

Development of Simulation and Optimization Tool for Heat Exchanger Design

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Abstract

The performance of high-performance engines, particularly in two-wheelers, often faces challenges due to inadequate cooling systems. Traditional heat exchangers, such as the cross-flow type, struggle to provide optimal heat dissipation, especially in engines exceeding 200cc. This research explores the use of Additive Manufacturing (AM), specifically Fused Deposition Modeling (FDM), to fabricate microchannel heat exchangers with flat and curved face geometries. The study aims to evaluate the thermal performance, heat transfer efficiency, and air resistance of these AM-produced heat exchangers compared to traditional designs. Through thermal analysis, Computational Fluid Dynamics (CFD) simulations, and experimental setups, the research identifies significant improvements in heat dissipation and cooling efficiency when using AM technology. The results reveal that the curved face design outperforms the flat face configuration in terms of thermal performance and pressure characteristics. Additionally, material properties such as ABS, PLA, and PETG were assessed, showing that ABS provided the best balance of durability and thermal performance. This study concludes that AM-based microchannel heat exchangers are a viable solution to overcome the limitations of conventional designs, offering enhanced performance and greater efficiency in modern cooling systems.

Keywords: Microchannel heat exchangers, Additive Manufacturing, Fused Deposition Modeling, thermal analysis, CFD, cooling efficiency

1. Introduction

Recently developed high-performance engines, like those used in automotive and aerospace technology, have created a growing need for smaller and more efficient heat exchangers (Abdullah & Zoynal Abedin, 2024). The simplest examples, like cross-flow heat exchangers used in many two-wheelers, have shown a number of constraints that limit their size and heat cooling capacity, especially for engines with a displacement greater than 200 cc. As a result, these systems have problems dissipating the heat generated while running, leading to engine overheating, a loss of engine performance and fuel economy. Thus, the improvement of thermal management systems for engines represents a growing area of technological innovation (Broatch et al., 2022). Microchannel heat exchangers (MCHX) stand out in this area as a result of better heat transfer, and lower weight and size (Han et al., 2012). These advantages come from the improved heat transfer of smaller flow channels. While smaller channels have greater resistance to heat flow, less flow area means higher flow rates. A larger pressure drop throughout the channels results from this. Microchannel MCHXs work the opposite of conventional heat exchangers in that heat flows from the MCHXs; thus, the heat of the working fluid (typically a coolant) flows to a secondary fluid (usually air) as the working fluid passes through the channels (Kim & Kim, 2021). Conventional manufacturing of microchannels is limited by the ability to construct and maintain higher order networks and by the ability to manufacture the networks in a manner that is both low cost and highly efficient. The limitations of traditional manufacturing processes, like melting and machining, have sparked an interest in Additive Manufacturing (AM) technologies, which are construction methods using fused deposition polymers that do not require extensive diverter systems and assembly, allowing for the construction of complex geometries.

This research looks into how Additive Manufacturing (AM), especially Fused Deposition Modelling (FDM), can be used to create and make microchannel heat exchanges with both flat and curved faces (Cano-Vicent et al., 2021). This

study aims to get around the problems that come with traditional manufacturing by using the flexibility of additive manufacturing (AM) to make heat exchangers in fast two-wheelers work better. The study will look at how well these AM-made microchannel heat exchangers work at transferring heat, comparing the flat face and curved face designs using simulations, computational fluid dynamics (CFD), and real-world testing (Cruz et al., 2022). As much heat movement as possible should happen while air resistance should be kept as low as reasonable. This is what the engine needs to work better and faster.

2. Literature Review

2.1 Literature Review Based on Microchannel Heat Exchangers and Fluids

Tuckerman et al. (1981) studied how to make forced fluid cooling work for planar circuits. They discovered the reason why improving cooling is challenging: refrigerant-cooling convective heat transfer between the fluid and the substrate. The authors suggested that the issue may be resolved by increasing the cooling channels' surface areas, particularly when it comes to the usage of conduits with a high aspect ratio. The research also designed and tested a cooling device for integrated circuits that was water-cooled and was designed to keep the temperature of the silicon integrated circuits at 71°C above the intake water temperature at an electrical density of 790 W/cm (Tuckerman & Pease, 1981). Kandlikar et al. (2004) proposed a roadmap for heat management and manufacturing systems for microchannels applied to microelectronics and high heat flux refrigeration. The authors explain microchannels as having flow paths with hydraulic diameters between 10 to 200 micrometers. The authors explain the efficiencies of increased passage sizes in high heat flux cooling and review the literature on microchannel exchangers performance enhancements (Kandlikar & Grande, 2004). Fallah and Rahni (2017) analyzed via numerical simulation the evolution of droplets in standard and bespoke T-junction microchannels. Their study employed the lattice Boltzmann method in its pseudopotential form to model multiphase flows through microchannels. The results obtained from this study corroborated the majority of prior experimental and computational investigations, underscoring the effectiveness of their modeling approach for flow characterization in microchannel heat exchangers (Fallah & Taeibi Rahni, 2017).

Ramya Vinoth and others (2023) looked at microchannel heat exchangers and how intermittent circular oblique fins improved their heat transfer efficiency. The findings demonstrated that, in comparison to conventional straight fins, oblique fins enhanced heat transmission by 75.6% in the mean Nusselt number and decreased total temperature impedance by 59.1%. The improvement was brought about by better heat transfer at a Reynolds number of 50–500, increased thermal boundary layer disturbance, and flow mixing with a low pressure drop (Vinoth et al., 2023).

2.2 Literature Review Based on Thermal Analysis of Header in Microchannel Heat Exchanger

Sevencan (2021) studies the condensation and pressure uniformity in microchannel heat exchangers. The author employed three different height channel arrangements to exhaust R410a vapor to liquid under certain operating conditions. The author reports that arrangements A and B are in the low Reynolds number range while arrangement C is in the high number range. The author also examines the extent to which new geometric designs reduce the misdistribution effects on the flow regime, achieving a 100% condensation effect at low flow rates (Furkan Tuğberk SEVENCAN, 2021). Mark Anthony Redo et al. (2020) designed a dual-compartment, modified vertical header to improve flow distribution in microchannel heat exchangers. The authors used R410A for experiments and visualizations to mimic real heat exchanger condition. The paper discussed the effects of different header tube depths on flow rates and vaporization temperatures. The authors concluded that increased inlet mass fluxes promoted better gas distribution at low moisture levels. The experiment illustrated the effects of gravity on water levels and flow in the header (Redo et al., 2020).

3. Methodology

This research combines both quantitative and qualitative methods to answer the study goals. Data is obtained through a positivistic paradigm which means quantitative data is used to support the research. Also, a deductive approach is used with Taguchi and grey relation analysis to help optimize the research. The research will make use of primary and secondary data collection which will include qualitative analysis of the literature and the data obtained through simulations and experiments performed on flat and curved face microchannel heat exchangers. The methodology will

encompass experimentation, explanation, and description. The methodology will employ purposive sampling for qualitative data and basic random sampling for quantitative data to ensure the accuracy and reliability of the data.

3.1 Tools Used

- a) UNIGRAPHIX NX-8.0 for Solid Geometry
- b) ANSYS WORK bench for Thermal Analysis
- c) ANSYS WORK bench for CFD Analysis
- d) MINITAB 18.0 for Optimization

3.2 Techniques used for designing (TEMA)

TEMA means Tubular Exchanger Manufacturers Association. This applies to one of many organizations that create and up keep standards for the manufacturing, designing and inspecting of heat exchanging equipment. The TEMA standards help give direction to the specifications for the reliability, efficiency and safety of heat exchangers applicable in various industries. Engineers and manufacturers select appropriate TEMA types and design modifications for the specific requirements of their systems. When choosing a TEMA type for a heat exchanger specific application, one must consider fluids, temperature differences, and maintenance.

3.2.1 2D Geometry of the Flat Microchannel Heat exchanger

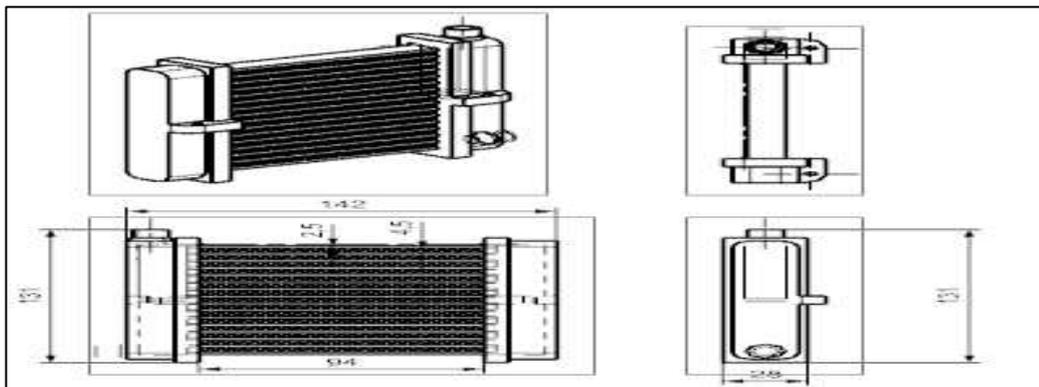


Fig 1. [a]: Flat Plate Heat Exchanger Microchannel Design and Dimensions

3.2.2 Geometry of Flat Plate Microchannel Heat Exchanger

A microchannel heat exchanger in its flat form was measured in three dimensions using the Unigraphics NX-8 Solid Geometry Tool. Additionally, the pieces' 3D geometry was exported as.STL files, which were then used as input by the 3D Printing UP Mini Software.

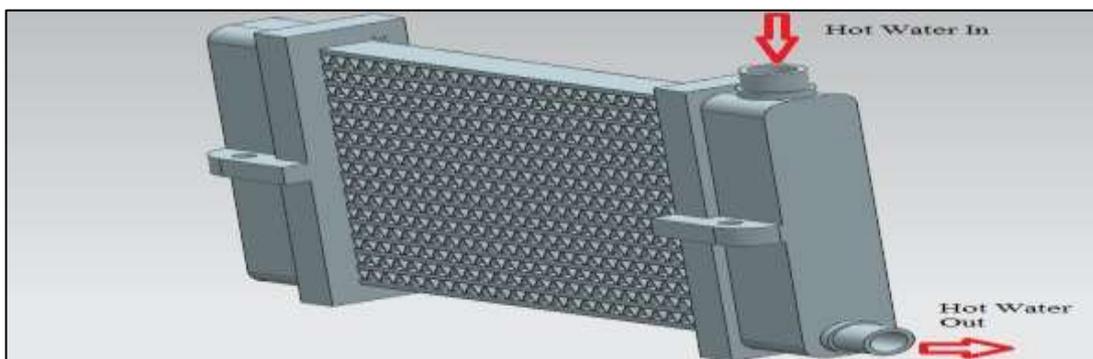


Fig 1. [b]: 3D Geometry of the Flat Microchannel Heat exchanger

3.2.3 Partition of Right Hand [RH] Header of Flat Shape Microchannel

The Unigraphics NX-8 Solid Geometry Tool was used to measure a microchannel heat exchanger in three dimensions in its flat form. Furthermore, the 3D geometry of the components was exported as.STL files, which the 3D Printing UP Mini Software utilised as input.

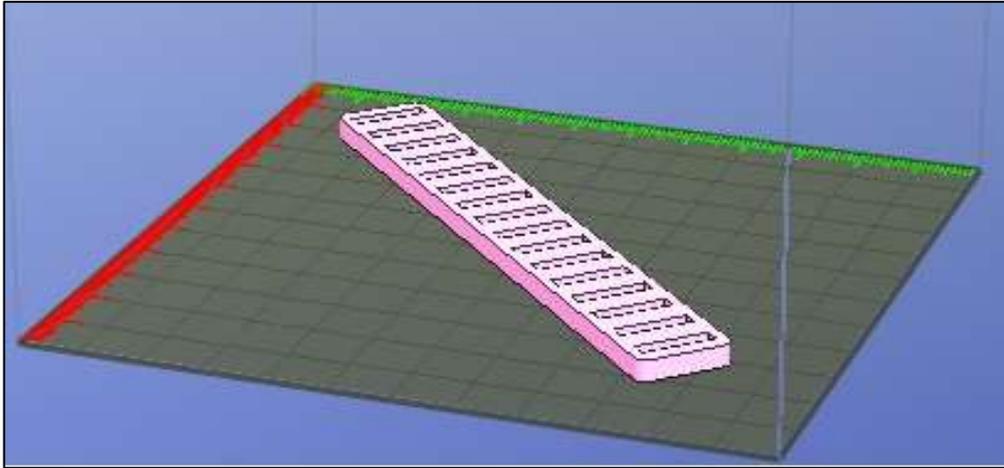


Fig 2: Partition of Right Hand [RH] Header of Flat Shape Microchannel

The actual 3D Printing of Right Hand [RH] Header of Flat Plate Shape Heat exchanger with microchannels as shown in Fig 3.

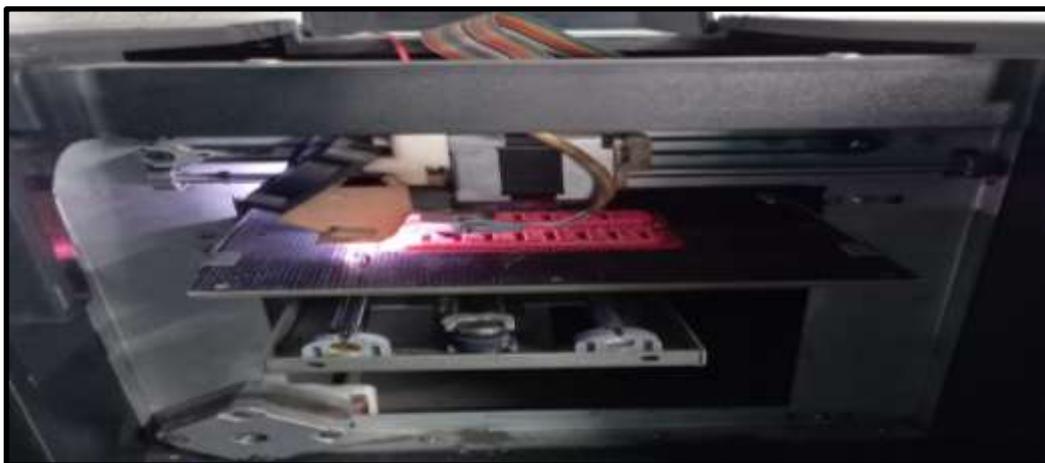


Fig 3: Actual 3D Printing of Right Hand [RH] Header of Flat Plate Shape Microchannel Heat Exchanger

3.3 Manufacturing of Curved Microchannel Heat Exchanger

The following process is used to produce the Curved Shape Heat Exchanger with Microchannels utilising 3D printed headers; the work flow is shown in Fig. 4 below.

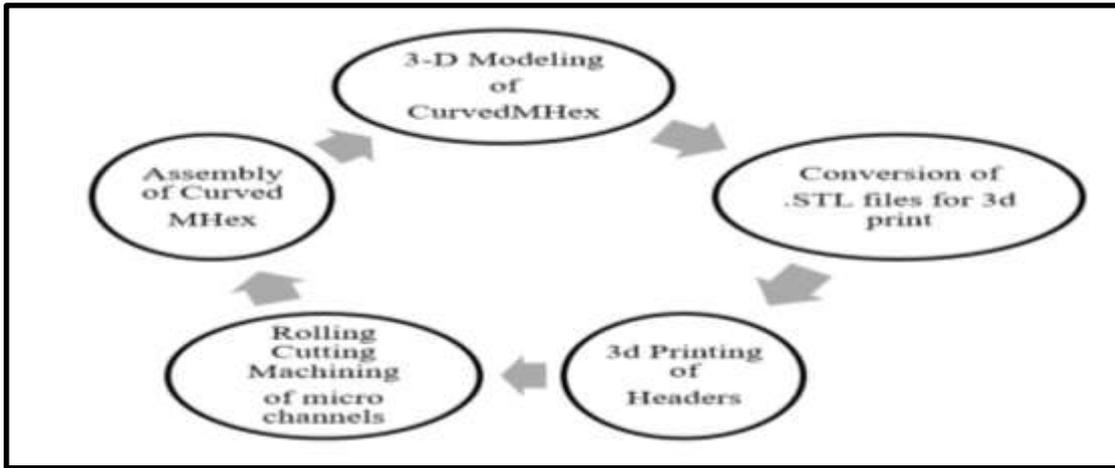


Fig 4. Manufacturing Process for Curved Plate Microchannel Heat Exchanger

3.3.1 3D printing of the parts of the Curved Shape Microchannel Heat Exchanger Left Hand [LH] Header

The heat exchanger microchannel headers were 3D printed using the STL file. Fig. 5 displays the Graphical User Interface [GUI] of the Up Mini Software. The 3D printing was completed when the proper printing settings were established.

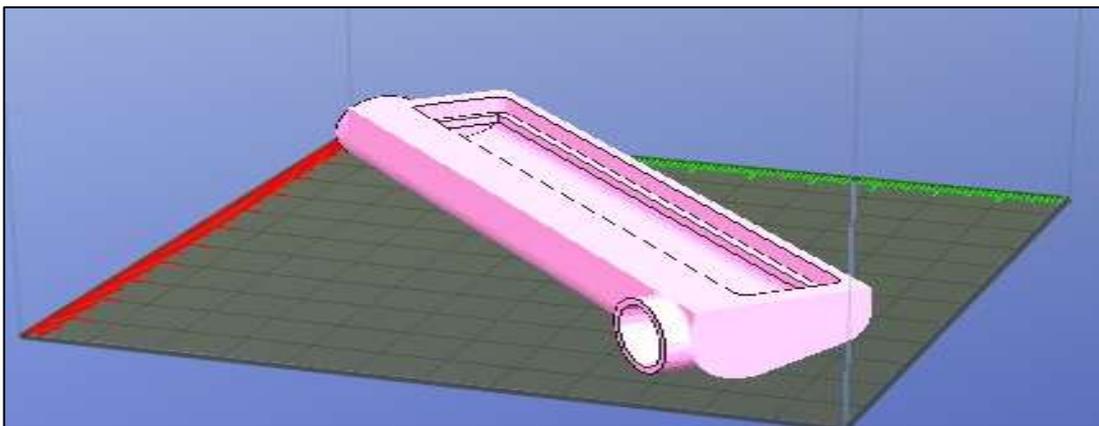


Fig 5. 3D Printing of Left Hand [LH] Header of Curved Shape Microchannel Heat Exchanger

3.4 Material Properties Used for The Geometry

The material characteristics of microchannel are given below.

Table 1: Material Properties

Sr. No.	Properties	Aluminum	Insulation Material
1	Thermal conductivity, k [W/m K]	237	0.2
2	Density, ρ [kg/m ³]	2700 kg/ m ³	300
3	Specific heat, Cp [J/kg K]	897	203

In evaluating materials for heat exchanger components, aluminum demonstrates superior thermal conductivity. Although aluminum has a higher density, its higher specific heat contributes to enhanced heat transfer efficiency. Radiators are typically made from aluminum due to its excellent thermal conductivity and lightweight nature, which aids in heat dissipation without adding excessive weight to the vehicle.

Table 2: Material properties of ABS Materials

Sr. No.	Property	Value
1	Young's Modulus [GPa]	2.28
2	Tensile Strength [MPa]	43
3	Flexural modulus [GPa]	2.48
4	Flexural Strength [MPa]	77
5	Density [g/cm ³]	1.0 - 1.05
6	Poisson Ratio	0.340

The above table shows material properties of ABS materials are characterized by specific values assigned to various properties.

3.5 Fixed Support of Left and Right Header

The more rigid type of connection or support is a fixed support. The member is unable to move or twist in any of the directions since it is constrained in all translating and rotations. The selected surface, edge, support, or point cannot be rotated or moved. a fixed support placed on the geometry's bottom surface.

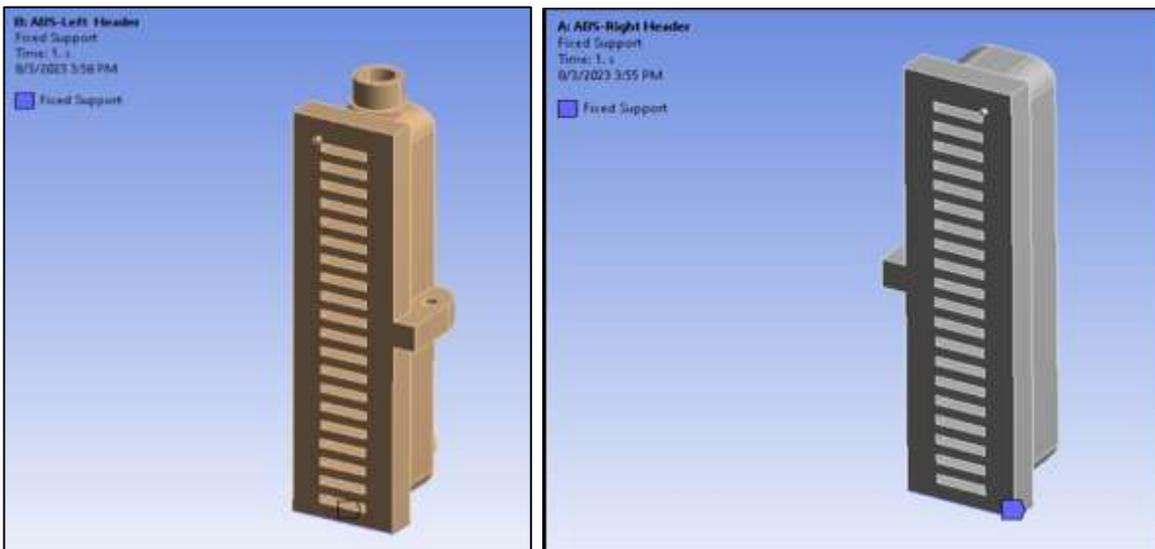


Fig.6 [a]: Left Header

Fig.6 [b]: Right Header

Fig.6. Fixed Support of Right and Left Header Geometry of Flat Plate Microchannel Heat Exchanger in Ansys

3.6 Graphical Results of Left and Right Header

Comparing the left and right headers of microchannel heat exchanger geometry is shown graphically in the findings.

Deformation of Left and Right Header [mm]

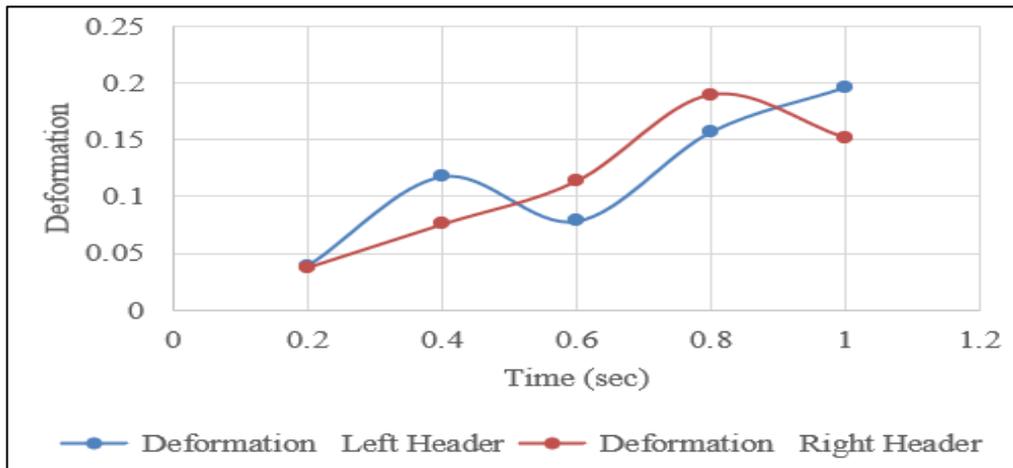


Fig.7: Deformation of Left and Right Header [mm]

The Left Header shows a deformation of 0.19625 mm at 86.8 degrees Celsius, while the Right Header shows a deformation of 0.18985 mm at the same temperature. As per the comparison of both Geometries, Deformation is maximum in Left Header Geometry and minimum in Right Header Geometry. So for the effective Geometry by comparing Deformation would be minimum so as compare to Right Header Geometry is effective.

Total Heat Flux of Left and Right Header [W/mm²]

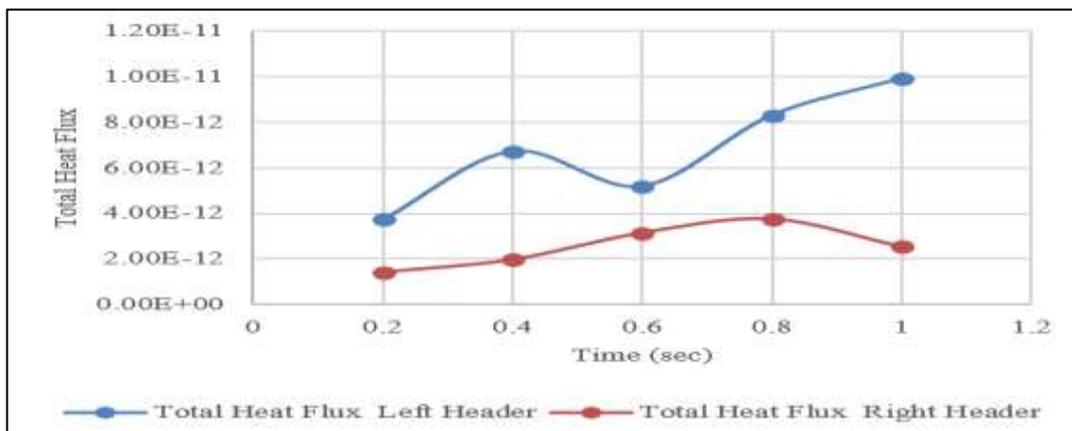


Fig.8: Total Heat Flux of Left and Right Header [W/mm²]

At a temperature of 86.8 degrees Celsius, the total heat flux observed in the Left Header Geometry is 9.90×10^{-12} W/mm², whereas the Right Header Geometry exhibits a total heat flux of 3.76×10^{-12} W/mm² at the same temperature. As per the comparison of both Geometries, Total Heat Flux is maximum in Left Header Geometry and minimum in Right Header Geometry. So for the effective Geometry deflection would be minimum so as compare to Left Header Geometry Right Header Geometry is effective.

3.7 Directional Heat Flux of Left and Right Header [W/mm²]

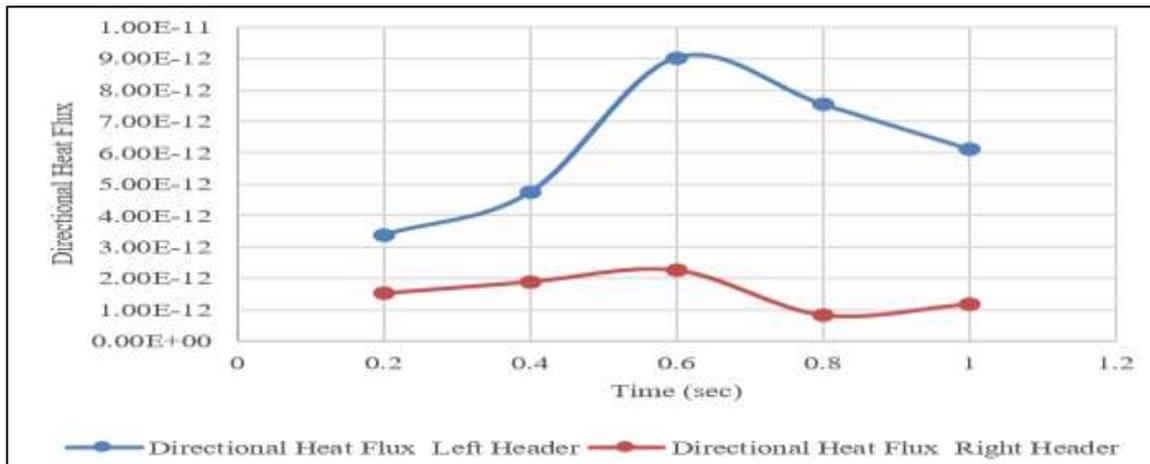


Fig.9: Directional Heat Flux [W/mm²]

At a temperature of 86.8 degrees Celsius, the directional heat flux observed in the Left Header Geometry is 9.02×10^{-12} W/mm², while the Right Header Geometry exhibits a directional heat flux of 2.26×10^{-12} W/mm² at the same temperature. The data shows that the directed heat transfer of the A microchannel Heat Exchanger's Left Header and Rt Header Geometries varies at the given temperature. According to the data, the directional heat flux of the Left Header Geometry is somewhat greater than that of the Left Header Geometry. Therefore, this difference in directional heat flux may imply that the Right Header Geometry is more effective at directing heat in a particular direction it towards a specific area compared to the Left Header Geometry.

5. Experimental Setup

5.1 Material Properties of Microchannel

The material properties of microchannel are given below in Table 3.

Table 3: Material properties of Microchannel

Sr. No	Properties	Aluminum	Insulation Material
1	Thermal conductivity, k [W/m K]	237	0.2
2	Density, ρ [kg/m ³]	2700	300
3	Specific heat, Cp [J/kg K]	897	203

The design of microchannel are given below in Fig 3. The material of the microchannel is aluminum. . The dimesions of microchannel is as per diagram shown below.

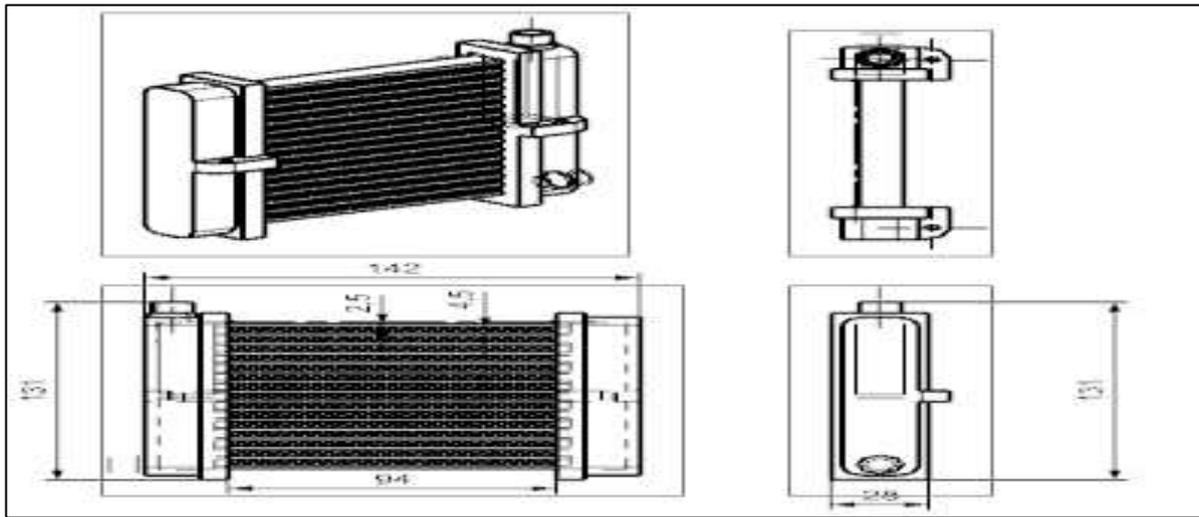


Fig.10: Design of Flat Plate Microchannel Heat Exchanger

5.2 Properties of water and Air

Characteristics of air and water are given below in Table 4.

Table 4: Properties of water and Air

Sr. No	Fluids	Thermal Conductivity	Specific Heat Capacity	Density	Viscosity
		K [W/m K]	Cp [J/kg K]	[kg/m ³]	kg/[m.s]
1	Water	0.6	4182	1000	0.001003
2	Air	0.024	1.012	1.225	1.81 × 10 ⁻³

5.3 Flow Measurement of Air

Specifications of Variable blower:

Manometer of Water = 600 mm

Air Volume = 2.3 m³/min = 138 m³/Hr

Power Input = 500 Watt

The table for conversion of air flow are given below in Table 5.

Table 5: Table for conversion of air flow

Sr. No	Blower Setting	Discharge [m ³ /hr]	Air Velocity [m/sec]	Mass Flow Rate [kg/sec]
1	STAGE-1	138	6.18	0.145666667
2	STAGE-2	117.3	5.25	0.123816667
3	STAGE-3	100.39	4.49	0.105967222
4	STAGE-4	71.27	3.19	0.075229444
5	STAGE-5	60.58	2.71	0.063945556
6	STAGE-6	51.5	2.3	0.054361111

The above table shows the observations for fan speed of flat face microchannel heat exchanger from the above table, as the stage setting of blower increases from 1 to 6 the discharge, air velocity and air flow rate also increases.

Governing Equation,

$$Q = U \times A \times \theta = m \times Cp \times \Delta T \quad \dots\dots (5.1)$$

Section of Area by CAD Daigram.

6. Layout of Experimental Setup

The production of the test rig and microchannel heat exchanger needed for experimental validation and analysis. The components of the test trial unit and specimen will be manufactured, fabricated, and assembled using the appropriate equipment and techniques. The layout of experimental setup are given below in Fig 11.

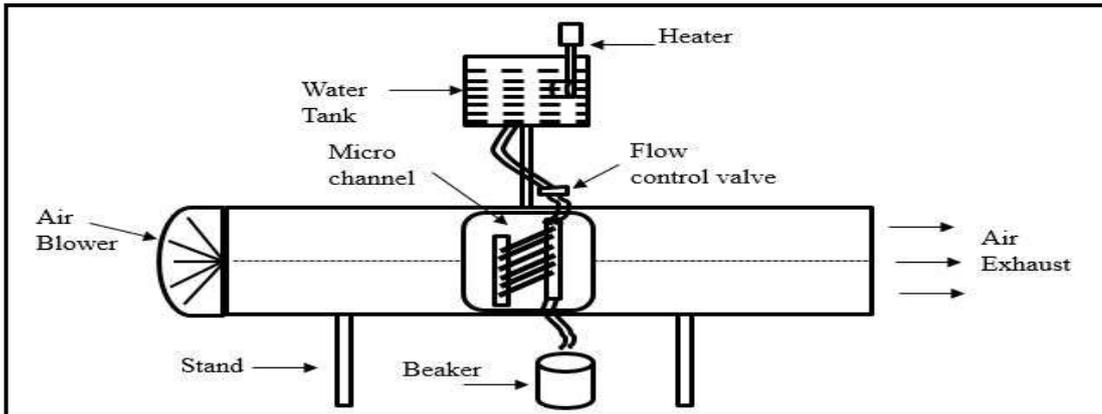


Fig.11: 2D Layout of Experimental setup

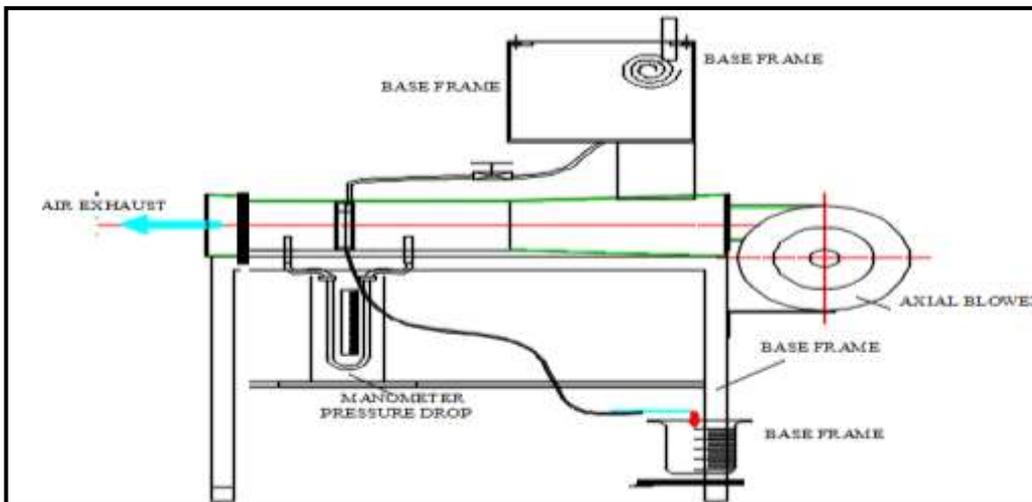


Fig.12: Layout of Experimental setup

6.1 2D Geometry of the Flat Microchannel Heat exchanger

The actual assembly of 3D Printed Header of Flat Plate Microchannel Heat Exchanger for application of Raditor as shown in Fig 13.



Fig 13: Assembly of 3D Printed Right Hand [RH] Header of Flat Plate Microchannel Heat Exchanger for application of Raditor

The actual assembly of 3D Printed Header of Flat Plate Microchannel Heat Exchanger with aluminum coating for application of Raditor as shown in Fig 14.



Fig 14: Assembly of 3D Printed Right Hand [RH] Header of Flat Plate Microchannel Heat Exchanger with aluminum coating for application of Raditor

6.2 Assembly of 3D Printed Header of Curved Plate Microchannel Heat Exchanger for application of Raditor

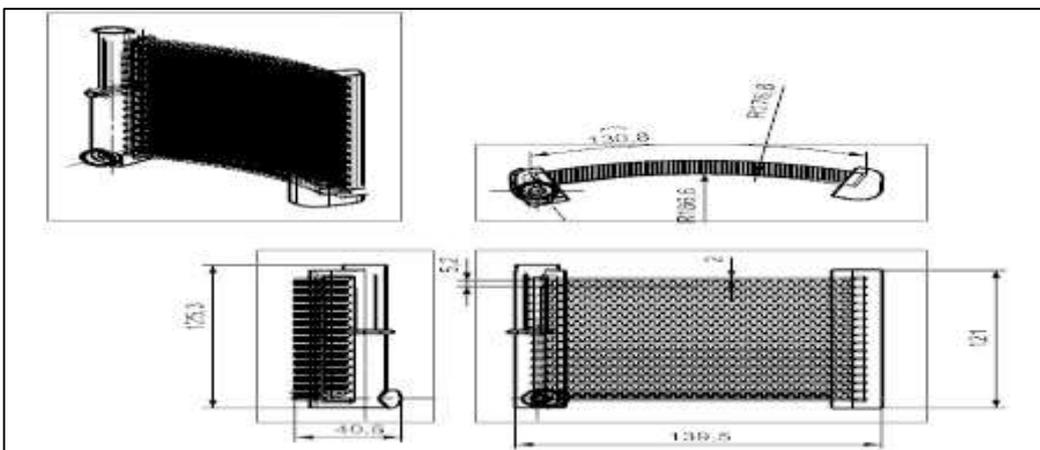


Fig 15: Curved Plate Heat Exchanger Microchannel Design and Dimensions

Without Right Hand [RH] Header and Left-Hand [LH] Header Curved Plate Microchannel Heat Exchanger for application of Raditor as shown in Fig 16.



Fig 16: Actual Curved Shape Microchannel Heat Exchanger

The actual assembly of 3D Printed Right Hand [RH] Header and Left Hand[LH] Header of Curved Plate Microchannel Heat Exchanger for application of Raditor as shown in Fig 17.



Fig 17: Assembly of 3D Printed Right Hand [RH] Header and Left Hand [LH] Header of Curved Plate Microchannel Heat Exchanger for application of Raditor

6.3 Geometry of Flat Face Microchannel

Using the Unigraphics NX-8 Solid Geometry Tool, the Flat Shape Microchannel Heat Exchanger's 3D geometry was created using the dimensions shown above. The pieces' 3D geometry was further exported as STL files, which were then used as input by the 3D printing UP Mini software.

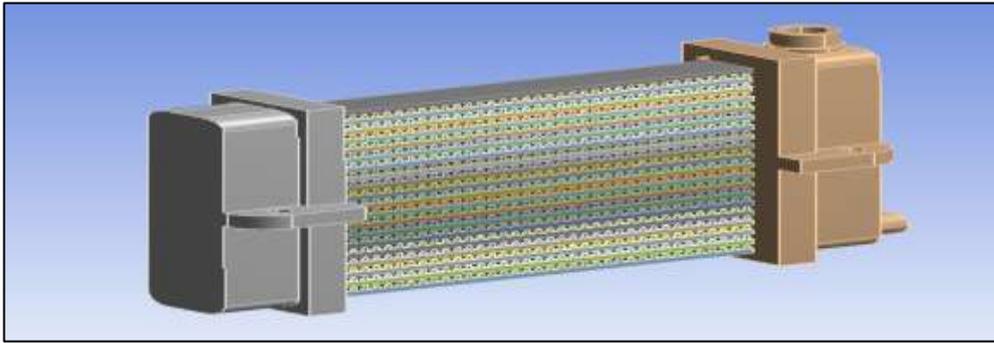


Fig 18: Geometry of Flat Face Microchannel

7. Thermal Analysis by Using Ansys

The main objective of the thermal analysis:

Understanding microchannel heat exchangers is essential since they are used in the building of all automobiles, aeroplanes, and home appliances, as well as in combinations. The main objective is Analysis of Flat Plate and Curved Face Microchannel Heat Exchanger using FEA Method.

Basic steps of finite element analysis:

There are three fundamental phases in this process:

- Pre-Processor [Building the Geometry [or] Geometry]
- Solution [Applying loads & solving]
- Post Processor [Reviewing the results]

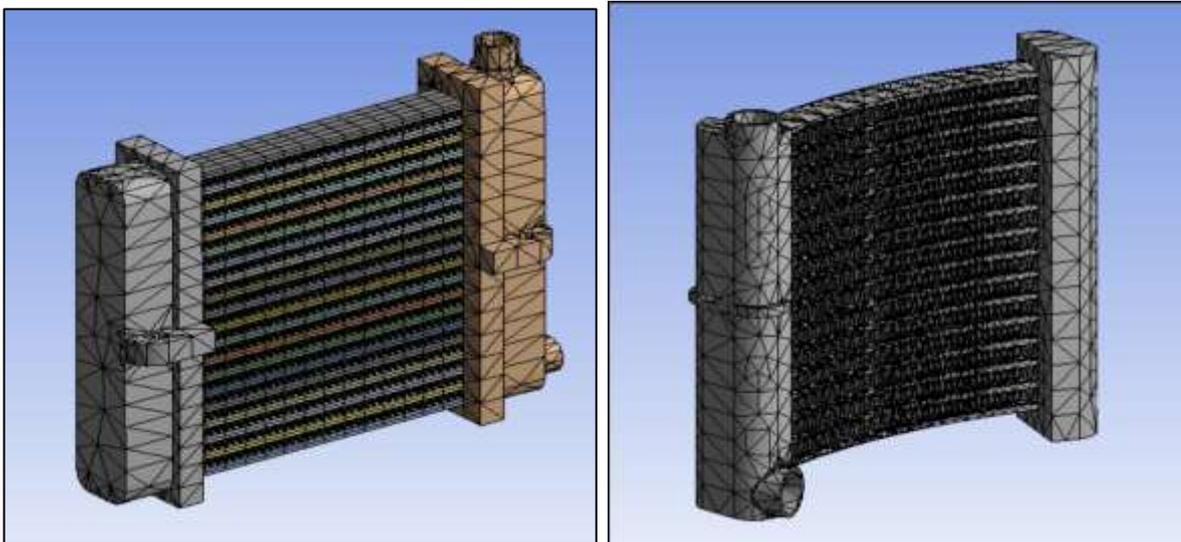


Fig 19: [a]: Meshing of Flat Face Microchannel [b]: Meshing of Curved Face Microchannel

Fixed Support of Flat Face and Curved Face Microchannel

Constant Support restricts the member to a single plane of movement and revolution in all transformations and spins]. One end is fixed [All D.O.F.] in the geometry.

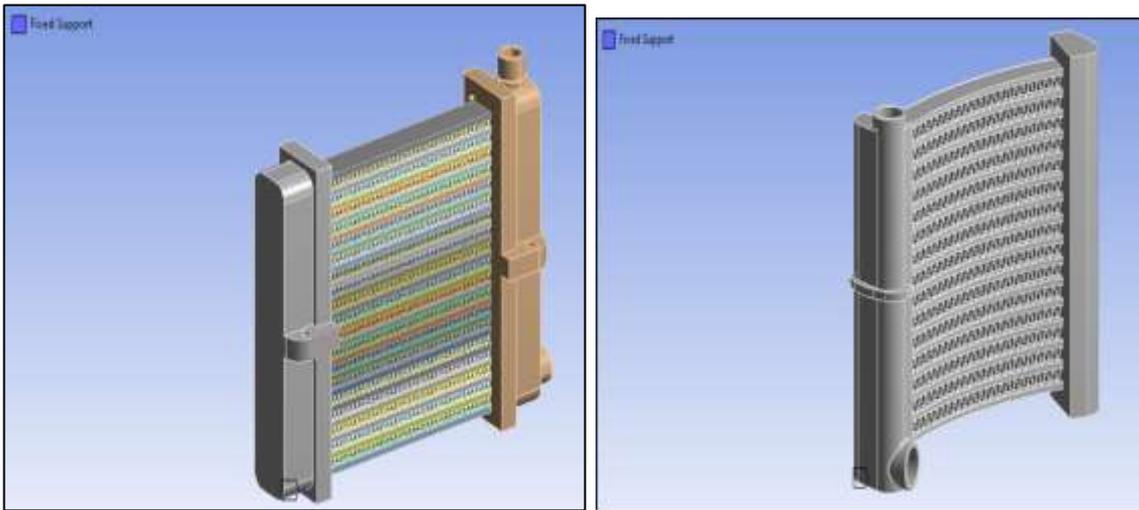


Fig 20: [a]: Fixed Support of Flat Face Microchannel [b]: Fixed Support of Curved Face Microchannel
CFD Analysis and Results

Temperature of Flat Face and Curved Face Microchannel

The maximum temperature in Figure Show CFD of Flat Geometry is 5120 K, whereas the temperature in Curved Geometry is 86 K.

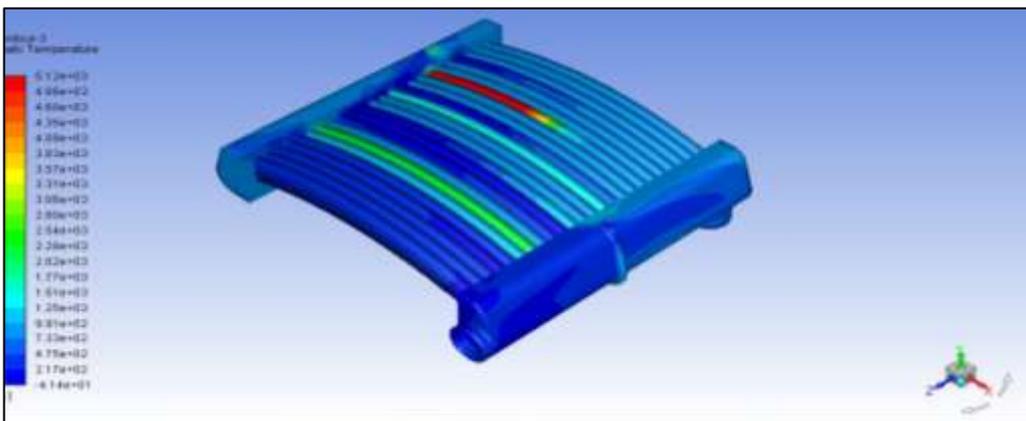


Fig 21: Temperature results in CFD analysis for Curved Face
Density of Flat Face and Curved Face Microchannel

In fig Show CFD of the maximum Density occurs in Flat Geometry is 982Kg/m³ and Curved Geometry Density is 998.2Kg/m³.

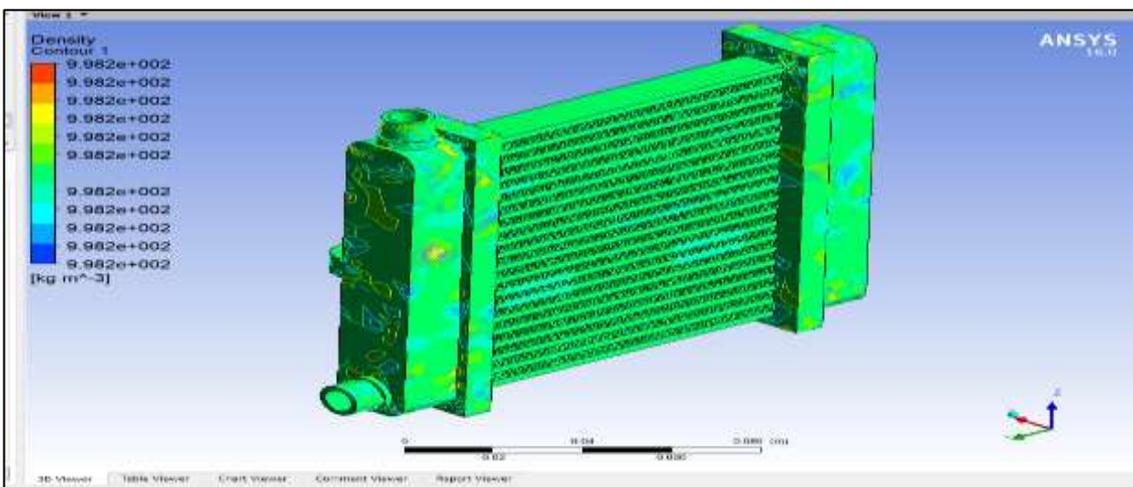


Fig 22: Density results in CFD analysis for Flat Face

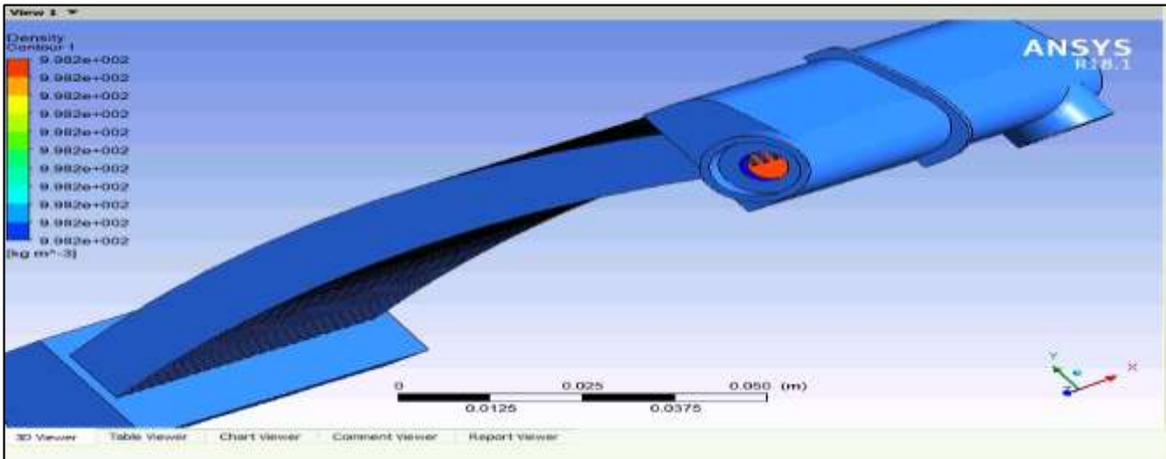


Fig 23: Density results in CFD analysis for Curved Face

Pressure of Flat Face and Curved Face Microchannel

The maximum pressure in Figure Show CFD of Flat Geometry is 43900 Pa, whereas the maximum pressure in Curved Geometry is 1.020×10^{13} Pa.

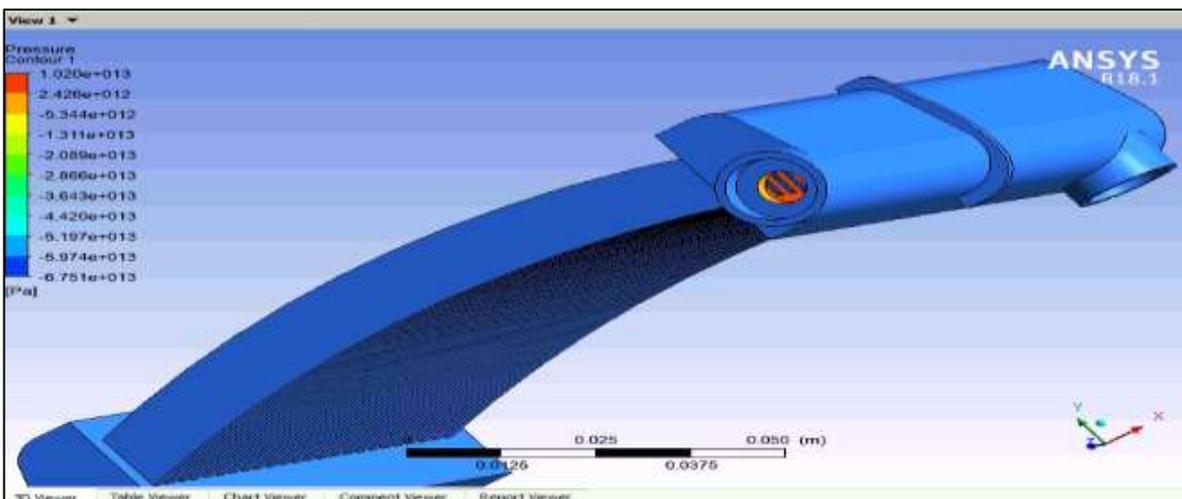


Fig 24: Pressure results in CFD analysis for Curved Face

Wall Shear of Flat Face and Curved Face Microchannel

In fig Show CFD of Curved Geometry the maximum Wall Shear occurs 111.5 Pa and Flat Geometry Wall Shear 8.753×10^6 Pa.

8. Results and Discussion

Temperature of Flat Face and Curved Face Microchannel

The figure above illustrates both curved and flat geometry. Data on temperature is shown in the latter. According to the figures, which are expressed in scientific notation, the Curved Geometry has a temperature of 5,120 units, which is much greater than the Flat Geometry's 2,000 units. According to the temperature simulations or measurements shown in these figures, the Curved Geometry is much warmer than the Flat Geometry, indicating a significant temperature difference between the two Geometries.

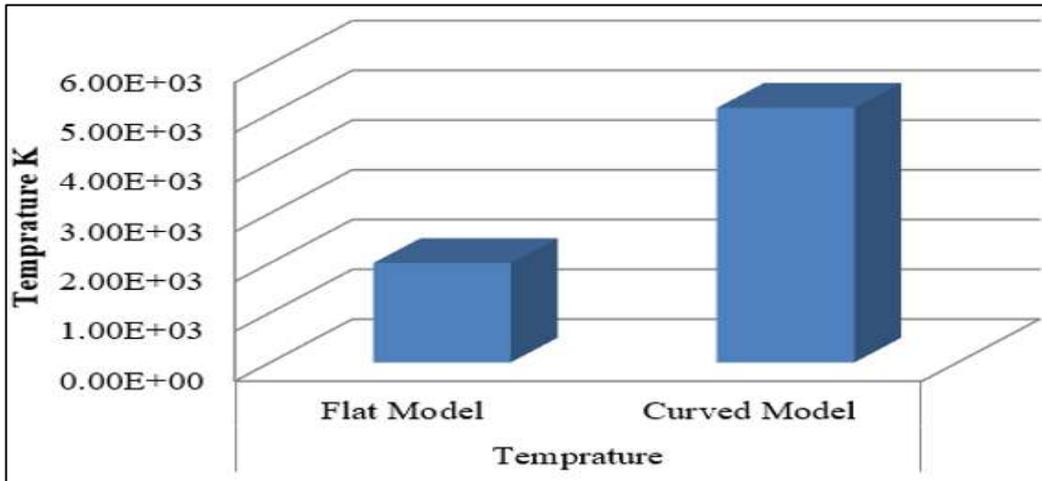


Fig 25: Temperature comparison of Flat and Curved Face Microchannel

Density of Flat Face and Curved Face Microchannel

Both flat and curved geometry are shown in the above figure. In terms of scientific notation, the density of both Geometries is about 998 units, or 9.98 10². This suggests that the density values of the two Geometries are identical and that there is no discernible difference between them.

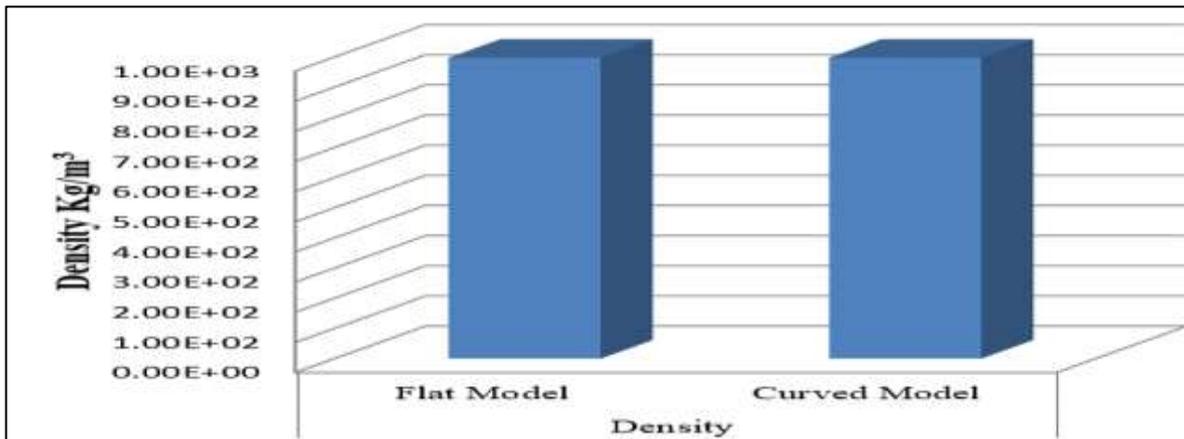


Fig 26: Density comparison of Flat and Curved Face Microchannel

Pressure of Flat Face and Curved Face Microchannel

Both flat and curved geometry are shown in the above figure. In terms of scientific notation, the density of both Geometries is about 998 units, or 9.98 10². This suggests that the density values of the two Geometries are identical and that there is no discernible difference between them.

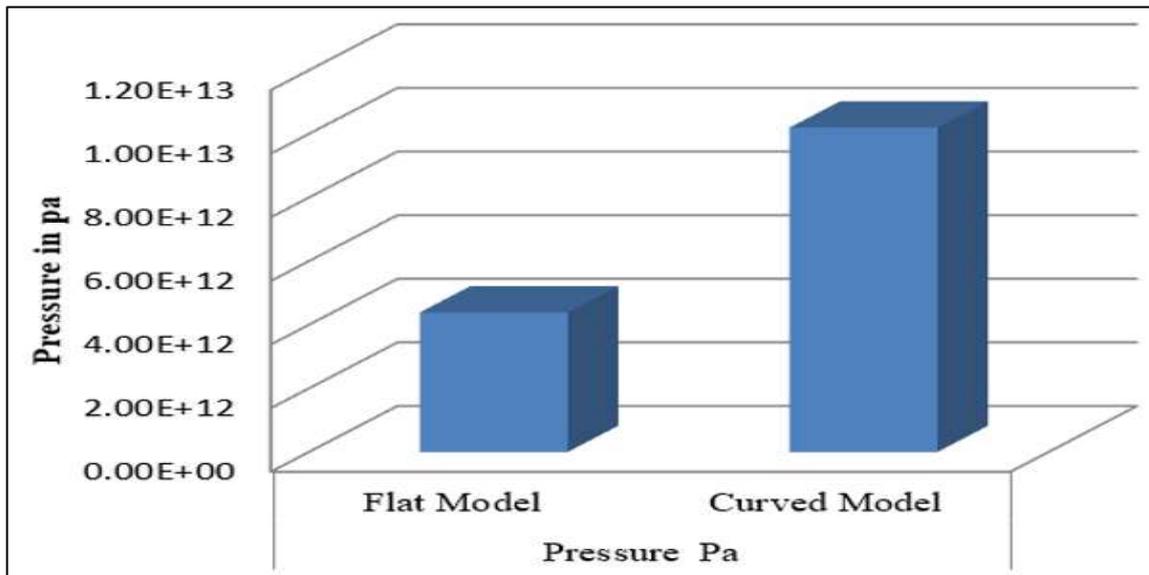


Fig 27: Pressure comparisons of Flat and Curved Face Microchannel

Wall Shear of Flat Face and Curved Face Microchannel

Curved geometry and flat geometry wall shear Pascals [Pa] are shown in the above figure. In technical terms, the Curved Geometry has a wall shear of around 8.75 million Pascals [8.75E106], which is much higher than the Flat Geometry's 2.95 million Pascals [2.95E106]. Based on the data, it seems that the Curved Geometry and the Flat Geometry have significantly different wall shear, indicating that distinct forces are acting on their various surfaces.

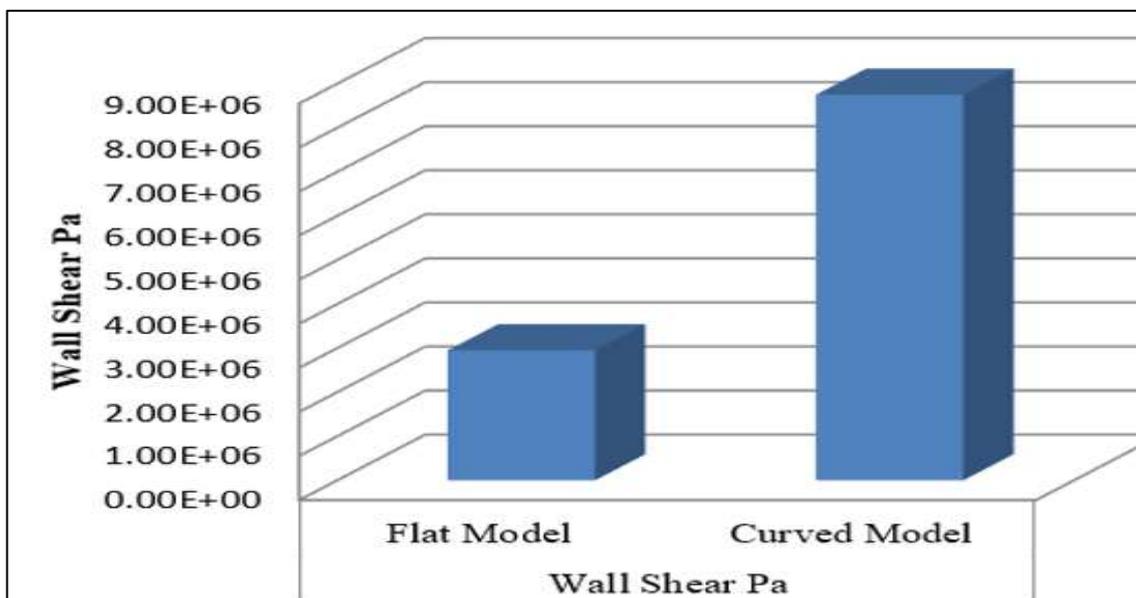


Fig 28: Wall Shear comparison of Flat and Curved Face Microchannel

Conclusion

The design and functionality of microchannel heat exchangers for high-performance engines, such as those used in two-wheelers, may be improved by using Additive Manufacturing (AM) technologies, particularly Fused Deposition Modelling (FDM), as this research shows. Traditional heat exchangers, including the cross-flow design used in many cooling systems, often face limitations in terms of efficiency, compactness, and ability to handle high heat loads, especially in engines above 200cc. Microchannel heat exchangers created by additive manufacturing (AM) may allow for innovative designs to enhance heat transfer and minimize air flow resistance. Research consists of thermal, CFD, and empirical studies comparing flat and curved face microchannel heat exchangers and prototypes using AM to develop

new designs for microchannel heat exchangers. Curved face microchannel heat exchangers demonstrate improved heat transfer and pressure loss compared to flat face microchannel heat exchangers. Material selection (e.g. ABS and PETG) was critical in defining the deformation, stress, and safety factor of the structure, and ABS exhibited the highest safety factor. These results show that AM, when paired with creative configurations, may significantly improve heat exchanger design, which will improve engine cooling and overall efficiency.

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