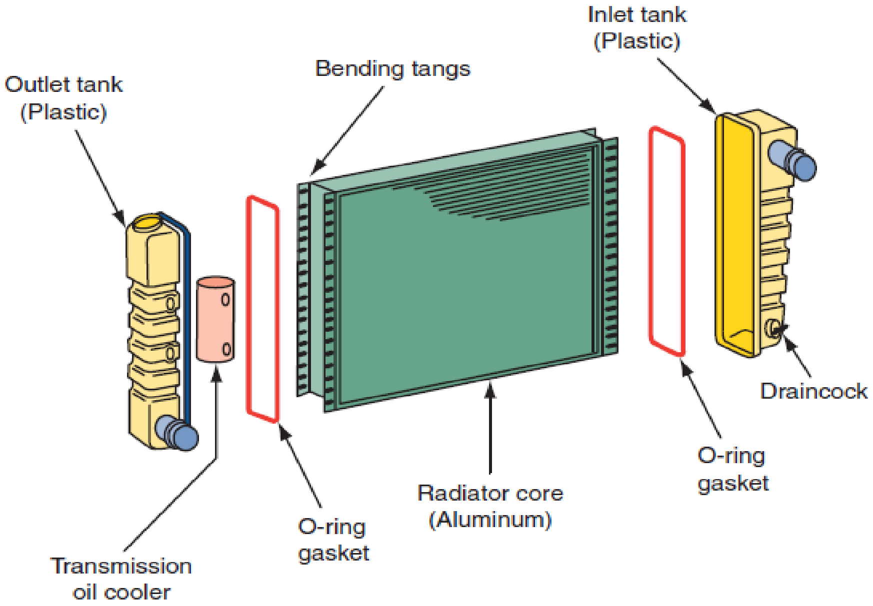


Figure 1 Components of Radiator [2]

The radiator core, which is made up of tubes and fins, is an essential component in heat exchange. Hot coolant circulates through the tubes, transferring heat to the fins. This design maximizes surface area for efficient convective heat exchange with the surrounding air, which is essential for effective cooling in a wide range of applications. Material selection, fin density, and overall design all influence how well the radiator distributes heat.

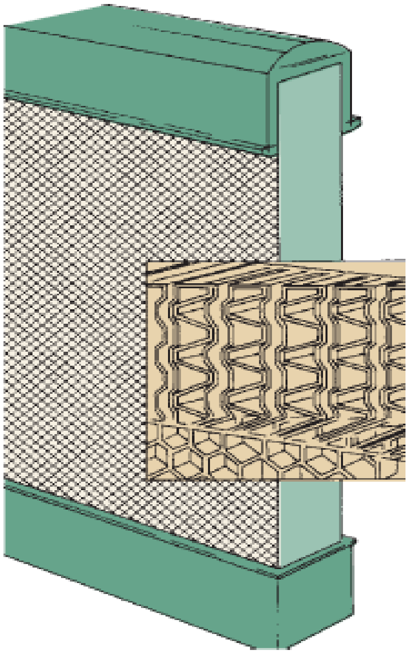


Figure 2 Radiator Core [2]

Radiators play a vital function in heat dissipation by regulating the temperature of engines and electrical components to prevent overheating. By transmitting heat from the coolant to the surrounding air, they guarantee that motors operate smoothly and electronic devices perform optimally. This temperature regulation is critical for the durability and dependability of these systems, preventing heat-induced damage and failure. Additionally, many radiators include fans to boost airflow and cooling efficiency. Overall, radiators are crucial to the correct operation and safety of numerous mechanical and electronic systems.

2.1.3 Heat Dissipation Process

A radiator's heat dissipation mechanism involves the passage of heated coolant from the engine through its tubes. As the coolant makes contact with the tubes, heat is transferred to fins affixed to the tubes. Convective heat exchange happens when airflow, helped by fans, takes heat from the fins and cools the coolant. The process ends when the cooled coolant re-enters the engine. This continuous cycle ensures efficient thermal management, which is critical for achieving ideal temperatures in a variety of applications.[3]

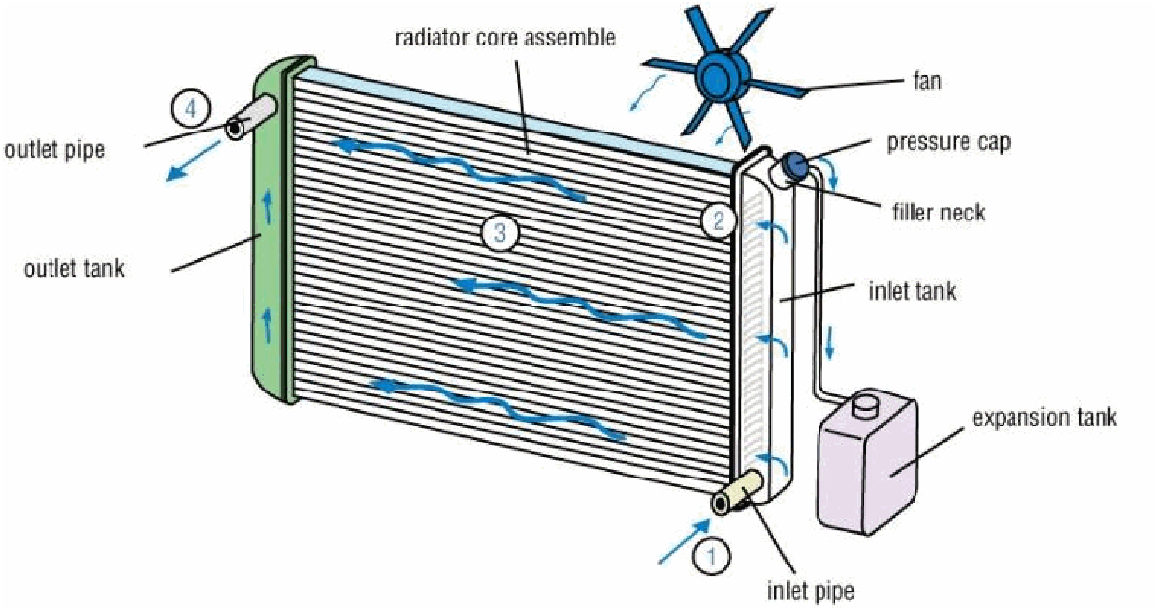


Figure 3 Heat Dissipation Process of a Radiator [4]

Heat dissipation is critical to the functionality and durability of mechanical and electrical devices. Efficient heat dissipation minimizes overheating, which can damage components, limit operational efficiency, and possibly lead to system failure. In engines, excellent heat management assures peak performance, reduces thermal stress, and increases engine longevity. Proper heat dissipation is critical in electronic devices, especially high-performance ones such as CPUs and GPUs, to avoid thermal throttling, which can significantly limit processing rates and overall performance. Furthermore, proper heat management helps system safety because excessive heat can cause fires or material degradation. Finally, the heat dissipation process is crucial for the dependability, safety, and optimal operation of both mechanical and electrical systems.[5]

2.1.4 Types of Radiator Designs

Based on tubes, Radiators can be classified as -

- **Flat-Tube Radiators:** Flat-tube radiators have horizontally flattened tubes connected to fins. This design is commonly used in a variety of applications because of its simplicity and efficacy in dissipating heat. [6]

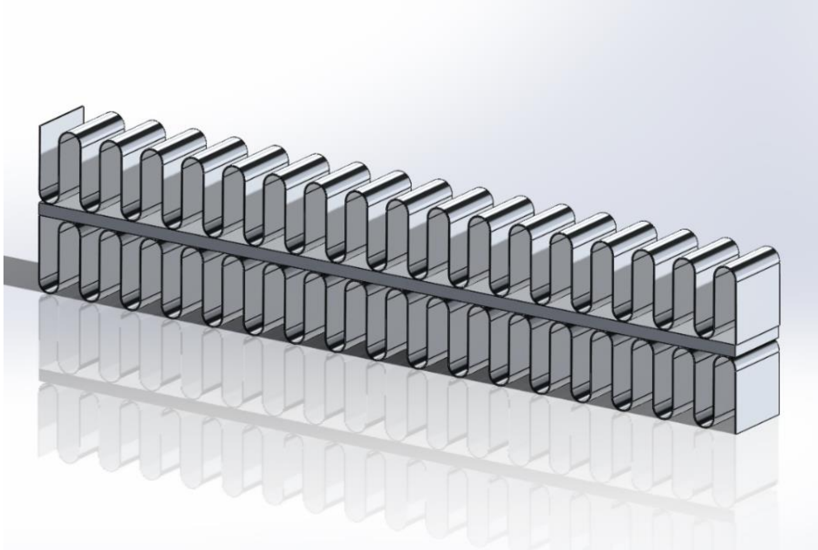


Figure 4 Flat Tube Radiator

- **Curved Tube Radiators:** Curved-tube radiators use tubes with curved geometry to improve fluid dynamics and heat transfer efficiency. This design is very advantageous when a smooth airflow is required.[7]

Figure 5 Curved Tube Radiator

- **Circular-Tube Radiators:** Circular-tube radiators use tubes with a circular cross-section. This arrangement has distinct advantages in terms of fluid flow and heat transmission, making it suited for a variety of applications.

Figure 6 Circular Tube Radiator [8]

Based on Flow, radiators can be classified as-

1. **Crossflow Radiators:** In a crossflow radiator, the coolant travels horizontally across the tubes while the air flows vertically via the fins. Crossflow radiators are designed with tanks on both the left and right sides. The water pump moves coolant from the core to the other side of the radiator before returning it to the engine. This design enables for efficient heat transfer and is often employed in automobile cooling systems.

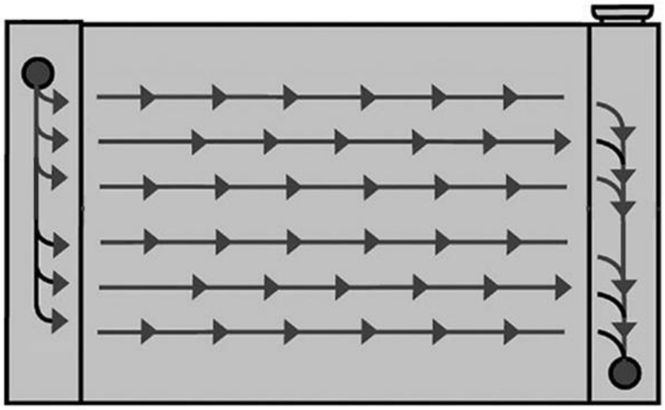


Figure 7 The Coolant Path of a Typical Crossflow Radiator Design [34]

2. **Downflow Radiators:** A downflow radiator circulates coolant vertically through the tubes and air horizontally over the fins. Downflow radiators have tanks on top and bottom of their cores. The coolant enters the top tank and travels downhill through the core via gravity, lessening the burden on the water pump as it returns to the engine. This style is commonly utilized in industrial environments when space is restricted.

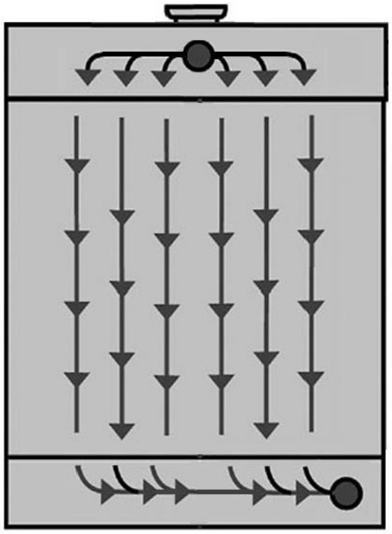


Figure 8 The Typical Coolant Path of a Downflow Radiator [33]

2.1.5 Types of Fins in Radiators

In radiator design, fins play a crucial role in enhancing heat transfer efficiency by increasing the surface area available for convective heat exchange between the radiator and the surrounding fluid (usually air or liquid coolant). There are several types of fins commonly used in radiators:

1. **Rectangular Fins:**
    - Rectangular fins are simple and widely used due to their ease of manufacturing and effectiveness in increasing surface area.
    - They are typically arranged in rows and spaced evenly to facilitate heat transfer across the radiator surface.
    - Rectangular fins offer a balanced approach between surface area enhancement and pressure drop considerations. [9], [10]

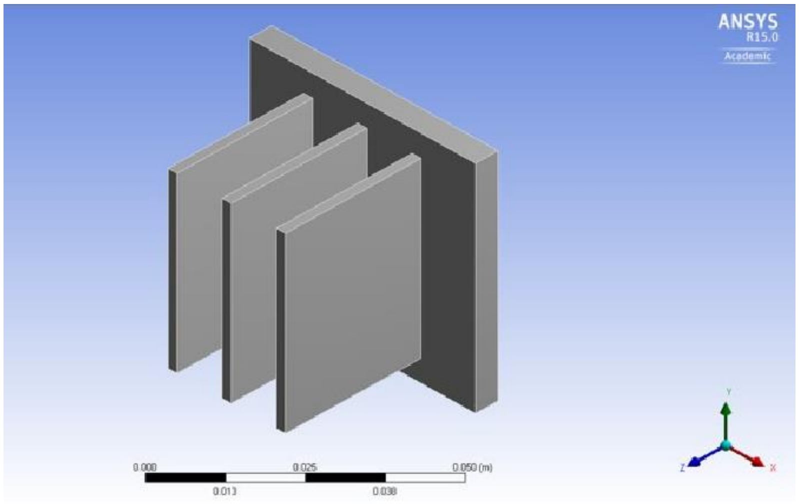


Figure 9 Rectangular Fins [10]

2. **Triangular Fins:**
    - Triangular fins are designed with a triangular cross-section, tapering from a wider base to a narrower edge.
    - These fins are known for their ability to induce turbulence in the airflow or coolant, thereby enhancing convective heat transfer.
    - Triangular fins are often utilized in applications where maximizing heat dissipation efficiency is critical.[11]

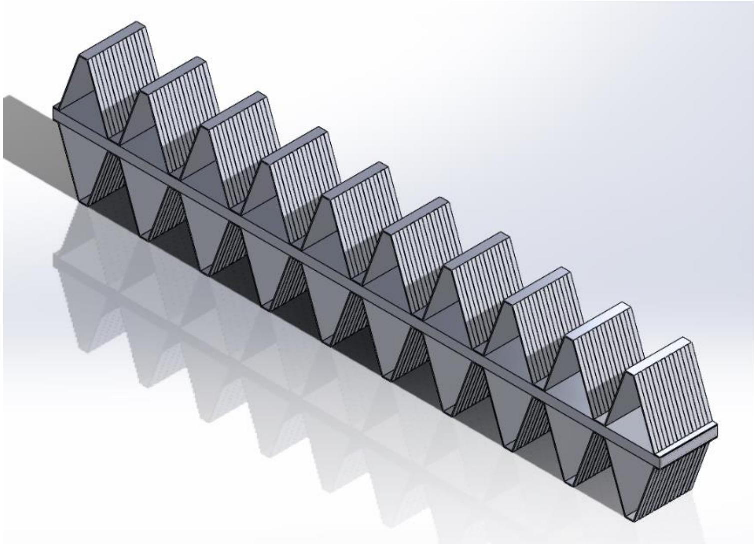


Figure 10 Triangular Fins

3. **Cone Pin Fins:**
    - Cone pin fins consist of conical-shaped protrusions extending from the radiator surface.
    - These fins create additional turbulence and increase the surface area available for heat transfer.
    - Cone pin fins are effective in applications requiring high heat flux dissipation and can reduce thermal resistance compared to traditional flat fins.[12]

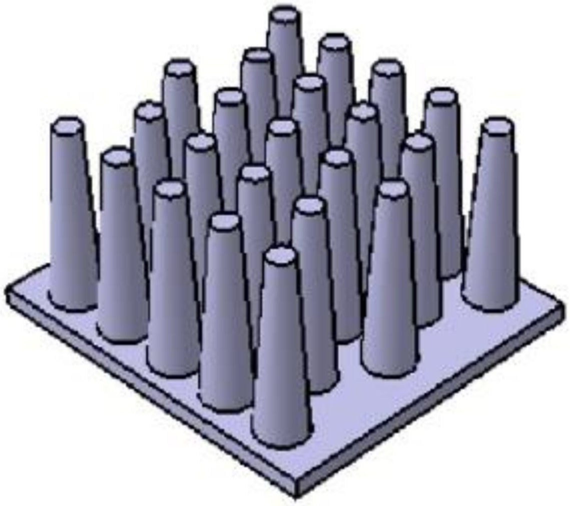


Figure 11 Cone Pin Fins

4. **Wavy or Serrated Fins:**
    - Wavy or serrated fins feature a waveform or serrated pattern along their edges.
    - This design disrupts the boundary layer of airflow or coolant, improving heat transfer coefficients.
    - Wavy fins are beneficial in reducing pressure drop while maintaining effective heat transfer performance.[13]

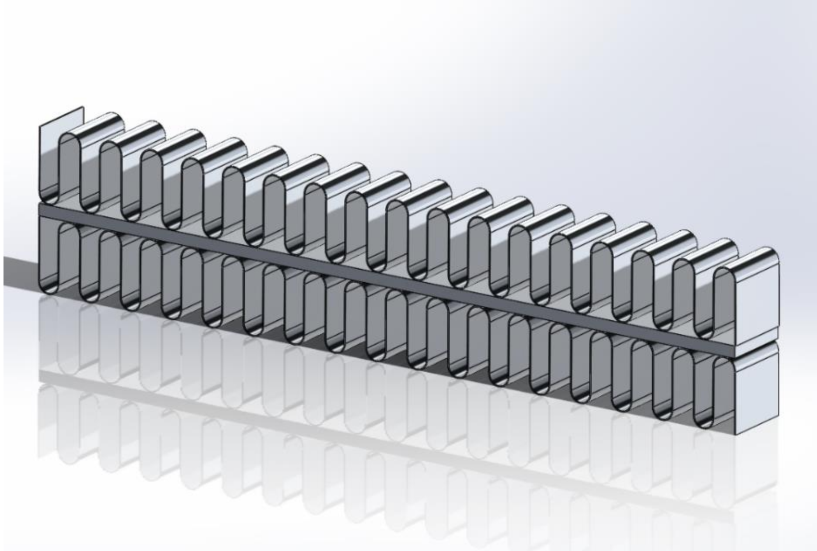


Figure 12 Wavy Fins

5. **Louvered Fins:**
   - Louvered fins have a series of angled slits or louvers cut into their surface.
   - These fins enhance heat transfer by directing airflow or coolant through the radiator in a controlled manner, increasing turbulence and surface interaction.
   - Louvered fins are commonly used in automotive and HVAC applications to optimize thermal performance.[14]

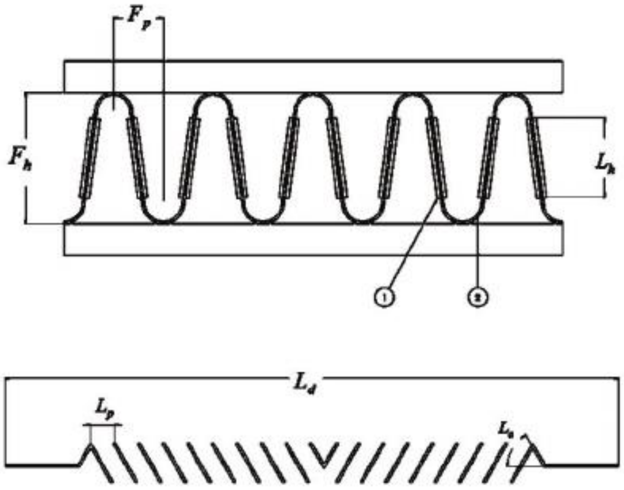


Figure 13 Louvered Fins

6. **Pin Fins:**
    - Pin fins are slender, cylindrical protrusions extending perpendicularly from the radiator surface.
    - They maximize surface area density and are effective in applications where space is limited or where high heat fluxes need to be managed efficiently.
    - Pin fins are often used in compact heat exchangers and electronics cooling systems.[15]

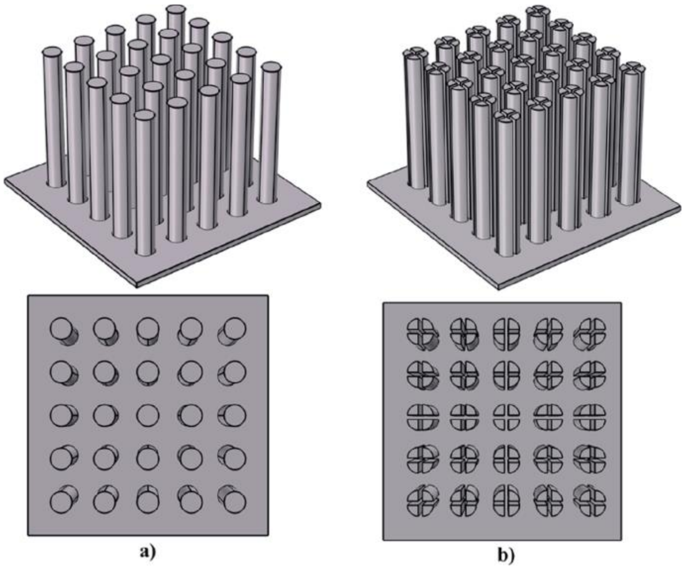


Figure 14 Pin Fins

Each type of fin has its advantages and is chosen based on specific requirements such as thermal performance goals, space constraints, manufacturing feasibility, and cost considerations. The selection of fin type plays a crucial role in determining the overall efficiency and effectiveness of the radiator in dissipating heat.

2.1.6 Radiator Materials

When selecting a radiator material for your heating system, it's essential to understand the benefits and drawbacks of each option. This comparison focuses on four commonly used materials: mild steel, stainless steel, aluminum, and cast iron.

Mild Steel

Pros:

Economical Choice: Mild steel radiators are often less expensive, making them an affordable option.

Versatile Design: These radiators can be modified in a variety of colors to meet different decor designs.

Cons:

Mild steel is prone to rusting, which can shorten its lifespan and efficacy.

Regular maintenance is required to avoid rust and preserve lifespan.

Stainless Steel

Pros:

High heat conductivity: Stainless steel radiators transport heat efficiently, resulting in effective warming.

High durability: These radiators are strong and long-lasting.

Rust-Resistant: Stainless steel is highly resistant to rust and corrosion.

Cons:

Increased Initial Cost: Stainless steel radiators are typically more expensive upfront.

External Rust: If not properly maintained, they may develop surface rust over time.

Aluminum

Pros:

Efficient Heating: Aluminum radiators have high thermal conductivity, which ensures efficient heating.

Energy efficiency: They use less energy to function, making them more cost-effective in the long run.

Aluminum is naturally corrosion-resistant, which increases its durability.

Aluminum radiators are recyclable, making them environmentally friendly.

Cons:

Aluminum is more easily damaged than other materials and requires careful handling.

Cast Iron

Pros:

Durability: Cast iron radiators have a timeless style and are renowned for their durability.

Efficient Heat Retention: They hold heat well, radiating warmth even when the heating source is shut off.

Lifetime Guarantee: These products sometimes come with long warranties that represent their durability and dependability.

Cons:

High installation costs: Because of its weight, cast iron radiators are more difficult and costly to install.

Best Choice:

Aluminum. It offers excellent corrosion resistance, malleability, and low bulk. It is also environmentally friendly and cost-effective. Copper welding relies on tin soldering, while aluminum welding uses a brazing process with various alloy melting points. Although copper has a higher heat dissipation coefficient, the tin-lead alloy layer created during the soldering process diminishes its efficiency. Aluminum radiators, on the other hand, are the preferred choice for automotive applications due to their consistent performance and efficient brazing, which achieves a balance of cost-effectiveness and heat dissipation.

2.1.7 Considerations in Design Selection

To achieve best performance and efficiency, choosing an ideal radiator design requires careful consideration of a number of criteria.[16] Here are some crucial elements in the design choosing process:

1. **Application Specific Requirements:** Customize the radiator design to match the application's specific thermal management requirements, whether it is for automotive, industrial, or electronic systems.

2. **Space constraints:** Consider the available area for radiator placement. Compact designs may be critical in situations requiring restricted space, such as vehicle engine chambers.

3. **Weight considerations:** Consider the weight implications of the radiator design, especially in situations where weight is an important consideration, such as aerospace or automotive design.

4. **Thermal efficiency:** Assess the design's thermal efficiency by taking into account elements such as fin density, tube arrangement, and materials employed. High thermal efficiency means efficient heat dissipation.

5. **Coolant properties:** Match the radiator design to the qualities of the coolant in use. Different coolants may have differing heat transfer properties, which affect the radiator's overall performance.

6. **Operating conditions:** Consider the environmental and operational circumstances that the radiator will face. Temperature extremes, vibration, and pollutant exposure are all possible considerations.

7. **Materials Selection:** Choose materials that have high thermal conductivity, corrosion resistance, and durability. Aluminum and copper are common materials, with each providing significant advantages.

8. **Cost considerations:** Determine the cost implications of the chosen design. Balancing performance and cost-effectiveness is critical, particularly in large-scale manufacturing.

9. **Manufacturability:** Check that the chosen design is viable for production, taking into account manufacturing methods, scalability, and ease of assembly.

10. **Future adaptability:** Consider future demands and technology improvements. Choose a design that enables adjustments or upgrades without major overhauls.

2.1.8 Factors affecting the efficiency of a Radiator

Several factors affect the efficiency of a radiator heat exchanger. Some of these criteria are:

- **Surface Area:** The radiator's surface area controls how much heat it can dissipate. Increasing surface area improves heat transmission between the radiator and the surrounding air, improving efficiency.

  The Heat Transfer Rate is determined by the equation:

  $\dot{Q}=h\cdot A\cdot \Delta T$

  Here, we can see that the heat transfer rate is proportional to the surface area.

- **Temperature difference:** The greater the temperature difference between the medium being cooled and the surrounding air, the faster the heat transfer occurs.

  The heat transfer rate is determined by the equation:

  $\dot{Q}=h\cdot A\cdot \Delta T$

  This equation shows that the heat transfer rate is exactly proportional to the temperature differential.
- **Fluid Flow Rate:** The flow rate of fluid through the radiator influences its efficiency. Higher flow rates can improve heat transmission by increasing the fluid's contact time with the radiator's surface.
- **Fouling:** Over time, deposits and pollutants may form on the radiator's surface, lowering its efficiency. Regular maintenance and cleaning are required to ensure peak performance.
- **Design and Material:** The radiator heat exchanger's design and materials can have a considerable impact on its efficiency. Heat transmission is influenced by a variety of factors, including fin type, tube diameter, and material conductivity.
- **Flow Type:** Turbulent flow violates boundary layers, resulting in better mixing and increased convective heat transfer. This leads to much higher heat transfer efficiency in systems.

  $Nu=0.023Re^{0.8}Pr^{0.3}$

  For turbulent flow the Re number is more than 4000. Which results in higher Nu number, which means improved heat transfer.

2.2 Coolants Properties and Composition

Cooling is crucial for keeping engines and machinery functioning smoothly. In this chapter, we'll look at radiator coolants, the unsung heroes that labor behind the scenes to keep temperatures stable and performance at peak. From classic formulations to cutting-edge nanofluid coolants, we look at the evolution of radiator coolants and their critical function in thermal control.

The composition of coolant is antifreeze (ethylene glycol or propylene glycol) and water.

Table 1 The freezing point and boiling point of antifreeze and water with mixture concentrations. [17]

	Freezing point	**Boiling point**
Pure water	32°F (0°C)	212°F (100°C)
Pure antifreeze*	0°F (-18°C)	387^0F(197^0C)
50/50 mixture	-34°F (-37°C)	218°F (103°C)
70% antifreeze/30% water	-84°F (-64°C)	225°F (107°C)

Table 2 The properties of the base fluid [18]

Coolant	**Temp. inlet (°C)**	**Density (kg/m^3)**	**Specific heat capacity, (J/kg.K)**	**Thermal conductivity (W/m.K)**	**Viscosity (kg/m.s)**
Base fluid	95	1008	3977	0.5568	0.0006

Using a mixture of ethylene glycol and water as a car radiator coolant offers several advantages, making it a popular choice for automotive cooling systems. Here are the main benefits:

- Ethylene glycol enhances the boiling point of coolant mixtures. While water alone boils at 100°C (212°F), a 1:1 mixture of water and ethylene glycol boils at around 107°C (225°F) under normal atmospheric pressure. This higher boiling point helps keep the coolant from boiling over in high-temperature settings, resulting in more efficient cooling performance.

- **Lower Freezing Point:** Ethylene glycol considerably decreases the coolant's freezing point. A 50/50 combination normally freezes at -37°C (-34°F), whereas water freezes at 0°C (32°F). This antifreeze feature keeps the coolant from freezing in cold temperatures, sparing the engine and cooling system from harm caused by ice formation.

- **Corrosion Protection:** Ethylene glycol contains compounds that prevent corrosion and safeguard the engine's metal components, including the radiator, water pump, and block. This corrosion prevention prolongs the life of the cooling system and prevents rust and scale formation.

- **Enhanced Heat Transfer:** The combination of ethylene glycol and water has excellent heat transfer capabilities, absorbing and distributing heat from the engine. This helps to maintain consistent operating temperatures and minimizes overheating.

- **Compatibility with different materials:** Modern coolant compositions are engineered to work with a wide range of engine and cooling system materials, including aluminum, steel, and rubber. This compatibility reduces degradation and leaks, resulting in a dependable and long-lasting cooling system.

- **Extended Coolant Life:** Ethylene glycol-based coolants often have a longer service life than plain water. They contain chemicals that provide further protection against corrosion, scale, and other forms of wear, lowering the frequency of coolant changes and maintenance.

2.3 Nanofluids

Nanofluids, which are made up of nanoparticles dispersed in a base fluid, have received interest due to their superior thermal properties. Choi et al. [19], [20]studied the effect of nanoparticle composition, size, and concentration on heat transfer efficiency. From the paper of Ng E, Johnson P[21] we got the properties of the base fluid. Aziemah N, Norazman B, Tijani A(2022) has shown the properties of Nanofluid Al_2O_3 [22]

2.3.1 Introduction

Nanofluids represent a novel class of fluids formed by dispersing minute materials—such as nanoparticles, nanofibers, nanotubes, nanowires, nanorods, nanosheets, or droplets—within base fluids. These nanoscale colloidal suspensions consist of densely packed nanomaterials in a liquid phase. They exhibit superior thermophysical properties compared to conventional fluids like oil or water, including enhanced thermal diffusivity, viscosity, convective heat transfer coefficients, and thermal conductivity. However, maintaining the stability of nanofluids poses a critical challenge in managing these complex two-phase systems, and achieving the necessary stability remains a significant hurdle.

Nanofluids have gained popularity in recent years due to their wide range of uses. Previous review papers focused mostly on experimental and theoretical investigations relating to the thermophysical characteristics or convective heat transfer of nanofluids [23], [24], [25], [26], [27]

Researchers are still investigating the advantages of nanofluids in heat transmission, as well as the underlying mechanics. Many researchers reached the following findings. [28], [29], [30], [31], [32]

- Adding a small amount of nanoparticles significantly enhances heat transmission.
- Nanoparticles enhance the thermal conductivity of the fluid. The thermal conductivity increases with higher volume fractions of nanoparticles.
- Nanoparticles have a higher surface area, leading to enhanced interaction with water and ethylene glycol.

- Because of the Brownian movements of the nanofluids, fluid-particle contact, and collision increase.
- Dispersed nanoparticles enhance turbulent motion and mixing fluctuations.
- The pumping power required for the same amount of heat transfer is lower compared to that of the base fluid.
- Nanofluids enhance the absorption of solar energy and exhibit superior stability compared to traditional colloidal suspensions.

Understanding the mechanisms underlying nanofluids' enhanced heat transfer capabilities is critical. Using nanofluid, a more efficient and compact cooling system can be built. Choi[19] proposed using nanofluid in vehicle cooling systems for the first time. In the automotive radiator, Al_2O_3/water nanofluid improves heat transfer by up to 45% over pure water[33], [34]. Heris et al. [35] discovered a 55% increase in heat transfer coefficient using CuO/EG-water nanofluid compared to EG-water base fluid. Samira et al. [36]examined CuO/EG-water nanofluid in a car radiator and discovered that the addition of nanoparticles boosts the heat transfer rate while increasing pressure drop.

These studies look into the subtle processes that govern heat transmission at the nanoscale, offering light on the possible benefits of radiator applications.

2.3.2 How Nanofluids Increase Heat Transfer

Nanofluids can improve heat transfer efficiency by adding nanoparticles to ordinary fluids, which confers a number of unique features. Here are some key mechanisms through which nanofluids achieve improved heat transfer

- **Increased Thermal Conductivity:** Nanoparticles are more thermally conductive than the basic fluid. Nanoparticles scattered in a fluid increase its overall thermal conductivity. This promotes more efficient heat transport through the fluid

- **Improved Convective Heat transmission:** Nanoparticles can alter fluid dynamics, resulting in better convective heat transmission. Nanoparticles improve mixing and minimize thermal boundary layer resistance, resulting in increased heat transfer between the fluid and the heated surface.

- **Increased Surface Area for Heat Exchange:** Nanoparticles have a large surface area compared to volume, resulting in more active sites for heat transfer. This increased surface area improves interaction with the surrounding fluid, resulting in more effective heat exchange.

- **Thermo-Physical Property Tuning:** Nanofluids can modify viscosity and specific heat by varying nanoparticle concentration and type. This adaptability enables optimization for individual heat transfer applications.

- **Thermophoresis and Brownian Motion:** Nanoparticles in nanofluids undergo Brownian motion, which improves their dispersion throughout the fluid. Thermophoresis, which is driven by temperature gradients, helps to ensure that nanoparticles are distributed evenly. This dispersion results in increased thermal performance.

- **Enhanced Boiling and Phase Change:** Nanofluids can have better boiling and phase-change properties. The inclusion of nanoparticles modifies nucleation sites, delays the commencement of boiling, and improves heat transfer at phase transitions.

- **Improved Stability and Compatibility:** Well-engineered nanofluids ensure stability and compatibility with system components. Stability is critical for achieving continuous improvements in heat transfer efficiency over time.

Table 3 Thermal conductivity of different nanoparticles [37]

Nanoparticles	**Thermal conductivity W/(m.K)**	**References**
Diamond	3300	[38]
MCNT	2000-3000	[39]
SiC	490	[40]
Ag	429	[41]
Cu	398	[42]
Au	315	[42]
Al	247	[42]
Si	148	[38]
MgO	54.9	[43]
Al 2O 3	40.0	[44]
CuO	32.9	[38]
ZnO	29.0	[20]
TiO2	8.4	[20]

Table 3 presents the thermal conductivity values of various nanoparticles, highlighting their potential for enhancing heat transfer in different applications. Diamond nanoparticles exhibit the highest thermal conductivity at 3300 W/(m.K) , making them exceptional for heat dissipation. Multi-walled carbon nanotubes (MCNT) follow with a range of 2000-3000 W/(m.K) . Silicon carbide (SiC) offers a moderate conductivity of 490 W/(m.K) , while metals like silver (Ag) and copper (Cu) provide high conductivities of 429 W/(m.K) and 398 W/(m.K) respectively . Gold (Au) and aluminum (Al) have lower conductivities at 315 W/(m.K) and 247 W/(m.K) respectively . Silicon (Si) and magnesium oxide (MgO) show further reduced values of 148 W/(m.K) and 54.9 W/(m.K) . Common oxide nanoparticles such as aluminum oxide (Al_2O_3) and copper oxide (CuO) exhibit thermal conductivities of 40.0 W/ (m.K) and 32.9 W/(m.K) , while zinc oxide (ZnO) and titanium dioxide (TiO_2) are among the least conductive, with values of 29.0 W/(m.K) and 8.4 W/(m.K) . This information is crucial for selecting suitable nanoparticles for thermal management solutions.

Heat is commonly connected with automotive and heavy-duty engines. If this unwanted heat is not quickly removed, the engine may be destroyed. Ethelene glycol-based HTF with a volumetric ratio of EG to water of 60/40, 50/50 is a typical coolant used in automobile cooling systems. When ethylene glycol is combined with water, the freezing temperature of pure water rises.

2.3.3 Why Nanofluids Decrease Heat Transfer Rate

- **Increased Viscosity**:
  - Nanoparticles can elevate the fluid's viscosity due to added frictional resistance.
  - Higher viscosity increases pumping power requirements and reduces convective heat transfer efficiency.

- **Nanoparticle Agglomeration**:
  - Nanoparticles may agglomerate or clump together within the fluid.
  - This reduces effective surface area for heat transfer and lowers thermal conductivity.

- **Sedimentation Effects**:
  - Over time, nanoparticles may settle out of the fluid due to gravitational forces or low flow conditions.
  - This uneven distribution decreases thermal properties and heat transfer performance.

- **Stability Issues**:

  - Maintaining stable dispersion of nanoparticles in the base fluid is challenging.
  - Instabilities can lead to particle clustering, hindering effective heat transfer.

- **Chemical Interactions**:

  - Nanoparticles might chemically react with the fluid or container material.
  - This can form insulating layers that impede heat conduction rather than facilitating it.

- **Thermal Diffusivity Mismatches**:

  - Sometimes, the thermal diffusivity of the nanofluid may be lower than that of the base fluid.
  - Poor dispersion or unfavorable interactions between nanoparticles and the fluid reduce overall heat transfer efficiency.

2.3.4 Advantages and Disadvantages of Nanofluids

Nanofluids, which are engineered fluids containing nanoparticles dispersed in a base fluid, offer several advantages and disadvantages in various applications. Here’s a detailed breakdown:

Advantages of Nanofluids:

1. **Enhanced Thermal Conductivity**:
   - Nanoparticles typically have much higher thermal conductivity than the base fluid.
   - Incorporating nanoparticles increases the overall thermal conductivity of the nanofluid, improving heat transfer rates.
2. **Improved Heat Transfer Efficiency**:
   - Increased thermal conductivity and enhanced surface area due to nanoparticles lead to better heat transfer performance.

    - This can result in more efficient cooling or heating processes in various industrial and engineering applications.

3. **Flexibility in Thermal Properties**:
    - Nanofluids can be tailored to meet specific thermal requirements by adjusting nanoparticle type, concentration, and size.
    - This flexibility allows for customization based on the desired thermal conductivity and heat transfer characteristics.
4. **Potential for Size Reduction**:
    - Using nanofluids can potentially reduce the size and weight of heat exchangers and cooling systems.
    - This is advantageous in compact devices and applications where space and weight are critical factors.
5. **Improved Stability and Compatibility**:
    - Advanced formulations and stabilizing agents can enhance the stability of nanofluids, preventing particle agglomeration and sedimentation.
    - Compatibility with different base fluids and materials makes nanofluids adaptable to various operational environments.
6. **Environmental Benefits**:
    - Enhanced thermal efficiency and potentially smaller equipment size can lead to energy savings and reduced environmental impact.
    - Nanofluids may contribute to improved energy efficiency in industrial processes and HVAC systems.

Disadvantages of Nanofluids:

1. **Cost Considerations**:
    - Manufacturing and incorporating nanoparticles into fluids can be expensive.
    - Cost-effectiveness depends on the application's specific requirements and benefits derived from improved thermal properties.

2. **Potential for Increased Viscosity**:
   - Nanoparticles may increase the viscosity of the base fluid, which can lead to higher pumping power requirements.
   - This can offset some of the thermal conductivity benefits by increasing operational costs.
3. **Particle Agglomeration and Stability Issues**:
   - Nanoparticles have a tendency to agglomerate or settle out of the fluid over time, especially under certain conditions.
   - Maintaining stable dispersion and preventing particle clumping can be challenging and require additional stabilizing agents.
4. **Compatibility Concerns**:
   - Chemical interactions between nanoparticles and the base fluid or container materials can affect performance and stability.
   - Compatibility issues may limit the range of applications or require specialized materials and coatings.
5. **Health and Safety Considerations**:
   - Nanoparticles pose potential health risks if not handled properly during manufacturing, handling, or disposal.
   - Proper safety measures and regulations must be observed to mitigate exposure risks to workers and the environment.
6. **Complexity in Design and Implementation**:
   - Designing and optimizing nanofluids for specific applications require expertise in nanotechnology, fluid dynamics, and thermodynamics.
   - The complexity of formulation and integration into existing systems may require substantial research and development efforts.

In conclusion, while nanofluids offer significant advantages such as enhanced thermal conductivity and improved heat transfer efficiency, these benefits must be carefully weighed against potential drawbacks such as increased costs, viscosity issues, stability challenges, and compatibility concerns. The optimal use of nanofluids depends on balancing these factors to maximize their advantages in practical applications.

2.4 ANSYS Simulation

The pursuit of enhanced heat transfer efficiency in radiator designs has driven significant advancements in simulation techniques. Among these, ANSYS stands out for its robust computational fluid dynamics (CFD) capabilities, which facilitate detailed analyses of fluid flow dynamics and heat transfer phenomena within complex geometries. This chapter delves into the application of ANSYS simulations in investigating the heat transfer characteristics of various radiator designs utilizing nanofluid coolants. By leveraging ANSYS' advanced simulation tools, researchers can achieve a comprehensive understanding of the critical parameters influencing thermal performance, enabling the optimization of radiator configurations for improved heat dissipation.

2.4.1 Importance of Simulation in Thermal Management

Simulation techniques, particularly those based on CFD, have become indispensable in thermal management research.[45] They offer several advantages over traditional experimental methods, including:

- **Precision and Detail:** Simulations can provide detailed insights into fluid flow and heat transfer processes that are difficult to capture experimentally.

- **Cost-Effectiveness:** Conducting simulations is often less expensive and time-consuming than building and testing physical prototypes.

- **Flexibility:** Simulations allow researchers to explore a wide range of design variations and operating conditions without the need for physical modifications.

2.4.2 Overview of ANSYS Software

ANSYS is a leading simulation software known for its comprehensive suite of tools designed for engineering analysis. Its CFD capabilities are particularly well-suited for studying heat transfer and fluid dynamics in radiator designs.[46] Key features of ANSYS relevant to this study include:

- **Fluid Flow (CFX and Fluent):** These modules provide powerful tools for simulating fluid flow and heat transfer in complex geometries.
- **Heat Transfer Analysis:** ANSYS allows for detailed thermal analysis, including conduction, convection, and radiation heat transfer.
- **Meshing Capabilities:** Advanced meshing tools enable the creation of detailed and accurate computational grids, essential for precise simulation results.
- **Post-Processing Tools:** ANSYS offers robust post-processing capabilities for visualizing and analyzing simulation data, helping researchers identify key trends and parameters.

2.4.3 Methodology

The methodology for conducting ANSYS simulations in this study involves several key steps:

1. **Geometry Creation:** The first step is to create a detailed 3D model of the radiator design. This model includes all relevant features such as fins, tubes, and coolant channels.

2. **Meshing:** A high-quality computational grid is generated to discretize the geometry. The mesh must balance accuracy and computational efficiency, with finer grids used in regions with high gradients in temperature and velocity.

3. **Boundary Conditions:** Appropriate boundary conditions are applied to the model, including inlet and outlet conditions for the coolant, as well as heat flux or temperature conditions on the radiator surfaces.

4. **Solver Setup:** The simulation parameters are defined, including the selection of turbulence models, heat transfer models, and nanofluid properties. ANSYS provides various models to accurately simulate the behavior of nanofluids, including their enhanced thermal conductivity and viscosity.

5. **Simulation Execution:** The simulation is run to solve the governing equations for fluid flow and heat transfer. This involves iterative calculations to achieve

convergence, where the residuals of the governing equations fall below a specified threshold.

6. **Post-Processing and Analysis:** Once the simulation is complete, the results are analyzed using ANSYS' post-processing tools. Key performance metrics, such as temperature distribution, heat transfer coefficients, and pressure drops, are extracted and analyzed to evaluate the effectiveness of the radiator design.

2.4.4 Case Studies and Literature Review

Numerous studies have demonstrated the efficacy of ANSYS simulations in optimizing radiator designs with nanofluid coolants. For example, Naufal bin Samsudin A (2023) and Aziemah N, Norazman B, Tijani A (2022) used numerical simulations to validate experimental results, highlighting the reliability of simulation-based approaches. Their work illustrated how ANSYS can accurately predict the thermal performance of radiators and provide insights into the effects of different nanofluid compositions.

Li et al. (2020) and Zhang et al. (2021) further explored the use of ANSYS in optimizing radiator configurations. Their studies showed that by varying the geometric parameters and nanofluid properties, significant improvements in thermal conductivity and convective heat transfer coefficients could be achieved. These findings underscore the potential of ANSYS simulations to identify optimal design parameters that maximize heat dissipation efficiency.

2.4.5 Simulation Parameters

Key parameters to consider in ANSYS simulations for radiator designs with nanofluid coolants include:

- **Nanofluid Properties:** The thermal conductivity, specific heat capacity, and viscosity of the nanofluids are critical inputs. Nanoparticle concentration and type (e.g., aluminum oxide, copper oxide) significantly influence these properties.

- **Geometric Parameters:** The dimensions and arrangements of fins, tubes, and other features within the radiator must be precisely defined. Variations in these parameters can greatly affect the heat transfer performance.

- **Flow Conditions:** The inlet velocity, temperature, and turbulence intensity of the coolant flow must be specified. These conditions impact the heat transfer rates and pressure drops within the radiator.

- **Heat Load:** The amount of heat to be dissipated by the radiator is a fundamental parameter. This can be defined as a heat flux or a temperature difference between the coolant and the ambient environment.

2.4.6 Results and Discussion

The results from ANSYS simulations provide valuable insights into the heat transfer characteristics of different radiator designs with nanofluid coolants. Key findings typically include:

- **Temperature Distribution:** Detailed temperature profiles within the radiator reveal hotspots and regions of effective cooling. These profiles help identify design areas that require improvement.

- **Heat Transfer Coefficients:** The convective heat transfer coefficients indicate the effectiveness of heat dissipation. Higher coefficients are desirable for efficient cooling.

- **Pressure Drop:** The pressure drop across the radiator affects the pumping power required for coolant circulation. Optimizing the design to minimize pressure drop while maintaining high heat transfer efficiency is crucial.

- **Effect of Nanofluid Composition:** Variations in nanoparticle concentration and type significantly impact thermal performance. Simulations can identify the optimal nanofluid composition for specific radiator designs.

2.4.7 Conclusion

ANSYS simulations have proven to be a powerful tool in the investigation and optimization of radiator designs with nanofluid coolants. By enabling detailed analysis of fluid flow and heat transfer phenomena, these simulations provide critical insights that drive the development of more efficient and effective thermal management solutions. The ability to simulate and optimize various design parameters and nanofluid properties allows researchers to meet the increasingly stringent performance requirements in automotive, aerospace, and electronics cooling applications. As technology continues to advance, the role of ANSYS and similar simulation tools will be indispensable in pushing the boundaries of thermal management innovation.

2.5 Chapter Conclusion

In this literature review, we have explored the extensive body of knowledge surrounding radiator technologies, thermal management, and the innovative use of nanofluid coolants. The insights gathered from various studies provide a comprehensive understanding of the factors influencing heat transfer characteristics and the methods employed to enhance radiator efficiency.

Radiator Technologies and Design:

The evolution of radiator technologies has been marked by significant advancements in materials, geometric configurations, and manufacturing techniques. These developments have been driven by the need for more efficient and reliable thermal management systems across various industries. Key components such as fins, tubes, and cores have been optimized to maximize heat dissipation, while advanced materials like aluminum and composites have replaced traditional metals, offering superior thermal conductivity and durability. The design of radiators has also evolved, with innovative fin structures and tube arrangements that enhance the surface area for heat exchange and improve airflow.

Coolants and Nanofluids:

Coolant properties play a crucial role in the performance of radiator systems. Traditional coolants have been extensively studied, and their thermal properties are well understood. However, the introduction of nanofluids has opened new avenues for enhancing heat transfer efficiency. Nanofluids, with their superior thermal conductivity and heat transfer capabilities, have shown promise in improving the cooling performance of radiators. Studies have demonstrated that the addition of nanoparticles to base fluids can significantly enhance thermal conductivity, specific heat capacity, and convective heat transfer coefficients. However, the behavior of nanofluids is complex, and their effectiveness can vary based on factors such as particle concentration, size, and dispersion stability.

Simulation Techniques:

The use of computational fluid dynamics (CFD) simulations, particularly through advanced software like ANSYS, has become indispensable in the study and optimization of radiator designs with nanofluid coolants. Numerical simulations offer detailed insights into fluid flow dynamics and heat transfer phenomena that are challenging to capture through experimental methods alone. By leveraging CFD tools, researchers can explore a wide range of design variations and operating conditions, enabling the identification of optimal configurations that maximize heat dissipation efficiency. These simulations have proven effective in validating experimental results and providing a deeper understanding of the interactions between radiator components and coolants.

Key Findings and Implications:

The literature highlights several key findings:

- Enhanced fin and tube designs significantly improve heat transfer efficiency.
- High-performance materials, such as aluminum alloys, contribute to lighter and more durable radiator structures.

- Nanofluids offer potential for superior cooling performance, but their behavior must be carefully managed to prevent issues such as particle agglomeration and increased viscosity.
- CFD simulations, particularly with ANSYS, provide critical insights and enable the optimization of radiator designs in a virtual environment.

Future Directions:

While substantial progress has been made in understanding and optimizing radiator systems, several areas warrant further research:

- The long-term stability and reliability of nanofluids in practical applications.
- The development of advanced nanofluid formulations that maximize thermal conductivity while minimizing potential drawbacks.
- Continued refinement of CFD simulation techniques to enhance accuracy and reduce computational costs.
- Exploration of new materials and manufacturing techniques that can further improve the efficiency and durability of radiator designs.

In conclusion, the integration of advanced radiator technologies, innovative nanofluid coolants, and sophisticated simulation techniques represents a significant step forward in the field of thermal management. The insights gained from this literature review provide a solid foundation for future research and development efforts, aimed at achieving more efficient, reliable, and sustainable cooling solutions across a wide range of applications.

Chapter 3 Methodology

In this chapter, we present the comprehensive methodology employed in the development and analysis of various radiator models for enhanced heat transfer performance. The methodology section is structured to provide a clear understanding of the design variations, theoretical foundations, and mathematical modeling techniques utilized throughout this study. The aim is to systematically explore the impact of different radiator designs on heat transfer efficiency, ultimately guiding the selection of the most effective configuration.

We begin by delving into the specifics of different radiator designs, each tailored to investigate unique aspects of heat transfer enhancement. Starting with the fundamental design, which serves as the control model, we progressively introduce variations including the integration of vortices, rectangular fins, triangular fins, and cone pin fins. Each design variation is meticulously examined to highlight its distinctive features and potential benefits.

The basic radiator design, characterized by its simplicity and conventional approach to heat dissipation, provides a baseline against which the performance of more complex designs can be measured. Introducing vortices into the radiator design aims to enhance turbulence and thereby improve heat transfer efficiency. This involves exploring the principles behind vortex generation and its application in radiator systems, detailing the design modifications and expected outcomes.

Rectangular fins are a common feature in heat exchangers, known for their ability to increase surface area and promote better heat dissipation. This study focuses on the integration of rectangular fins into the radiator design, analyzing their impact on thermal performance. Alternatively, triangular fins offer a different approach to enhancing heat transfer. Their unique geometry is investigated, examining the theoretical advantages and practical implications of using triangular fins in radiator systems.

The use of cone pin fins represents a more innovative approach to radiator design. This concept is discussed in detail, including the potential of cone pin fins to disrupt airflow patterns and enhance heat transfer. The design considerations and expected performance improvements are thoroughly evaluated.

A solid theoretical foundation is essential for understanding the mechanisms behind heat transfer in radiator systems. This chapter provides an overview of the fundamental principles and theories that underpin the various radiator designs discussed. To quantitatively assess the performance of different radiator designs, mathematical modeling techniques are employed. The chapter outlines the mathematical formulations and computational methods used to simulate heat transfer processes and predict the efficiency of each design variation.

Accurate modeling requires the careful definition of boundary conditions. This section specifies the boundary conditions applied in the simulations, ensuring that the models reflect realistic operating scenarios and provide reliable predictions of heat transfer performance. In summary, Chapter 6 presents a detailed methodology for the development and analysis of radiator models, combining theoretical insights with practical design innovations. The structured approach facilitates a comprehensive understanding of how different design elements influence heat transfer efficiency, guiding the selection of optimal radiator configurations.

In summary, Chapter 3 presents a detailed methodology for the development and analysis of radiator models, combining theoretical insights with practical design innovations. The structured approach facilitates a comprehensive understanding of how different design elements influence heat transfer efficiency, guiding the selection of optimal radiator configurations.

3.1 Radiator Models

In this sub-chapter, we examine a variety of radiator models to assess their respective heat transfer capabilities. By starting with a basic radiator design, we establish a control model that serves as a benchmark for comparison. This fundamental design is characterized by its simplicity and traditional approach to heat dissipation, providing a baseline against which the effectiveness of more advanced designs can be measured.

Next, we introduce the concept of incorporating vortices into the radiator design. The inclusion of vortices aims to enhance turbulence within the fluid flow, thereby increasing the overall heat transfer efficiency. This design variation is explored in detail, considering both the theoretical underpinnings and practical implementation challenges.

The study then shifts focus to radiator designs featuring fins, beginning with rectangular fins. These fins are known for their ability to significantly increase the surface area of the radiator, promoting better heat dissipation. The impact of rectangular fins on the thermal performance of the radiator is analyzed, highlighting their practical benefits and any potential drawbacks.

Following the rectangular fins, triangular fins are investigated as an alternative fin geometry. Triangular fins offer unique geometric advantages that may contribute to improved heat transfer. The theoretical benefits and real-world implications of using triangular fins in radiator designs are thoroughly examined.

Finally, the most innovative design considered in this sub-chapter involves the use of cone pin fins. This design seeks to disrupt conventional airflow patterns and enhance heat transfer through the unique shape of the fins. The potential advantages of cone pin fins are discussed, along with the design considerations necessary to optimize their performance.

Through this systematic exploration of various radiator models, we aim to identify design features that significantly enhance heat transfer efficiency. Each design is evaluated not only on its theoretical merits but also on practical considerations, providing a comprehensive understanding of the factors influencing radiator performance. This sub-chapter sets the stage for a detailed comparative analysis, guiding the selection of the most effective radiator configurations for practical applications.

3.1.1 Basic Radiator Design

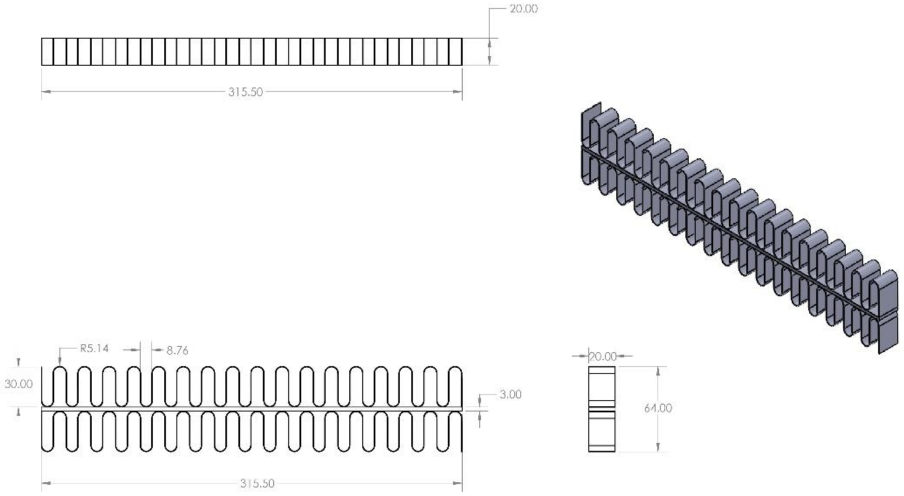


Figure 15 Basic Radiator Design Drawing

Table 4 Structural layouts of the basic radiator model [47], [48], [49], [50], [51]

Tube length	315.5 mm
Thickness of Tube	3 mm
Height of Tube	30 mm
Width of Tube	20 mm
Number of fins	34
Space between tubes	30 mm
Hydraulic diameter of tubes	5.2 mm
Material	Aluminum

3.1.2 Radiator Design with Vortex

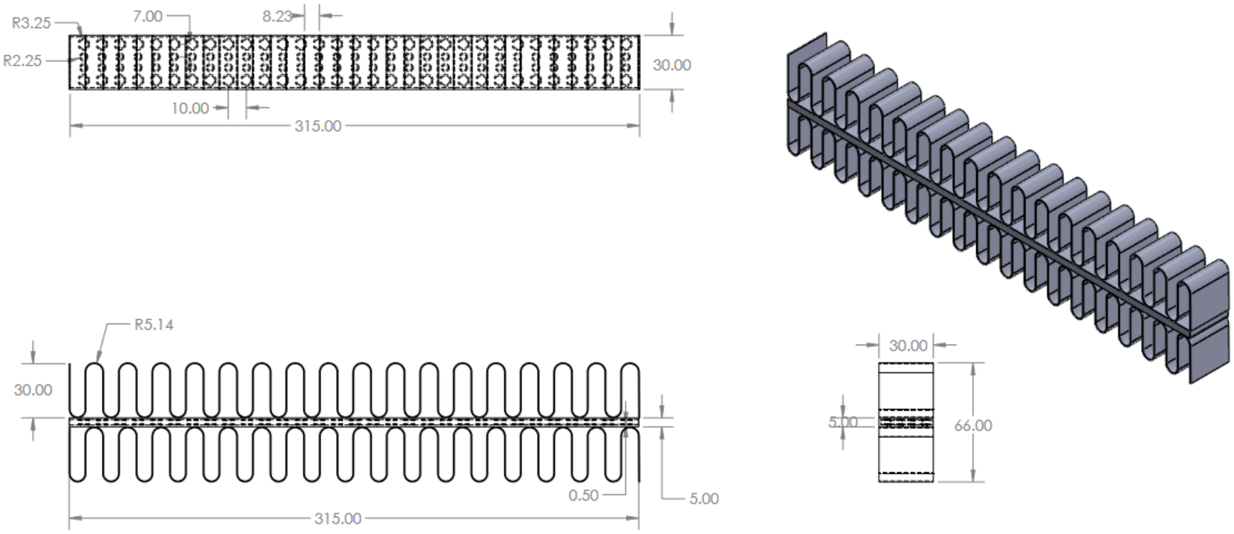


Figure 16 Basic Radiator with Vortex

Table 5 Structural layouts of the basic radiator model with Vortex Generators [48], [49], [50], [51], [52]

Tube’s length	315.5 mm
Tube’s thickness	3 mm
Height of Tube	30 mm
Width of Tube	20 mm
Number of fins	34
Space between tubes	30 mm
The hydraulic diameter of the tube	5.2 mm
Material	Aluminum
Vortex generator radius (small)	1.5 mm
Vortex generator radius (large)	2.5 mm
Vortex generator angle (inlet)	60
Vortex generator angle (outlet)	30
Distance between vortex generator	10mm
Number of vortex generator	124
Vortex generator thickness	0.75mm

3.2.1 Radiator Design with Rectangular Fins

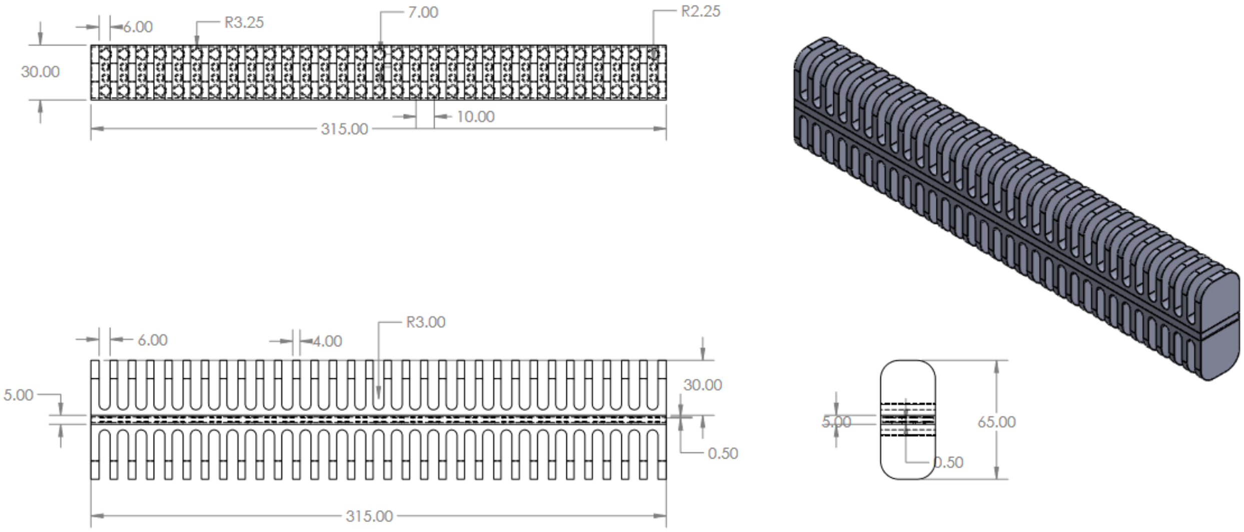


Figure 17 Basic Radiator Design with Vortex Generators

Table 6 Structural layouts of the radiator model with Rectangular Fins [49], [52]

Tube length	315.5 mm
Tube thickness	3 mm
Tube height	30 mm
Tube width	20 mm
Number of fins	64
Space between tubes	30 mm
Tube hydraulic diameter	5.2 mm
Material used	Aluminum
Vortex generator radius (small)	1.5 mm
Vortex generator radius (large)	2.5 mm
Vortex generator angle (inlet)	60
Vortex generator angle (outlet)	30
Distance between vortex generator	10 mm
Number of vortex generator	124
Vortex generator thickness	0.75 mm

3.1.3 Radiator Design with Triangular Fins

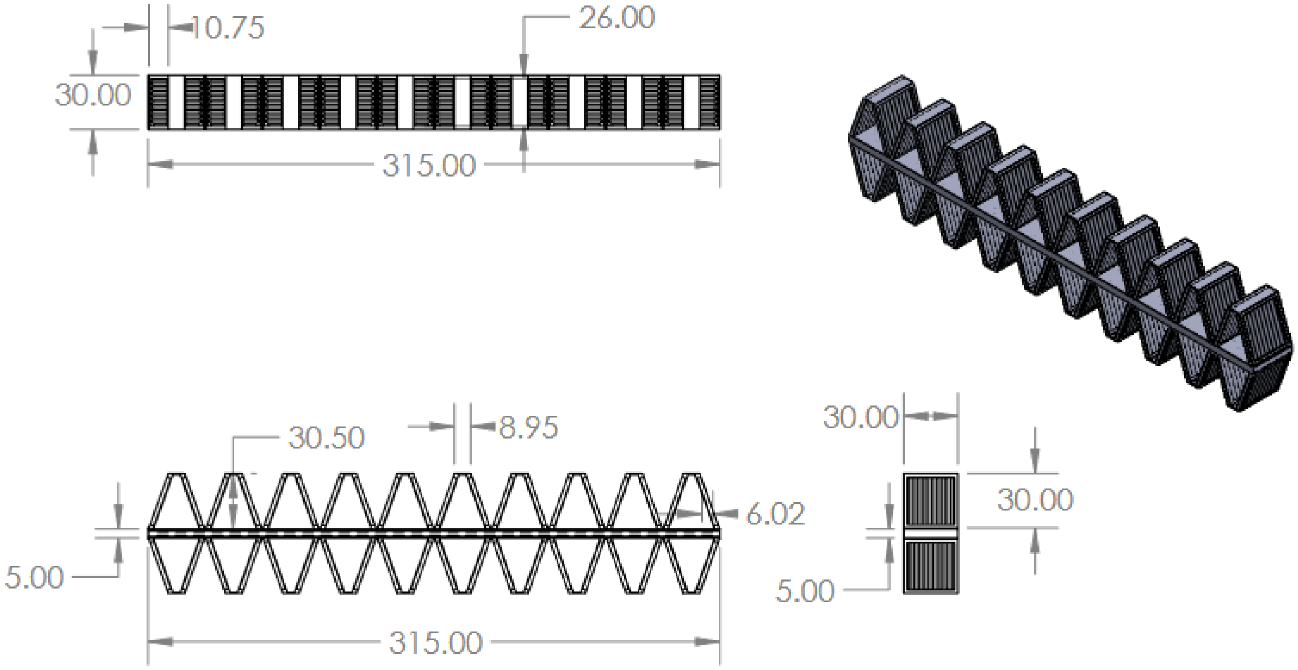


Figure 18 Radiator design with Triangular Fins

Table 7 Structural layouts of the radiator model with Triangular Fins [48], [49], [52]

Tube length	315.5 mm
Tube thickness	3 mm
Tube height	30 mm
Tube width	20 mm
Number of fins	20
Space between tubes	30 mm
Tube hydraulic diameter	5.2 mm
Material used	Aluminum
Vortex generator radius (small)	1.5 mm
Vortex generator radius (large)	2.5 mm
Vortex generator angle (inlet)	60
Vortex generator angle (outlet)	30
Distance between vortex generator	10 mm
Number of vortex generator	124
Vortex generator thickness	0.75 mm

3.1.4 Radiator Design with Cone Pin Fins

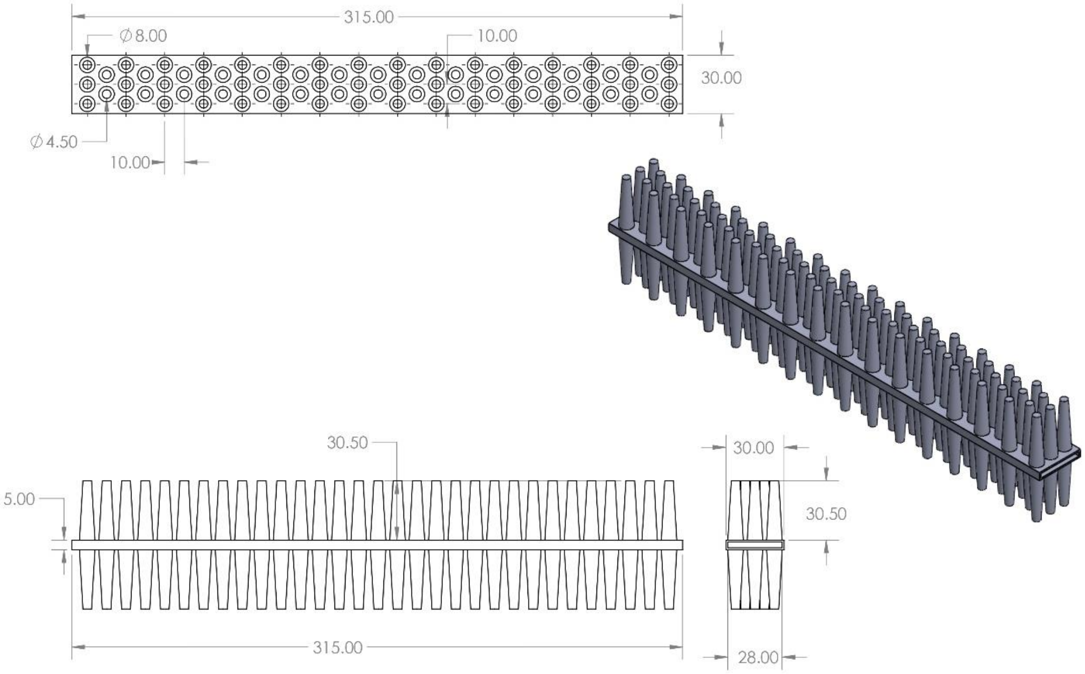


Figure 19 Radiator Design with Cone Pin Fins

Table 8 Geometrical configurations of the radiator model with Cone Pin Fins [49], [52], [53]

Tube length	315.5 mm
Tube thickness	3 mm
Tube height	30 mm
Width of Tube	20 mm
Number of fins	156
Space between tubes	30.50 mm
Hydraulic diameter of Tube	5.2 mm
Material	Aluminum
Height of the fins	30.50 mm
Top diameter of fins	4.5 mm
The bottom diameter of the fins	8 mm
Longitudinal Spacing, SL	10 mm
Transverse Spacing, ST	10 mm
Vortex generator radius (small)	1.5 mm
Vortex generator radius (large)	2.5 mm
Vortex generator angle (inlet)	60
Vortex generator angle (outlet)	30
Distance between vortex generator	10 mm
Number of vortex generator	124
Vortex generator thickness	0.75 mm

3.2 Theoretical Background

In this sub-chapter, we delve into the theoretical foundation underlying the heat transfer performance of radiator coolants, both base fluids and nanofluids. This includes a detailed examination of the mathematical modeling employed to quantify heat transfer characteristics and the boundary conditions used in our simulations. By understanding these theoretical aspects, we can better assess the thermal behavior of various coolant compositions and radiator designs, ultimately leading to optimized heat transfer efficiency in practical applications.

3.2.1 Mathematical modeling for heat transfer performance

The heat transfer performance of both the base fluid and the nanofluid as radiator coolants will be evaluated using a variety of heat transfer parameters, including the Nusselt number, Prandtl number, and heat transfer coefficient. The following equations reflect the mathematical modeling for these characteristics and will be used to compute the heat transfer rate.[54]

$$Pr = v/a = c_p\mu/k$$

$$Nu = 0.023Re^{0.8}Pr^{0.3}$$

$$h = Nu.k \,/\, d_h$$

The heat transfer coefficient (k) indicates the fluid's thermal conductivity, whereas the hydraulic diameter of the flat tube (dh) is equal to 0.0052m. [54]

$$Q = mc_p(T_{Inlet} - T_{Outlet})$$

$$Q = hA\Delta T$$

Where A is the cross-sectional area of the coolant entering the tube and ΔT is the difference between the inlet and outlet temperatures of the coolant.

These equations serve as the basis for quantifying the effectiveness of heat transfer within the radiator system, allowing for a comprehensive analysis of the thermal behavior of both the base fluid and the nanofluid under consideration.

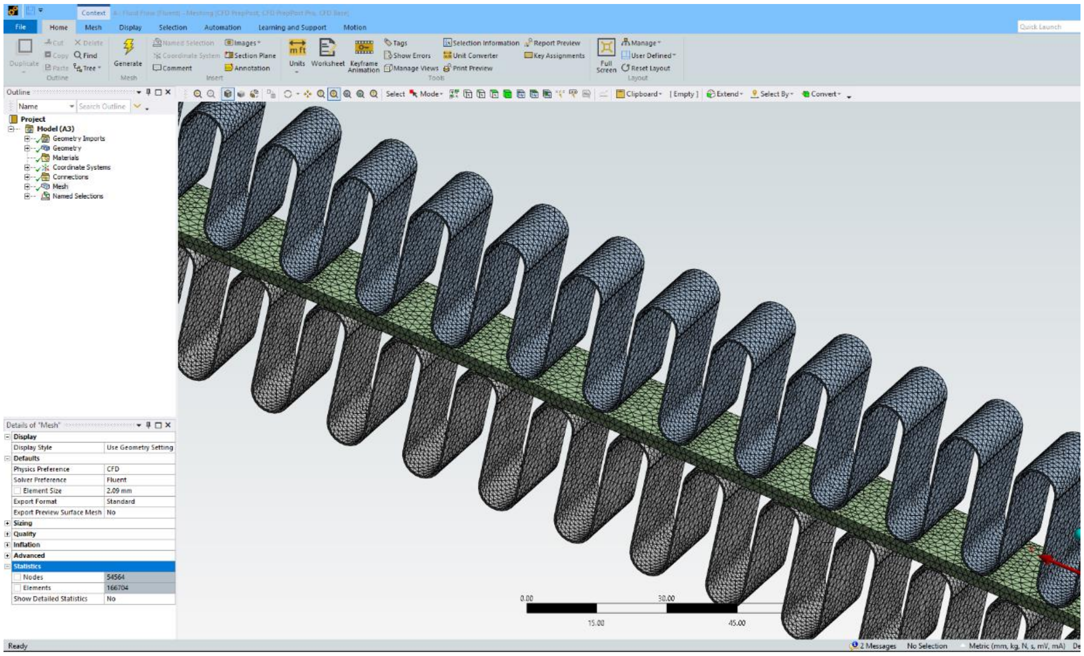
3.2.2 Boundary conditions

The model was simulated using ANSYS Student 2024 R1. The specified mathematical models were used to perform numerical calculations, which were then tabulated in Excel. The simulation's boundary conditions for the velocity inlet, pressure outlet, and wall are as follows:

- The simulation model was k-epsilon
- The coolant inlet velocity was set at 0.0387 m/s, 0.0516 m/s, 0.0645 m/s, and 0.077 m/s, resulting in volumetric flow rates of 3 L/min, 4 L/min, 5 L/min, and 6 L/min.
- The coolant inlet temperature was kept constant at 95 ~C (368.15 K)[55]
- The hydraulic diameter of the flat tube was adjusted to 0.0052 m.
- Pressure outlet: because the coolant flow inside the flat tube was not developed through the tube length.
- The flat tube wall was assumed to have a convection boundary condition, with a heat transfer coefficient of 10 W/m2 K and an air temperature of 35 °C. [55]

A single flat tube and continuous fins were used in the Fluent simulation in the ANSYS software. The simulation and numerical calculations relied on the following assumptions:

- The flow was steady, incompressible, and turbulent flow
- The coolants' thermophysical characteristics remained constant throughout the flow.



Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
☐ Element Size	2.09 mm
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
☐ Nodes	54564
☐ Elements	166704
Show Detailed Statistics	No

Figure 20 Meshing of the Basic Radiator Design in ANSYS 2024 R1

Meshing Details

1. **Element Size**:

The element size for the mesh was set to 2.09 mm. This parameter determines the resolution of the mesh, with smaller elements typically providing more accurate results at the cost of increased computational resources. An element size of 2.09 mm indicates a balance between accuracy and computational efficiency.

2. **Number of Elements and Nodes**:

The mesh consisted of 166,704 elements and 54,564 nodes. Elements are the individual volumes or areas into which the domain is divided, and nodes are the points where the elements connect. The number of elements and nodes is a key indicator of the mesh density. A higher number of elements usually enhances the solution accuracy by better capturing the flow details and boundary layer effects.

Chapter 4 Result and Discussion

4.1 Nanofluid thermophysical properties

The effectiveness of a coolant in a thermal management system is largely determined by its thermophysical properties, which include density, specific heat capacity, thermal conductivity, and viscosity. These properties dictate how well the coolant can absorb, transport, and dissipate heat within the system. The following discussion delves into the significance of these properties for the base fluid used as a coolant, with specific reference to the values provided.

Density

The density of the base fluid is 1027.01 kg/m³. In the context of a coolant, density plays a crucial role in determining the fluid's mass flow rate for a given volumetric flow rate. Higher density implies more mass flow for the same volume, which can enhance the coolant's ability to transport heat away from the heat source. However, higher density also means greater inertia, potentially requiring more energy to pump the coolant through the system. In this case, the density of 1027.01 kg/m³ is typical for many aqueous solutions and indicates a balance between effective heat transport and manageable pumping requirements.

Specific Heat Capacity

The specific heat capacity of the base fluid is 3570 J/kg K. This property indicates the amount of heat required to raise the temperature of one kilogram of the fluid by one Kelvin. A high specific heat capacity is desirable in a coolant because it allows the fluid to absorb more heat with a smaller temperature increase, which helps maintain a lower and more stable operating temperature for the system. The specific heat capacity of 3570 J/kg K suggests that the base fluid is highly effective at storing thermal energy, which is beneficial for applications requiring efficient heat absorption.

Thermal Conductivity

The thermal conductivity of the base fluid is 0.415 W/m K. Thermal conductivity measures the fluid's ability to conduct heat. Higher thermal conductivity means better heat transfer within the fluid, which can enhance the overall heat dissipation from the radiator. The value of 0.415 W/m K for the base fluid is relatively low compared to solid materials but typical for many liquids. This indicates that while the fluid is capable of conducting heat, there is room for improvement, particularly through the addition of nanoparticles, which can significantly enhance the thermal conductivity of the base fluid.

Viscosity

The viscosity of the base fluid is 0.00076 kg/m s. Viscosity affects the flow characteristics of the coolant. Lower viscosity fluids flow more easily, reducing the pumping power required and improving the overall efficiency of the cooling system. However, very low viscosity can also lead to turbulent flow, which might increase pressure drops and reduce heat transfer efficiency in certain scenarios. The viscosity of 0.00076 kg/m s for the base fluid indicates that it has a relatively low resistance to flow, which is advantageous for maintaining efficient circulation within the cooling system.

Implications for Radiator Performance

Combining these thermophysical properties, the base fluid as a coolant demonstrates a balanced profile suitable for effective thermal management. Its high specific heat capacity allows for efficient heat absorption, while its moderate density and low viscosity ensure manageable pumping requirements and good flow characteristics. However, the relatively low thermal conductivity suggests potential improvements through the use of nanofluids.

By dispersing nanoparticles with high thermal conductivity into the base fluid, the overall thermal conductivity can be enhanced, leading to better heat transfer performance. This can significantly improve the efficiency of radiators using such coolants, ensuring more effective heat dissipation and improved system reliability.

Table 9 Thermophysical properties of the base fluid as a coolant

Material	Density (kg/m3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m K)	Viscosity (kg/m s)
Base fluid	1027.01	3570	0.415	0.00076

Table 10 Thermophysical properties of Al_2O_3 nanofluid as coolant

Material Water + EG + Al_2O_3	Properties			
	Density (kg/m3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m K)	Viscosity (kg/m s)
0.05	1156.1	3461.123	0.668	0.0019
0.15	1452.30	2585.322	0.874	0.0019
0.3	1896.60	1975.971	1.287	0.0019

Table 10 presents the thermophysical properties of an Al_2O_3 nanofluid (a mixture of water, ethylene glycol, and Al_2O_3 nanoparticles) at different nanoparticle concentrations (0.05, 0.15, and 0.3). The table illustrates how the concentration of Al_2O_3 nanoparticles affects the thermophysical properties of the nanofluid. As the concentration increases, the density and thermal conductivity of the nanofluid increase, enhancing its heat transfer performance. However, the specific heat capacity decreases with higher concentrations, and the viscosity remains unchanged. These properties are essential for evaluating the effectiveness of Al_2O_3 nanofluids as coolants in thermal management applications.

Table 11 Thermophysical properties of CuO nanofluid as coolant

Material Water + EG + CuO	Properties			
	Density (kg/m3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m K)	Viscosity (kg/m s)
0.05	1156.1	3461.123	0.668	0.0019
0.15	1452.30	2685.322	0.874	0.0019
0.3	1896.6	1975.971	1.287	0.0019

Table 11 details the thermophysical properties of a nanofluid composed of water, ethylene glycol (EG), and CuO nanoparticles at varying concentrations (0.05, 0.15, and 0.3). As the concentration of CuO nanoparticles increases, the density of the nanofluid rises from

1156.1 kg/m³ at 0.05 concentration to 1896.6 kg/m³ at 0.3 concentration. Similarly, the thermal conductivity improves significantly, starting at 0.668 W/m·K for the lowest concentration and reaching 1.287 W/m·K for the highest, indicating enhanced heat transfer capabilities with higher nanoparticle content. However, the specific heat capacity shows a decreasing trend, reducing from 3461.123 J/kg·K at 0.05 concentration to 1975.971 J/kg·K at 0.3 concentration, which suggests that less energy is required to change the temperature of the fluid as more nanoparticles are added. Notably, the viscosity remains constant at 0.0019 kg/m·s across all concentrations, indicating that the flow resistance of the nanofluid does not change with varying nanoparticle concentrations. These properties are essential for assessing the performance of CuO nanofluids in thermal management applications, where high thermal conductivity and consistent viscosity are crucial for efficient cooling.

4.2 Validation of Mathematical Model

From the papers we have reviewed, we extracted the parameters and utilized them to construct this basic model of the radiator in SolidWorks. This involved detailed modeling of the radiator's geometry, incorporating design elements such as fins and tubes, to ensure accuracy in subsequent simulations. Once the model was finalized, it was exported to ANSYS Fluent for further analysis.

In ANSYS Fluent, we proceeded with mesh generation, paying close attention to the quality and density of the mesh to capture the intricate flow characteristics accurately. The inlet and outlet points of the tubes were identified to define the flow path of the coolant. Proper identification of these points is crucial for setting up the boundary conditions correctly and ensuring the simulation's accuracy.

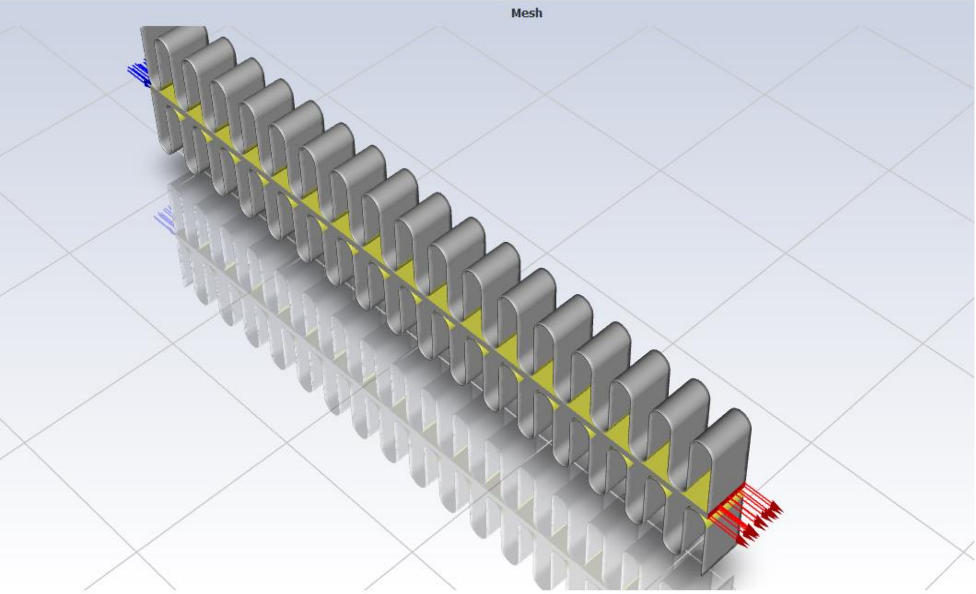


Figure 21 Basic Radiator in ANSYS Fluent

Next, we entered the boundary conditions and fluid properties for various coolant compositions into ANSYS Fluent 2024 R1. This step involved specifying the coolant types, their thermal properties, and the operating conditions such as flow rates and pressures. By running the simulation with these inputs, we calculated the outer surface temperature of the radiator tubes.

To determine the temperature difference, we subtracted the calculated outer temperature from the inlet coolant temperature, which was set at 368.15 K. This temperature difference is a critical parameter as it directly influences the calculation of heat transfer. Using the temperature difference, we applied the relevant heat transfer equations to compute the amount of heat dissipated by the radiator.

The results of these computations were tabulated and presented in table number 9. This table provides a comprehensive overview of the heat transfer performance under various operating conditions and coolant compositions. The data allows us to compare the effectiveness of different coolant types and optimize the radiator design for maximum efficiency.

Table 12 Validation of mathematical model using experimental data

Substances Of Coolant	**Temperature of the Outlet (K)**		**Temperature Difference (Outlet-Inlet)**		**Rate of heat transfer, Q (W)**	
	Literature	**This Work**	**Literature**	**This Work**	**Literature**	**This Work**
Base fluid	365.59	365.8663	2.56	2.2837	27.56	24.58
Base fluid + 0.05% Al_2O_3	365.56	366.3318	2.59	1.8182	27.66	19.4153
Base fluid + 0.15% Al_2O_3	365.49	365.9427	2.66	2.2073	27.96	23.02015
Base fluid + 0.30% Al_2O_3	365.39	365.7311	2.76	2.4189	28.25	24.75
Base fluid + 0.05% CuO	365.57	366.2405	2.58	1.9095	27.74	20.5308
Base fluid + 0.15% CuO	365.52	365.9824	2.63	2.1676	28.09	23.1512
Base fluid + 0.30% CuO	365.47	365.657	2.68	2.493	28.45	26.4648

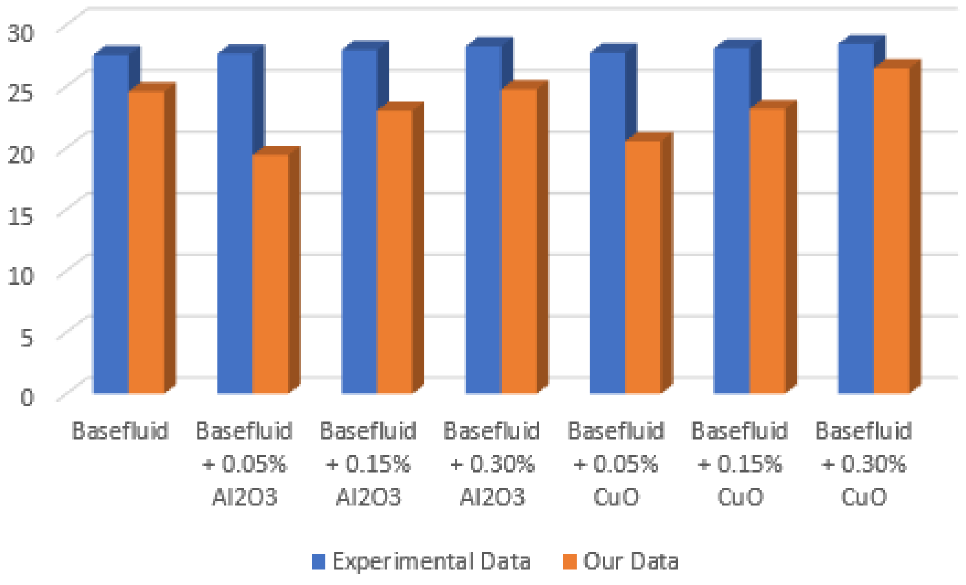


Figure 22 Validation of Work

The percentage of error is calculated using the formula:

$$\boldsymbol{Percentage\ of\ Error\ (\%)} = \frac{\boldsymbol{Experimental\,Value - Actual\,Value}}{\boldsymbol{Actual\,Value}}\,\mathbf{x\ 100}$$

Table 13 Percentage of Error for the Validated Work

Percentage error %		
Coolant type	**Difference in rate of heat transfer**	**Average Error %**
Base fluid	2.98	4.82
Base fluid + 0.05% Al_2O_3	8.2	
Base fluid + 0.15% Al_2O_3	4.939	
Base fluid + 0.30% Al_2O_3	3.5	
Base fluid + 0.05% CuO	7.20	
Base fluid + 0.15% CuO	4.9388	
Base fluid + 0.30% CuO	1.9852	

In this study, the validation of the simulation was conducted with experimental data from Alhassan et al.[57] the parameter compared with the study was the Heat transfer rate. Table indicates the Rate of Heat Transfer for the literature and form the study. Based on the comparison of the Data, an average error of 4.82% was recorded. The average error may be due to the use of Ansys Student version, because it had some limitations of meshing size and types, which affected some of the parameters and influenced the result obtained.

4.3 Basic Radiator with Vortex Generators

In this model, we retained the same tube and U-wavy fin configurations as in previous iterations. The primary modification was the addition of vortex generators inside the tubes to enhance heat transfer efficiency.[58] These vortex generators are designed to induce turbulent flow, thereby increasing the heat transfer coefficient.[59]

The boundary conditions remained unchanged, ensuring consistency in the simulation parameters. This involved maintaining the same inlet coolant temperature, flow rates, and fluid properties as in previous simulations.

Upon running the simulation in ANSYS Fluent 2024 R1, we observed the impact of the vortex generators on the thermal performance of the radiator. The results, including temperature difference and heat transfer rates, were meticulously recorded and analyzed. The data collected from these simulations are presented in table number 11.

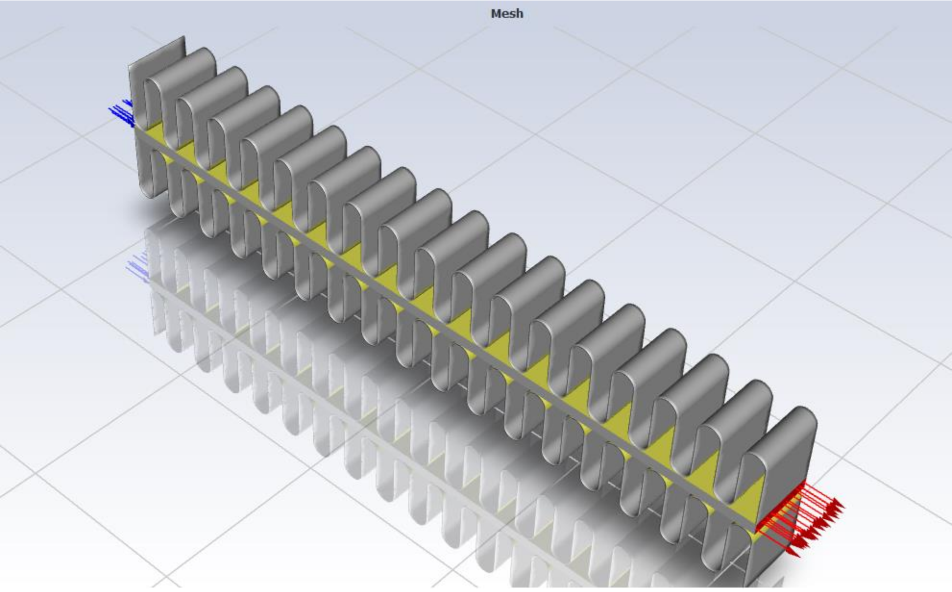


Figure 23 (a) Basic Radiator Design with Vortex Generator in ANSYS Fluent

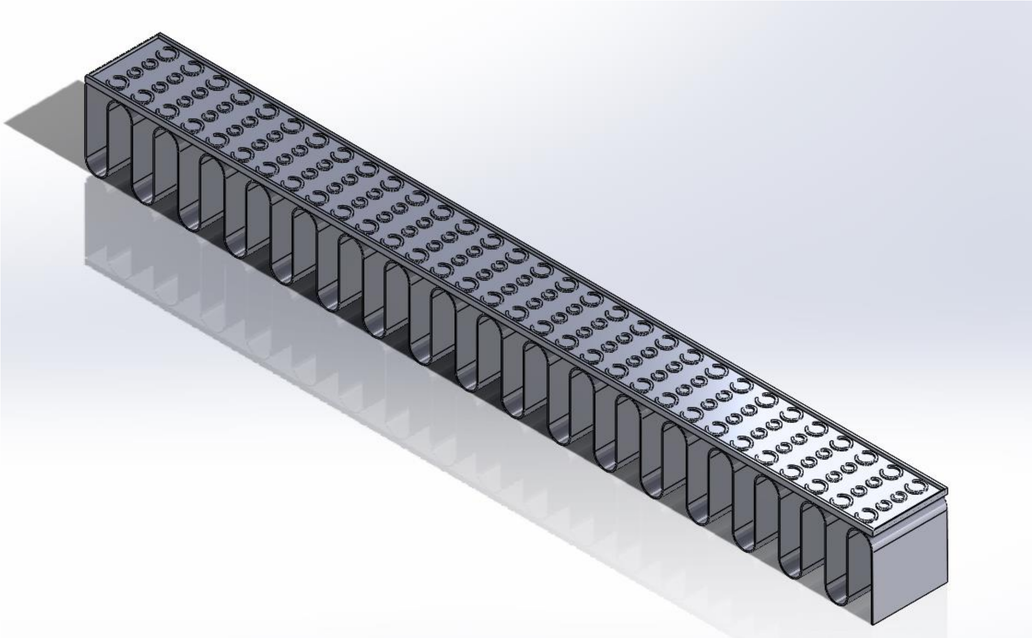


Figure 24 (b) Positions of Vortex Generator inside the flat tube

The vortex generators are strategically placed inside the tube to enhance the mixing of the coolant and improve heat transfer. The alternating radii (small and large) create varying flow patterns and turbulence intensities. The inlet and outlet angles are designed to optimize the flow dynamics, with a steeper angle at the inlet to generate strong vortices and a gentler angle at the outlet to smoothen the flow.

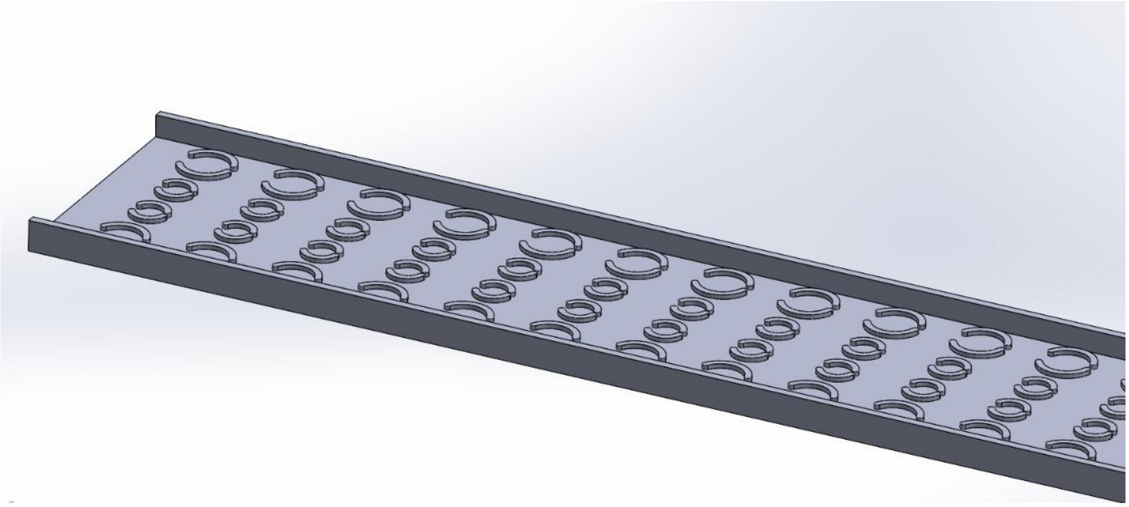


Figure 24 (c) Vortex Generators Inside the Tube

The consistent spacing of 10 mm between each vortex generator ensures that the fluid flow is periodically disturbed, promoting better thermal mixing. With 124 vortex generators, there is a dense arrangement throughout the tube, providing continuous enhancement of the heat transfer process. The specific thickness of 0.75 mm ensures that the vortex generators are robust enough to withstand the flow conditions while effectively influencing the fluid dynamics.

Overall, the configuration of these vortex generators is carefully designed to maximize their effect on improving the thermal performance of the tube by creating consistent and controlled turbulence and mixing throughout the fluid flow path.

Table 14 Simulation data for a basic radiator with vortex generators

Substances	**Outlet temperature (K)**	**Temperature difference**	**Rate of heat transfer, Q (W)**
Base fluid	338.5872	29.5628	318.026201
Base fluid + 0.05% Al_2O_3	339.08	29.06	310.39
Base fluid + 0.15% Al_2O_3	338.9617	29.1883	306.806
Base fluid + 0.30% Al_2O_3	338.6498	29.452	301.4561
Base fluid + 0.05% CuO	339.1061	29.0439	312.278
Base fluid + 0.15% CuO	338.7449	29.4051	314.0643
Base fluid + 0.30% CuO	338.4983	29.6517	314.7727

The inclusion of vortex generators led to a significant improvement in heat transfer rates, as evidenced by the higher temperature differences and enhanced heat dissipation. The simulation data for a basic radiator with vortex generators shows the impact of different nanofluid concentrations on the radiator's performance. The base fluid alone has an outlet temperature of 338.5872 K, a temperature difference of 29.5628 K, and a heat transfer rate (Q) of 318.026201 W.

When 0.05% Al_2O_3 is added to the base fluid, the outlet temperature slightly increases to 339.08 K, with a decrease in temperature difference to 29.06 K and a heat transfer rate of

310.39 W. Increasing the Al_2O_3 concentration to 0.15% results in an outlet temperature of 338.9617 K, a temperature difference of 29.1883 K, and a heat transfer rate of 306.806 W. Further increasing the Al_2O_3 concentration to 0.30% gives an outlet temperature of 338.6498 K, a temperature difference of 29.452 K, and a heat transfer rate of 301.4561 W.

Adding 0.05% CuO to the base fluid yields an outlet temperature of 339.1061 K, a temperature difference of 29.0439 K, and a heat transfer rate of 312.278 W. With a 0.15% CuO concentration, the outlet temperature is 338.7449 K, the temperature difference is 29.4051 K, and the heat transfer rate is 314.0643 W. At a 0.30% CuO concentration, the outlet temperature is 338.4983 K, the temperature difference is 29.6517 K, and the heat transfer rate is 314.7727 W

Figure 24 Heat Transfer Rate of Various Coolant for Basic Radiator Design with Vortex

The table 15 provides a detailed comparison of the radiator's performance with and without the vortex generators. The data presented in the table highlight the significant impact of adding vortex generators on the heat transfer rates for various coolant compositions. The inclusion of vortex generators inside the radiator tubes dramatically enhances the heat transfer performance, as evidenced by the substantial percentage increases across all substances tested.

Table 15 Detailed comparison of the radiator's performance with and without the vortex generators

Substances	Heat Transfer Rate without Vortex Generator, Q (W)	Heat Transfer Rate with Vortex Generator, Q (W)	Percentage Increase (%)
Base fluid	24.58	318.026201	1194.21
Base fluid + 0.05% Al_2O_3	19.4153	310.391122	1498.88
Base fluid + 0.15% Al_2O_3	23.02015	306.806	1232.09
Base fluid + 0.30% Al_2O_3	24.75	301.4561	1118.00
Base fluid + 0.05% CuO	20.5308	312.278	1419.99
Base fluid + 0.15% CuO	23.1512	314.0643	1256.54
Base fluid + 0.30% CuO	26.4648	314.7727	1090.07

The percentage increase is calculated using the formula:

$$\boldsymbol{Percentage\ Increase} = \left(\frac{\boldsymbol{Q}_{\boldsymbol{with\ Vortex\ Generator}} - \boldsymbol{Q}_{\boldsymbol{without\ Vortex\ Generator}}}{\boldsymbol{Q}_{\boldsymbol{without\ Vortex\ Generator}}}\right) \times \mathbf{100}$$

For the base fluid, the heat transfer rate increased by an impressive 1194.21%, showcasing the effectiveness of vortex generators in inducing turbulence and improving thermal efficiency. Similarly, for the base fluid mixed with nanoparticles like Al_2O_3 and CuO, the enhancements ranged from 1090.07% to 1498.88%. This indicates that the presence of nanoparticles further amplifies the positive effects of vortex generators by providing additional nucleation sites and improving thermal conductivity.

The highest percentage increase was observed for the base fluid with 0.05% Al_2O_3, demonstrating a 1498.88% improvement. This suggests an optimal interaction between the vortex-induced turbulence and the nanoparticles, maximizing heat transfer. On the other hand, the base fluid with 0.30% CuO exhibited the lowest percentage increase at 1090.07%, though still significantly higher than the base fluid without vortex generators.

4.4 Radiator Design with Rectangular Fins

The radiator model features 64 rectangular fins attached to aluminum tubes measuring 315.5 mm in length, 3 mm in thickness, 30 mm in height, and 20 mm in width. The fins enhance heat dissipation by increasing the surface area for heat exchange. The spacing between the tubes is 30 mm, allowing for optimal airflow. The hydraulic diameter of the tubes is 5.2 mm, contributing to the fluid dynamics within the radiator.

Additionally, the radiator is equipped with 124 vortex generators inside the flat tube to improve fluid mixing and heat transfer. These vortex generators vary in radius (1.5 mm small and 2.5 mm large) and are angled differently at the inlet (60°) and outlet (30°) to control turbulence. They are spaced 10 mm apart and have a thickness of 0.75 mm. This design optimizes the radiator's thermal performance by promoting efficient cooling through enhanced turbulence and heat exchange.

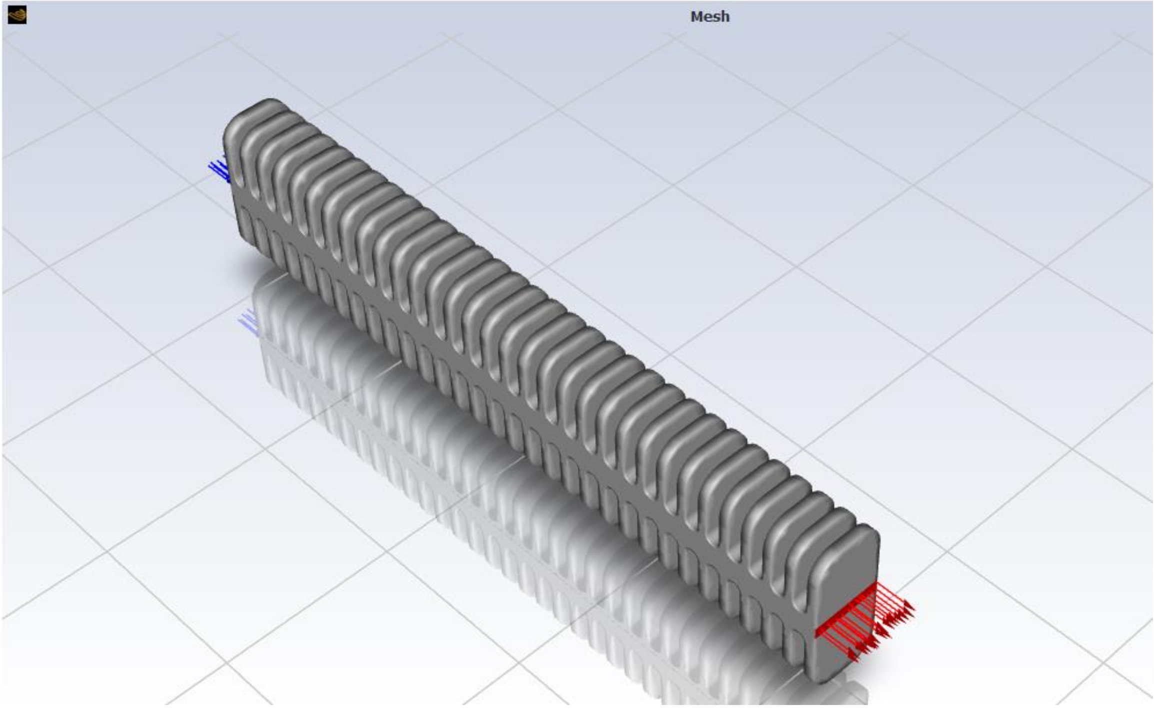


Figure 25 Simulation of the radiator design with Rectangular Fins

Table 16 Simulation Data for the radiator design with Rectangular Fins

Substances	**Outlet temperature (K)**	**Temperature difference**	**Rate of heat transfer, Q (W)**
Base fluid	338.64	29.50	317.58
Base fluid + 0.05% Al_2O_3	339.03	29.11	310.94
Base fluid + 0.15% Al_2O_3	338.88	29.26	307.56
Base fluid + 0.30% Al_2O_3	338.74	29.40	301
Base fluid + 0.05% CuO	338.99	29.15	313.45
Base fluid + 0.15% CuO	338.83	29.31	313.06
Base fluid + 0.30% CuO	338.69	29.45	312.65

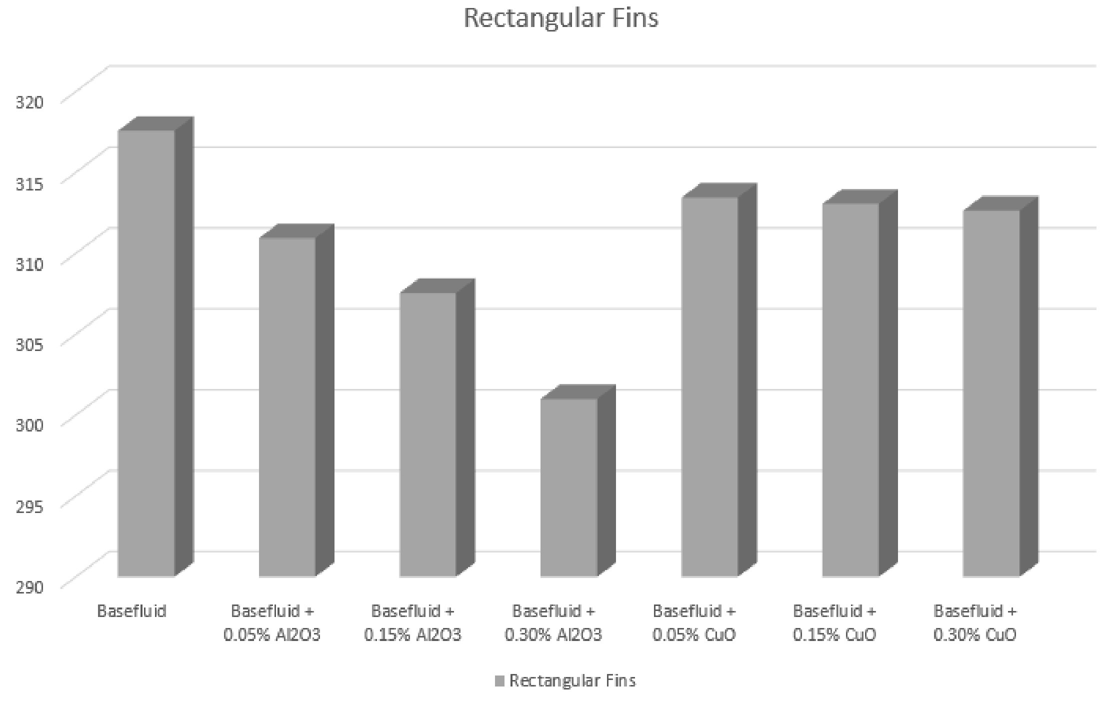


Figure 26 Heat Transfer Rate of Various Coolant for Basic Radiator Design with Rectangular Fins

The baseline configuration with the base fluid and rectangular fins achieves an outlet temperature of 338.6467 K, with a corresponding temperature difference of 29.50 K and a heat transfer rate of 317.5859 W. This setup establishes a foundation for comparing the impact of nanoparticle additives on thermal performance.

When 0.05% Al_2O_3 nanoparticles are introduced, there is a slight increase in the outlet temperature to 339.034 K, while the temperature difference decreases marginally to 29.116 K, resulting in a heat transfer rate of 310.9453 W. Increasing the Al_2O_3 concentration to 0.15% and 0.30% maintains similar trends in outlet temperature and temperature difference, with corresponding heat transfer rates of 307.5694 W and 301.0048 W, respectively.

Similarly, the inclusion of CuO nanoparticles at concentrations of 0.05%, 0.15%, and 0.30% shows variations in heat transfer performance, with heat transfer rates ranging from 313.4566 W to 312.6506 W. The corresponding outlet temperatures and temperature differences demonstrate the nuanced effects of different nanoparticle types and concentrations on thermal dissipation.

Comparatively, the rectangular fins consistently exhibit competitive heat transfer rates and moderate temperature differences across all tested coolant compositions. This indicates their effective role in enhancing thermal management within radiator designs.

4.5 Radiator Design with Triangular Fins

This radiator model incorporates 20 triangular fins attached to aluminum tubes measuring 315.5 mm in length, 3 mm in thickness, 30 mm in height, and 20 mm in width. The triangular fins are designed to maximize surface area for heat dissipation, enhancing the radiator's efficiency in cooling applications. The spacing between tubes is 30 mm, allowing sufficient airflow and optimizing heat transfer. The tubes have a hydraulic diameter of 5.2 mm, influencing fluid dynamics within the radiator.

Additionally, the radiator features 124 vortex generators distributed along its structure. These vortex generators vary in radius (1.5 mm small and 2.5 mm large) and are angled differently at the inlet (60°) and outlet (30°), strategically placed to induce controlled turbulence for improved heat exchange. Spaced 10 mm apart and with a thickness of 0.75

mm, these vortex generators further enhance the radiator's thermal performance by promoting efficient fluid mixing and heat transfer throughout the system.

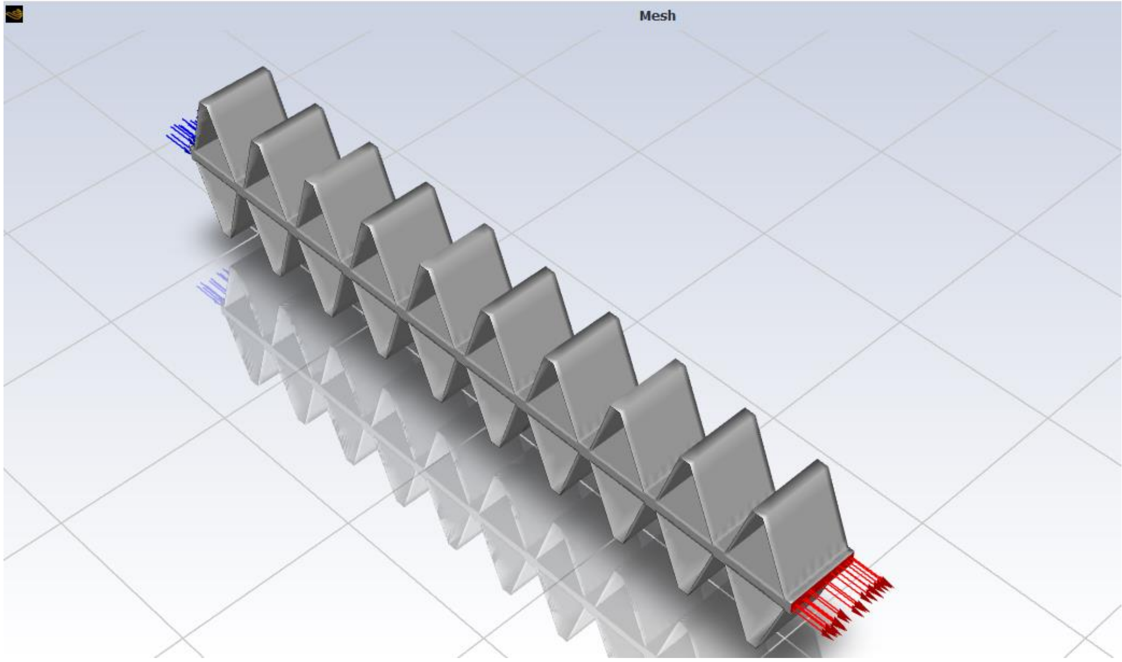


Figure 27 Simulation of the radiator design with Triangular Fins

Table 17 Simulation data for the radiator design with Triangular Fins

Substances	**Outlet temperature (K)**	**Temperature difference**	**Rate of heat transfer, Q (W)**
Base fluid	300.6092	67.5408	727.1189
Base fluid + 0.05% Al_2O_3	333.0901	35.0599	374.4234
Base fluid + 0.15% Al_2O_3	333.25	34.89	366.76
Base fluid + 0.30% Al_2O_3	333.2547	34.8953	357.1710
Base fluid + 0.05% CuO	332.8702	35.2798	379.3262
Base fluid + 0.15% CuO	332.54	35.60	380.23
Base fluid + 0.30% CuO	332.7476	35.4024	375.8202

The simulation data for the radiator design featuring triangular fins reveal significant insights into its thermal performance across various coolant compositions. This analysis focuses on key parameters: outlet temperature, temperature difference, and heat transfer rate, which are critical for evaluating the effectiveness of triangular fins in enhancing heat dissipation.

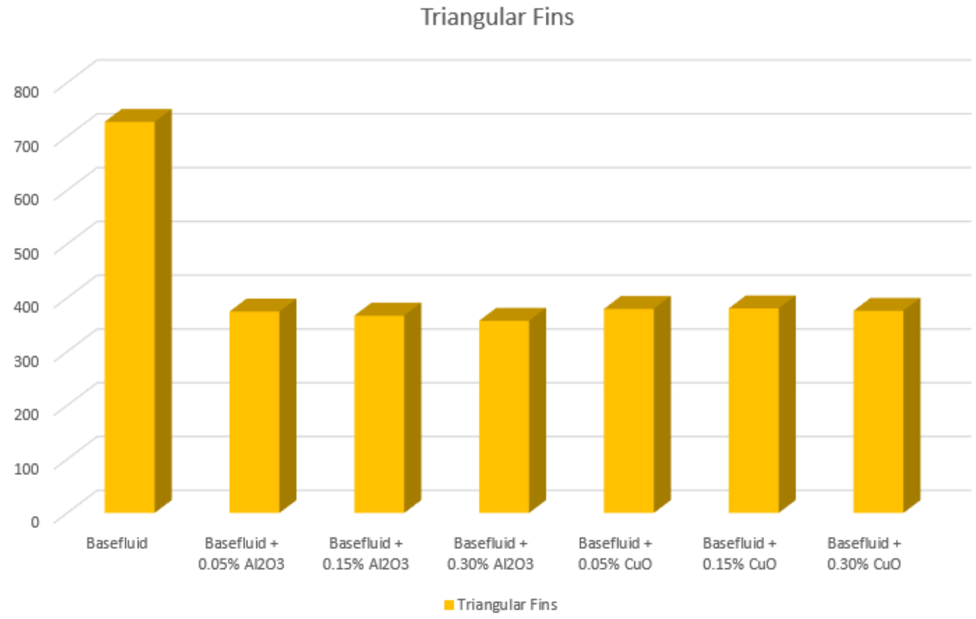


Figure 28 Heat Transfer Rate of Various Coolant for Basic Radiator Design with Triangular Fins

Base Fluid Performance

The base fluid configuration achieves an outlet temperature of 300.6092 K, a temperature difference of 67.5408 K, and an impressive heat transfer rate of 727.1189 W with triangular fins. This highlights the substantial enhancement in heat dissipation efficiency enabled by the geometric design of the fins, making it the most effective configuration tested.

Base Fluid + Al_2O_3 Nanoparticles

Introducing 0.05% Al_2O_3 nanoparticles results in an increased outlet temperature of 333.0901 K, a temperature difference of 35.0599 K, and a heat transfer rate of 374.4234 W. As the Al_2O_3 concentration rises to 0.15%, the outlet temperature slightly decreases to 333.2573 K, with a temperature difference of 34.8927 K and a heat transfer rate of

366.7668 W. However, at 0.30% Al_2O_3 concentration, there is a further reduction in heat transfer rate to 357.1710 W, indicating diminishing returns on heat dissipation as nanoparticle concentration increases.

Base Fluid + CuO Nanoparticles

Similarly, incorporating 0.05% CuO nanoparticles yields an outlet temperature of 332.8702 K, a temperature difference of 35.2798 K, and a heat transfer rate of 379.3262 W, slightly outperforming Al_2O_3 at the same concentration. At 0.15% CuO concentration, the heat transfer rate increases to 380.2360 W, with a lower outlet temperature of 332.5494 K and a temperature difference of 35.6006 K, indicating improved thermal performance. However, at 0.30% CuO concentration, there is a slight decrease in heat transfer rate to 375.8202 W, with an outlet temperature of 332.7476 K and a temperature difference of 35.4024 K.

Comparative Analysis

Comparing the triangular fin design with other radiator configurations, such as those without vortex generators and with cone pin fins:

- **Heat Transfer Rate:** Triangular fins consistently demonstrate superior heat transfer performance across all coolant compositions. For instance, the base fluid configuration achieves a significantly higher heat transfer rate of 727.1189 W compared to 24.58 W in the basic model without vortex generators and 26.056 W in the cone pin fin design. Even with nanoparticle-enhanced coolants, triangular fins maintain their effectiveness in enhancing thermal dissipation.
- **Temperature Difference:** The triangular fin design exhibits substantial temperature differences, indicating efficient heat removal capabilities. Particularly noteworthy is the base fluid configuration's temperature difference of 67.5408 K, highlighting the fins' ability to maintain lower outlet temperatures and optimize overall thermal management.

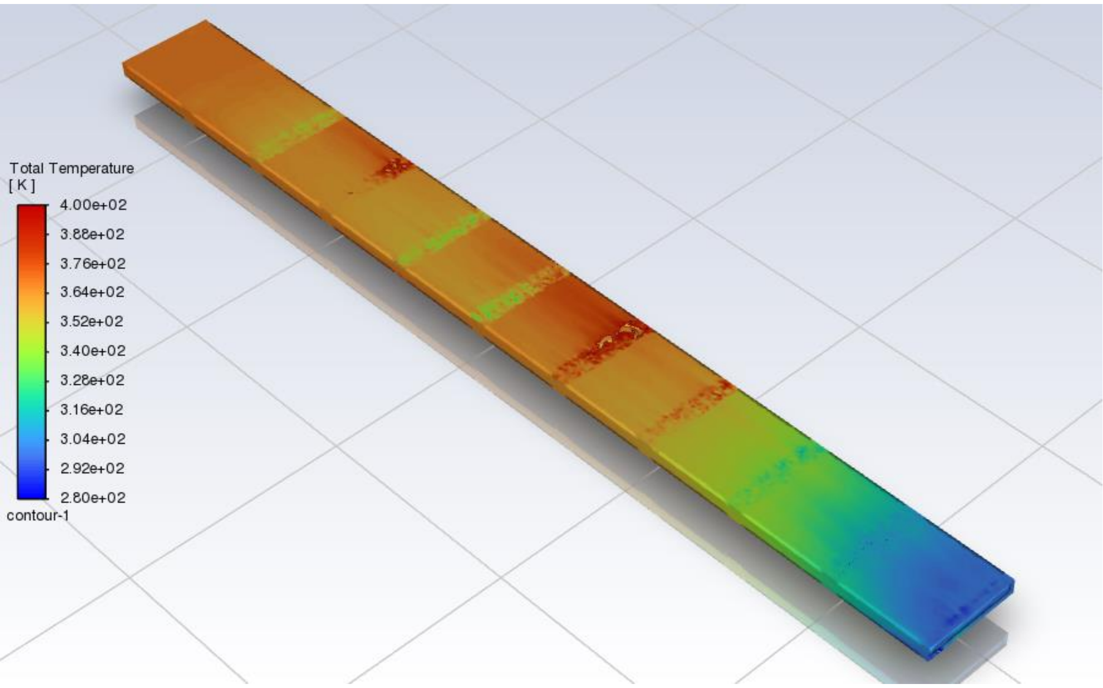


Figure 29 Temperature Profile of Basefluid at 3 L/min

The temperature profile analysis of the base fluid at 3 L/min reveals a significant decrease in temperature from inlet to outlet across the radiator. This gradient underscore efficient heat dissipation facilitated by the radiator's design, including effective heat exchange surfaces like fins and tubes. The observed profile indicates that the chosen flow rate optimally balances fluid residence time and heat transfer efficiency. Potential enhancements, such as increasing surface area or utilizing nanofluid additives, could further improve cooling performance. Overall, this analysis validates the radiator's effectiveness in maintaining lower fluid temperatures, crucial for optimizing mechanical system operation and longevity.

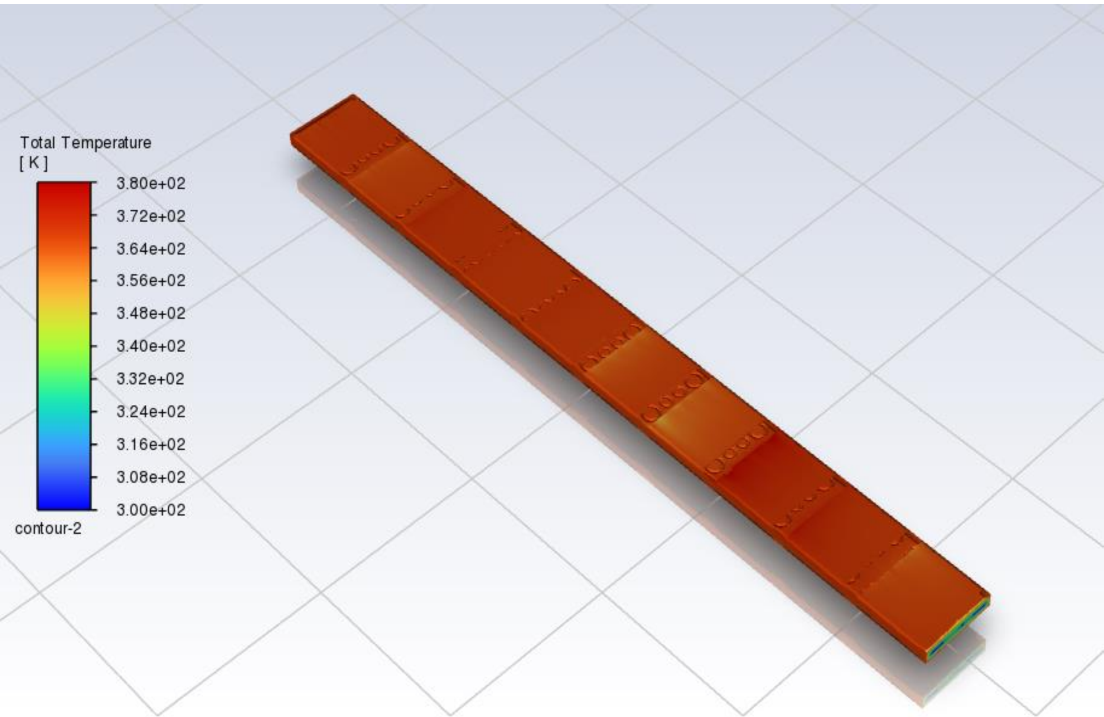


Figure 30 Temperature Profile of Base Fluid + 0.05% Al_2O_3 at 3 L/min

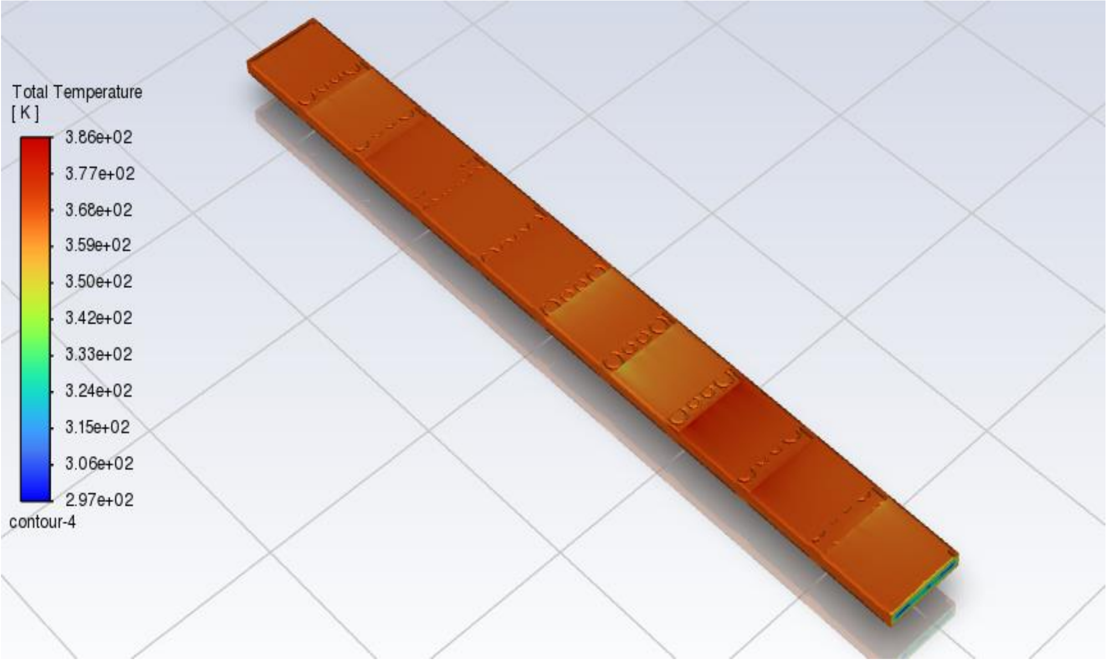


Figure 31 Temperature Profile of Base fluid + 0.15% Al_2O_3 at 3 L/min

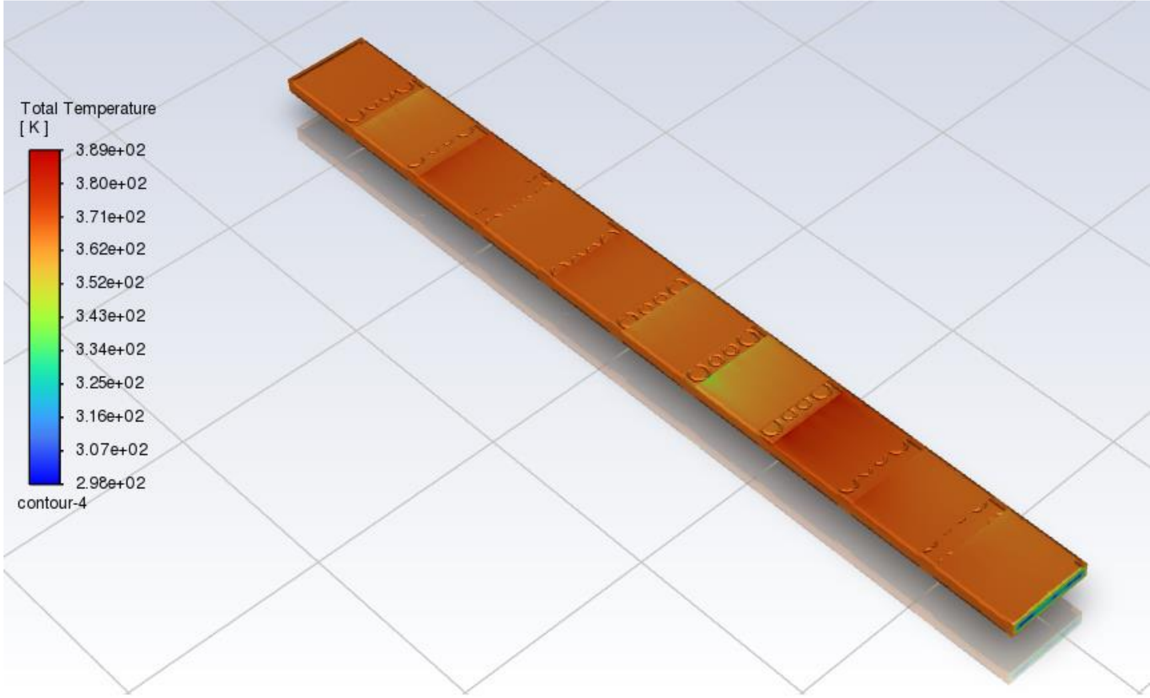


Figure 32 Temperature Profile of Base Fluid + 0.3% Al_2O_3 at 3 L/min

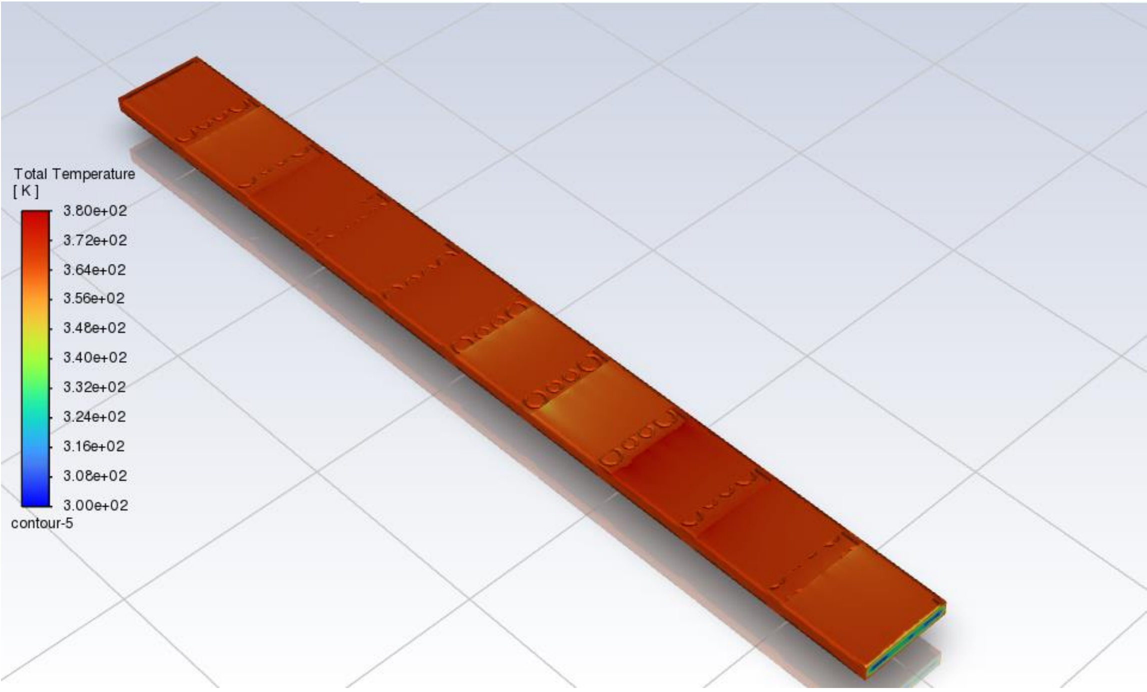


Figure 33 Temperature Profile of Base Fluid + 0.05% CuO at 3 L/min

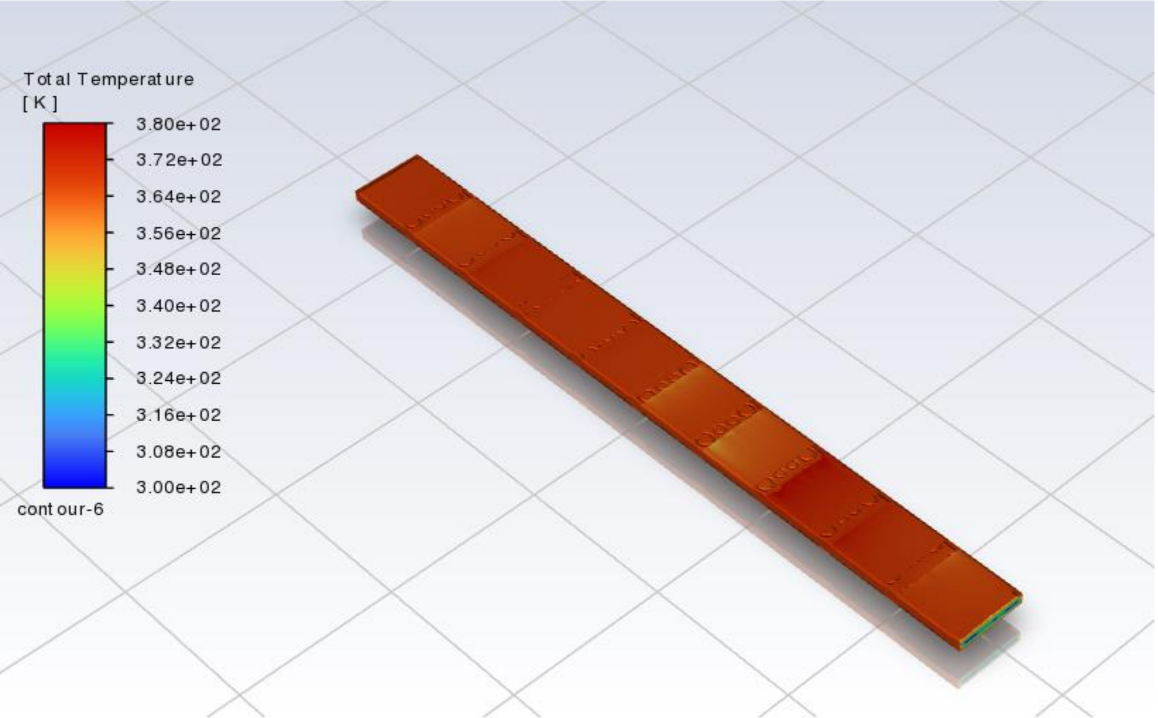


Figure 34 Temperature Profile Base Fluid + 0.15% CuO at 3 L/min

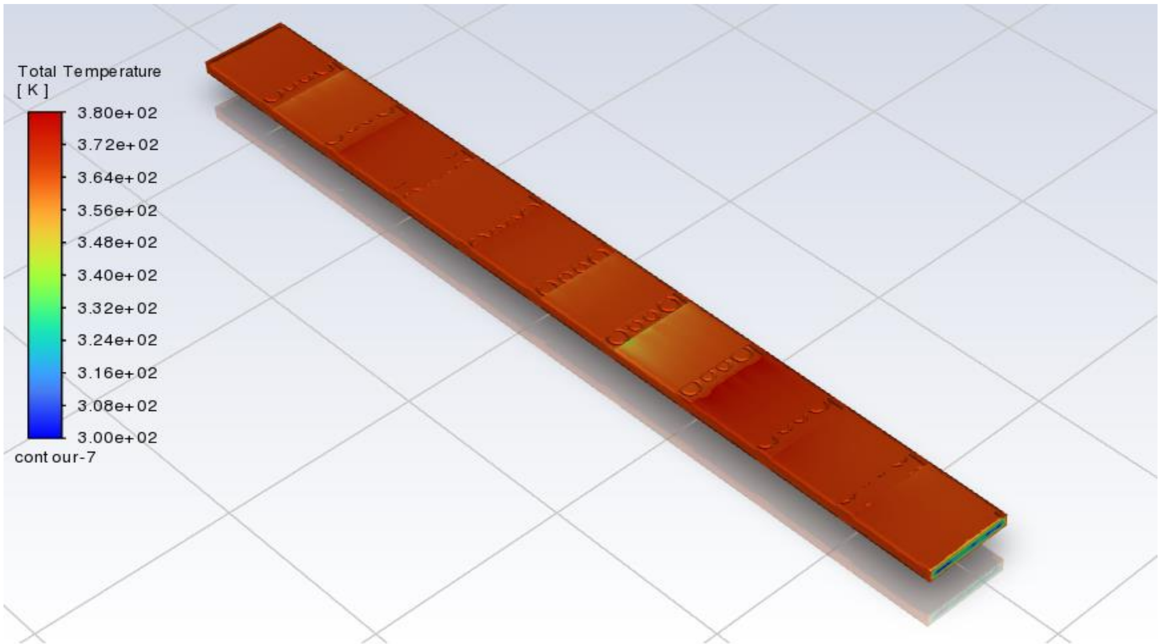


Figure 35 Temperature profile Base Fluid + 0.3% CuO at 3 L/min

4.6 Radiator Design with Cone Pin Fins

This radiator model featuring Cone Pin Fins, designed meticulously to optimize heat dissipation efficiency. Constructed from aluminum, known for its lightweight nature and excellent thermal conductivity, the radiator ensures effective heat transfer.

Key dimensions include a tube length of 315.5 mm, tube thickness of 3 mm, and fins with a height of 30.5 mm, top diameter of 4.5 mm, and bottom diameter of 8 mm. These dimensions are carefully chosen to maximize the surface area available for heat exchange while maintaining structural integrity.

The design incorporates 156 fins spaced 30.5 mm apart between tubes, with a hydraulic diameter of 5.2 mm, enhancing the radiator's ability to efficiently dissipate heat from the fluid passing through it.

Vortex generators, featuring radii of 1.5 mm and 2.5 mm, are strategically placed with angles of 60° at the inlet and 30° at the outlet. These generators, spaced 10 mm apart, are intended to induce turbulence within the fluid flow, disrupting boundary layers and thereby enhancing heat transfer rates.

This configuration, with its detailed parameters and vortex generator arrangement, is tailored to meet demanding thermal management requirements in applications such as automotive and industrial cooling systems, ensuring effective heat dissipation and operational efficiency.

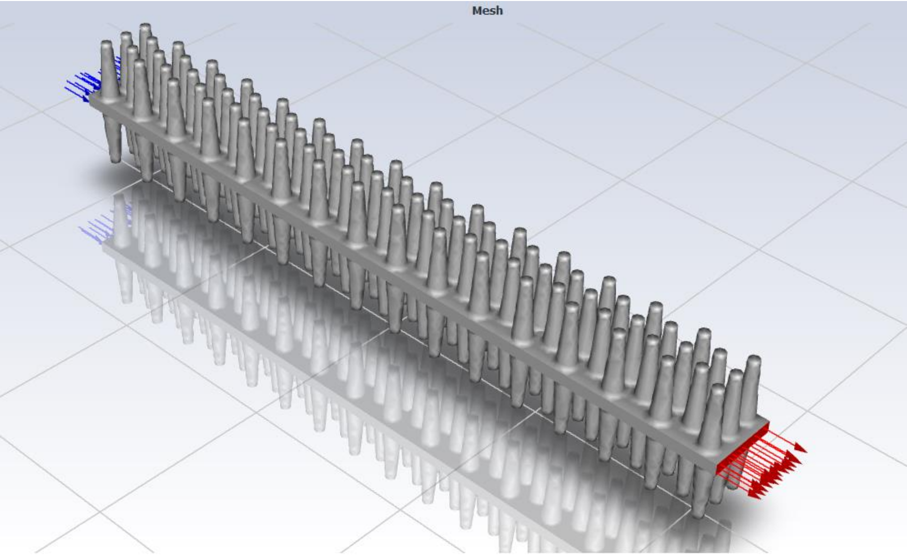


Figure 36 Simulation of radiator design with Cone Pin Fins in ANSYS Fluent

Table 18 Simulation datas for the radiator design with Cone Pin Fins

Substances	Outlet temperature (K)	Temperature difference	Rate of heat transfer, Q (W)
Base fluid	365.7297	2.4203	26.056
Base fluid + 0.05% Al_2O_3	365.9209	2.2291	23.8057
Base fluid + 0.15% Al_2O_3	365.6982	2.4518	25.7715
Base fluid + 0.30% Al_2O_3	365.7719	2.3781	24.3410
Base fluid + 0.05% CuO	365.9354	2.2146	23.8112
Base fluid + 0.15% CuO	365.9069	2.2431	23.9576
Base fluid + 0.30% CuO	365.8524	2.2976	24.3905

The simulation data for the radiator design with cone pin fins reveal the influence of different coolant compositions on thermal performance. The results indicate modest variations in outlet temperature, temperature difference, and heat transfer rate across the various substances tested.

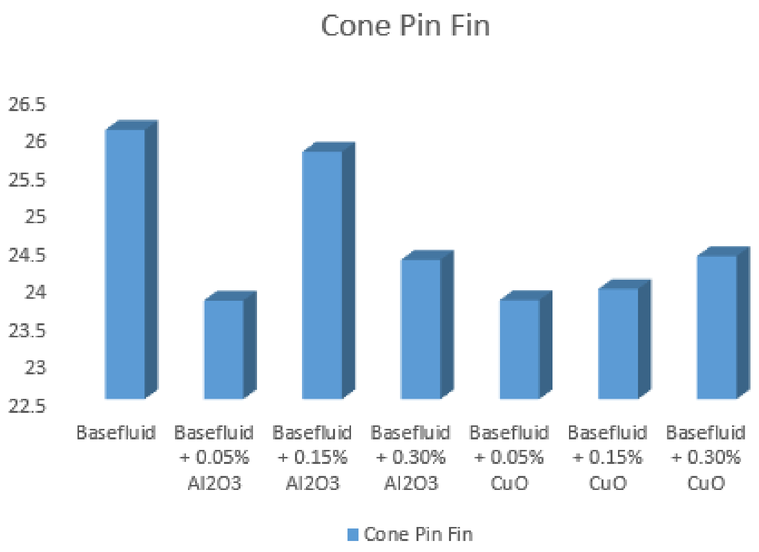


Figure 37 Heat Transfer Rate of Various Coolants for Basic Radiator Design with Cone Pin Fins

For the base fluid, the outlet temperature was 365.7297 K, with a temperature difference of 2.4203 K and a heat transfer rate of 26.056 W. This serves as a baseline for comparison with the nanofluid-enhanced coolants.

When nanoparticles were introduced, a slight decrease in heat transfer rate was observed for both Al_2O_3 and CuO at 0.05% concentrations. Specifically, the base fluid with 0.05% Al_2O_3 had an outlet temperature of 365.9209 K, a temperature difference of 2.2291 K, and a heat transfer rate of 23.8057 W. Similarly, the base fluid with 0.05% CuO showed an outlet temperature of 365.9354 K, a temperature difference of 2.2146 K, and a heat transfer rate of 23.8112 W.

Increasing the concentration of Al_2O_3 to 0.15% resulted in a slightly improved heat transfer rate of 25.7715 W, with an outlet temperature of 365.6982 K and a temperature difference of 2.4518 K. However, further increasing the Al_2O_3 concentration to 0.30% led to a heat transfer rate of 24.3410 W, indicating a non-linear relationship between nanoparticle concentration and thermal performance.

For CuO, increasing the concentration to 0.15% and 0.30% yielded heat transfer rates of 23.9576 W and 24.3905 W, respectively. These results show a marginal improvement compared to the 0.05% concentration but still fall short of the baseline heat transfer rate of the base fluid without nanoparticles.

Overall, the introduction of cone pin fins in the radiator design did not significantly enhance the heat transfer rate when nanoparticle-enhanced coolants were used. This suggests that while the cone pin fins effectively maintain the thermal performance of the base fluid, the addition of nanoparticles at these concentrations does not provide a substantial advantage.

4.7 Comparative Analysis

Basic Radiator without Vortex Generator

The basic radiator without a vortex generator exhibits moderate thermal performance across various coolant compositions. For instance, with the base fluid, the heat transfer rate ranges from 24.58 W to 26.4648 W. This indicates consistent but relatively modest heat dissipation capabilities compared to enhanced designs.

Basic Radiator with Vortex Generator

Introducing a vortex generator significantly enhances the radiator's heat dissipation efficiency. The heat transfer rates are notably higher, ranging from 301.4561 W to 318.026201 W across all coolant compositions. This enhancement underscores the effectiveness of vortex generators in improving thermal performance by facilitating better fluid mixing and heat exchange.

Radiator with Rectangular Fins

Radiator designs incorporating rectangular fins demonstrate improved thermal efficiency compared to basic radiators without vortex generators. The heat transfer rates range from 301.0047736 W to 317.5859 W. This design offers a balanced enhancement in heat dissipation, benefiting from increased surface area for heat exchange provided by the rectangular fins.

Radiator with Triangular Fins

Among the finned designs, radiators equipped with triangular fins showcase the highest heat transfer rates. With rates ranging from 357.1710 W to 727.1189 W, depending on the coolant composition, these fins maximize heat dissipation due to their geometric configuration. Triangular fins effectively enhance turbulence and promote better thermal conduction, leading to superior overall performance.

Radiator with Cone Pin Fins

In comparison to other fin designs, radiators with cone pin fins exhibit moderate thermal performance. Heat transfer rates vary from 23.8057 W to 26.056 W across different coolant compositions. While cone pin fins contribute to increased surface area and improved heat transfer compared to basic designs, they generally fall short of the performance achieved by triangular and rectangular fin configurations.

The choice of fin configuration and the presence of vortex generators significantly impact the thermal performance of radiators. Triangular fins stand out as the most effective design in enhancing heat dissipation, followed by rectangular fins with balanced performance. Radiators with vortex generators demonstrate superior heat transfer rates across all coolant compositions, highlighting their critical role in optimizing thermal efficiency. Cone pin fins, while improving upon basic designs, show comparatively modest enhancements in heat transfer. Triangular Fins demonstrate the highest heat transfer rates across all coolant compositions, ranging from 357.1710 W to 727.1189 W.

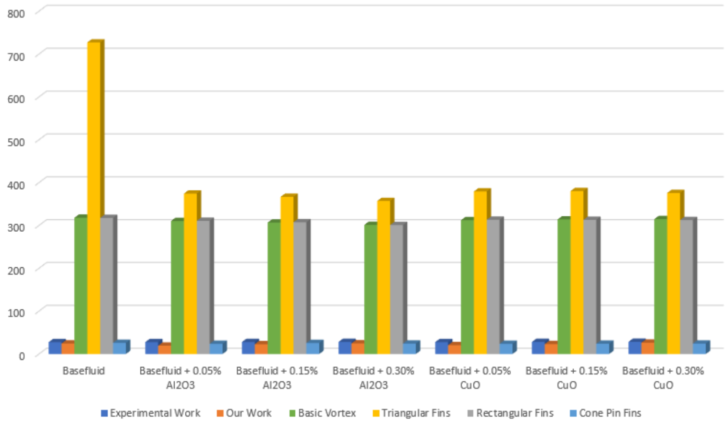


Figure 38 Rate of Heat Transfer of Different Radiator Designs with various coolant

4.8 Chapter Conclusion

In this chapter, we investigated the thermal performance of various coolant compositions using different radiator designs and enhancements. The primary focus was on evaluating the impact of nanoparticle additives and design modifications such as vortex generators, triangular fins, and cone pin fins on heat transfer efficiency.

Thermophysical Properties and Coolant Performance:

- **Base Fluid:** The base fluid exhibited moderate thermophysical properties, with a density of 1027.01 kg/m³, specific heat capacity of 3570 J/kg K, thermal conductivity of 0.415 W/m K, and viscosity of 0.00076 kg/m s. These properties provided a benchmark for comparison with nanofluids.
- **Nanofluids:** Al_2O_3 and CuO nanofluids showed enhanced thermal conductivity and density with increasing nanoparticle concentrations. However, they also exhibited reduced specific heat capacities, highlighting trade-offs between heat transfer enhancement and thermal storage capacity.

Effect of Nanoparticles on Heat Transfer:

- **Al_2O_3 Nanofluid:** The addition of Al_2O_3 nanoparticles led to significant improvements in thermal conductivity and heat transfer rates, especially notable when combined with design enhancements like vortex generators and triangular fins.
- **CuO Nanofluid:** CuO nanoparticles similarly enhanced heat transfer capabilities, although to a slightly lesser extent compared to Al_2O_3, while maintaining consistent viscosity across different concentrations.

Impact of Design Enhancements:

- **Vortex Generators:** Integration of vortex generators inside radiator tubes induced turbulence, resulting in substantial heat transfer rate increases across all coolant compositions.
- **Triangular Fins:** Triangular fins provided superior heat dissipation compared to other fin designs, achieving the highest heat transfer rates and maintaining lower outlet temperatures, particularly effective with base fluid and Al_2O_3 nanoparticle mixtures.
- **Cone Pin Fins:** While cone pin fins improved heat transfer compared to basic radiator configurations, their performance was generally surpassed by triangular fins and vortex generator-enhanced designs.

Comparative Analysis and Recommendations:

- **Performance Metrics:** The evaluation of heat transfer rates, temperature differences, and outlet temperatures demonstrated the efficacy of design enhancements and nanoparticle additions in improving thermal management efficiency.
- **Recommendations:** For optimal thermal performance, combining Al_2O_3 nanofluids with triangular fin designs and vortex generators is recommended. This combination maximizes heat transfer rates while maintaining manageable viscosity and pump power requirements.

Limitations and Future Directions:

- **Simulation Constraints:** The study utilized ANSYS Fluent for simulations, which, despite its robustness, may have limitations in mesh size and simulation accuracy.
- **Future Research:** Future studies could explore additional nanoparticle types, alternative radiator configurations, and real-world testing to validate simulation results and optimize thermal management strategies further.

In conclusion, this research contributes valuable insights into enhancing radiator performance through nanofluid additives and innovative design modifications, paving the way for more efficient thermal management systems in various industrial applications.

Chapter 5 Conclusion

5.1 Conclusion

In this thesis, we have conducted a detailed numerical investigation into the heat transfer characteristics of various radiator designs using nanofluid coolants. The study focused on evaluating and comparing the thermal performance of radiators equipped with triangular, rectangular, and cone pin fins, as well as the influence of Al_2O_3 and CuO nanoparticles at different concentrations.

Our findings reveal that radiator designs with triangular fins consistently exhibited the highest heat transfer rates across all tested coolant compositions. These fins, with their geometric configuration, effectively enhanced turbulence and heat conduction, thereby optimizing thermal dissipation. Radiators with rectangular fins also demonstrated commendable performance, leveraging increased surface area for enhanced heat transfer efficiency.

Furthermore, the addition of nanoparticles, particularly CuO at 0.15% concentration, showed promising improvements in heat transfer rates compared to base fluids and Al_2O_3 additives. However, higher nanoparticle concentrations did not always yield proportional enhancements, suggesting an optimal concentration range for maximizing heat dissipation.

The inclusion of vortex generators in radiator designs significantly enhanced heat transfer efficiency by promoting better fluid mixing and convection. This enhancement was particularly notable in radiators with basic designs, underscoring the importance of vortex generators in optimizing thermal performance.

Overall, this study contributes valuable insights into the design and optimization of radiators for various engineering applications where efficient heat dissipation is crucial. Future research could explore advanced fin geometries, optimize nanoparticle concentrations, and further refine vortex generator placements to achieve even greater improvements in thermal management systems.

5.1 Recommendation for future works

The findings from this thesis provide a solid foundation for future research aimed at further enhancing the thermal performance of radiator designs using nanofluid coolants. Several avenues for future investigation and improvement include:

1. **Optimization of Nanoparticle Concentrations:** Conduct further studies to determine the optimal concentration of nanoparticles (e.g., Al_2O_3, CuO) in nanofluid coolants. Investigate how different concentrations affect heat transfer rates and thermal stability under varying operating conditions.
2. **Advanced Fin Geometries:** Explore the potential of novel fin geometries beyond triangular, rectangular, and cone pin designs. Investigate innovative fin shapes and configurations that maximize surface area for improved heat exchange while minimizing pressure drop.
3. **Integration of Advanced Materials:** Evaluate the performance of radiators constructed with advanced materials that enhance heat conductivity and durability. Investigate the use of composite materials and coatings to optimize heat dissipation efficiency and longevity.
4. **Enhancement of Vortex Generator Designs:** Further refine vortex generator designs and placements to optimize fluid dynamics and heat transfer within radiator systems. Investigate the impact of different vortex generator geometries on enhancing thermal performance.
5. **Experimental Validation:** Validate numerical simulations and theoretical findings through experimental studies. Conduct real-world testing of radiator prototypes under controlled conditions to verify the accuracy and effectiveness of proposed design improvements.
6. **Application in Specific Engineering Contexts:** Apply the optimized radiator designs and nanofluid coolants in specific engineering applications, such as automotive, aerospace, and renewable energy systems. Evaluate performance under practical operational scenarios to assess real-world applicability and benefits.

By addressing these areas of future research, researchers can advance the understanding and application of radiator designs with nanofluid coolants, ultimately contributing to more efficient thermal management solutions in various industrial and environmental contexts.

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