Design and Thermal Analysis of an Automotive Radiator for enhancing Flow Uniformity using CFD

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Abstract - A radiator is a device that reduces the amount of heat generated by internal combustion engines. These heat exchangers are widely used to cool the engine block while maintaining the optimal temperature. Coolant is permitted to flow through channels in the engine block. Recent innovations have revolutionized the way manufacturers choose materials for vehicle radiators, such as aluminium. Many of the large power supply engines seen in supercars, locomotives, and airplanes necessitate a long-lasting radiator. To increase the radiator's life, the flow homogeneity in the radiator tank must be improved. To achieve improved flow homogeneity, a three-pass radiator is used, which has better impact on radiator performance. The design parameters of an automotive radiator have been optimised by lowering the tube size of single-pass radiator and transforming it to a three-pass radiator. The ANSYS FLUENT software is used to carry out the CFD analysis and Thermal analysis. The design will be dependable, lighter, and more efficient.

Keywords: automotive radiator, heat exchangers, CFD analysis, thermal analysis, ANSYS FLUENT

1. Introduction

In terms of performance, fuel economy, aesthetics, and safety, the automobile industry is constantly in a competitive position to deliver the greatest vehicle designs. Radiators, air conditioner condensers, and so forth are air-cooled heat exchangers that have a considerable influence not only on product weight, but also on the development of front-end modules, which has a profound effect on the aerodynamic performance of a car. In order to achieve the greatest possible design balance in terms of performance, size or shape, and weight, improved procedures are required for given challenges.

An intake tank, an exit tank, and a core are the three sections of an automotive radiator. Two sets of passageways, tubes, and fins make up the core. The radiator core is commonly made out of a flat metal tube with zigzag aluminium fins connecting it. In engine cooling systems, two types of operating fluid are used: air and coolant. The coolant's purpose is to circulate and absorb heat throughout the engine block. Then, into the radiator tank, hot coolant is been injected. Coolant fluid enters the radiator core through the tubes. When the fluid returns to the counter tank, the majority of the heat is transmitted to the radiator tube, which then distributes the heat to the fins across each row of tubes. Heat is transmitted from the coolant fluid to the air as it passes through the radiator. The role of air is to collect heat from the fluid and returns to the radiator at lower temperature than it was when it first arrived.

CFD analysis has been utilised to solve a range of thermodynamic and heat transfer problems, including evaluating heat exchanger performance. Computational Fluid Dynamics (CFD), in addition to analytical and experimental methods, has become an important tool for solving and analysing fluid dynamics and heat transfer as a result of breakthroughs in engineering capabilities and computational information technology over the last two decades. Because of its use in the design process, CFD applications in industries including automotive and aerospace have increased in recent years. Commercial CFD software packages like as Autodesk CFD, Simscale, and Ansys Fluent have arisen as the industry's usage of CFD has grown.

The effect of varying the length of the inlet and outflows on the pressure drop and the distribution of the maximum flow velocity were combined using a two-dimensional model of the water tank and radiator pipes, with the Golden Section used to find the optimal exit location for a given one, that is the height of the entryway, according to Laila Guessous and Sridhar Maddipatla [1]. According to R. Paul Linga Prakash, M. Selvam, A. Alagu Sundara Pandian, S. Palani, K. A. Harish [2], The Nozzle effect provides additional cooling to the engine by reducing pressure, increasing speed, and lowering the temperature, which is directly proportional to the pressure, depending on the combined gas law. As a consequence, the radiator and engine's cooling efficiency is enhanced, and the engine's life is extended. The suggested radiator's efficiency increased by 5.37 percent.

Automotive radiators are constructed with automotive engines in mind, and mass flow rates along the tubes are calculated using CFD analysis. To obtain greater uniformity in flow rates across the tubes, the single pass radiator design is revised by lowering the tube size and reconstructed to a three-pass radiator. Thermal analysis is carried out to validate that the three-pass radiator improves flow rates over the basic radiator. The analysis is done in ANSYS FLUENT software. The objectives of this research were:

1. Changing tube size to maintain flow uniformity.
2. To Find Mass flow rate through each tube.
3. To Find Total heat transfer.
4. To Report coolant temperature at outlet.
5. To analyze mass flow distribution in tube.
6. To reduce tube corrosion and contamination.
7. To Extend the Life of the Radiator.

2. Methodology

2.1. Procedure

1. Problem Definition: To improve flow uniformity in radiator by converting single pass type radiator into three-pass type by reducing tube size.
2. Geometry Preparation: Prepared geometry of a Radiator in Catia V5 software.
3. Geometry Cleanup: Geometry cleanup, water tight geometry is prepared for meshing.
4. Meshing: Meshing with proper naming for inlet, outlet and wall is carried out with polyhedral elements, quality is less than 0.85 volumetric skewness.
5. Model setup and Analysis is done in fluent solver.
6. CFD Post is used for Results and post processing.
7. Initially results are calculated for single pass, later same method is applied for three-pass.
8. Results for both the radiator models are compared.

2.2. Flow Uniformity

A radiator's performance and service life may be assessed using a variety of approaches. Initially, CATIA software was utilised to create a base radiator. Performance is measured using the flow non-uniformity coefficient, which is calculated with the purpose of enhancing pipe flow uniformity.

Flow non-uniformity coefficient: To avoid contamination and pipe corrosion caused by underflow, each radiator pipe should have the same mass flow rate as the rest of the radiator pipes.

$$\dot{m}_{t,ideal} = \frac{\dot{m}}{K}$$

where K is the total number of pipes or tubes and $\dot{m}$ is the total mass flow through the radiator. The pipe mass flow rate fraction is used to calculate the departure of a single radiator pipe from this ideal behavior.

$$c_k = \frac{\dot{m}_k}{\dot{m}} \qquad k=1,...,K$$

The mass flow rate through the pipe with the number k is denoted by $\dot{m}_k$. The ideal value for c_k is 1/K. However, using a single objective function to determine how evenly the heat exchanger flow is shared over several pipes would be more convenient. This coefficient c_f is the modulus of the divergence of each tube's mass flow rate from its ideal mass flow rate, normalised to the tube's ideal mass flow rate, and represented as follows:

$$C_f = \frac{\sqrt{\sum_{k=1}^{K} \left(\dot{m}_k - \dot{m}_{t,ideal}\right)^2}}{\dot{m}_{t,ideal}}$$

c_f should be exactly equal to zero for an optimal flowrate distribution. If one or more tubes have zero flowrate, c_f should be more than one (>1). As a result, a value as near to zero as possible is preferred. The optimization strategy is depicted in figure 1.

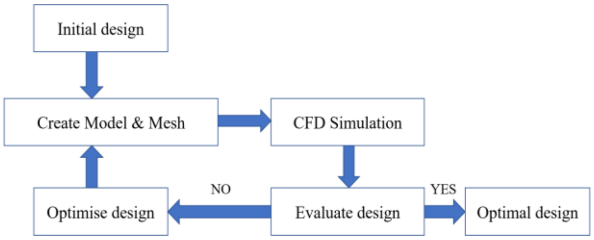


Figure 1. Optimization strategy

3. Design and Analysis of Radiator

3.1. Design Considerations

1. CATIA V5 R21 software was used to design the radiator models.

2. Radiator models is made up of aluminum consists of two rows, each with 42 tubes.

3. Radiator models are designed with a crossflow design.

4. Ansys Fluent software is used to do the Flowrate and Thermal analysis for CFD study.

5. Two types of radiators are designed as shown in Table I.

6. Dimensions of Radiator are shown in Table II.

Table I. Radiator types under consideration

S. No	Geometry
1	Single Pass Radiator
2	Three Pass Radiator

Table II. Dimensions of Radiator

Parameters	(mm)
Inlet diameter	31.75
Outlet diameter	44.45
Length of tube	712
Width of tube	25.4
Tube height	1.8

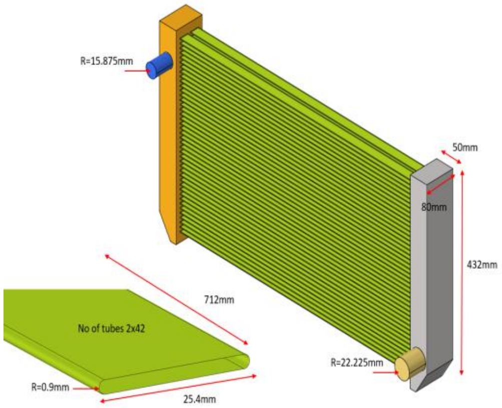


Figure 2. Geometry of Single Pass Radiator

3.2. Meshing

Meshes can also be categorized according to the size and type of elements they include. Meshing is classified based on connectivity and based on elements. Elements-based classification consists of Mesh shapes that can be 2-dimensional (2D) or 3-dimensional (3D) depending on the type of analysis and the requirements of the solution. Triangles and rectangles are typical features of 2D. All the mesh nodes in the 2D mesh lay in the same plane. The 2D mesh node is usually on an XY plane, but may be on another Cartesian or user-defined plane. Quadrilaterals and triangles are the most common 2D mesh elements.

Nodes in a 3D mesh are not required to lie on a single plane. Hexahedra, tetrahedral, square pyramids and extruded triangles are the most common 3D mesh elements. Polyhedral elements, which can be constrained by any number and type of faces, are also supported by several modern solvers. Even though all 3D elements are defined by 2D elements, 3D meshes have clearly exposed 2D elements at their edges.

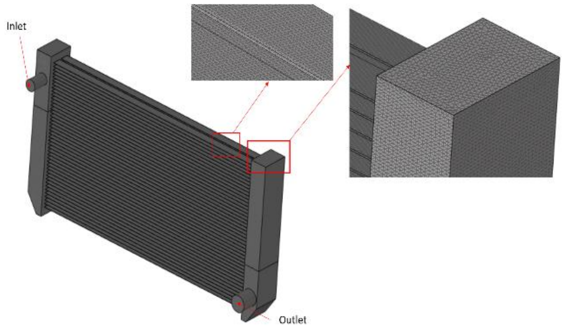
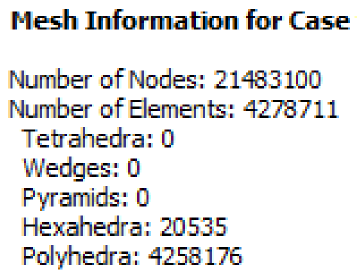


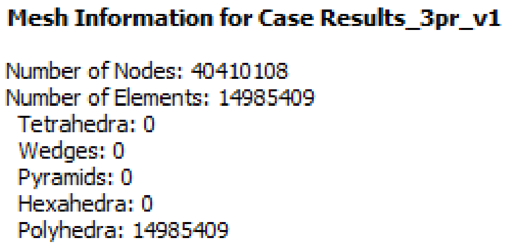
Figure 3. Meshing of Radiator



Mesh Information for Case

Number of Nodes: 21483100
Number of Elements: 4278711
Tetrahedra: 0
Wedges: 0
Pyramids: 0
Hexahedra: 20535
Polyhedra: 4258176

Figure 4. Mesh Information for Single pass Radiator



Mesh Information for Case Results_3pr_v1

Number of Nodes: 40410108
Number of Elements: 14985409
Tetrahedra: 0
Wedges: 0
Pyramids: 0
Hexahedra: 0
Polyhedra: 14985409

Figure 5. Mesh Information for three pass Radiator

3.3. Flow Rate Analysis

3.3.1. Boundary Conditions:

- Velocity inlet: 0.153741 m/s
  The rate is estimated using a 0.12 LPM volume flow rate inside the radiator.
- Pressure at outlet = 0pa
- Walls: There is no risk of slipping.
- Every surface is a wall at this point.

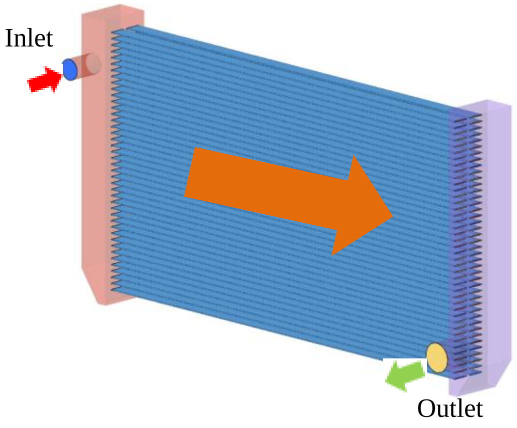


Figure 6. CFD Model of Single Pass Radiator

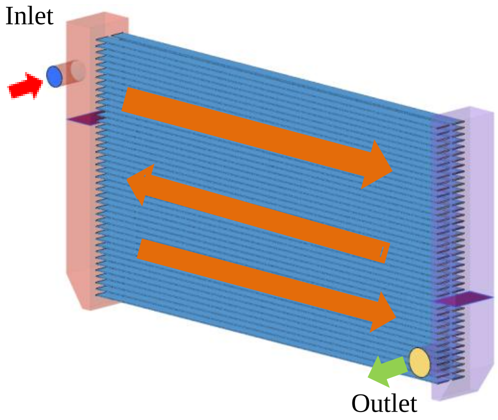


Figure 7. CFD Model of Three Pass Radiator

3.3.2. Velocity contours:

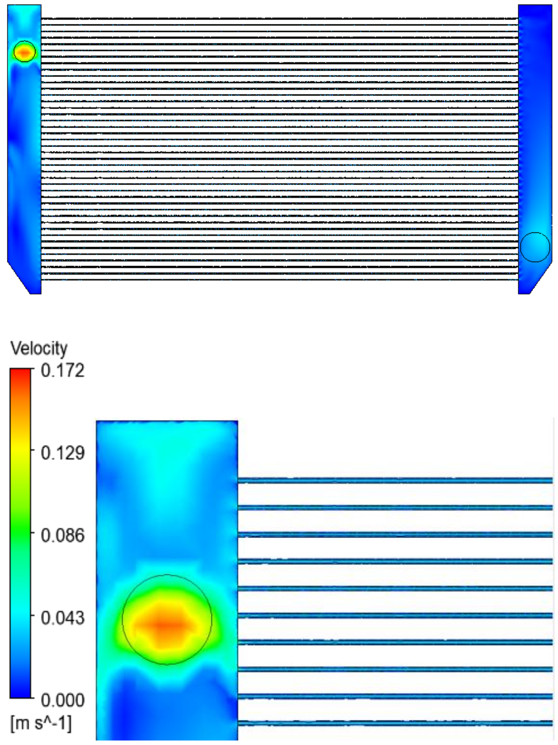


Figure 8. Velocity contour of a single pass Radiator

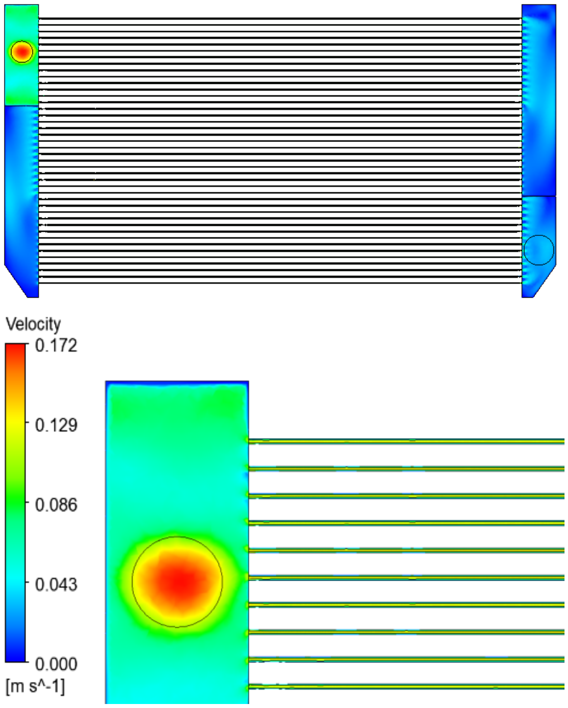


Figure 9. Velocity contour of a three pass Radiator

The velocity contour is performed to verify the change in velocity across the tubes and we can observe that there is an improvement in velocity of flow from the above contours (Figure 8 and Figure 9)

3.3.3. Pressure contours:

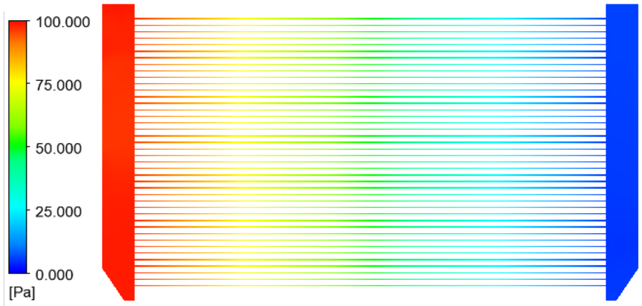


Figure 10. Pressure contour of a single pass Radiator

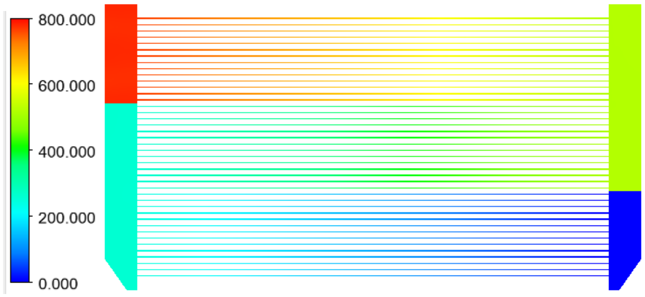


Figure 11. Pressure contour of a three pass Radiator

Pressure contours are generated to verify the improvements in pressure drop and that can be observed from the above contours generated (Figure 10 and Figure 11).

3.3.4. Streamlines:

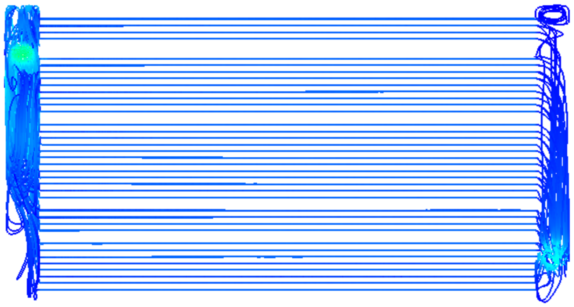


Figure 12. The Streamlines of a single pass Radiator

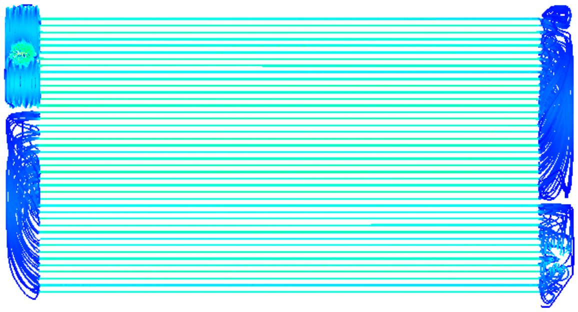


Figure 13. The Streamlines of a three pass Radiator

Streamlines are generated to verify flow uniformity and from the above contours (Figure 12 and Figure 13), we can observe the improvement in uniform flowrate.

3.4. Thermal Analysis

3.4.1. Boundary Conditions

Table III. Boundary conditions

Properties for Oil-Sand erosion	
Mass flow rate at inlet	0.119784 Kg/sec
Temperature at inlet	110 ^{0}C
Pressure at outlet	0 Pa
Heat Flux at tube surface	30 Watt/m^2

3.4.2. Material Properties

Table IV. Materials and their Properties

Material Name	Density (Kg/m3)	Thermal Conductivity (w/m-k)	Specific Heat (J/Kg-K)	Viscosity (Kg/m-sec)
Aluminium	2719	202.4	871	-
Water	998.2	0.6	4182	0.001003

3.4.3. Temperature contours on wall of radiator

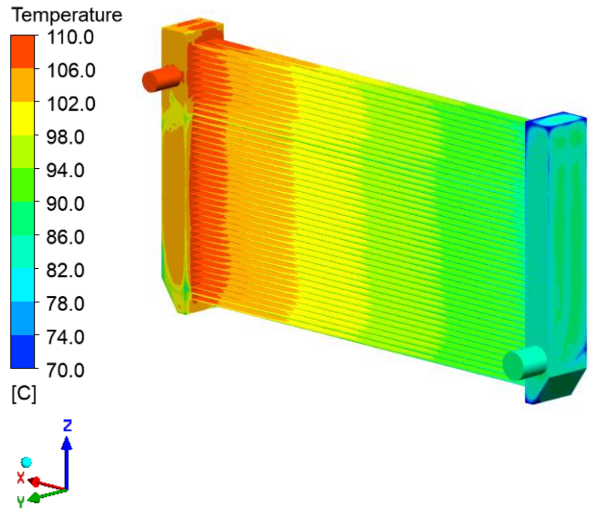


Figure 14. Temperature contour of a single pass radiator

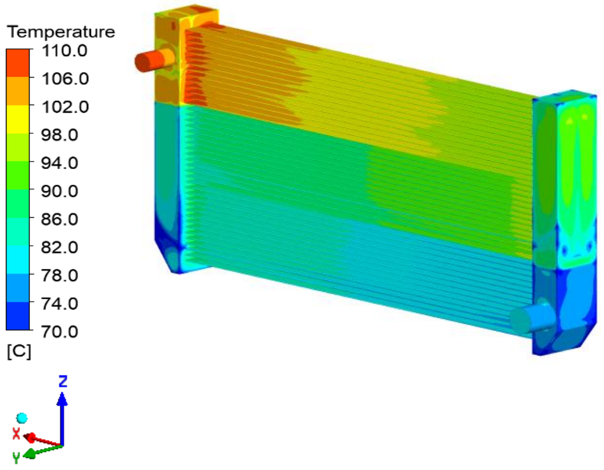


Figure 15. Temperature contour of a three pass radiator

Outlet temperature for three pass model is less compared to single pass that can be observed from above contours (Figure 14 and Figure 15).

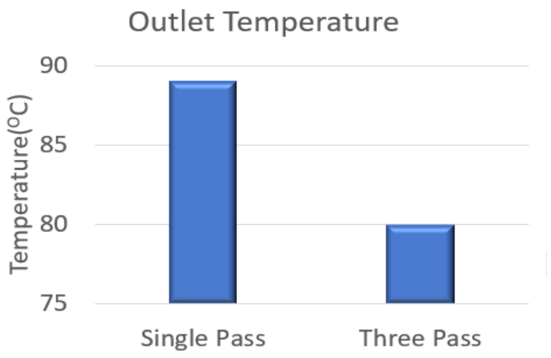


Figure 16. The Graph shows the temperature drop between single pass type radiator and three pass type radiator

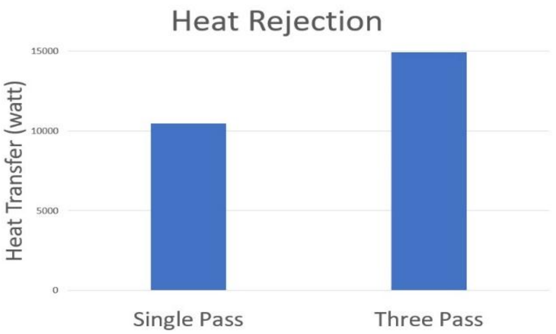


Figure 17. The Graph shows the Heat Rejection Rate between single pass type radiator and three pass type radiator.

4. Calculations

4.1. Flow Non-Uniformity Coefficient Calculation

4.1.1. For Single pass Radiator

The mass flow rates obtained for Base Radiator is
$\dot{m}_{t,ideal}$ = 0.086

$$C_f = \frac{\sqrt{\sum_{k=1}^{K} \left(\dot{m}_k - \dot{m}_{t,ideal}\right)^2}}{\dot{m}_{t,ideal}}$$

$$\sum_{k=1}^{K} \left(\dot{m}_k - \dot{m}_{t,ideal}\right)^2 = 9.15\text{E-05}$$

$$\sqrt{\sum_{k=1}^{K} \left(\dot{m}_k - \dot{m}_{t,ideal}\right)^2} = 0.010$$

$$C_f = 0.112$$

4.1.2. For Three-pass Radiator

The mass flow rates obtained for Base Radiator is

$\dot{m}_{t,ideal}$ = 0.257

$$C_f = \frac{\sqrt{\sum_{k=1}^{K} \left(\dot{m}_k - \dot{m}_{t,ideal}\right)^2}}{\dot{m}_{t,ideal}}$$

$$\sum_{k=1}^{K} \left(\dot{m}_k - \dot{m}_{t,ideal}\right)^2 = 1.49\text{E-04}$$

$$\sqrt{\sum_{k=1}^{K} \left(\dot{m}_k - \dot{m}_{t,ideal}\right)^2} = 0.012$$

$$C_f = 0.048$$

4.2. Theoretical Calculation of Total Heat Transfer Rate

4.2.1. For Single Pass Radiator

$$Q = m * C_p * \Delta T$$

Where, Q is Total Heat Transfer Rate
C_p is Specific Heat, for water $C_p = 4.187$
ΔT is Change in temperatures of inlet and outlet

$$Q = 0.119784 * 4.187 * (110 - 89)$$
$$Q = 10.532247768\ KW$$
$$Q = 10532.247768\ watt$$

4.2.2. For Three Pass Radiator

$$Q = m * C_p * \Delta T$$

Where, Q is Total Heat Transfer Rate
C_p is Specific Heat, for water $C_p = 4.187$
ΔT is Change in temperatures of inlet and outlet

$$Q = 0.119784 * 4.187 * (110 - 80)$$
$$Q = 15.04606824\ KW$$
$$Q = 15046.06824\ watt$$

4.3. Observations from Thermal Analysis

Table V. Outlet coolant temperatures and Heat Rejection rate obtained from thermal analysis

Type of Radiator	Inlet coolant temperature (⁰C)	Outlet coolant temperature (⁰C)	Heat Rejection (watt)
Single-Pass Radiator	110	89	10473.52
Three-Pass Radiator	110	80	14929.632

5. Results

1. Flow Non-Uniformity coefficient has reduced by 0.064.
2. In both Single pass and three pass models' coolant inlet temperature is same i.e., 110 ⁰C.
3. Outlet temperature of coolant is 89 ⁰C for single pass and 80 ⁰C for three pass radiator model.
4. Theoretical calculation of Total Heat Transfer Rate in single pass radiator is 10532.24 watt and Total Heat Transfer Rate in three pass radiator is 15046.06 watt.
5. Thermal Analysis observations of Total Heat Rejected in single pass radiator is 10473.52 watt and Total Heat rejected in three pass radiator is 14929.63 watt.

6. Conclusions

According to the findings in flow rate analysis, the C_f value of three pass radiator is reduced by 57% when compared to the single pass radiator. The drop in C_f value shows the increase in flow uniformity along the tubes in three pass radiator. As a result, the flow homogeneity of three pass radiator is improved which increases the life time of radiator and prevents tube corrosion and contamination.
Thermal analysis results a temperature drop of 21^{0}C for single pass Radiator and 30^{0}C for three pass Radiator. A difference in temperature drop of 9 ^{0}C is observed for three-pass radiator compared to single pass radiator. The total heat transfer rate is increased by 42% in three pass radiator compared to single pass radiator. As three pass model has more heat rejection rate and obtained less coolant temperature at outlet, we can conclude that three pass radiator is better and preferable than single pass radiator.

7. Future Scope

The next part of this research will likely focus on fins with various shapes. Fins plays an important role in improving heat transfer rate. Using fins with different geometries in three-pass radiator would improve efficiency of radiator.

8. References

[1] Improving Radiator Design with Shape Optimization, Proceedings of the IMECE2002 ASME International Mechanical Engineering Congress and Exhibition, New Orleans, Louisiana, 17-22 November 2002. IMECE2002-33888

[2] IC Engine Cooling System Radiator Design and Modification to Improve Efficiency and Lifespan, KA Harish, R. Paul Linga Prakash, M. Selvam, A. Alagu Sundara

[3] Using nanofluids to improve the performance of car radiators, M. El Haj Assad, Ahmed Amine Hachicha, Evangelos Bellos, et. al, Renewable and Sustainable Energy Reviews 112 (2019) 183–194, Elsevier Ltd. Zafar Said, M. El

[4] Using Multi-Walled Carbon Nano Tubes to Improve Heat Transfer Coefficient in an Automobile Radiator (MWCNTS), Manikantan Kota, et. alASME 2014 International Mechanical Engineering Congress

[5] Parametric radiator research in automobiles, Applied Thermal Engineering 27 (2007) 2033-2043, Elsevier Ltd, C. Oliet, A. Oliva, J. Castro, C.D. Perez-Segarra

[6] Raju Jadar, K.S. Shashishekar, S. R. Manohara, Nanotechnology Integrated Automobile Radiator, Proceedings 4 (2017) 12080–12084, 2214–7853, 2017 Elsevier Ltd