Optimizing Heat Transfer Efficiency of Pipe Fin by Shape Parameter Through Analysis of Fin Geometry

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Abstract:- In this research, the heat transfer performance of a fin is analyzed by designing fins with various sections, such as square, triangular, and circular shapes, while maintaining the same cross-sectional area for all three sections. The heat transfer performance of fins with different geometries, but the same area, is compared. Fins with various shapes are designed using the software ANSYS, and the analysis of fin performance is conducted using the same software.

In the realm of heat transfer, fins serve as surfaces that extend from an object to increase the efficiency of heat exchange with the environment by improving convection. The quantity of heat that an object transfer depends on its properties related to conduction, convection, or radiation. Improving heat transfer efficiency can be achieved by increasing the temperature difference between the object and its surroundings, enhancing the convection heat transfer coefficient, or increasing the surface area of the object. Sometimes it is not feasible or economical to modify the first two options. Thus, adding a fin to an object increases the surface area and can sometimes provide an economical solution to heat transfer problems.

Keywords*:* Fins, CFD, shape optimization etc.

1. Introduction

In recent years, the development of mechanical fins has emerged as a promising avenue to address these limitations. These innovative systems integrate principles of biomimicry and advanced engineering to replicate the fluid dynamics of aquatic organisms such as fish and marine mammals. By leveraging mechanisms such as servo motors, pneumatic actuators, or even shape-memory alloys, mechanical fins offer the potential for dynamic control and precise manipulation of underwater propulsion.

These fins come in different types, each designed to address specific needs and optimize performance. Straight fins, for instance, offer simplicity and cost-effectiveness, while plate fins provide a larger surface area for improved heat dissipation or fluid flow. Lanced fins feature slits to increase surface area and induce turbulence, contributing to enhanced heat transfer efficiency. Wavy fins, with their corrugated profile, offer high efficiency by maximizing surface area. Pin fins, characterized by cylindrical protrusions, are ideal for applications requiring high surface density in confined spaces. Lastly, swirl fins utilize a twisted geometry to induce swirling motion, promoting better mixing and heat transfer. By carefully selecting the appropriate fin type based on the application requirements, engineers can ensure optimal performance and efficiency in industrial systems.

2. Literature Survey

Isak Kotcioglu, Gokhan Omeroglu and Sinan Caliskan, (1) have investigated thermal efficiency and pressure drop, finding that higher air Reynolds numbers reduce plate temperatures. Among pin-fin shapes, hexagonal arrays show the highest temperatures at 90°C inlet air. Cylindrical pin-fins have the lowest pressure drop compared to square and hexagonal arrays. Additionally, increasing inlet air temperature boosts the Nusselt number, indicating improved heat transfer. These findings underscore the importance of pin-fin geometry and inlet conditions in enhancing heat exchanger performance.

Antonio Acosta-Iborra a, Antonio Campo, (2) have investigated the analysis of annular fins with uniform thickness, focusing on overcoming the challenge posed by the variable coefficient 1/r the quasi-one-dimensional heat conduction equation. The paper aims to simplify this coefficient using the mean value theorem for integration, specifically targeting its application to 1/r within the annular fin domain. By employing this approach, the study demonstrates the attainment of approximate analytic temperature profiles of high quality, avoiding the complexities associated with exact analytic solutions involving four modified Bessel functions. The findings offer significant benefits to instructors and students in heat transfer courses, facilitating the calculation of temperatures and heat transfer rates for realistic combinations of normalized radii ratios and thermo-geometric fin parameters. Additionally, the approximate temperature solutions derived through the mean value theorem exhibit remarkable accuracy and ease of use, potentially surpassing classical exact analytic profiles based on four modified Bessel functions, while remaining within acceptable levels of inaccuracy relative to typical assumptions in heat transfer analysis.

Pulkit Agarwal, Mayur Shrikhande and P. Srinivasan (3) have investigated CFD models in GAMBIT and FLUENT to study how wind velocity and air temperature affect heat transfer in motorcycle engines. Their findings match experimental results and show how these factors impact heat transfer rates. They also looked at different ambient temperatures to reduce overcooling and improve engine efficiency. CFD simulations revealed non-uniform heat transfer along fin surfaces, which is important for optimizing engine performance. Researchers also identified areas of high heat loss, especially in sub-zero temperatures, which can help conserve fuel. They suggested using diffusers to change airflow and improve engine performance by reducing heat loss.

Hajare Swapnali R., Dr. Kore Sandeep S. (4) investigate improving the thermal performance and heat transfer abilities of waveform straight pin fins and radial pin fins to better cool electronic devices. With electronics becoming more compact and powerful, efficient cooling systems are increasingly vital. The study focuses on optimizing heat transfer rates using waveform pin fins, critical for maintaining system reliability and performance. It identifies pressure drop across the heat sink as a key factor influencing thermal performance in forced convection environments. Key findings stress the significance of overall heat transfer coefficient, heat transfer ability (watt/min), and airflow obstruction in evaluating different fin structures' effectiveness. Recommendations will aim to enhance cooling efficiency and system reliability by optimizing the application of these fin structures in experimental setups.

Zhipeng Duan, Y. S. Muzychka (5) have investigated pressure drop in impingement air-cooled plate fin heat sinks. Challenges in prediction and mitigation underscore the need for further research. Overall, this review emphasizes the importance of pressure drop analysis in enhancing heat sink efficiency.

M. Abu Madi, R. A. Johns, and M. R. Heikal (6) This study investigates heat exchanger performance, testing 28 samples across various geometries. Correlations were developed based on Reynolds number and geometrical parameters, offering improved accuracy. Findings show that fin type significantly influences heat transfer and friction factor. Accurate correlations aid in optimizing heat exchanger design for diverse applications.

C.K. Loh, Bor-Bin Chou, and Dan Nelson and D.J. Chou(7) have investigated solder bonding focusing on material properties and process parameters, while adhesive bonding research emphasizes material selection and curing conditions. Comparisons between the two methods consider thermal performance, reliability, and cost. Understanding these aspects is crucial for optimizing heat sink design and application.

C.K. Loh, Bor-Bin Chou, Dan Nelson, and D.J. Chou (8) delve into the thermal characteristics of solder and adhesive-bonded folded fin heat sinks. This study contributes to the understanding of heat dissipation mechanisms crucial in electronic cooling. By examining the performance of different bonding methods, the authors provide insights into optimizing heat sink designs for enhanced thermal management. Their findings likely offer valuable guidance for engineers and researchers striving to improve the efficiency and reliability of electronic devices subjected to heat stress.

H. Nemati, M.A. Moghimi, P. Sapin, and C.N. Markides (9) explore the optimization of air-cooled finned-tube heat exchangers. This research investigates the most effective shapes for enhancing heat transfer in these exchangers, crucial for applications ranging from refrigeration to power generation. By employing advanced optimization techniques, the authors shed light on how varying the geometry of fins and tubes can maximize heat transfer efficiency. Their study likely provides valuable insights for engineers seeking to design more efficient and compact heat exchangers, with implications for improving energy efficiency and reducing environmental impact.

Jiansheng Wang and Xiao Wang (10) delve into fluid dynamics and transport phenomena. Specifically, they focus on optimizing heat transfer by modifying the shape of conical fins. This study likely contributes to enhancing the efficiency of heat exchangers and thermal management systems. By investigating how alterations in fin geometry affect heat transfer characteristics, the authors offer insights valuable for designing more effective cooling solutions in various engineering applications.

3. Problem Statement

The current landscape of fin designs within industrial and consumer applications is fraught with inefficiencies stemming from excessive material usage and suboptimal thermal performance. This research endeavours to confront this challenge head-on by delineating three core objectives. Firstly, the study aims to minimize raw material usage by devising novel methodologies tailored to reduce the material requirements for fin production. This endeavour prioritizes maintaining structural integrity and functionality while achieving material minimization. Secondly, the research delves into shape optimization for superior heat dissipation, necessitating the identification of fin geometries that maximize fin effectiveness Through meticulous analysis and experimentation on diverse geometric configurations, the study seeks to ascertain the most effective shapes conducive to efficient heat dispersion. Lastly, the research endeavors to enhance fin effectiveness by amalgamating insights gleaned from material minimization and shape optimization endeavors. This holistic approach aims to elevate the overall thermal performance of systems employing fins for heat dissipation, emphasizing optimization at both individual fin and system levels. Through these concerted efforts, the research aspires to redefine the paradigm of fin design, fostering advancements marked by unparalleled efficiency and performance.

4. Objectives

Heat is required to be transferred from one place to another in many engineering applications like exchangers, boilers, refrigerators, etc. It controls excess heating in some cases and achieves heating in others. Heat transfer can be achieved by increasing the temperature difference between different temperature zones. Nevertheless, it is not always achievable to augment the temperature difference. Increasing surface area is one of the widely used techniques to achieve more heat transfer. This is done by using fins.

The surface area of the fins can also be increased by adding more fins to the base material in order to enhance the total heat transfer from the fins. It should be noted that an excessive number of fins will reduce the distance between two adjacent fins. The reduced gap between the two fins will hamper the airflow and cause boundary layer interference, which will affect the heat transfer coefficient. Thus, fins are widely used in various engineering applications such as electronic cooling, water heating, process fluid cooling, air preheating, engine cooling, etc. Due to ease of manufacturing, parallel fins with square fin geometry are commonly used for sinks. In forced convection, fin parameters depend highly on airflow, enclosed space, etc. Optimal values for deciding fin parameters depend on the specific application being considered. There are always limitations on the size of fins due to space constraints, surface geometry, and pitch. Moreover, too large an area will be uneconomical due to limitations on heat transfer. Heat transfer can be increased or decreased using fans, fin area, different fin shapes, etc.

In this approach, experimental analysis of changes in shape parameters to measure changes in heat transfer coefficient (h) is conducted. During this analysis, the effective area of fins and parameters like separation of the fins (pitch/gap between two adjacent fins), material of the fin, method of welding, inlet water temperature, forced air flow, base material, etc., are considered. The experiment aims to examine the effect of changing fin shape on heat transfer experimentally, thereby evaluating the impact of shape factor changes on the heat transfer coefficient while keeping the area constant.

5. Analysis Procedure

A. Analysis of Different Fin Geometries (Circular, Square, and Triangular) Using Ansys

The analysis of various fin geometries, such as circular, square, and triangular, using Ansys involves a systematic approach integrating thermal analyses. This process evaluates heat transfer efficiency and fin effectiveness The following methodology outlines the steps undertaken:

1) Geometry Creation:

CAD Modeling: Each fin geometry (circular, square, triangular) was meticulously modelled in Ansys to precise dimensions, ensuring geometrical accuracy and adherence to intended boundary conditions.

2) Meshing:

Mesh Generation: Ansys was used to generate a detailed mesh for each fin geometry. The mesh density was optimized to capture thermal gradients effectively and ensure accurate structural response. Nodes generated at the intersections of mesh elements (triangles, quadrilaterals, tetrahedrons, etc.), carry material properties and are used in solving finite element equations. This study considered fine meshing sizes with triangular shape elements for meshing.

3) Material Assignment:

Material Properties: Properties such as thermal conductivity, Young's modulus, and Poisson's ratio were assigned to the fin materials, typically considered carbon steel for this study considers carbon steels for both fin and pipe.

4) Boundary Conditions:

Thermal Boundary Conditions: Boundary conditions, such as heat flux or specified temperatures at the base and ambient conditions around the fin surfaces, were applied to simulate realistic thermal environments.

5) Analysis Setup:

Heat Transfer Analysis: Steady-state or transient thermal analyses were conducted to predict temperature distributions across the fin surfaces and through the material, providing insights into heat dissipation characteristics.

6) Solver Settings:

Solver configurations were adjusted to meet specific analysis requirements, ensuring convergence and accuracy in thermal simulations.

7) Post-Processing:

Temperature Distribution Analysis: Results were analyzed to visualize temperature distributions along the fin surfaces, offering insights into heat transfer efficiency.

8) Validation and Optimization:

Comparative analysis of results from different fin geometries (circular, square, triangular) provided insights into optimal design choices for enhanced heat transfer efficiency or structural robustness. This structured approach utilizing Ansys facilitates a comprehensive investigation into the thermal behaviour of different fin geometries, contributing valuable insights to heat transfer and mechanical design optimization.

B. Considerations for Testing:

- Placement of the pipe fin in the frame assembly.
- Insertion of the heating coil in the pipe fin.
- In natural convection processes, no external air or fluid flow is utilized, whereas in forced convection, a continuous supply of airflow is generated using an Air Blower.
- Insert the Air Blower in the frame assembly for forced convection results.
- Use an Anemometer for airflow measurement.
- Regulate the temperature of the heater coil using a temperature regulator.
- Measure the temperature at different points and take at least 10 to 15 readings for these four types or shapes of fins.
- Average out all the readings.

Then, conclude the optimum fin from the above readings.

6. Methodology

This study analyzes the heat transfer performance of fins by designing fins with square, triangular, and circular shapes while maintaining equal cross-sectional areas. Fins are created using the ANSYS software, and their performance is analyzed using the same software. The comparison is made between fins of different geometries but with identical areas. This research aims to understand how varying fin shapes affect heat transfer efficiency.

A. Fin shapes

In this experiment, three fin shapes are considered for analysis under

- *Circular fin*
- *Square fin*
- *Triangular fin*

B. Variable and definition

As the experiment is to examine the shape factor effect on heat transfer and heat transfer coefficient all other parameters and variables will be maintained similarly. The parameters that are kept constant are as under: -

- Area: - The area of the individual fin is kept constant for all three shapes/types,
- Pitch / Spacing between fins,
- Material and Size of pipe
- Fin material,
- Welding material and methodology,
- Inlet water temperature,
- Mass flow rate of water,
- The rate of airflow and its source on fins

C. Specimen dimension and experimental setup

- ***Circular fin***

The specimen used for the experiment was fabricated with a meter ½” (10S) pipe. The ID and OD of the pipe specimen are 17.08 mm and 21.30 mm. The wall thickness of the selected tube is 2.11 X 2 mm.

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Hence calculations to maintain the area constant of the fins of all three types of constants are as below: -

Tube ID: -17.08 mm

Tube OD: -21.30 mm

Tube Wall thickness X_2: - 4.22 mm

Circular Fin height: - 40 mm

Total OD of Fin: - 101.3

Surface Area of fin = Total area – Area of tube cross-section

Now,

Tube Area= πr^2= 356.4707 mm^2

Area of one side face of fin= πr^2=7706.2857 mm^2

Fin thickness area= πDL= 477.5571 mm^2 (L is fin thickness)

Total fin surface area = (2 X Single surface area) + Fin thickness area = 15890.128 mm^2.

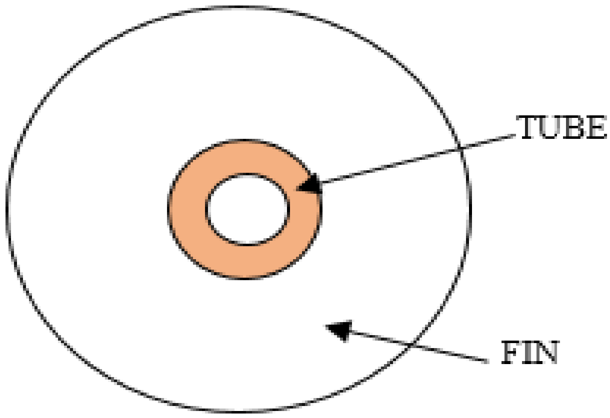

Fig. 1 Cross Section of Circular Fin (16)

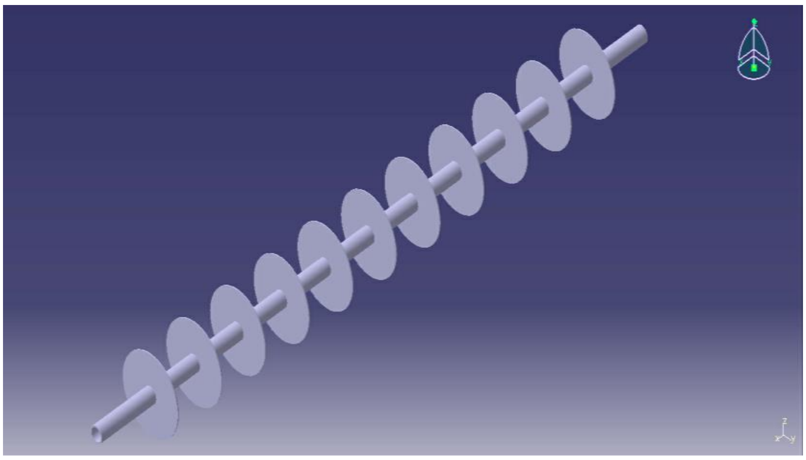

Fig 2 3D model of pipe with circular fin.

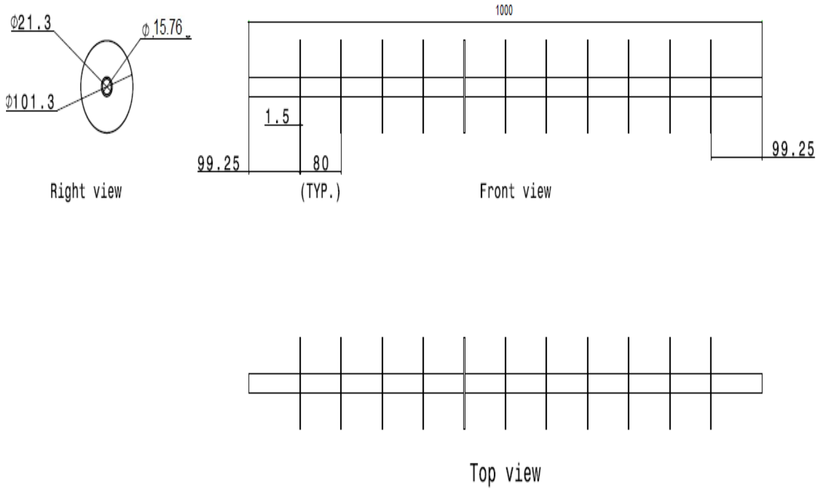

Fig. 3 Details of the circular fin arrangement

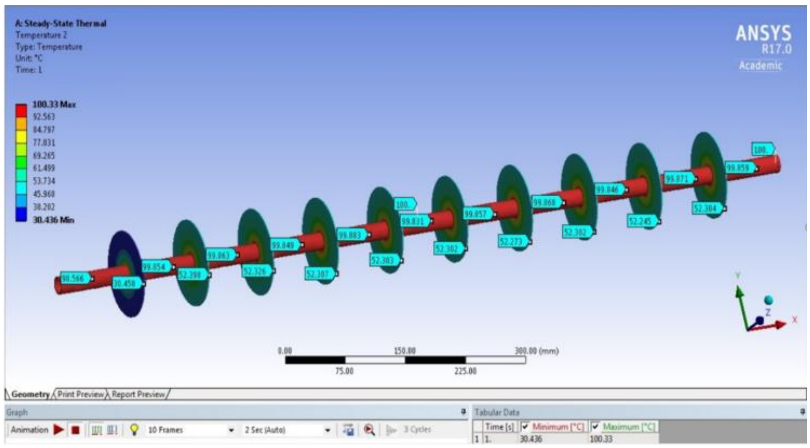

Fig. 4 Temp distribution in circular fin assembly

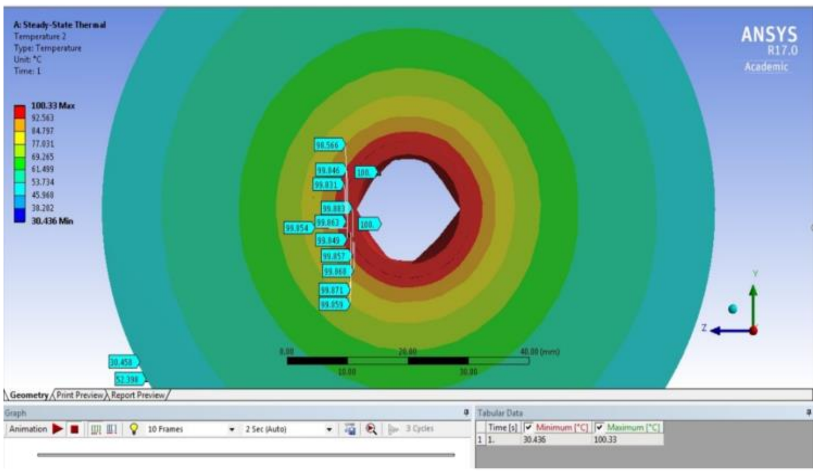

Fig. 5 Study state temp at the x-axis

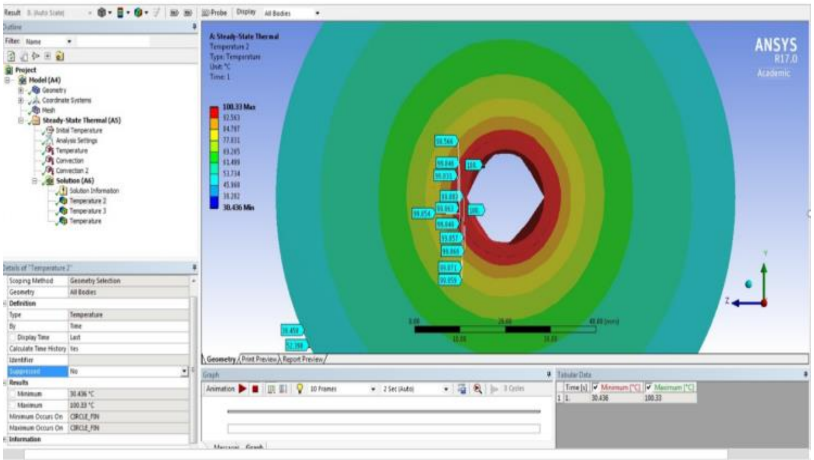

Fig. 6 Study state temperature at Out to in 2 (12.5mm)

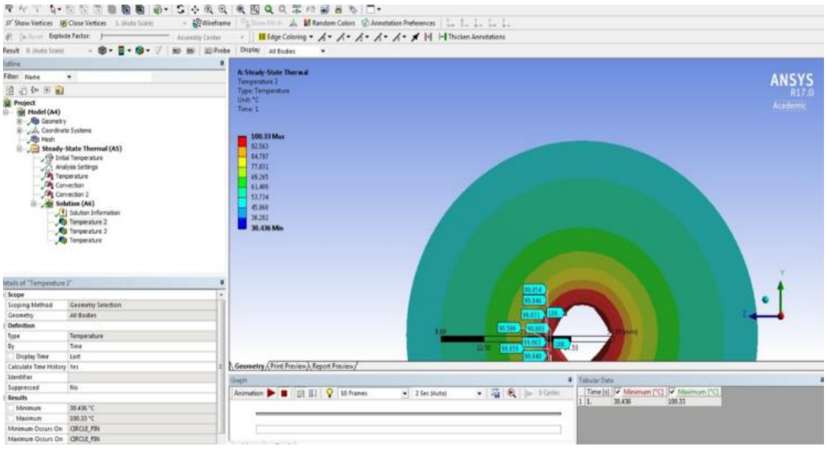

Fig. 7 Study state temp at Out to in 3 (6 mm)

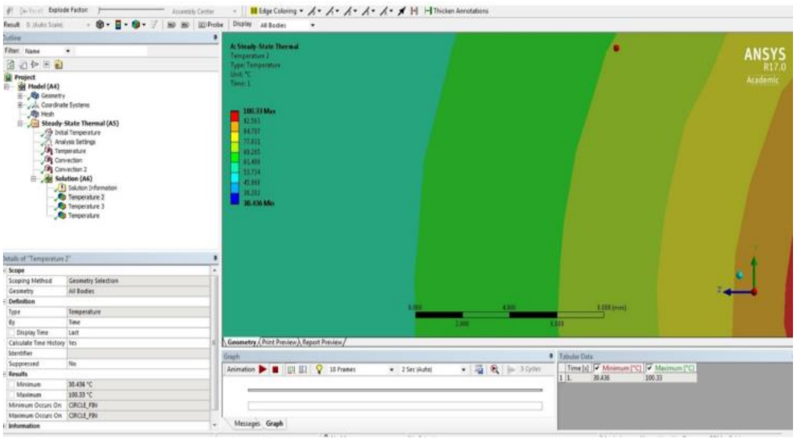

Fig. 8 Study state temp at Out to in 4 (3 mm)

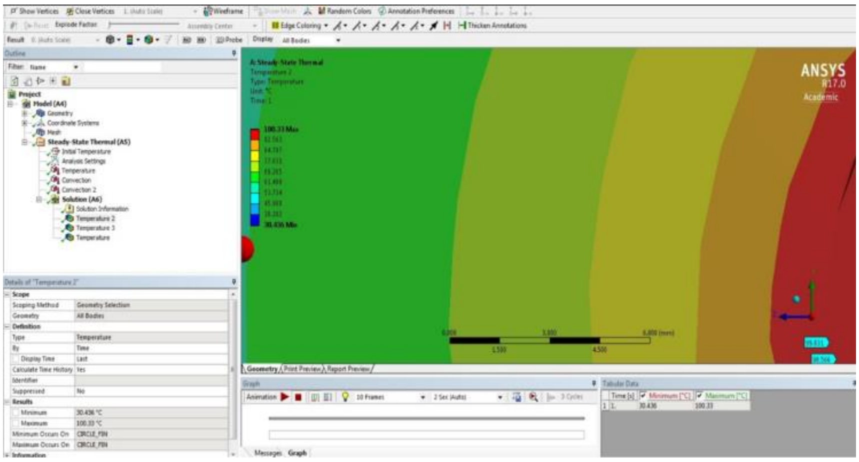

Fig. 9 Study state temp at Out to in 5 (2.5 mm)

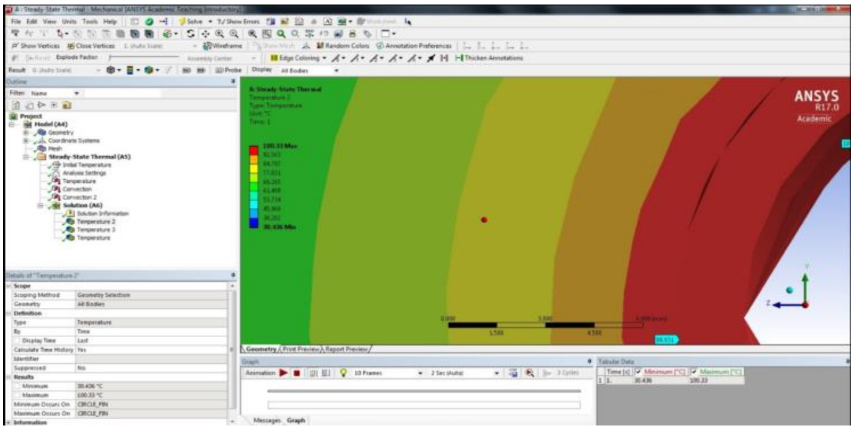

Fig. 10 Study state temp at Out to in 6 (2 mm)

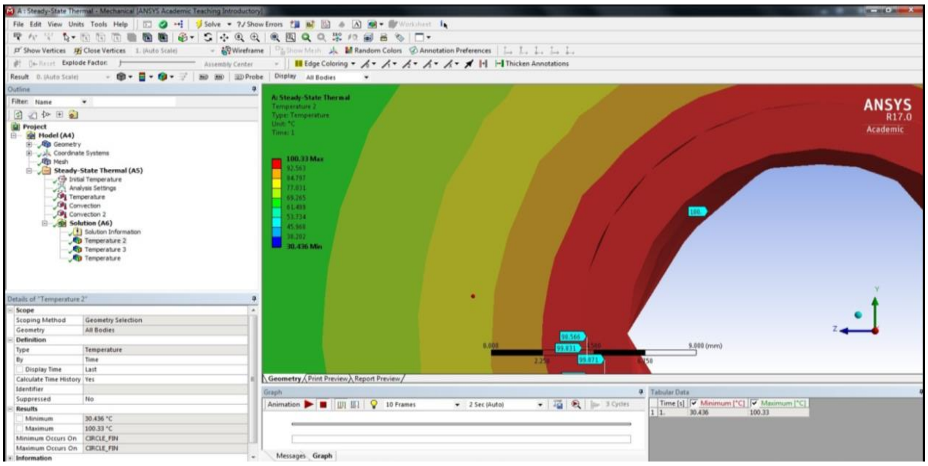

Fig. 11 Study state temp at Out to in 7 (1.5 mm)

- ***Square fin***

  Tube ID: - 17.08 mm

  Tube OD: - 21.30 mm

Tube Wall thickness X_2:- 4.22 mm

Given that the surface area remains constant in all scenarios i.e., 15890.12857 mm^2 Fig. 12

Cross Section of Square Fin Area = (2 X Area of square fin) + Fin thickness area

15890.12857 mm^2 = (2 X Area of square fin) + (4 X 1.5 X Length of one side of the square)

Solving this we get a square side length of 89.6251 mm

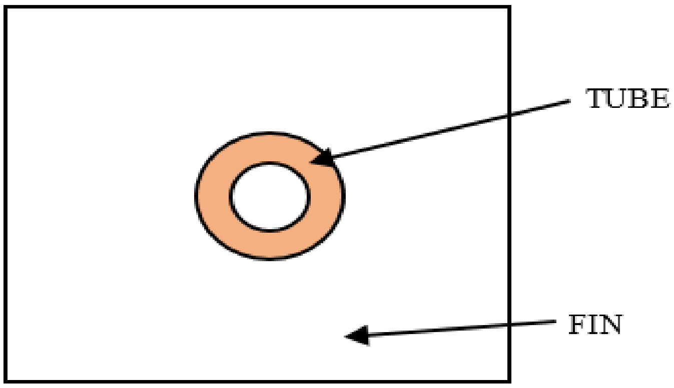

Fig. 12 Cross Section of Square Fin (16)

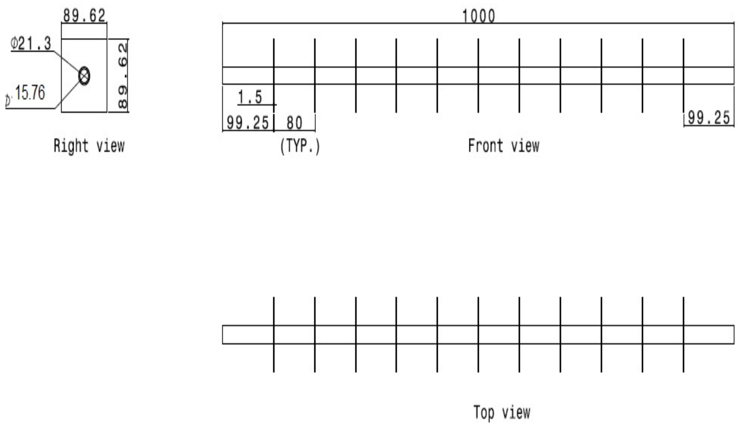

Fig. 13 Details of the square fin arrangement

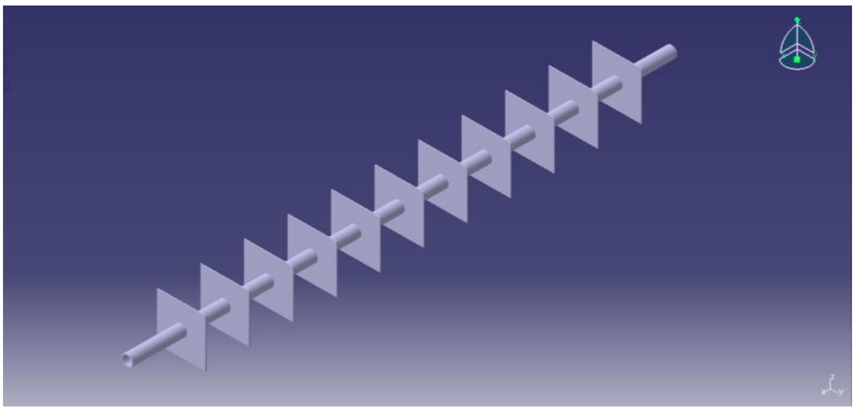

Fig 14 3D Model of pipe with Square Fin

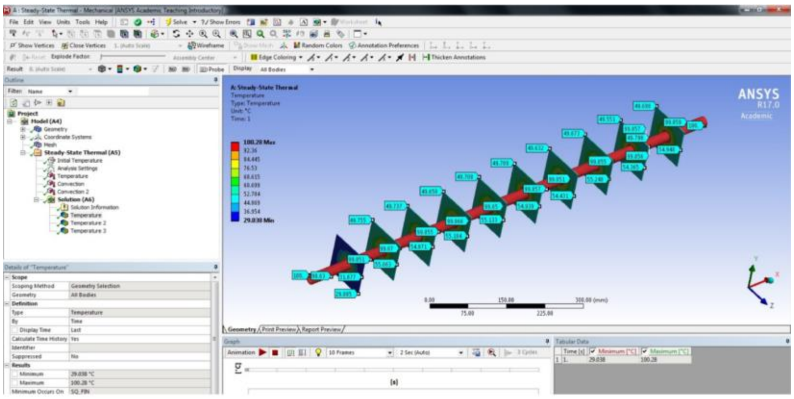

Fig. 15 Temperature distribution in square fin

- ***Triangular fin***

Tube ID: -17.08 mm

Tube OD: -21.30 mm

Tube Wall thickness X_2: - 4.22 mm

Given that the surface area remains constant in all scenarios i.e., 15890.12857 mm^2

Area = (2 X Area of triangular fin) + Fin thickness area

15890.12857 mm^2 = (2 X Area of triangular fin) + (3 X 1.5 X Length of one side of the triangle)

Solving this we get the triangle side length as 135.8829 mm

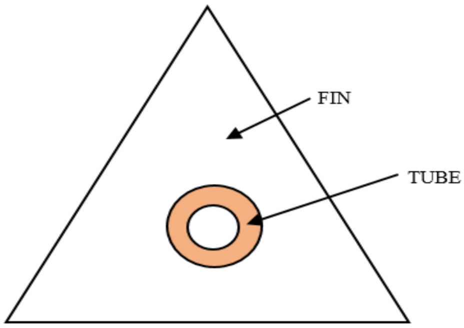

Fig. 16 Cross Section of Triangular Fin (16)

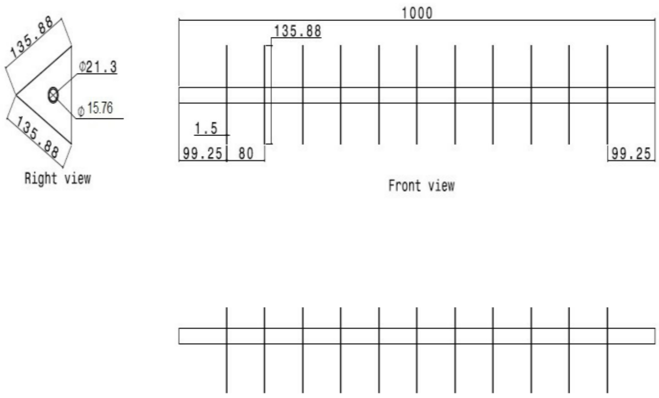

Fig. 17 Details of the square fin arrangement

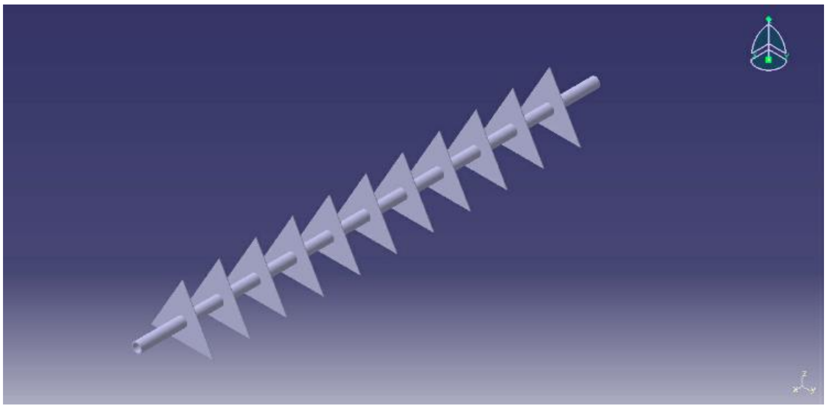

Fig. 18 3D Model of pipe with Triangular Fin

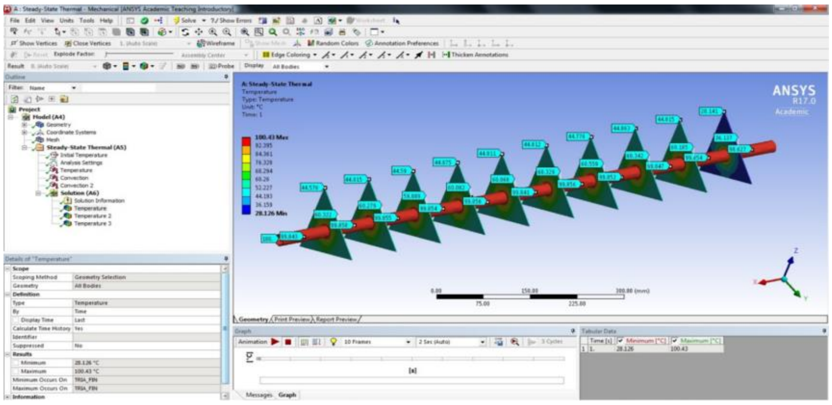

Fig. 19 Study state temp distribution in triangular fin

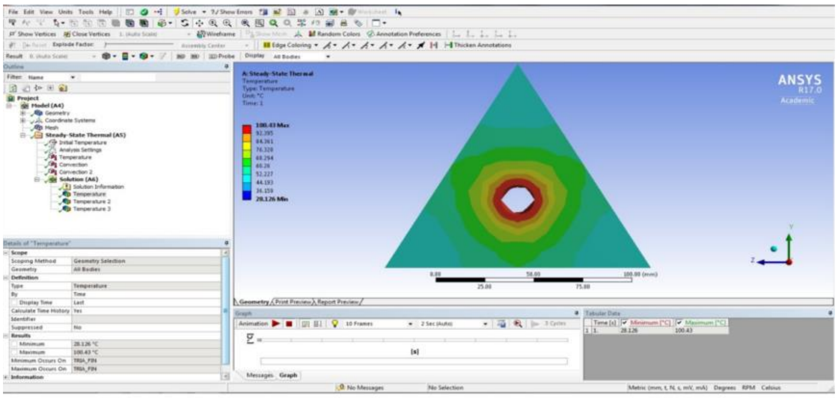

Fig. 20 Study state temp at the core of the triangular fin

Triangular fins are employed to enhance heat transfer by increasing surface area and optimizing the temperature gradient.

D. Material and additional factors

- Carbon steel is used for both pipe and fins. Argon seal welds are used to weld the fin with pipe.
- The seal welds are made from one side of the fin due to the very low thickness of the fins.

- Water is constantly maintained at 100 degrees / boiling point throughout the experiment
- All the fins are cut with a leaser to avoid any damage.

7. Computational Methodology

To perform the computational modeling, 'Ansys 17.0,' which is standard CFD simulation software for fluid flows, is used.

A. The computational modeling is undertaken with the following objectives in mind:

- To establish meshing for proper heat transfer in different fin geometries.
- To find the tip temperature of various fin geometries, such as annular, square, triangular, and modified triangular shape fins.
- To calculate the tip temperature at a constant boundary condition of 8 m/s air velocity.

B. Procedure:

- The geometry of the problem is designed in 'Ansys Design Modular.' Here, different 3D fin geometries are exported from SolidWorks to Ansys in (. step) / Step AP203 or (.x_t) / Parasolid format.
- These fin geometries consist of a 1000 mm long cylindrical pipe on which 11 fins are attached at equidistant intervals of 80 mm.
- Then, an enclosure is established for fixed boundary conditions in 'Ansys Design Modular,' and inlet and outlet sections for air are generated.
- Meshing is obtained using the standard meshing tool available in 'Ansys Workbench 17.0.'
- After proper iteration, a mesh size of 1.5mm is chosen for a constant number of nodes and elements for all fin geometries.
- The number of nodes and elements depends entirely on the meshing size.

C. Material selection

Carbon steel is often the preferred material for machine components.

D. Following properties to be focused on when selecting material

- Availability: Mild steel is commonly found in the market.
- Cost-effectiveness: It offers an economical solution.
- Standardization: It comes in readily available standard sizes.
- Machinability: Mild steel boasts favorable
- Mechanical properties, facilitating easy machining.
- Factor of safety: It strikes a balance with a moderate factor of safety, avoiding excessive material waste or risk of failure.
- Tensile strength: Mild steel exhibits high tensile strength, enhancing durability.
- Thermal stability: It possesses a low coefficient of thermal expansion, contributing to dimensional stability under temperature variations.

8. Result and Discussion

A. CAD geometry

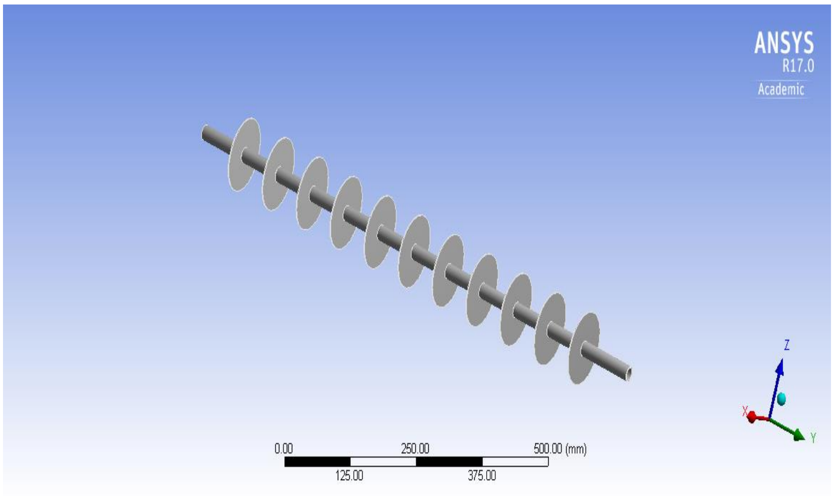

Fig. 21 Arrangement for circular fin in CAD mode.

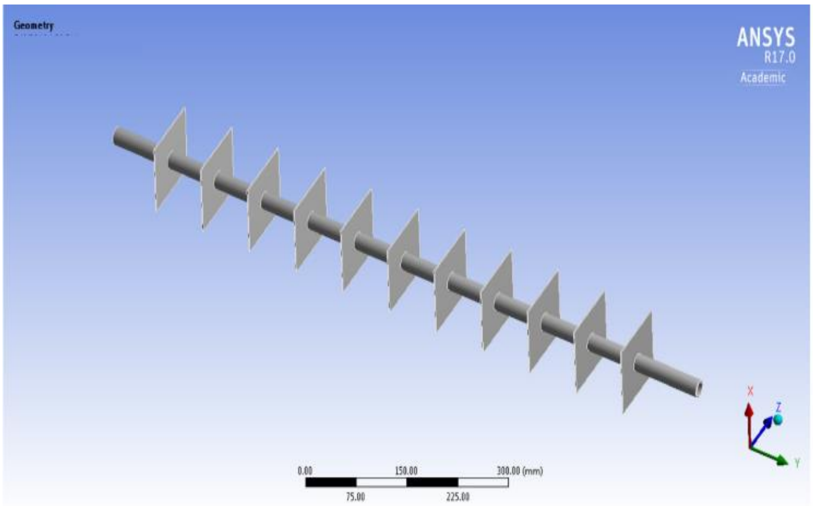

Fig. 22 Arrangement for square fin in CAD mode.

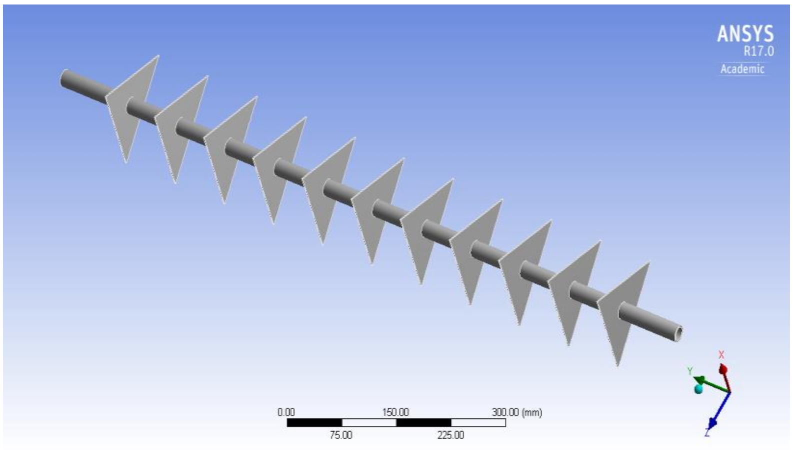

Fig. 23 Arrangement boundary conditions for circular fin

B. Boundary conditions

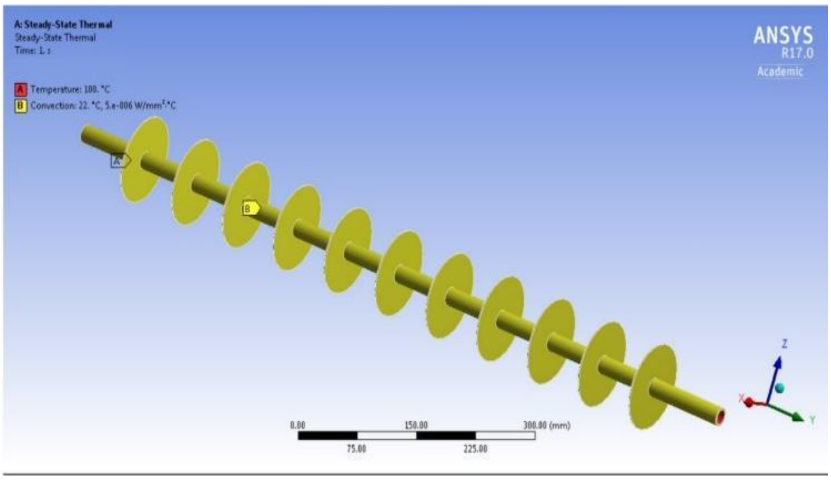

Fig. 24 Arrangement boundary conditions for circular fin

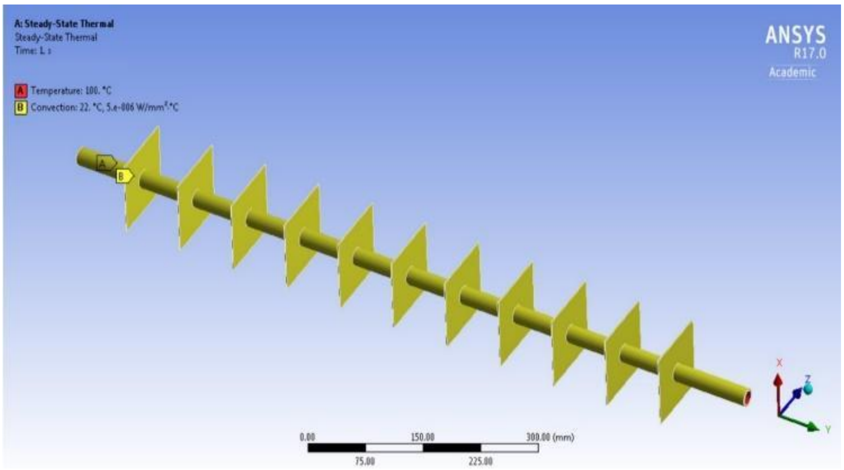

Fig. 25 Arrangement boundary conditions for square fin

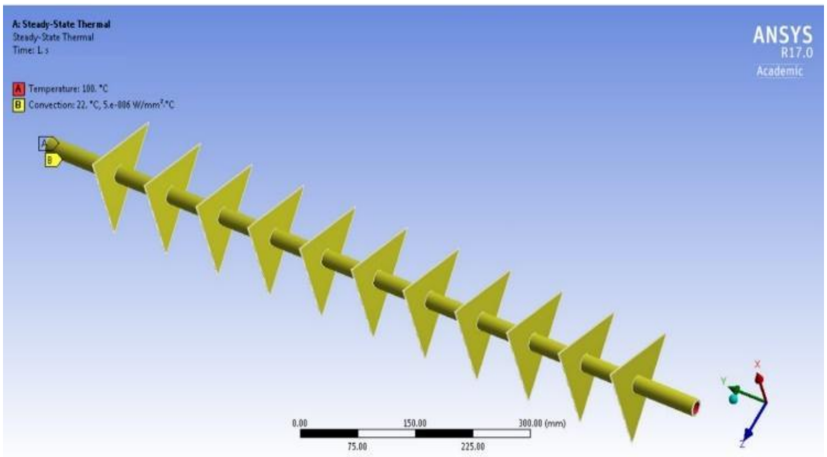

Fig. 26 Arrangement boundary conditions for triangular fin

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C. Mashing analysis

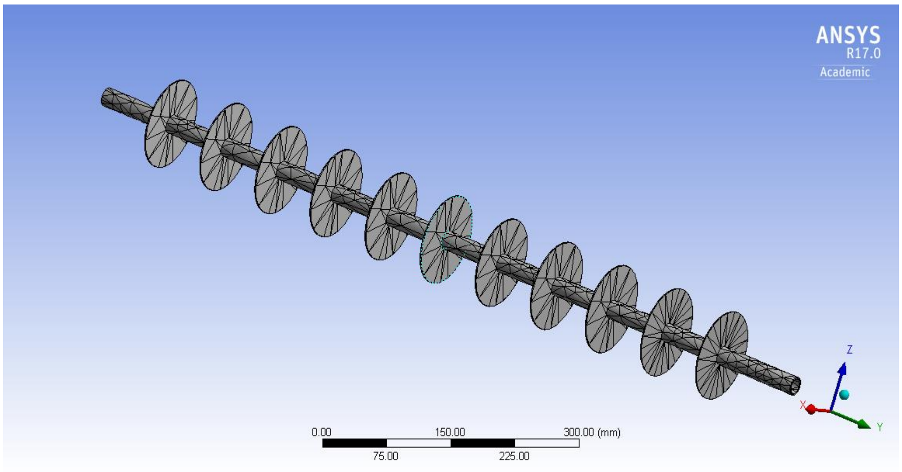

Fig. 27 Meshing arrangement for circular Fin

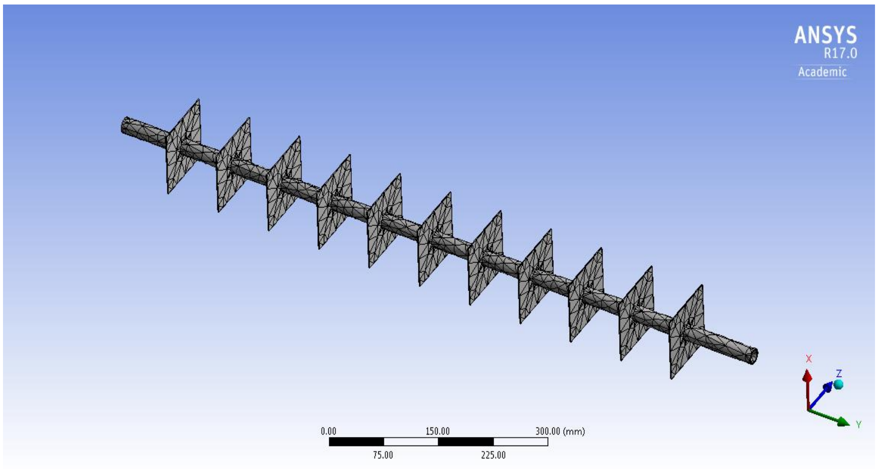

Fig. 28 Meshing arrangement for square Fin

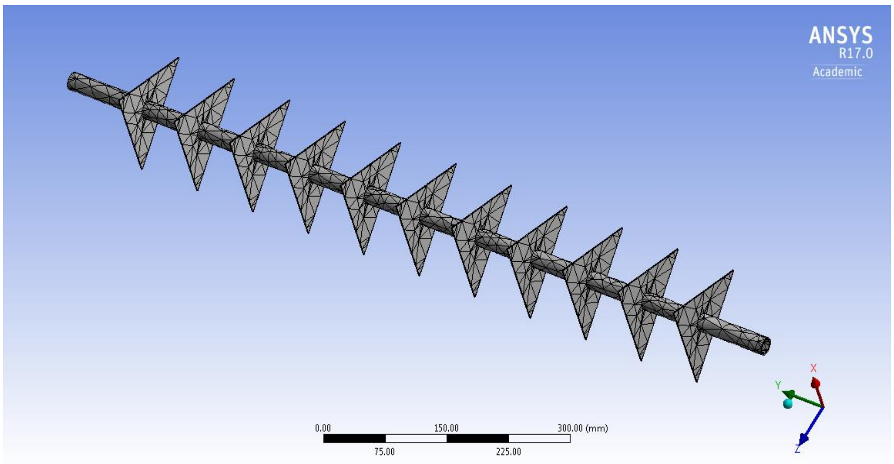

Fig. 29 Meshing arrangement for triangular Fin

D. Distribution of temperature

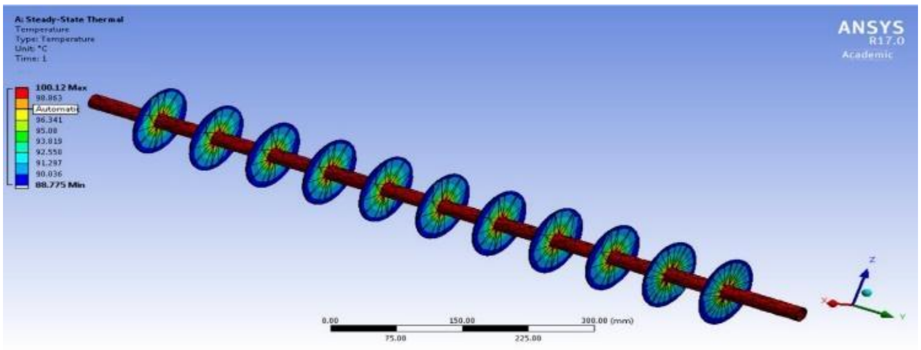

Fig. 30 Analysis of temperature for circular fin

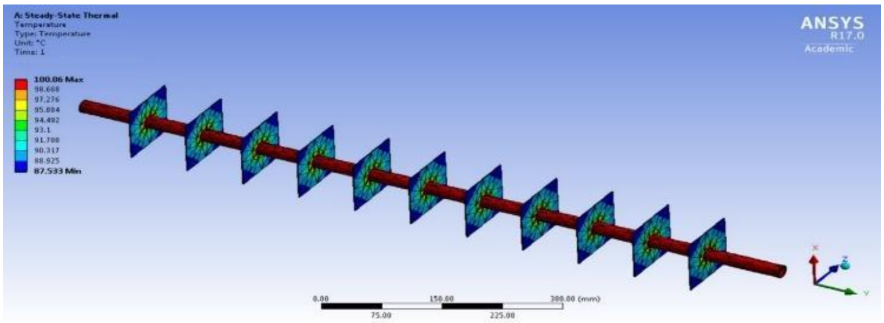

Fig. 31 Analysis of temperature for square fin

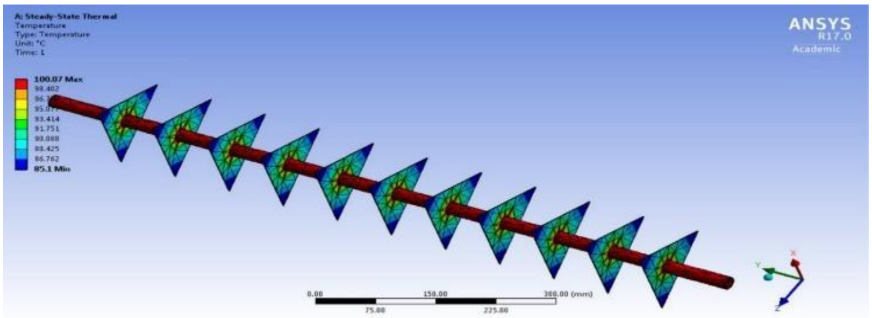

Fig. 32 Analysis of temperature for triangular fin

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E. Flux comparison

In ANSYS, flux comparison involves comparing the distribution of magnetic flux densities in electromagnetic simulations to evaluate device performance and optimize design configurations.

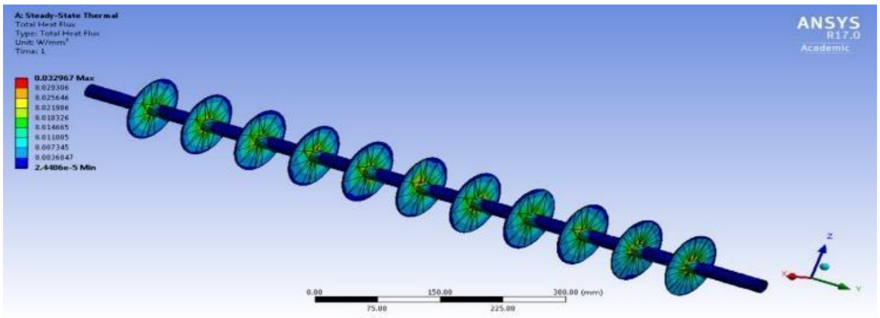

Fig. 33 Flux companions for circular fin

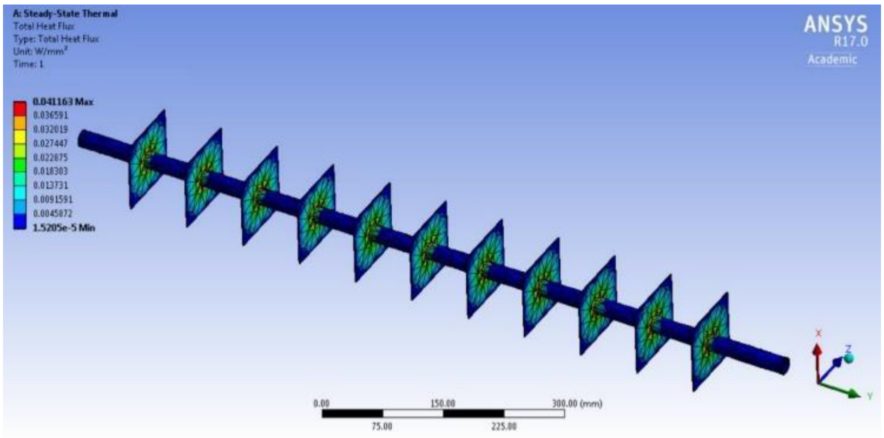

Fig. 34 Flux companions for square fin

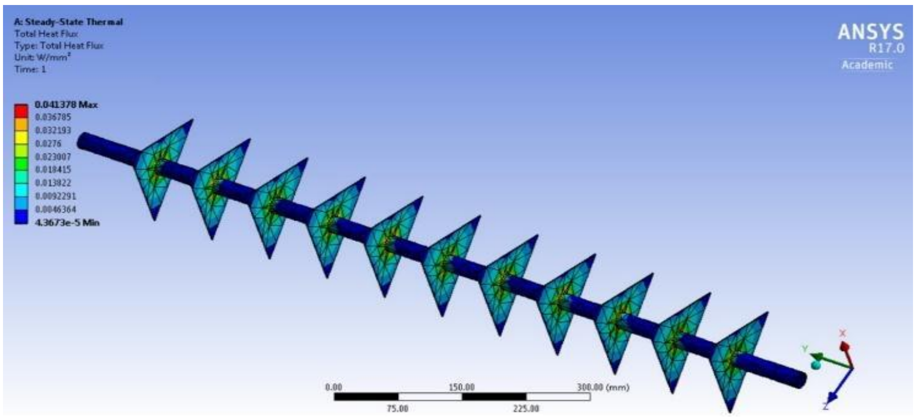

Fig. 35 Flux companions for triangular fin

The findings from this research analysis demonstrate that the Triangular model is more effective across all three aspects.

A. Modified triangular fin

In analyzing triangular fins, it is observed that triangular fin offers greater fin effectiveness and reduced temperature gradients.

Further optimization of triangular fins by adding notches in exiting triangular fin.

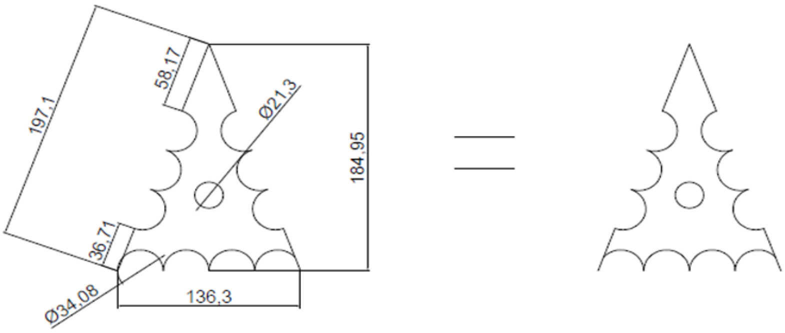

Fig. 20 Modified cross-section area of triangular shape fin.

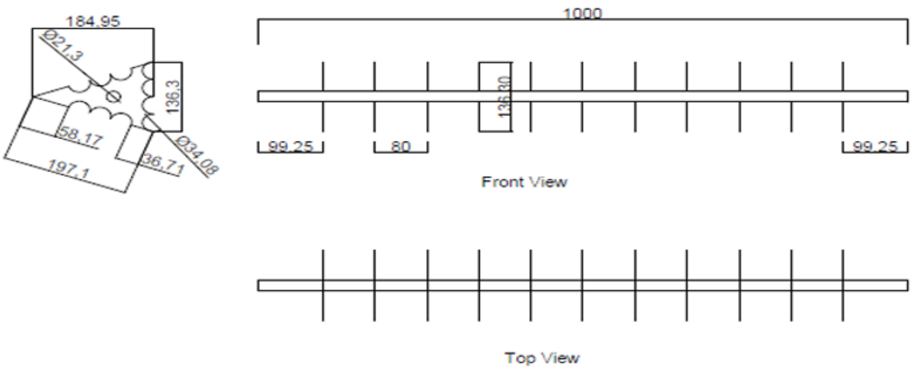

Fig. 36 Details of the modified triangular fin arrangement

B. Distribution of temperature

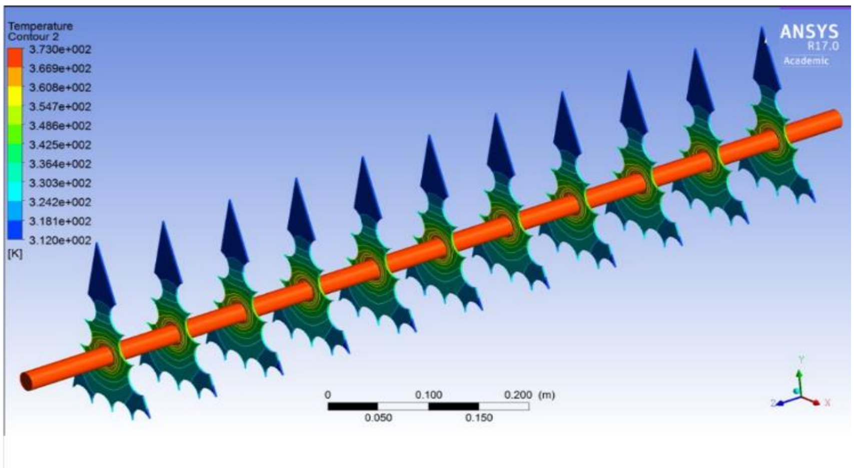

Fig. 37 Distribution of temperatures in modified triangular fin

C. Comparative Analysis of the Following Geometrical Shapes fins:

Table no 1. Fin comparisons

Fin Shape	Surface area (mm^2)	Fin tip temp. distribution (°c)	Flux comparisons Q_{max} (w/ mm2)
Square Fin	16701.464	88.775	0.32967
Annular Fin	16160.589	87.533	0.041163
Triangular Fin	**16806.964**	**85.100**	**0.041378**
Modified triangular Fin	**26590.680**	**38.851**	**0.065465**

9. Conclusions

The investigation focuses on analyzing heat transfer rates within various fin geometries, including square, annular, triangular, and modified triangular fins. These fins undergo random allocation within the Ansys workbench software for computational analysis, generating diverse outcomes regarding their heat transfer rates. Comparative analysis reveals the superiority of the triangular fin configuration, with the modified triangular fin showing even higher optimality. Additionally, theoretical calculations align with computational findings. In future also simulate the results of different fin geometries with varied velocity magnitudes using Ansys Fluent, finalizing the design of fins in square, annular, and triangular shapes, modifying the triangular fin to enhance surface area, conducting temperature measurements at various points for each fin type, and summarizing experimental results to determine the optimum fin configuration for heat transfer.

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