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Numerical Investigation and Geometrical Comparison of Triangular Fins Using CFD

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Abstract -In this review presents a comprehensive assessment of computational investigations on the coupled effects of natural convection and surface radiation in extended surfaces with various fin geometries, including annular, star, square, and triangular configurations. Emphasis is placed on three-dimensional numerical studies employing the finite volume method, commonly implemented using the ANSYS Fluent solver, to solve the governing conservation equations of mass, momentum, and energy. Buoyancy effects are typically modelled using the ideal gas assumption, and numerical results are validated against previously published data.

The review synthesizes findings on the thermal behaviour and heat transfer performance of different fin geometries under a wide range of operating conditions. Key parameters such as Rayleigh number (10^3–10^6), fin spacing, surface emissivity, aspect ratio, fin orientation, and geometric modifications are systematically examined to elucidate their influence on coupled convective and radiative heat transfer mechanisms. Reported temperature distributions, flow structures, and heat transfer interactions are analysed to identify performance trends and governing transport phenomena. In addition, the review highlights the development of empirical and semi-empirical correlations linking the Nusselt number with Rayleigh number and geometric parameters for selected fin configurations. Overall, this work provides a critical and structured overview of recent numerical advances in convection–radiation heat transfer from complex fin geometries, offering valuable insights for the design and optimization of extended surfaces in heat exchangers and thermal management systems.

Keywords:- Natural Convection, Surface Radiation, Fin Geometry, Heat Transfer, Computational Fluid Dynamics, Three-Dimensional Analysis.

1.Introduction

The study of heat transfer phenomena surrounding finned configurations represents a fundamental area of study in thermal engineering, which is critical for optimizing the efficiency and heat exchangers, cooling systems, and various thermal devices. Standard fin shapes such as straight or rectangular fins have been thoroughly studied. However, there is increasing interest in evaluating the thermal behaviour of intricate fin shapes such as annular, star, square, and triangular fins. These nonconventional geometries pose distinct challenges and possibilities because of their unique flow patterns and surface attributes, making them a fascinating subject for exploration. The motivation behind this investigation stems from the necessity to comprehend the interconnected impacts of natural convection and surface radiation on the heat transfer surrounding non-conventional fin configurations. Convective flow driven by temperature variation significantly influences the movement of the fluid and heat transfer in the vicinity of the fin surfaces. Surface radiation, which is dependent on the surface temperature and emissivity, introduces an additional layer of intricacy to the heat transfer, particularly in three-dimensional (3-D) scenarios. The interplay between natural convection and surface radiation becomes notably significant in complex fin geometries, where phenomena such as flow separation, recirculation regions, and variations in surface orientation markedly affect the heat transfer rates. Delving into these phenomena is imperative for advancing our understanding of thermal regulation in practical contexts, where unconventional fin shapes are utilized to augment heat dissipation. The specific aims of this study are as follows:

- Collective impacts of natural convection and surface radiation around annular, star, square, and triangular fin geometries as shown in figure 1.
- Exploring the influence of geometric factors (e.g., fin shape, dimensions, and spacing) and thermal boundary conditions on heat transfer efficiency as shown in figure 2.

Computational fluid dynamics, (CFD), is a specialized branch of engineering that analyzes and resolves fluid flow-related issues using numerical techniques and algorithms. In this sense, fluids can refer to both liquids and gasses. In several industries, including aerospace, automotive, energy, environmental engineering, and more, CFD has become a vital tool.

Without the need for physical prototypes, the main goal of CFD is to simulate the behavior of fluids in many settings, giving scientists and engineers new perspectives on fluid dynamics, heat transfer, and related phenomena. Complex flow patterns, turbulence, heat exchange, and other fluid-related phenomena that may be expensive or challenging to investigate experimentally can all be studied with this computer method.

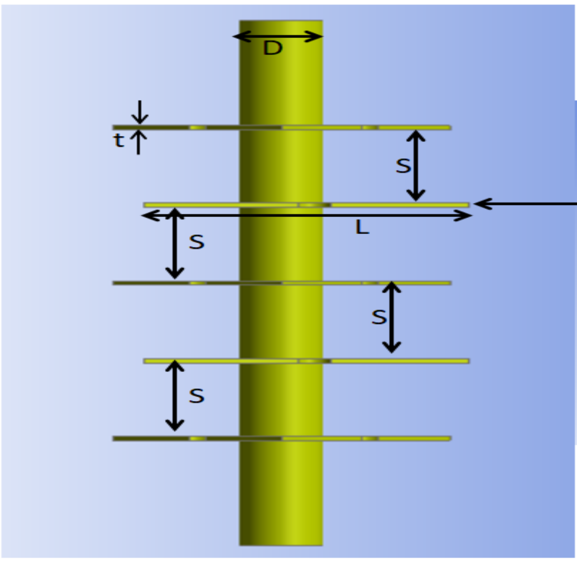


Figure 1: Different Fin Geometries

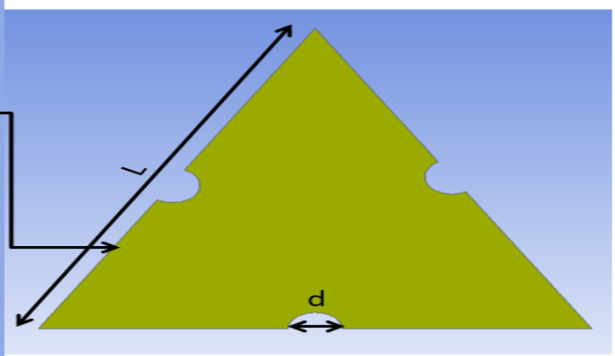


Figure 2: Oriented Notched Triangular Fin

Passive thermal management using finned surfaces is a cornerstone of thermal engineering, enabling reliable heat dissipation in devices and systems where forced convection is impractical, undesirable, or energy-intensive. The present thesis examines the coupled effects of buoyancy driven natural convection and surface radiation around unconventional fin geometries annular, star, square, and triangular-with the aim of clarifying how geometry and radiative properties jointly determine heat removal under realistic three-dimensional (3-D) configurations

While straight or rectangular fins have been thoroughly characterized, nonconventional shapes introduce distinctive flow topologies, edge and tip effects, mutual shading, and view factor interactions that can modify both convective and radiative transport. These complexities, exacerbated by 3-D orientation and array spacing, motivate the development of a unified computational framework that resolves momentum and energy transport while accounting for radiative exchange across multiple surfaces.

The research is motivated by the need to quantify the collective impacts of convection and radiation in complex fin arrays and to translate these insights into actionable design guidance. Specifically, this work interrogates how fin shape, dimensions (height, thickness, length), pitch/spacing, orientation (aligned vs. alternately oriented at 45°), and surface emissivity influence temperature fields, plume dynamics, and overall heat-transfer rates. A high-fidelity CFD approach (pressure-based solver, absolute velocity formulation) is adopted, with rigorous grid refinement in near-wall regions and strict convergence criteria to ensure physically consistent solutions across cases.

From an applications perspective, unconventional fins are compelling for compact heat sinks, cylindrical housing, and constrained enclosures. Annular fins align naturally with axisymmetric bases, star fins increase perimeter-to-area ratio via multiple lobes, square fins exploit sharp corners to thin boundary layers, triangular fins leverage pronounced tip effects to intensify local transport. Yet, systematic 3-D comparisons that include radiation are sparse, making geometry-dependent guidelines difficult to generalize withoutcomprehensive numerical interrogation

1.1 Scope and Contributions

This thesis advances a consistent, validated numerical framework for conjugating heat transfer in finned assemblies under natural convection with surface radiation. The computational domain is extended sufficiently beyond the fins to avoid boundary interference; isothermal fin surfaces and a pressure outlet ambient condition are prescribed to emulate canonical passive cooling scenarios. The following contributions are emphasized:

(i) Geometry-comparative analysis across annular, star, square, and triangular fins under matched boundary conditions, enabling like-for-like performance assessment.

(ii) Parametric sweeps in fin spacing (S), fin length (L), thickness (t), orientation, and emissivity (2), revealing sensitivity of Nusselt number (Nu), total heat-transfer rate, and temperature nonuniformity to design variables.

(iii) Examination of radiative participation in total heat transfer as a function of a and operating temperature, including cases where radiative losses dominate convective contributions.

(iv) Development of compact power-law correlations for Nu as functions of aspect ratio (L/S) and Rayleigh number (Ra), facilitating rapid performance estimation and preliminary design.

1.2 Physical Mechanisms: Buoyancy, Boundary Layers, and Radiation

Natural convection arises from density variations due to temperature differences, generating buoyant plumes that entrain ambient fluid around heated fins. The structure and strength of plumes depend on Ra, surface orientation, geometric sharpness, and array spacing. Corners and tips introduce local accelerations and separation, while gaps can host recirculation pockets that either enhance mixing or inhibit exchange depending on spacing and alignment.

Surface radiation, governed by emissivity and geometric visibility, contributes a fourth-power temperature dependence to heat exchange. In fin arrays, mutual shading and angular orientation modulate view factors, creating nonuniform radiative fluxes that feed back into convective transport by altering surface temperatures. The coupled convection-radiation field is therefore highly sensitive to geometry, making integrated modeling essential for predictive design.

1.3 Importance of Fin Geometry

The geometry of fins plays a decisive role in determining thermal performance. While conventional rectangular fins provide uniform conduction paths, they may suppress fluid motion in closely spaced arrays. In contrast, non-uniform geometries such as triangular, star, or notched fins can promote enhanced mixing, reduce thermal resistance, and improve convective heat transfer.

Different fin geometries exhibit distinct characteristics:

Annular fins provide axisymmetric heat transfer but often suffer from flow stagnation near inner regions.

Star fins introduce radial protrusions that enhance surface area and induce localized flow acceleration.

Square fins generate corner-induced vortices that influence boundary layer development.

Triangular fins, especially when oriented or notched, promote asymmetric flow separation and improved thermal mixing.

The present work systematically investigates these geometries under identical operating conditions to isolate the effect of shape on natural convection heat transfer.

1.4 Research Objective

The enhancement of heat transfer using various geometries of fin. Below is the outcome of the research:

- Analysis of Finned Surfaces: Study the geometry, structure, and characteristics of Finned Surfaces and their impact on natural convection.
- Heat Transfer Analysis and Weight Reduction: Analyze the heat transfer mechanisms and rates involved in the natural convection process, focusing on temperature gradients and flow patterns.
- Effect of Fin Parameters: Investigate how varying parameters such as fin height, thickness, spacing, and arrangement influence natural convection and subsequent heat transfer.
- Simulation and Modeling: Utilize computational tools to simulate and model the natural convection phenomenon around finned surfaces with air as the fluid material.

1.5 Research Gap

- According to the aforementioned literature survey, the majority of research projects focus on fluid flow analysis near finned surfaces
- There is no 3D geometry with different fin shapes.
- Surface radiation not included.
- Fin was long
- There is no 3D simulation available.
- That's why I made the decision to embark on a simulation based Natural convection study in 3D geometry.

2.Literature Review

Adam et al. (2020) In this research paper focused on fin-and-tube heat exchangers, investigating heat transfer enhancement and pressure drop reduction. His work showed that increased fluid velocity consistently improved heat transfer and pressure drop, regardless of tube shape or configuration.

Sebastian et al. (2020) In this research paper conducted a comprehensive investigation into the heat transfer characteristics of finned heat exchanger configurations. His research included innovative designs featuring integrated pin fins, designed to enhance both conduction and air-side heat transfer.

Anjali et al. (2021) In this research paper investigates natural convection heat transfer in vertical plate fin arrays using computational studies, comparing different fin shapes and configurations. Seven combinations of fin arrays are analysed, including plain rectangular, notched, inverted notched, and hybrid notched fins. The highest average heat transfer coefficient is found for the inverted hybrid square-semi-circular notched fin array**.**

Krishnayatra et al. (2022) In this research paper conducted in this study utilizes Ansys Fluent software for a comprehensive numerical analysis aimed at examining the influence of fin length, fin thickness, number of fins, and fin material on the heat transfer rate and effectiveness of the system. The results underscore the critical significance of optimizing these parameters to achieve peak efficiency in heat transfer processes.

Dogmas et al. (2022) In this research paper Conducted an experimental study on functionally graded (FG) and aluminium annular fins' thermal performance under natural convection. They used numerical analyses to determine the ideal FG fin volume distribution and observed that FG fins outperformed aluminium fins significantly. The Nusselt number for FG fins was 40% higher, and FG fins enhanced net heat transfer by 59% on average.

Attouchi et al. (2022) In this research paper focused on natural convection heat transfer in square cavities with finned surfaces and periodic wall temperature. The study also highlighted the effectiveness of three fins on the hot sidewall and consistent Nusselt numbers on the cold sidewall.

Wang et al. (2022) In this research paper conducted a numerical study on transient combined natural convection and surface radiation in a cylindrical cavity, highlighting the significant impact of surface emissivity on radiative heat transfer.

Amine et al. (2022) In this research paper focuses on studying the interaction of natural convection with thermal radiation in a cylindrical enclosure filled with air, emphasizing the impact of surface radiation on temperature distribution and flow patterns at higher Rayleigh numbers. The authors introduce dimensionless parameters to characterize the system and provide boundary conditions for the numerical simulations, enabling a comprehensive analysis of the heat transfer processes in the enclosure. The study also highlights the importance of accurately predicting the total average Nusselt number to ensure a comfortable thermal environment in buildings, underscoring the practical implications of the research findings.

Subhasisa et al. (2022) In this research paper conducted a comprehensive study on heat dissipation from heat-generating electronic devices using natural convection. The research focused on the thermal performance of radial heat sinks with longitudinal wavy fins and included three-dimensional numerical computations.

Attouchi et al. (2023) In this research paper conducted a numerical investigation of natural convection in a rectangular cavity equipped with a finned surface, where the bottom wall temperature varies linearly. The study focused on laminar, steady-state flow conditions to analysed the coupled thermal and hydrodynamic behaviour of the internal fluid. Vertical walls were considered thermally insulated, while the top wall was maintained at a constant cold temperature and the bottom wall at a linearly varying hot temperature. The governing equations of fluid flow and heat transfer were solved using a finite volume method implemented in a Fortran 90 code. Simulations were carried out for Rayleigh numbers ranging from to with a fixed Prandtl number of 0.71, representing air. The results demonstrated significant effects of Rayleigh number and fin-induced flow modification on temperature distribution, streamlines, velocity fields, and mean Nusselt number, highlighting the role of finned surfaces and non-uniform heating in enhancing natural convection heat transfer within enclosed cavities.

Kim and Kim et al. (2024) In this research paper conducted the first systematic experimental study on curved finned horizontal cylinders under natural convection. The effects of cylinder temperature, fin number, and fin height on heat transfer performance were experimentally investigated. A new Nusselt number correlation was proposed for Rayleigh numbers between 20 and 50,000, predicting the convective heat transfer coefficient within ±10% error. The proposed correlation showed significantly better accuracy than existing correlations. The study also identified optimal fin number and fin thickness, demonstrating that curved finned cylinders provide approximately 20% higher thermal performance compared to conventional finned cylinders. Complementing experimental studies,

Le et al. (2024) In this research paper numerically investigated natural convection in a differentially heated cubical cavity with solid fins. Using a finite-difference method with velocity–vorticity formulation, they analysed the effects of Rayleigh number, fin length, fin location, and fin number. The study revealed that properly placed solid fins enhance heat transfer, while excessive fin length at high Rayleigh numbers can reduce the average Nusselt number. Optimal fin configuration was shown to be crucial for maximizing thermal performance.

Sultan et al. (2024) In this research paper conducted a 3D numerical study on a horizontal heat sink with rectangular fin arrays under natural convection. Using the finite volume method, they demonstrated that increasing heat flux intensifies natural convection, leading to substantial increases in the average heat transfer coefficient and Nusselt number. The numerical results showed good agreement with experimental data, confirming the reliability of the model.

Matuszczak et al. (2024) In this research paper experimentally studied finned tube heat exchangers operating under natural convection conditions. The authors demonstrated that a novel wavy-fin geometry significantly improved heat rejection compared to conventional designs, with heat flux density enhancements ranging from 12% to 24% as fin spacing increased. The study further highlighted the strong influence of fin spacing, exchanger orientation, and casing height on thermal efficiency, showing that wider fin spacing and higher casing heights markedly enhance natural convection heat transfer.

Bawazeer (2025) In this research paper convection a finite element-based numerical study on laminar natural convection in a square cavity with a horizontal fin attached to the heated wall. The study highlighted the critical role of fin position, geometry, and thermal conductivity in controlling flow structure and heat transfer, particularly at higher Rayleigh and Prandtl numbers. Optimal fin placement at mid-height enhanced thermal mixing and symmetry, while thicker fins improved conductive heat transfer. A normalized Nusselt ratio was introduced to assess fin effectiveness beyond surface area effects, offering practical insights for passive thermal management in enclosed system.

Zhang et al. (2025) In this research paper the role of fins in phase change material (PCM) melting, highlighting that fins do not always enhance melting performance due to their potential to suppress natural convection. To address this limitation, the authors proposed the use of non-contact fins and numerically examined their influence on convection-driven melting. The results showed that melting time could either decrease by up to 10.1% or increase by 11%, depending on the fin mounting configuration. The study revealed that narrow fin spacing weakens local convection and increases momentum loss as liquid PCM interacts with fin surfaces, thereby hindering heat transfer. Additionally, the authors identified the velocity within the mushy zone and the normal velocity at the solid–liquid interface as more reliable indicators for evaluating fin effectiveness during the melting process.

Ali et al. (2025) In this research paper numerically investigated natural convection heat transfer from a vertical cylinder equipped with perforated annular fins. Using a conjugate heat transfer model in the laminar regime, the study analysed the effects of Rayleigh number and fin pitch-to-diameter ratio on thermal performance. The results showed that perforated fins significantly enhance heat transfer compared to solid fins, with Nusselt number improvements of up to 49% at higher Rayleigh numbers and smaller fin spacing. The enhanced performance was attributed to improved fluid circulation through the perforations, which strengthened buoyancy-driven flow.

Mora et al. (2025) In this research paper performed CFD simulations to analyse natural convection heat dissipation from a finned MMRTG operating under low-density CO_2 Martian atmospheric conditions. Their results showed laminar buoyancy-driven plume formation, with fin-induced thermal plumes merging at higher elevations. The evaluated dimensionless numbers confirmed laminar natural convection, providing valuable insights for passive thermal management and finned heat-dissipating systems in space applications.

Dogmaz et al. (2025) In this research paper examined the thermal performance of functionally graded annular fins mounted on a horizontal cylinder under natural convection. The results showed that functionally graded fins substantially outperform conventional aluminium fins, achieving up to 59% higher heat transfer rates and a 40% increase in convective heat transfer coefficient, highlighting the importance of material gradation and fin spacing in natural convection enhancement.

Peng Ding et al. (2025) In this research paper numerically investigated a novel twisted fin configuration to enhance natural convection–driven melting of phase change material (PCM) in a shell-and-tube latent heat storage system. Using the enthalpy–porosity method, the study examined the effects of fin twist angle and system orientation (vertical and horizontal) on thermal performance. Results showed that twisted fins significantly mitigate natural convection suppression compared to conventional annular fins, leading to faster PCM melting. A twist angle of 35° provided the best performance, increasing the average heat storage rate by 10.7% in vertical and 14.8% in horizontal orientations. Enhanced convection patterns were clearly demonstrated through streamline visualization, confirming the effectiveness of the proposed fin design.

3.Research Methodology

ANSYS Design Modeler is used to create computational models. Boundary conditions are prescribed on interfaces and the physical boundary of the computational domain. The isothermal condition at the fin surface was used. A thorough grid sensitivity analysis was done. The strict convergence criterion was followed. The pressure-based solver with absolute velocity formulation is used, which includes time steps for a stable solution. The simulation results such as streamlines, temperature distributions, and velocity vectors are analysed in detail to find the heat transfer characteristics among the fins. For the study, a vertical cylinder with radius (r) with uniform thickness (t) and constant fin spacing is taken into consideration. While several critical dimensional values are reported in the study, the majority of the data are presented in a non-dimensional style. An isometric image of a vertical cylinder equipped with a triangular fin, is displayed in in Fig (1). A steady temperature (T) is maintained on the cylinder and fin surfaces. Calculating the natural convection heat transfer for a vertical cylinder with fins spacing and examining the fluid flow pattern surrounding the cylinder and the fins are the main goals. In this work, numerical simulations of the whole N-S problem in conjunction with the energy equation for a vertical cylinder with linked cavities of various shapes were carried out using the algebraic multi-grid solver of Ansys fluent. It is assumed that the fluid is Boussinesq and that the flow is laminar and steady state.

3.1 Governing Equation

The governing equation for natural convection heat transfer in polar coordinates describes the conservation of mass, momentum, and energy for a fluid undergoing natural convection.

3.1.1 Conservation of Mass

The continuity equation in polar coordinates:

$$\frac{\partial(\rho)}{\partial t}+\frac{1}{r}\frac{\partial(\rho v_r r)}{\partial r}+\frac{1}{r}\frac{\partial(\rho v_\theta)}{\partial \theta}+\frac{\partial(\rho v_z)}{\partial z}=0 \qquad (1)$$

3.1.2 Conservation of Momentum Equation

The momentum equations in polar coordinates for the radial (v_r), azimuthal (v_θ), and axial (v_z) directions are given by

$$\mathbf{r-component:}\quad \rho\left(\frac{Dv_r}{Dt}-\frac{{v_\theta}^2}{r}\right)=-\frac{\partial p}{\partial r}+\mu\left(\nabla^2 v_r+\frac{v_r}{r^2}-\frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}\right) \qquad (2)$$

$$\mathbf{\theta-component:}\quad \rho\left(\frac{Dv_\theta}{Dt}+\frac{v_r v_\theta}{r}\right)=-\frac{1}{r}\frac{\partial p}{\partial \theta}+\mu\left(\nabla^2 v_\theta+\frac{2\,\partial v_r}{r^2\partial\theta}-\frac{v_\theta}{r}\right) \qquad (3$$

$$\mathbf{z-component:}\quad \rho\left(\frac{Dv_z}{Dt}\right)=-\frac{\partial p}{\partial z}+\mu(\nabla^2 v_z)+\rho g_z \qquad (4)$$

Where

$$\frac{D}{Dt}=\frac{\partial}{\partial t}+v_r\frac{\partial}{\partial r}+\frac{v_\theta}{r}\frac{\partial}{\partial \theta}+v_z\frac{\partial}{\partial z}$$

$$\nabla^2=\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}+\frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}+\frac{\partial^2}{\partial z^2}$$

3.1.3 Conservation of Energy:

The energy equation for natural convection in polar coordinates is given by:

$$\rho C_p\left(v_r\frac{\partial T}{\partial r}+\frac{v_\theta}{r}\frac{\partial T}{\partial \theta}+v_z\frac{\partial T}{\partial z}\right)=k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}\right] \qquad (5)$$

3.2 Formulation for Surface Radiation

For various fin geometries, the radiation heat transfer equation is dependent on some of the variables, including form, orientation, surface characteristics, and ambient conditions. I am going to provide a general expression for heat transfer from radiation from a fin surface.

$$Q_{rad} = \varepsilon\, A_f\, Fr\, \sigma\, (T - Ta) \qquad (6)$$

$$Ra = Gr \times Pr \qquad (7)$$

$$Gr = \frac{g\beta(T - Ta)S^3}{\vartheta^2} \qquad (8)$$

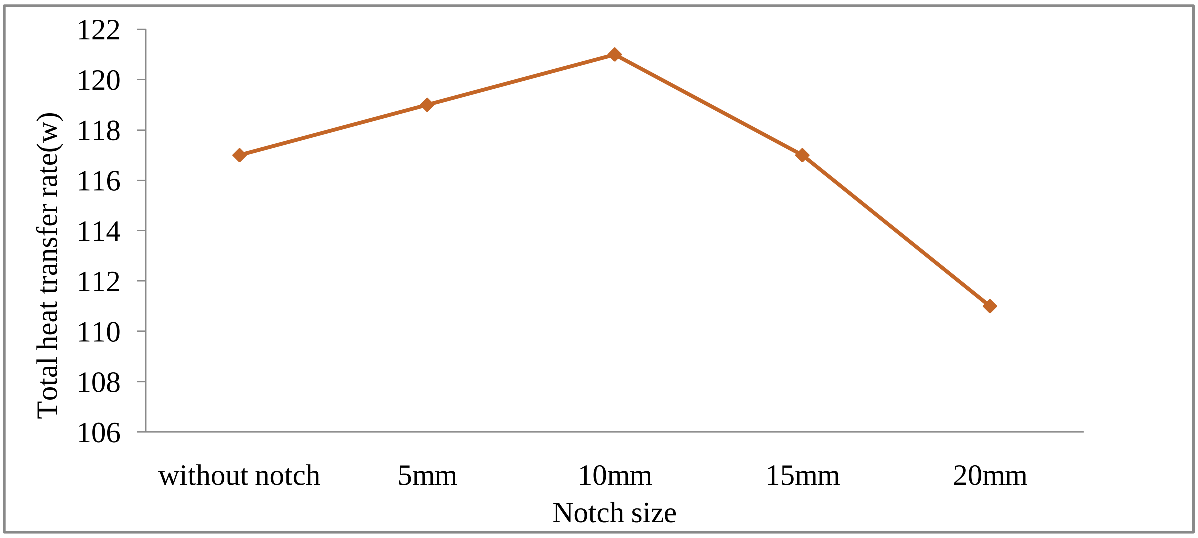
Where:

Q_{rad} is the rate of heat transfer through radiation (W),

σ is the Stefan-Boltzmann constant ($5.67\times10{-}8 W/m^2K^4$),

4.Results and Discussion

An analysis was conducted on different fin shapes (annular, star, square, and triangle) and alignments (aligned and 45-degree oriented). It was found that the triangular fins, whether

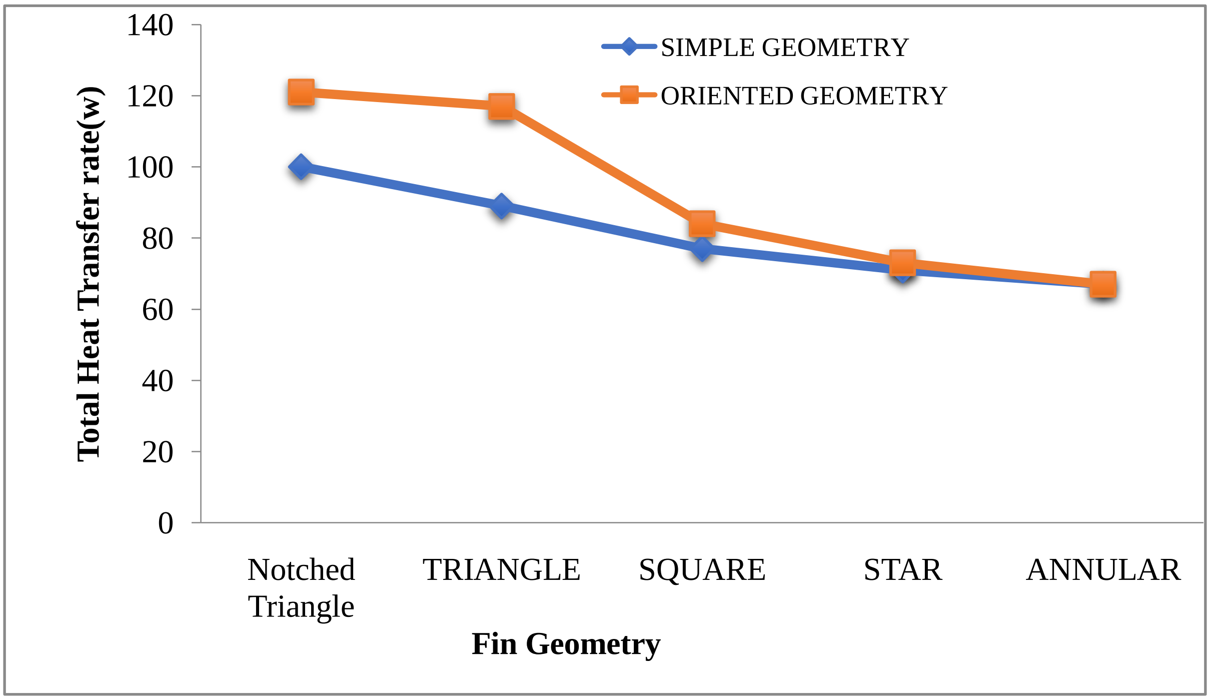


aligned or oriented, exhibited the highest heat transfer rates. Conversely, the annular fins demonstrated the lowest heat transfer rates, with the star fins showing a 9.8% improvement, the square fins showing a 26.4% improvement, and the triangular fins demonstrating a substantial 76% improvement compared to the annular fins, as depicted in figure [3]. Additionally, when the alternate fins were oriented at 45 degrees and notched at the edges of the triangular fin geometry, a 31.5% increase in the heat transfer rate was observed for the oriented fin and a 21% increase for the notched fin in the oriented arrangement. Figure [4] demonstrates the total heat transfer rate across various notch dimensions within the triangular fin configuration. The addition of notches contributes to the enhancement of the heat transfer rate, with a 19% rise for a 5 mm notch and a 21% rise for a 10 mm notch. Conversely, with notch dimensions of 15 mm and 20 mm, there is a decline in the heat transfer rate. Figure [5-6] illustrates the comparison of velocity vector and temperature contour of various fin geometries. The temperature contour indicates that the coldest zone is situated on the lower surface of the fin, in contact with fresh and cool airflow. The annular fin surrounds a central core. The temperature exhibits a radial gradient, with higher temperatures closer to the core and lower temperatures towards the outer edge of the fin and shows asymmetrical temperature contour with decrease in temperature from the inner to the outer radius.A star fin, on the other hand, consists of a central core with multiple outward extending arms, resembling the shape of a star.

Figure 3: Comparison of total heat transfer rate from different fin geometries with and without orientation.

Figure 4: Comparison of total heat transfer rate at different notch size in triangular fin geometry

The distribution of temperature is anticipated to display a complex pattern, typically with high temperatures near the core and decreasing temperatures towards the ends of the arms. In contrast, a square fin features a cross-section that is in square in shape. The temperature contours illustrate a gradient from the base of the fin, where it connects to the main body, to the tip. While the contours may appear more consistent along the length compared to other geometries, variations in temperature distribution could be observed at the edges and corners of the square. However, a triangular fin exhibit temperature contours showing a gradient from the base where it is attached to the main body. The contours display a sharper incline near the



base and gradually level off towards the tip of the triangle. Circular patterns around the fin surfaces are maintained by the velocity vectors in all cases. Notably, the flow path in the notched triangular fin retains a more circular pattern compared to the annular fin.

The temperature contours were defined in the simulations provides a visual expression of the thermal fields at various places, revealing the evolution of temperature distribution over the fin surface. The mixing effects were distinguishable across different fin geometries, and the mixing effect was stronger in notched triangular fin geometry at 10mm notched size leading to a cooler thermal field. The temperature contours depict flow separation, and the temperature contour of fins geometries differed as shown. The fin geometry model had more significant temperature differences at the bottom of the fin surface and less at the top of the fin surfaces. The velocity vector is used in three-dimensional studies to analyse finned configuration with various fin geometries, such as annual, star, square, and triangular. The finite volume method uses the velocity vector with flow characteristics among the various fin heat exchangers. The velocity vector in the numerical simulations helps to understand the flow behaviour and flow pattern in the heat exchanger system for different fin geometries at different locations as shown in fig [5,6]. We found that the velocity of the fluid is minimum in triangular fin geometry and maximum in annular fin geometry.

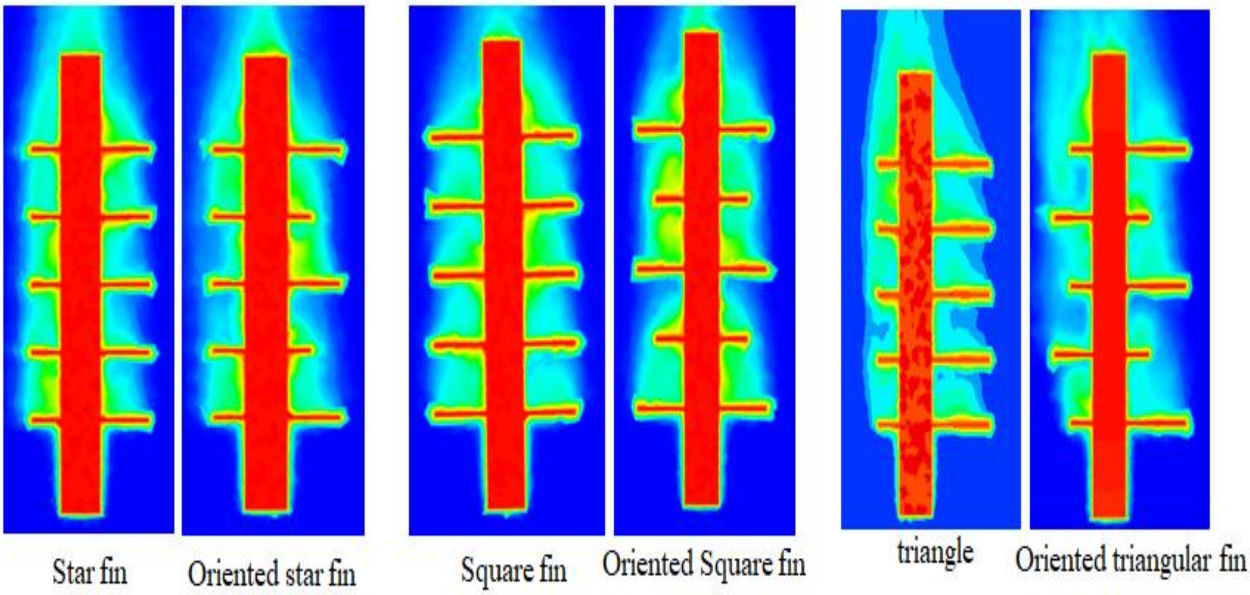
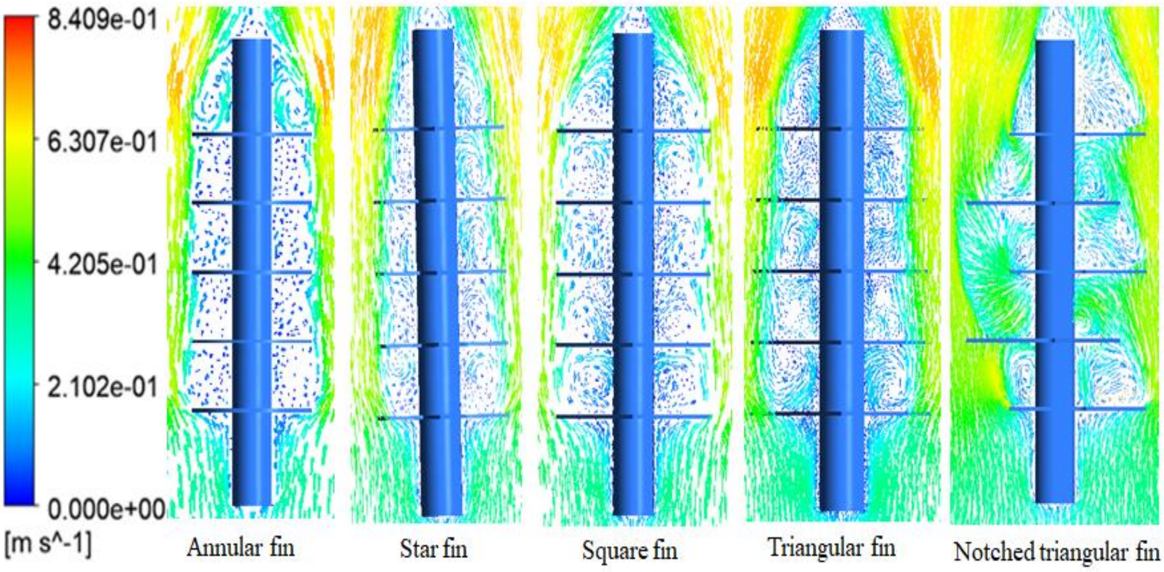


Figure 5: Comparison of temperature contour with simple and 45^0 oriented fin geometries



4.1 Notched triangular fin geometry

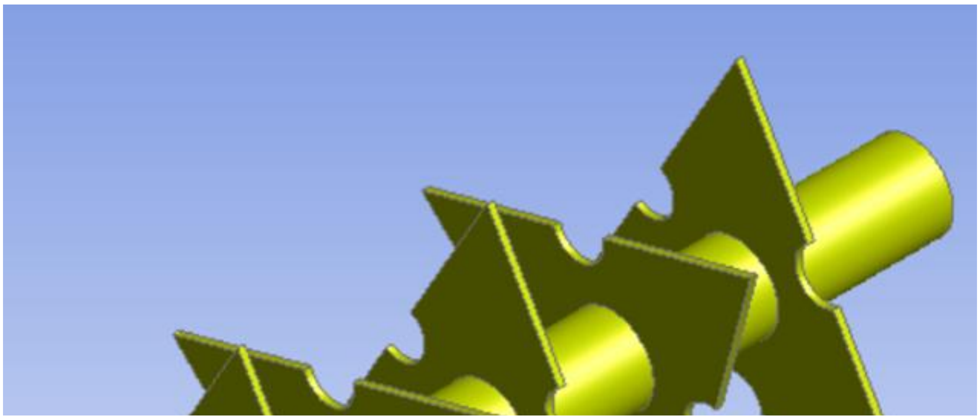


Figure 6: Comparison of velocity vector of different fin geometries.

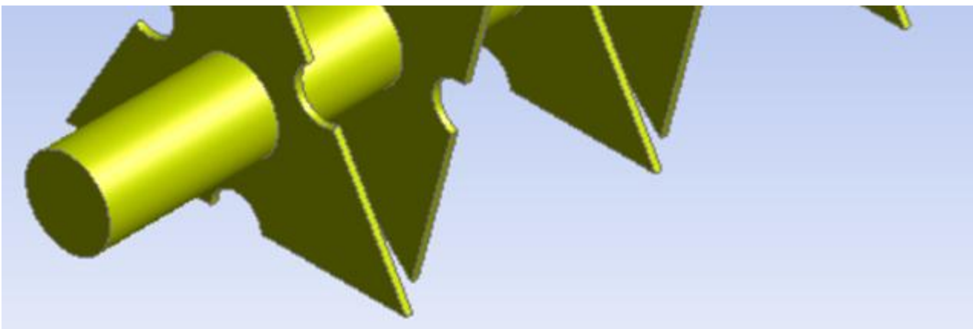


Figure 7: Notched triangular fin geometry.

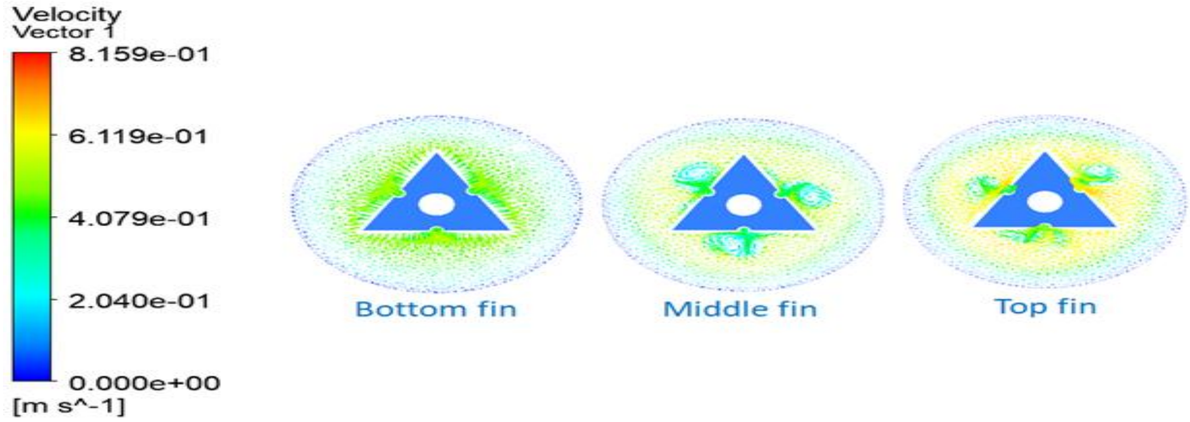


Figure 8: Velocity vector at three different locations in notched triangular fin geometries

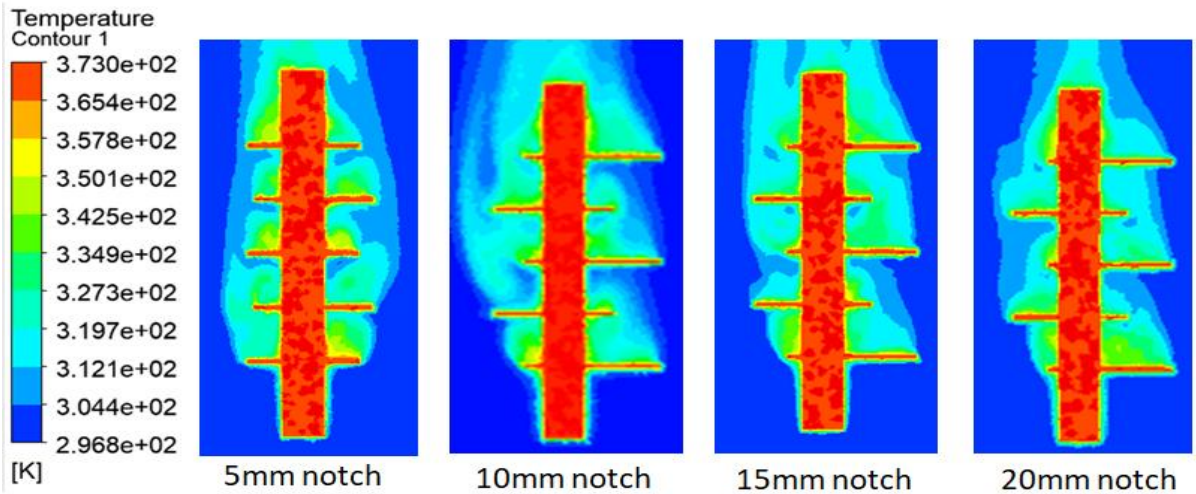


Figure 9: Comparison of temperature contour at different notch size with 45^{o} oriented triangular fin geometry

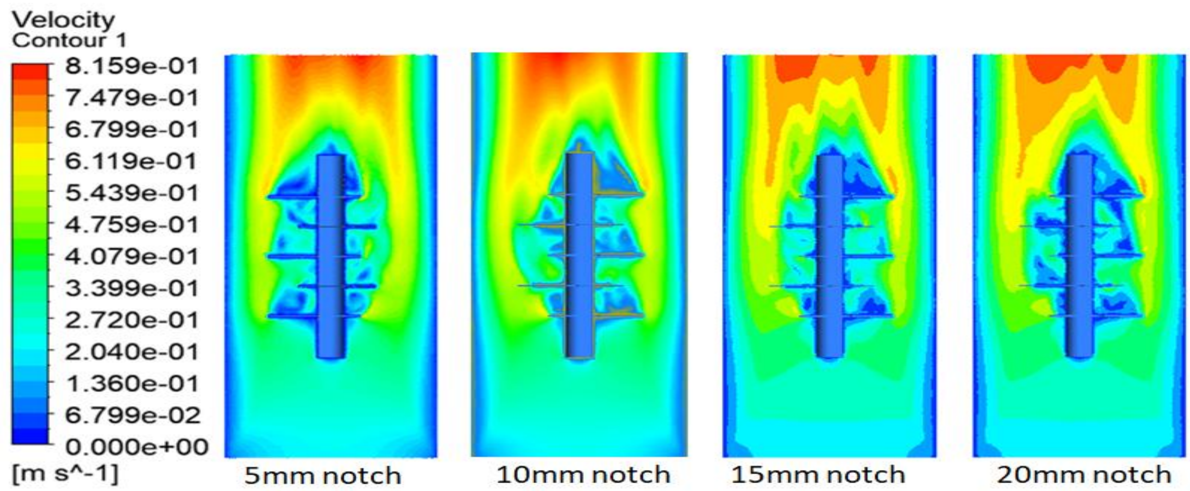


Figure 10: Comparison of velocity contour at different notch size of 45o oriented triangular fin.

We observe the highest heat transfer rate at the 10mm notch size as shown in fig [7]. Because the notch size balances geometric integrity with surface area for heat exchange, it is ideal for accelerating heat dissipation. Temperature contours would show that the fin surface has low-temperature gradients and effectively dissipates heat as shown in fig [8]. The heat transfer rate starts to decline when the notch size goes over the ideal 10mm. The bigger notches make it harder for heat to pass through the fin, which increases thermal resistance and decreases heat-dissipation efficiency. Because of the decreased capacity to dissipate heat, temperature contours are likely to exhibit larger temperature gradients and hotspots accumulating around the fin surfaces. Velocity vectors and velocity contour would indicate minimal flow separation and fairly uniform fluid velocities. Convective heat transfer is encouraged by fluid flow around the fin that is to be well-distributed and efficient at the ideal 10 mm notch size. Consistent flow patterns with good fluid penetration through the notches would be displayed by velocity vectors as shown in fig [9]. Larger notches have the potential to increase flow resistance and decrease convective heat transfer by causing turbulent fluid flow. The flow patterns surrounding the notches get disturbed, with more flow separation zones seen in the velocity vectors as shown in fig [11].

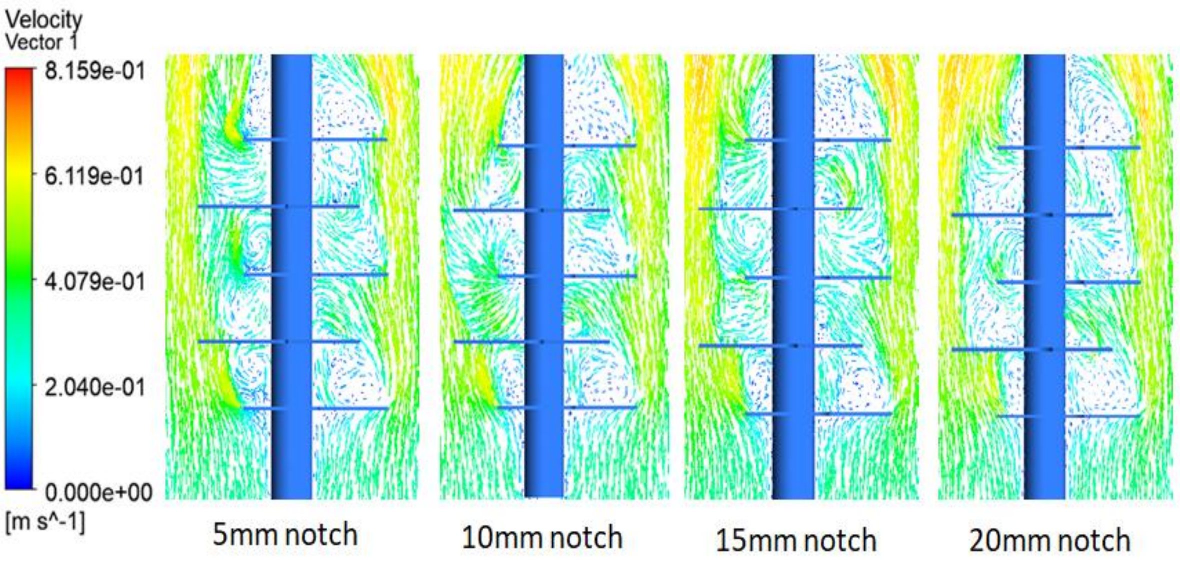


Figure 11: Comparison of velocity vector at different notch size of 45^{o} oriented triangular fin

4.2 Notched Triangular Fin Geometry with Surface Radiation

In this case, radiation heat transfer makes a significant contribution to the overall heat transfer rate. The predominant process, surface radiation, has a major impact on the fin surface's overall heat dissipation. Interestingly, when surface radiation is the dominating mode, the overall heat transfer rate is about twice as high as when natural convection is the main mode. This highlights how crucial it is to take radiation effects into account, particularly in situations when traditional heat transmission methods are not as effective. Velocity vectors depict the direction and magnitude of fluid flow around the fin geometry as shown in fig [12]. The temperature contours will be greatly impacted by surface radiation as well as convective heat transfer from the surrounding fluid when surface radiation is predominant as shown in fig [12]. Radiation is responsible for a significant amount of the heat dissipation from the fin because heat transfer rate is almost twice as much as that of natural convection. This is particularly noticeable at higher temperatures or when the surface has a reasonably high emissivity value. The fin's overall heat transfer rate is impacted by this reduction in radiation, especially when compared with natural convection as shown in fig [13].

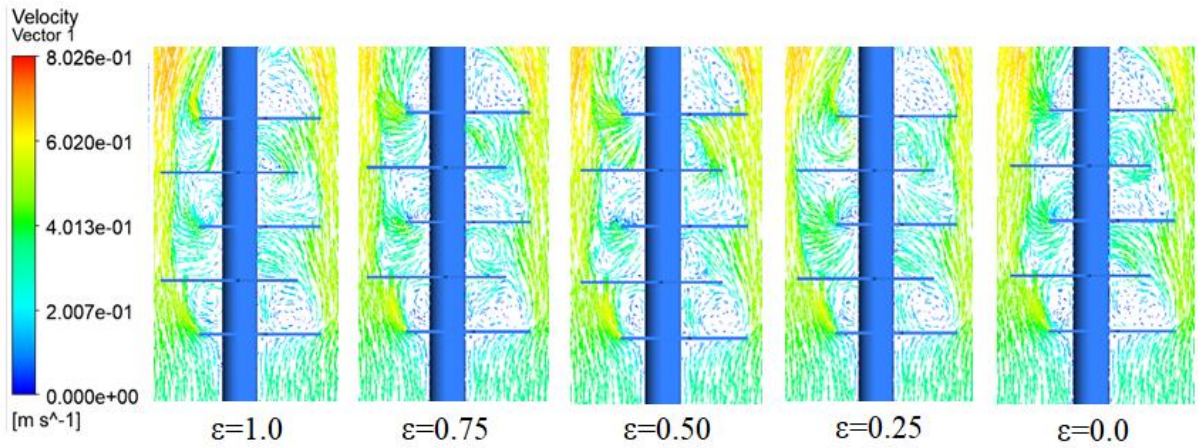


Figure 12: Comparison of velocity vector at different value of ε of 45o oriented 10mm notched triangular fin.

Figure 16: Comparison of temperature contour at different value of ε of 45o oriented 10mm notched triangular fin.

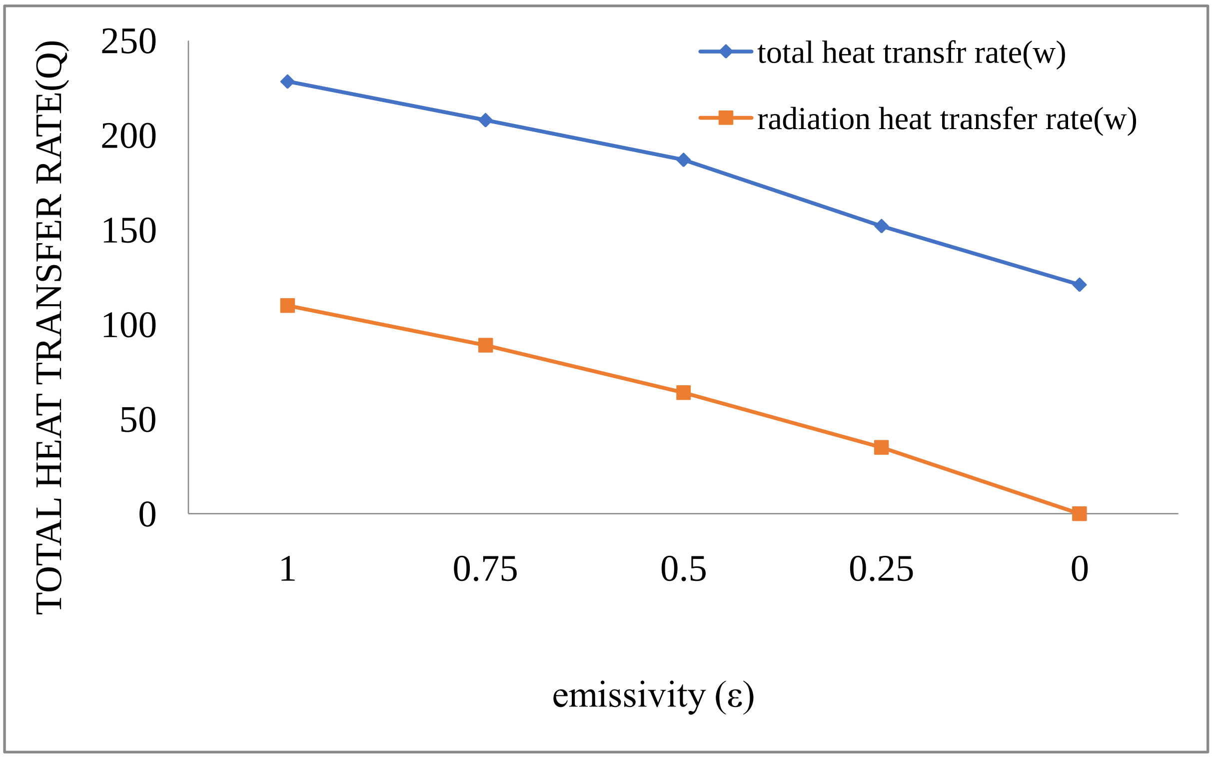


Figure 13: Contribution of radiation heat transfer rate in total heat transfer rate.

The emission of heat radiation from the surface decreases with decreasing emissivity. Heat transmission from surface radiation is therefore decreased with decreasing emissivity. Moreover, the variation of Nu with emissivity at different cavities is shown in fig [14].The radiative characteristics of the cavity surfaces, particularly their emissivity, have an impact on the Nusselt number in every surface radiation case. This has an impact on the rate of net heat transfer between the cavity and its surroundings. Since radiative heat transfer and emissivity have an exponential relationship (the Stefan-Boltzmann law), Nu's dependence on ε is also exponential. The Nusselt number for a particular cavity and its boundary conditions are affected by increasing emissivity since it increases radiative heat transfer rates. Since radiative heat transfer rate is a major component of the overall heat transfer rate, the variation of the Nusselt number with emissivity in various cavities is closely related to this effect. High radiative heat transfer has been seen in Cavity C_1. Radiative heat transfer rates are intermediate in cavities C_2 and C_3. Compared to the other cavities, C_4 has less radiative heat transfer rate. Nusselt number and emissivity most likely have an exponential relation, as a result, the Nusselt number fall exponentially as emissivity drops (from C1 to C4).

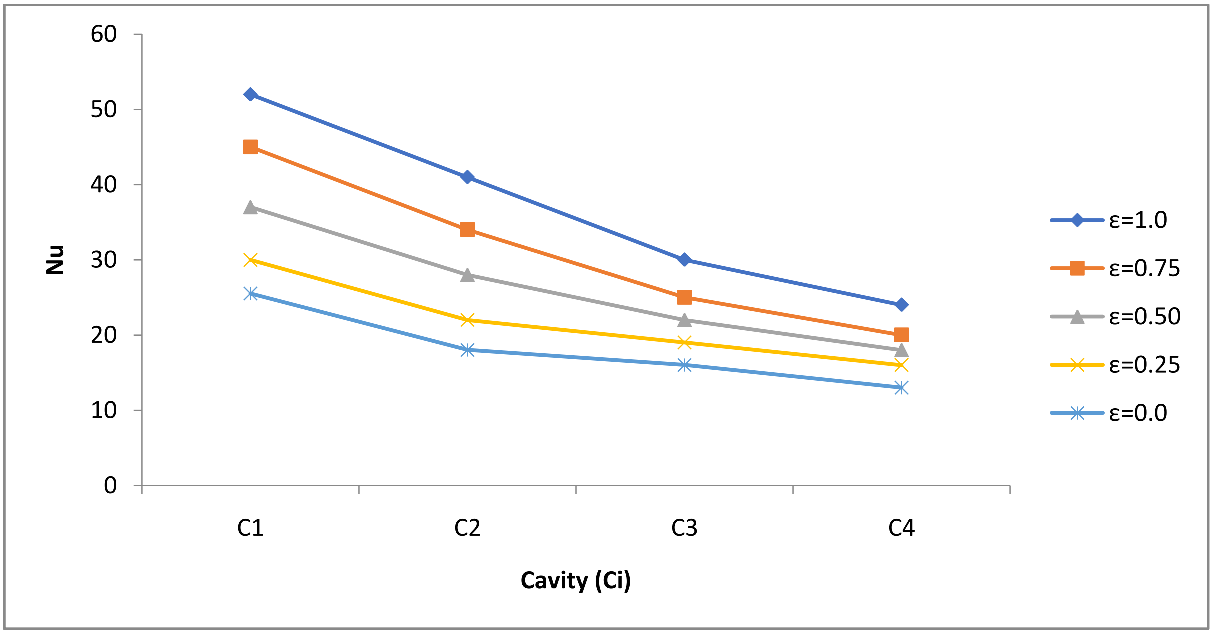


Figure 14: Variation of Nusselt (Nu) number with emissivity at different cavities.

5.Conclusions and Future Scope

5.1 Conclusions

Numerical analysis was conducted to examine the impact of natural convection heat transfer on various fins geometry for laminar flow. The following are the key conclusion from the study.

Triangular fin geometry has the maximum heat transfer rate as compared to the annular, star, and square fin geometries. The asymmetric flow behaviour in the triangular fin with notch is observed as compared to other fin geometries studied. The fin efficiency was found to be decreased beyond 10mm notch size. It can be seen that the HTR decreased for 15mm and 20 mm notch size by 3.5% and 8.3% respectively. It is also observed that the first half of the portion of the cylindrical surface has 70% heat removal as compared to upper part of the cylinder. The radiation heat transfer significantly impacts the overall heat transfer rate of a fin surface, with surface radiation being the predominant process. This is due to its heat transfer rate being twice as high as natural convection. High radiative heat transfer is observed in Cavity C1, while intermediate rates are observed in Cavities C2 and C3. The analysis of fin spacing in notched triangular fin geometry reveals a drop in fluid velocity and Nu as fin spacing decreases. This results in a limited surface area for heat exchange, leading to hotter fin surfaces and increased temperature gradients. The correlation between Nu and aspect ratio is nonlinear, illustrating a significant dependency of Nu on the aspect ratio.

5.2 Future Scope

Despite significant progress in numerical investigations of coupled natural convection and surface radiation from extended surfaces, several research opportunities remain open for further exploration. Future studies can extend the current body of work by incorporating transient and unsteady analyses, as most existing investigations are limited to steady-state conditions. This would provide deeper insight into the dynamic thermal response of finned systems subjected to variable heat loads and ambient conditions.

The inclusion of temperature-dependent thermo-physical properties, non-grey radiation models, and participating media effects can further improve the realism and accuracy of simulations. Additionally, the influence of turbulent natural convection at higher Rayleigh numbers ($Ra > 10^6$) remains relatively unexplored and warrants systematic investigation.

Future research may also focus on advanced and bio-inspired fin geometries, including fractal, lattice, perforated, and functionally graded fins, to enhance heat transfer performance while minimizing material usage and weight. The combined effects of conjugate heat transfer, contact resistance, and manufacturing constraints such as surface roughness and additively manufactured imperfections should also be addressed.

The application of optimization techniques and machine learning approaches (e.g., ANN, genetic algorithms, and surrogate modeling) offers promising avenues for rapid design optimization and the development of generalized heat transfer correlations. Moreover, limited experimental validation exists for complex three-dimensional convection–radiation interactions; therefore, high-fidelity experimental studies are essential to validate and refine numerical models and correlations.

Finally, extending these numerical frameworks to real-world thermal management applications, such as electronics cooling, battery thermal management, solar thermal collectors, and compact heat exchangers, will enhance the practical relevance and industrial applicability of future studies.

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