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Computer Aided Design and Computer Aided Engineering of Diesel Engine Intake Manifold

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Abstract : This study explores the pivotal role of a well-designed Intake Manifold (IM) in optimizing the performance of Internal Combustion (IC) engines. The intake manifold serves to evenly distribute the combustion mixture—or air alone, in the case of direct injection engines—thereby enhancing engine intake performance. Uniform distribution is essential for maximizing efficiency and improving overall engine functionality, as uneven airflow can result in diminished volumetric efficiency, higher fuel consumption, and power loss. The primary aim of this research was to analyze flow distribution within an intake manifold under steady-state turbulence conditions through computational methods. For this purpose, a numerical model of an intake manifold designed for a 3-cylinder engine was developed and examined. The geometric model, created with approximate dimensions utilizing curves and points, was prepared using ANSA as a preprocessing tool. Subsequently, the flow analysis was carried out using STAR CCM+, which combines solver and post-processing capabilities integrated with the cylinder head(s).

IndexTerms **- Intake Manifold, Internal Combustion engine, Flow distribution, Volumetric efficiency, Computational analysis, CATIA (Pre-processing tool), ANSYS (Solver and Simulation tool).**

1. INTRODUCTION

1.1 Intake Manifold:

Since the groundbreaking invention of the 4-stroke engine in 1876 by Nikolaus August Otto and Eugen Langen, the field of engine technology has seen remarkable advancements. Innovations such as embedded electronics, improvements in fuel and oil properties, and the adoption of novel manufacturing techniques and materials have collectively revolutionized engine efficiency. Among naturally aspirated engines, significant attention has been directed towards the intake manifold due to its critical role in optimizing performance. The intake manifold is a system designed to channel air into the engine through pipes, known as runners, connected to each cylinder. The selection of pipe lengths—and, to some extent, diameters—is crucial, as they directly impact the manifold's resonant frequencies[5]. While some engines employ active intake manifolds capable of altering plenum geometry to adapt to varying engine speeds, this solution is structurally complex. A more straightforward approach for cost-effective vehicles involves maintaining a fixed manifold geometry optimized during the design phase for a specific engine speed.Over recent decades, researchers have extensively studied airflow dynamics within engine manifolds using one-dimensional numerical simulation methods. design for instance, investigated the design of inlet and exhaust systems for stationary natural gas engines by evaluating various parameters, including valve timing, valve diameter, valve lift profiles, exhaust manifold diameter, pipe lengths, and pipe junction geometry[9]. The findings highlighted significant potential for improvement in engine performance across the studied configurations. The intake manifold is a vital component in diesel engines, tasked with supplying air to the cylinders for combustion. Unlike spark-ignition engines, which use a spark to ignite the air-fuel mixture, diesel engines rely on air compression and fuel injection to initiate combustion.

1.2 Intake Manifold efficiency and performance :

The efficiency and performance of the intake manifold are vital in defining an engine's overall functionality and output. This component ensures the smooth and uniform delivery of air—or an air-fuel mixture in spark-ignition engines—to each cylinder. Such uniformity is crucial for balanced combustion, directly affecting fuel economy, power generation, and emission levels[8]. Volumetric efficiency, which measures an engine's ability to intake air compared to its theoretical capacity, is a key factor in intake manifold performance. An optimized manifold reduces pressure losses, enhances airflow, and minimizes turbulence, enabling maximum air delivery to the cylinders. Critical design elements, such as runner length, diameter, and plenum size, significantly influence airflow dynamics. Longer runners generally support improved low-end torque, while shorter runners are better suited for high-rpm power.

1.3 Selection of the materials for Intake Manifold:

The intake manifold is an essential engine component that channels air or an air-fuel mixture into the cylinders for combustion. The choice of material for this part is determined by factors like durability, weight, heat tolerance, cost, and ease of production.Commonly used materials include aluminum, which is lightweight and sturdy, making it ideal for performance-driven applications[7]. Plastic and composite materials have gained popularity for being cost-effective, lightweight, and easily shaped into intricate designs. Cast iron, known for its robustness and heat resistance, was historically preferred but is now less common due to its heaviness and susceptibility to rust [11]. Stainless steel, though heavier and more expensive, offers outstanding corrosion resistance and is used in specialized settings.

2. PROBLEM DESCRIPTION:

The process of simulating and designing an intake manifold for a diesel engine focuses on accomplishing specific goals aimed at enhancing the engine's overall performance, improving efficiency, and minimizing emissions[6]. The following are key objectives often targeted during the simulation and design phase of an intake manifold for a diesel engine.

2.1 Airflow Optimization:

Optimizing airflow within an intake manifold ensures efficient and uniform distribution of air to all the engine's cylinders. Achieving this requires careful design to minimize resistance and turbulence, allowing for a smooth and consistent flow of air. By refining the manifold's geometry, runner dimensions, and plenum structure, engineers can enhance combustion efficiency, which leads to improved engine performance, greater fuel economy, and reduced emissions. Advanced tools like computational fluid dynamics (CFD) are integral to fine-tuning the manifold's design, ensuring maximum efficiency and functionality in real-world conditions.

2.2 Throttle Response Improvement:

Enhancing throttle response in an intake manifold involves ensuring that air is delivered to the engine as quickly and efficiently as possible when the throttle is opened[10]. This is achieved by refining the manifold's design to minimize airflow resistance and delay. The geometry of the manifold, as well as the plenum volume and runner length, are optimized to facilitate rapid air movement, especially in performance-focused engines. By improving the dynamics of airflow, the intake manifold enables the engine to react swiftly to throttle inputs, resulting in better acceleration and a more responsive driving experience.

2.3 Fuel-Air Mixing Efficiency:

Fuel-air mixing efficiency within the intake manifold refers to the process of effectively combining air and fuel before it enters the engine cylinders for combustion. Challenges in this area can arise from factors such as uneven airflow, excessive turbulence, or a poorly designed manifold, all of which can lead to suboptimal blending[15]. When mixing efficiency is compromised, it can result in incomplete combustion, diminished engine performance, higher fuel consumption, and increased emissions. Achieving proper mixing requires careful design of the manifold, including optimized geometry and flow dynamics, to ensure uniform blending and consistent delivery to the cylinders.

2.4 Material Selection:

The selection of materials for an intake manifold is a critical aspect of its design, as it significantly influences the manifold's functionality, durability, cost, and manufacturing process[3]. Challenges arise when the chosen material fails to meet the necessary requirements for heat resistance, mechanical strength, or weight optimization. For instance, using excessively heavy materials can impact fuel efficiency, while materials with inadequate thermal properties may degrade under high-temperature conditions.

3. METHODOLOGY:

3.1GeometricDesign:

The velocity of a piston within the context of an intake manifold is often calculated based on its motion within the cylinder. This motion is generally sinusoidal due to the rotary-to-linear conversion from the crankshaft.

$$v_P = \mathrm{rw}\left(\sin\theta + \frac{\sin 2\theta}{2n}\right)$$

$$\sin 2\theta = 1 \qquad \sin\theta = \frac{1}{\sqrt{2}}$$

3.2 Angular Velocity:

Angular velocity, in the context of an intake manifold, refers to the rotational speed of the engine's crankshaft, which governs the movement of the pistons during the intake stroke. This parameter is crucial as it directly influences the timing and speed of air intake into the engine's cylinders. When the crankshaft rotates at a specific angular velocity, it causes the pistons to move in a sinusoidal pattern, generating suction within the intake manifold.

$$W = \frac{2\pi N}{60}$$

3.3 Velocity of air at inlet port:

The velocity of air at the inlet port of an intake manifold is a key factor in determining engine performance, as it influences the efficient delivery of air to the cylinders. This velocity depends on factors such as the engine's operating conditions, the design and geometry of the intake manifold, and the pressure differential between the inlet and the cylinders.

$$v_i = \frac{A_C \times V_p}{A_i}$$

3.4 Computational Fluid Dynamics [CFD] Analysis:

Computational Fluid Dynamics (CFD) analysis plays a vital role in optimizing intake manifold designs by simulating airflow behavior within the manifold. This technique helps engineers understand critical aspects such as velocity distribution, pressure variations, and turbulence effects. A 3D model of the intake manifold is created using CAD software and analyzed in a CFD simulation tool.

3.5 Structural Analysis:

Static structural analysis of an intake manifold focuses on assessing its ability to endure mechanical stresses and loads without compromising its structural integrity. This process ensures the manifold can withstand pressure fluctuations, thermal expansion, and engine vibrations during operation[4]. Using advanced Finite Element Analysis (FEA) tools, engineers simulate the manifold's response to various static loads. Key factors such as stress distribution, deformation, and material strain are evaluated to identify weak points. Through this analysis, the manifold's design and material composition are optimized to enhance strength, durability, and performance while maintaining lightweight characteristic.

4. CALCULATIONS:

- **Velocity of piston at 1800 rpm**

$$v_P = \mathrm{rw}\left(\sin\theta + \frac{\sin 2\theta}{2n}\right)$$

- **Cross – section area of intake port:**
  $A_i = \frac{\pi}{4} \times d^2$
- **Velocity of air at inlet port:**

$$v_i = \frac{A_C \times V_p}{A_i}$$

- **Bernoulli's equation:**

$$P = \frac{\rho_{a_i r \times V_i^2}}{2}$$

5. COMPUTER AIDED DESIGN OF INTAKE MANIFOLD:

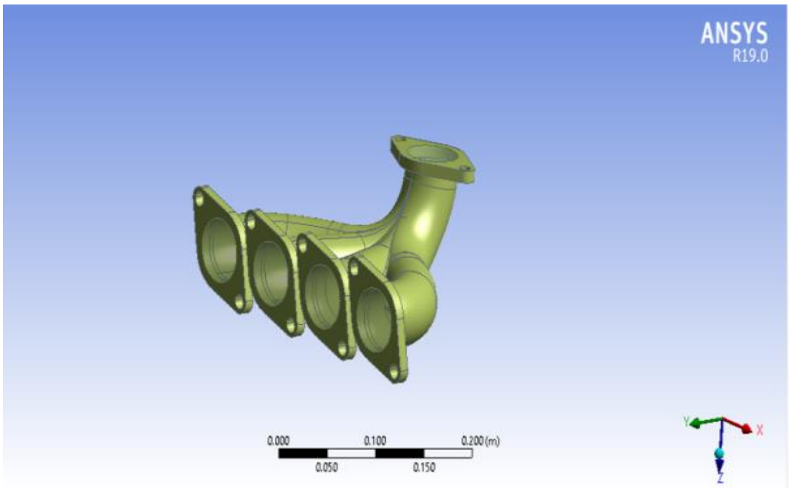

figure.1: Designed part of manifold

Computer-aided design (CAD) is essential in developing intake manifolds for internal combustion engines, as it enhances their performance, efficiency, and emission control[1]. Using CAD tools, engineers can refine manifold geometry for uniform air distribution, reduce turbulence and pressure losses, analyze thermal and fluid dynamics, and simulate real-world conditions to perfect designs before manufacturing.

6. COMPUTATIONAL FLUID DYNAMICS ANALYSIS:

Computational Fluid Dynamics (CFD) analysis is a versatile technique used to simulate and study the behavior of fluids, heat transfer, and related physical processes. By solving complex equations like the Navier-Stokes equations, it allows for accurate predictions of fluid dynamics under various conditions.

6.1 Geometry of intake manifold:

The geometry of an intake manifold is a crucial factor in engine performance, as it influences the distribution of air or the air-fuel mixture to the cylinders. Key design elements include the plenum, which affects airflow and pressure distribution, and the runners, whose length and diameter are fine-tuned to optimize airspeed and volume. Smooth tapering and curvature minimize turbulence and pressure losses, ensuring efficient airflow. Additionally, modern manifolds with variable geometry designs allow adjustments to enhance performance across varying engine speeds.

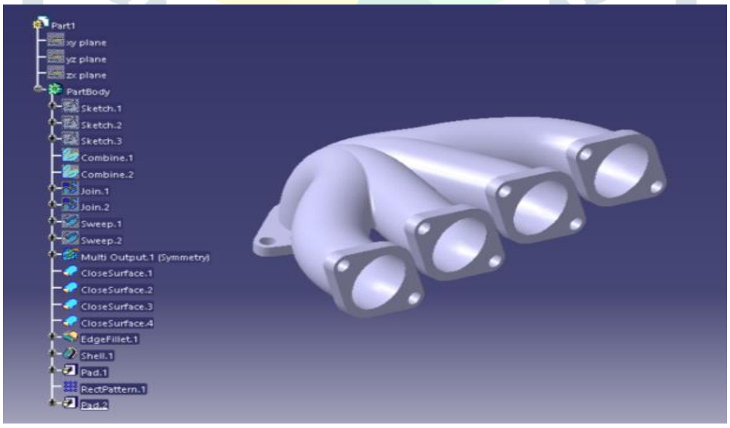

figure.2: Intake manifold geometry

6.2 Fluid Domain of Intake manifold:

The fluid domain of an intake manifold refers to the internal pathways where air or the air-fuel mixture flows from the plenum to the engine cylinders. In computational analyses like CFD, this domain is modeled to study fluid behavior[2]. Key features include the plenum volume, which impacts airflow distribution, and the runner geometry, which ensures uniform and efficient flow. Smooth internal surfaces reduce turbulence, while boundary conditions simulate real-world factors such as engine speed, pressure, and temperature. fluid domain is created as below for analysis of the fluid nature inside the intake manifold.

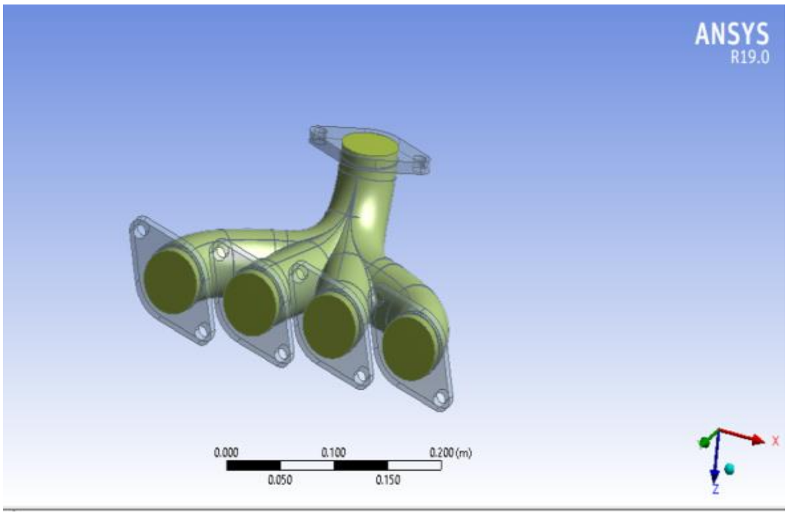

figure.3: Fluid Domain of Intake manifold

6.3 Finite Element Analysis:

Finite Element Analysis (FEA) is a computational method used to assess the structural performance of components like intake manifolds. It allows engineers to analyze stress distribution, deformation, and vibrations caused by operational factors such as pressure changes, thermal loads, and engine forces. By simulating real-world conditions, FEA helps identify weak points, optimize designs, and reduce reliance on physical prototypes, ultimately saving time and costs in the development process.

6.3.1 Mesh file of Intake Manifold:

Mesh files are integral to the design, analysis, and enhancement of intake manifold performance, as they provide an intricate depiction of the manifold's geometry[13]. These files are indispensable for conducting advanced simulations mesh files consist of discrete components, such as nodes and elements, representing the manifold's physical attributes. High-quality mesh construction ensures precise simulation outcomes by capturing geometric details while maintaining computational efficiency, aiding in manifold optimization and performance reliability. The meshed file of the fluid domain with nodes are 45715 and elements are 243363.

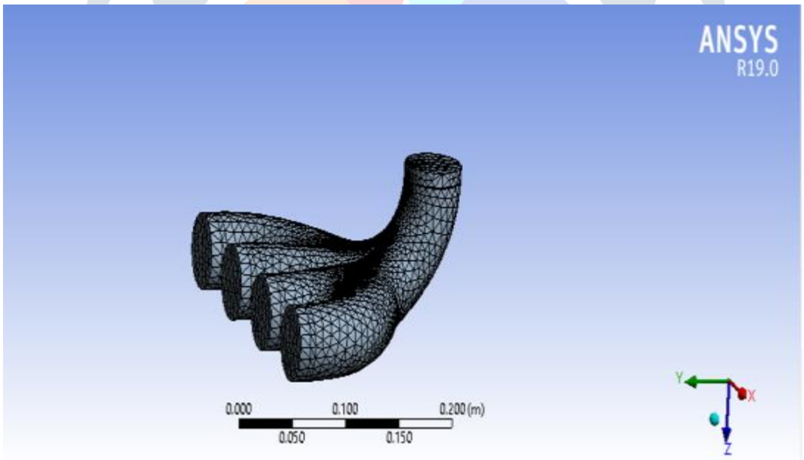

figure.4: Meshed file of Intake manifold

6.3.2 Residual Graph:

Residuals graphs in simulations of an intake manifold are vital for monitoring the numerical solution's convergence during Computational Fluid Dynamics (CFD) analysis. These graphs track residual values of variables like velocity, pressure, and temperature across iterative steps.

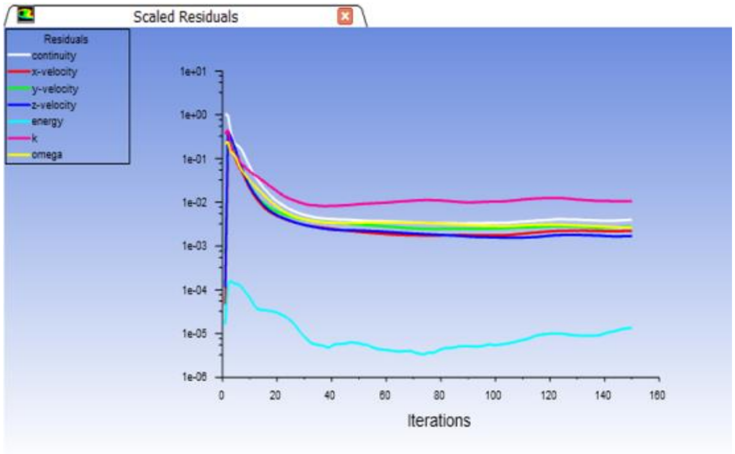

figure.5: Residual Graph

6.4 Results of CFD Analysis:

CFD analysis results for an intake manifold provide comprehensive insights into critical factors such as pressure distribution, temperature profiles, and heat transfer coefficients. These outputs are essential for understanding and improving airflow dynamics and thermal management within the manifold[16]. Pressure distribution maps highlight areas of pressure loss or stagnation, ensuring uniform airflow to all cylinders for better volumetric efficiency. Temperature analysis identifies heat accumulation within the manifold, aiding in optimizing thermal management to maintain air density and combustion efficiency. The heat transfer coefficient evaluates the rate of thermal exchange, allowing engineers to address overheating issues and preserve the manifold's structural integrity. These results guide the refinement of manifold designs for enhanced performance and reliability.

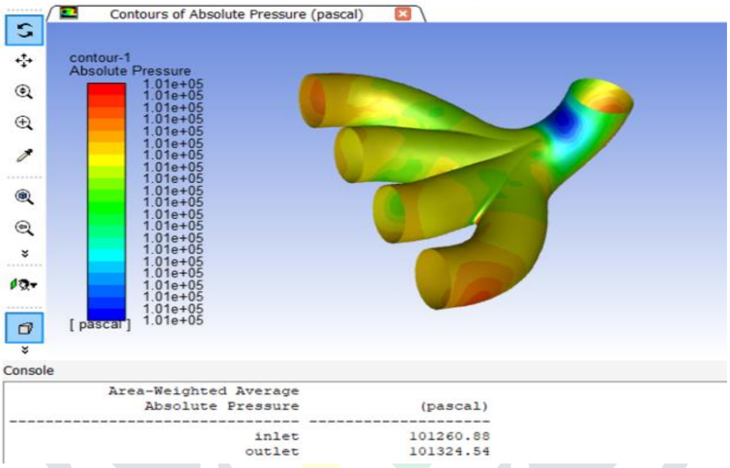

figure.6: Pressure Variation in Simulation:

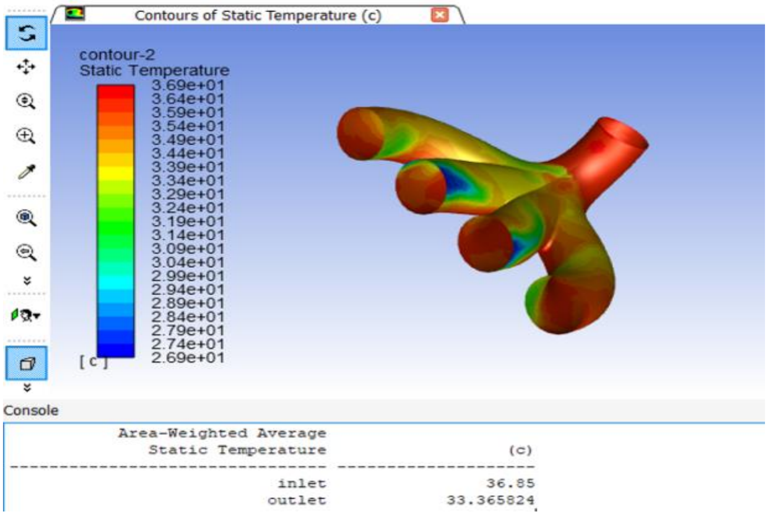

figure.7: Temperature Variation in Simulation

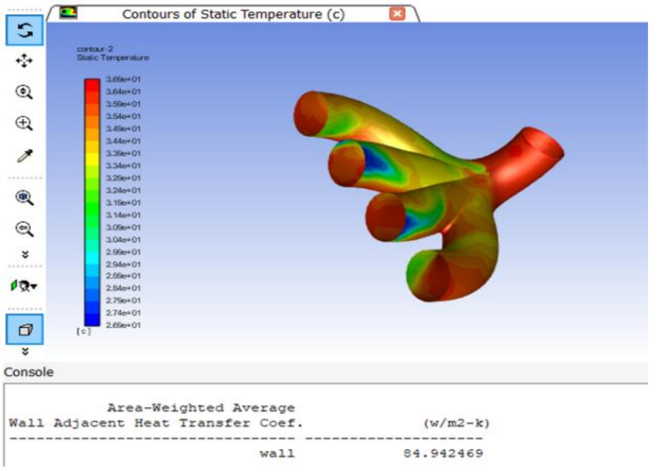

figure.8: Heat transfer co-efficient in Simulation

6.5 Different Air flow Velocities in different Properties (Pressure, Temperature and Heat transfer Co-efficient):

	Velocity at 5 m/s	Velocity at 10 m/s	Velocity at 15 m/s	Velocity at 20 m/s	Velocity at 30 m/s
Inlet Pressure (Pa)	101322.48	101308.48	101294.45	101260.88	101184.94
Temperature (C)	33.250899	33.251167	33.267501	33.365824	33.741686
Heat Transfer Coefficient $(w / m^2 k)$	42.283731	52.127891	70.821979	84.942469	109.25214

Table.1: Different Air flow Velocities in different Properties (Pressure, Temperature and Heat transfer Co-efficient):

6.5.1 Velocity Streamline:

The Velocity Streamline Counter represents the distribution of air as it flows from the inlet to the outlet[16]. To visualize the streamlines, results can be utilized by selecting the streamline option, specifying the number of streamlines to display, and rendering the image to observe their behavior. From the analysis, it was noted that the streamlines are approximately evenly distributed, ensuring uniform airflow through the system.

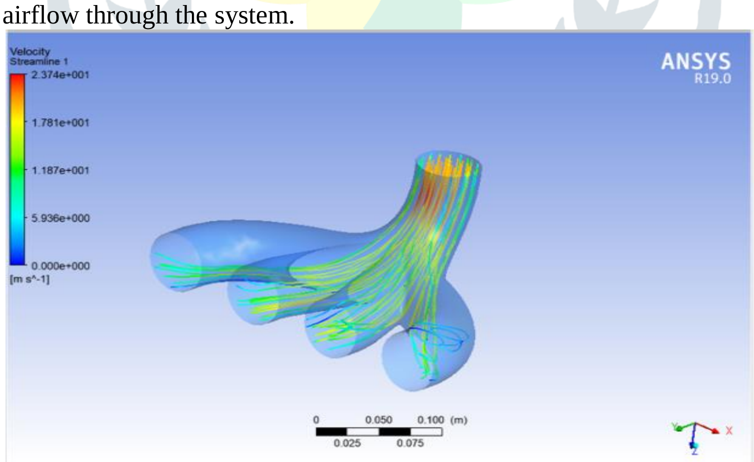

figure.9: Velocity Streamline of Intake manifold

7. Material Analysis of Intake Manifold:

Material analysis of an intake manifold involves evaluating various materials based on their mechanical, thermal, and durability properties to ensure optimal performance under operational conditions[12]. For stainless steel, its high strength and thermal resistance make it ideal for extreme conditions, though its heavier weight can be a limitation. Aluminum alloy offers lightweight and good thermal conductivity, making it suitable for modern, fuel-efficient engines, but it has lower strength compared to stainless steel. Gray cast iron, known for its affordability and high damping capacity, is appropriate for cost-sensitive applications, though it is heavier and less corrosion-resistant.

7.1 Total Deformation of Intake manifold:

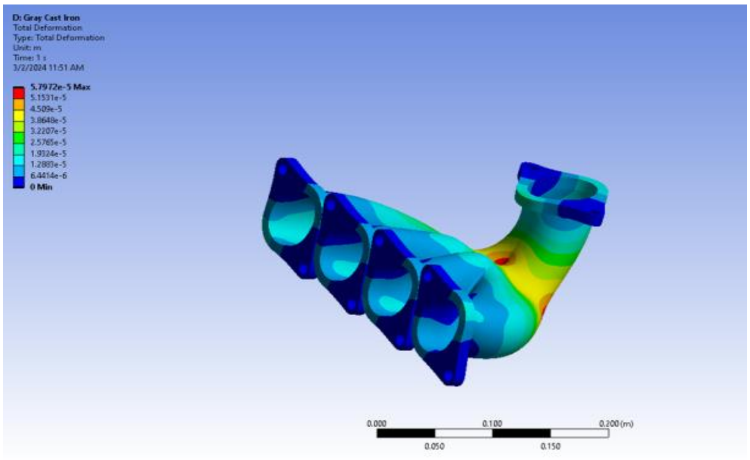

figure.10: Total Deformation of Grey Cast Iron

7.2 Equivalent Stress of Intake Manifold:

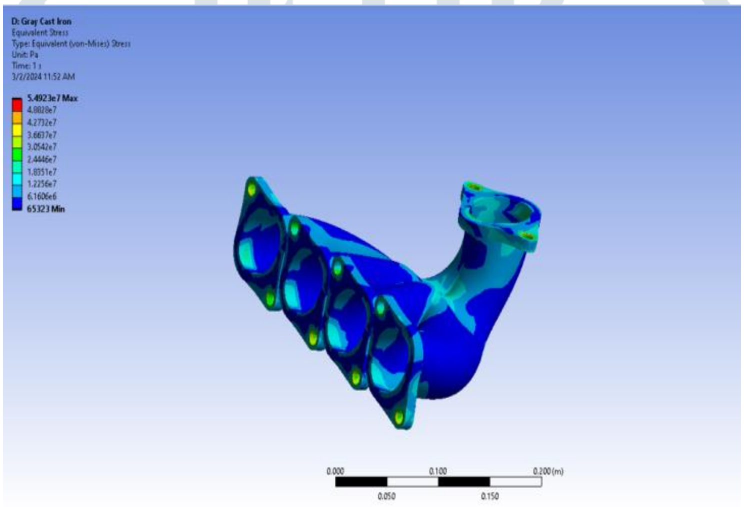

figure.11: Equivalent stress of Grey Cast Iron

7.3 Equivalent elastic Strain:

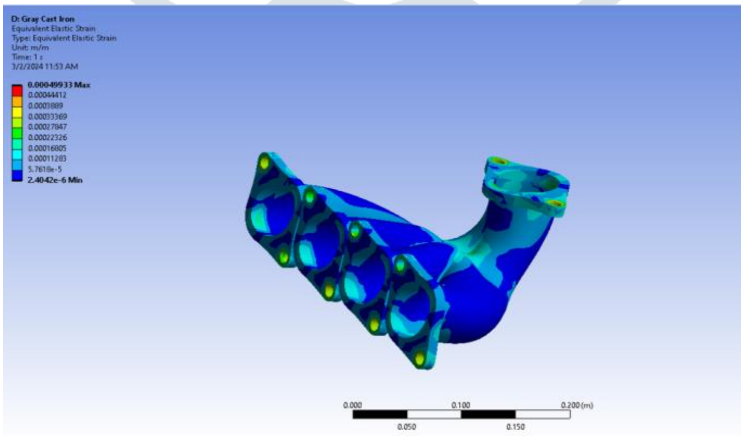

figure.12: Equivalent elastic strain of Grey Cast Iron

8. Results for Material Analysis:

Table 8.1 Different Stress, Strain and Deformation Values for Different Material:

Material	Max. Deformation	Max. Equivalent stress	Max. Equivalent elastic strain
Stainless steel	$8.9571e^{-5}$	$1.5165e^{8}$	0.00078579
Aluminum alloy	$1.211e^{-4}$	$7.6549e^{7}$	0.0010782
Gray cast iron	$5.7972e^{-5}$	$5.492e^{7}$	0.000499

Table.2: Different Stress, Strain and Deformation Values for Different Material:

9. Results:

The depicted graph illustrates the relationship between pressure, velocity, and heat transfer in an intake manifold. Higher manifold pressure signifies a greater air concentration, reducing available space and restricting airflow velocity. Conversely, lower pressure allows freer movement, increasing velocity[5]. Pressure, as a measure of force per unit area, influences air molecule movement, thereby affecting velocity.

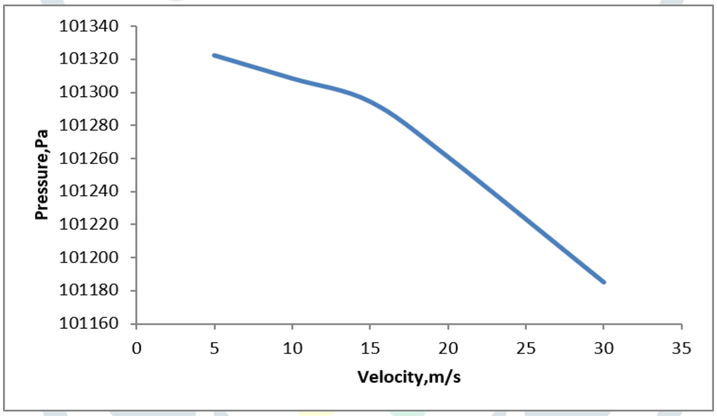

Figure.12: Velocity vs Inlet Pressure

Increased manifold pressure reduces airflow velocity by compressing air, while lower pressure enhances velocity by allowing freer air movement. Pressure reflects the force driving air molecule motion, influencing airflow dynamics.

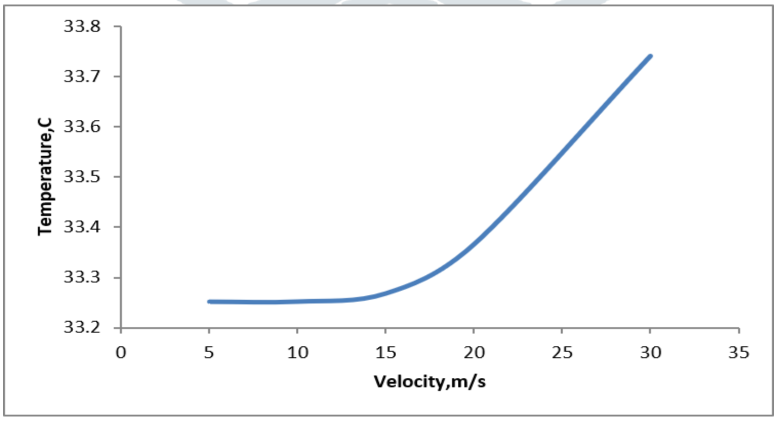

Figure.13: Velocity vs Outlet Temperature

The ideal gas law explains that increased temperature within a constant manifold volume raises gas density, potentially boosting mass flow rate if velocity is stable. However, the modest temperature rise likely causes only a slight velocity increase.

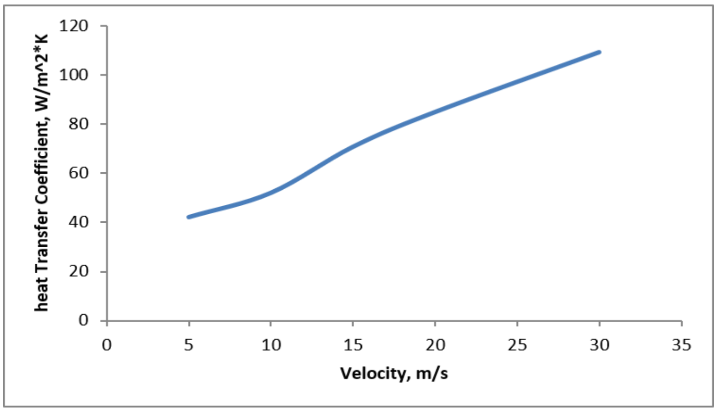

Figure.14: Velocity vs Heat Transfer Co-efficient

Convection-driven heat transfer occurs due to fluid motion. Increased airflow velocity enhances fluid particle movement, improving heat transfer efficiency from the intake manifold walls to the air and raising the heat transfer coefficient.

10. Conclusion:

The analysis reveals a direct relationship where increased pressure leads to higher airflow velocity. While temperature variations show a subtle positive correlation, their impact on velocity is minor compared to other influencing factors. Additionally, higher air velocity enhances heat transfer from the intake manifold walls to the cooler air. Among the materials tested, Gray Cast Iron emerges as the best choice, exhibiting minimal deformation compared to stainless steel and aluminum alloy, all of which remain within their yield strength.

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