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An Analysis of The Material and Design of an Exhaust Manifold for A Single-Cylinder Internal Combustion Engine

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ABSTRACT

This study aims to find the best material for the manifold and improve airflow in the UniMAP Automotive Racing Team (uniART) exhaust manifold. The exhaust manifold is a part of the exhaust system that collects and delivers exhaust gases from the cylinder head to the exhaust outlet. The exhaust manifold's design is significant to the engine performance. The current design and new designs of the exhaust manifold were modelled using SOLIDWORKS software. Stainless steel, cast iron and mild steel were chosen as materials for manifold and were studied by conducting the Steady-State Thermal analysis. The flow of the air in the manifold is analysed and evaluated in terms of pressure and velocity. The fluid flow and thermal analysis are simulated in Computational Fluid Dynamics analysis software known as ANSYS. Results of thermal analysis prove that Stainless steel is better than other materials since it has a high temperature difference and low heat flux. The results of fluid flow analysis were compared between the current design and new designs of the exhaust manifold. The outcome indicated that validated Design 2 has a higher velocity value at the outlet and lower pressure at inlets which improves the airflow in the exhaust manifold.

1. Introduction

The Society of Automotive Engineers International (SAE) conducts Formula SAE (FSAE) which is a student design racing car competition. Each student team is responsible for designing, building, and testing a prototype race car by adhering to the rules and regulations in order to ensure that the car is safe to drive on track. The car is rated in a number of static and dynamic events including technical inspections, reports of cost, design, engineering properties, time attacks performance and high-performance endurance challenge. UniMAP Automotive Racing Team (UniART) competed in Formula SAE Asian with a vehicle powered by a Suzuki GSX-R K5 (600cc) engine. In FSAE, there are only a few rules for the exhaust system, and UniART adheres to all the rules. UniART has also conducted

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numerous automobile-related studies in the past to aid in the improvement of automotive knowledge [1-9].

An exhaust manifold is known as a part of the exhaust system that stores exhaust gases from the head of the cylinder and delivers those gases to the exhaust outlet. The manifold is mounted to the engine component that regulates the exhaust outflow. A normal automobile engine's exhaust valve opens at the end of the exhaust stroke, allowing the exhaust gas to exit at high pressure from the cylinders into the exhaust manifold [10]. The exhaust manifold's design is crucial to eliminate its back pressure. The engine can lose power through back pressure, consequently affecting the engine's performance. The equal distribution of exhaust gases flow in the manifold is a key to the race car's performance.

Material selection is one of the most important aspects when designing the exhaust manifold. Therefore, certain factors should be considered when selecting materials for the exhaust manifold. Primarily, the material must be able to withstand the high pressure produced by the exhaust gases as it exits the exhaust valve. When the exhaust gases are released by the engine through the exhaust valve, the exhaust materials gas has a high temperature due to the pressure and velocity. In that manner, the material must have high thermal conductivity and high resistance to thermal fatigue. As a result of the material's reactions with the exhaust gases, the exhaust manifold not only corrodes but also weakens. Hence, the selected material should be able to resist oxidation and have high strength. Therefore, this study aims to improve airflow in the exhaust manifold and choose the best material for the UniART race car's exhaust manifold.

2. Overview on Exhaust Manifold's Design and Material Analysis

2.1 Exhaust Manifold

Exhaust gases from each engine cylinder will be collected by an exhaust manifold. The direction of flow will be the only difference between an intake and an exhaust manifold. In the intake manifold, the fuel and air mixture will be flowing into the combustion chamber, while in the exhaust manifold, the exhaust gases will be flowing outside the combustion chamber. Therefore, an exhaust manifold's design is important to maintain a smooth gas discharge and increase engine performance.

The temperature of the gas in the exhaust manifold can reach up to 800 °C at maximum engine rpm. The exhaust manifold is blazing red as a result of the extremely high temperature. This situation might easily occur when the airflow around the manifold for cooling purposes is obstructed. In terms of manufacturing, the exhaust manifold is usually made of welded steel pipes or cast iron. Since different materials have different surface roughness, the surface friction that is introduced to the fluid flow will also vary. This proves that the type of material has an impact on the exhaust system's gas flow [10].

2.2 Exhaust Manifold Geometry and Its Effect on The Performance

Researchers have studied various manifold geometries and their performance evaluation by using investigational methods as well as numerical method, CFD. Polygonal edges are correlated to power loss as high number of edges contributes to a lower power loss [11]. The shape of the exhaust manifold was varied to be either sharp bend, short bend, or long bend. Using an experimental method, they measured backpressure, brake thermal efficiency, and heat utilisation of various manifolds as the load changed. Meanwhile, in the numerical method, they analysed three different shapes of exhaust manifold by using pressure and velocity analysis. By comparing the results, they concluded that a long bend manifold makes the flow of exhaust gases better with minimum backpressure and high velocity compared to the other two models. The percentage of unaccounted heat is low and brake thermal efficiency is higher for the long bend model. Using both methods, the researchers successfully proved that the long bend is way better than sharp and short bend manifolds [12].

Similarly, another researcher conducted a CFD analysis on the influence of pipe bending on backpressure to prove the theory of pressure loss due to the bent pipe. It can be seen from the pressure contour that pressure rises in the bend area. When the exhaust valve opens, the velocity of the exhaust will be extremely high, and the bend will create a barrier in its high-velocity pathway, causing the pressure to rise. As a result, it is possible to say that backpressure rises with each bend [13].

2.3 CFD Analysis on Different Design of Exhaust Manifold

Researchers have studied two different exhaust manifolds namely type A and type B. They modelled the manifolds using SOLIDWORKS software and Computational Fluid Dynamics (CFD) method was used to analyse the models. They also used three different fluid materials such as gasoline, alcohol and LPG in the flow analysis. For each manifold, the burned gases of gasoline, alcohol, and LPG fuels were considered major flowing materials. Pressure, velocity and temperature differences were analysed and compared at various points at the manifold. Due to the properties of gasoline fuel for type A of manifold, lower pressure and velocity were obtained when compared to the other two fuels. The pressure drops to atmospheric pressure as the velocity increases approaching the exhaust outlet. From the results, type A exhaust manifold has higher pressure and velocity values than type B exhaust manifold. High pressure values at the outlet of type A were obtained for all fuels, which can increase the engine's performance and efficiency. Finally, it was found that type A exhaust manifold is better than type B exhaust manifold [14]. A high inlet angle was proven to contribute of lowering pressure at the inlet duct [15].

2.4 Criteria for Material Selection

Material selection for exhaust systems is important since it is influenced by factors such as temperature usage and application. Material selection is particularly critical since the exhaust material is a component that raises warranty and regulatory obligations [16]. Certain researchers have conducted research and come to some conclusions on the features of materials used in exhaust systems.

One of the researchers has considered many factors such as tolerance to high temperature and the ability to resist corrosion. He also classified the exhaust component according to its exposure temperature and failure properties the components withstand throughout the process as shown in Table 1 [17].

Table 1
Material properties for a component of a vehicle’s exhaust system [16]

Criteria	Exhaust Manifold	Muffler	Tail Pipe
Service temperature	750-900 °C	100-400 °C	100-400 °C
Required Properties	High temperature resistance Thermal Fatigue life Resist Oxidation	Able to resist Corrosion Resist Oxidation	Able to resist Corrosion Resist Oxidation

The researcher also stated the characteristics to select the materials in order to design an exhaust system [15]. The characteristics are as follows

i. The material must have a high melting point and service temperature above 800 °C for the exhaust manifold and 400 °C for the tail pipe and muffler box
ii. Resist corrosion in any environment
iii. Low density material for fuel economy
iv. High thermal conductivity and resistance to thermal fatigue across the system for even distribution of heat across the system and withstanding high heat in the system
v. High young modulus and fracture toughness to withstand vibration and propagation of cracks in the system.

2.5 Exhaust Manifold's Thermal and Modal Analysis Using Various Materials

Material selection is one of the important factors that should be considered when designing an exhaust manifold. Researchers have studied the exhaust manifold of three materials; grey cast iron, carbon steel and stainless steel. The finite element method was used to investigate the thermal and modal analysis of the exhaust manifold of a multi-cylinder engine. The boundary conditions include an inner surface temperature of 800 °C and air convection of approximately 100 W/m2 °C. They also analyzed the heat flux, temperature distribution and modal analysis of the various manifold materials. In thermal analysis, stainless steel has the lowest heat flux and lowest temperature compared to cast iron and carbon steel. Total deformation and frequencies were compared in modal analysis. Four modes were carried out to obtain the deformations. From the results, less deformation are seen in carbon steel and stainless steel. Hence, it can be concluded that stainless steel is superior to the other two materials and is preferred for multi-cylinder engine exhaust manifolds [18].

2.6 Thermal Analysis of High Temperature Resistant Materials Coated with Exhaust Manifold

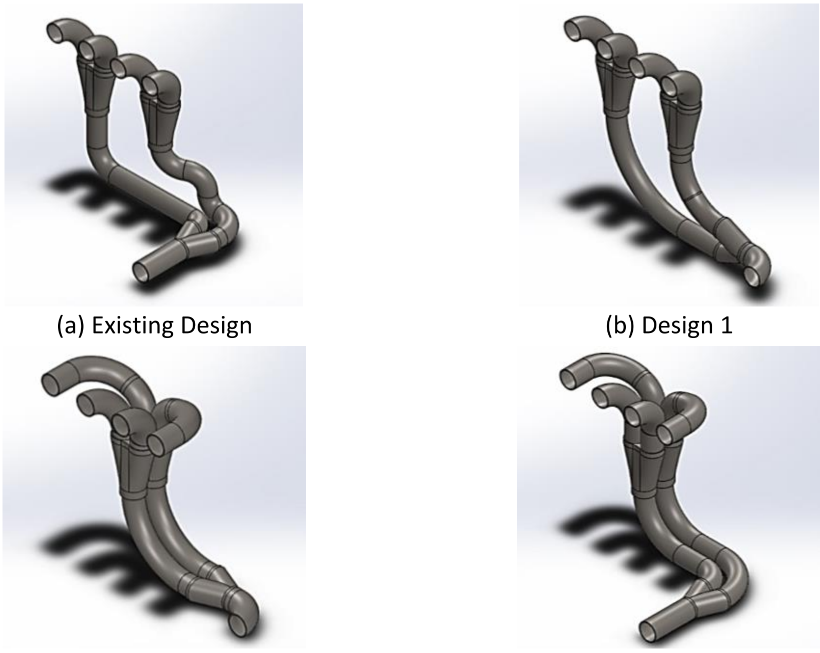
In this study, an exhaust manifold with different coatings was designed. Catia V5 R20 was used for modelling the manifold, while ANSYS 15.0 and Finite Element Method were used to calculate the temperature distribution ad thermal stress concentrations. Cast Iron, Silicon Nitride and Zinc Oxide have been examined in the analysis. Cast iron was discovered to have the best ability to release heat quickly while also being able to absorb heat fast. Silicon Nitride and Zinc are poor conductors but can insulate better than Cast Iron. Furthermore, exhaust system clogging can be prevented, and the backpressure circumstances avoided because these materials do not chip over time. Flow obstructing geometry also increases transmission of heat derived from the hot surface to the surrounding air [19]. Based on the results, Zinc Oxide was selected as the most suitable material with a better life span. Moreover, the cost of the manifold can be reduced if it is used as coatings on the manifold [20].

3. Methodology

The design of the exhaust manifold is developed with the help of SOLIDWORKS. Two types of analysis namely Steady-State Thermal and Fluid Flow (Fluent) were conducted using ANSYS. Steady-state thermal analysis is used to evaluate the thermal equilibrium of the exhaust manifold in which the temperature remains constant over time. The temperature distribution and heat flux were obtained at the end of this analysis. Fluid Flow (Fluent) analysis was also carried out to study the airflow in the exhaust manifold. The analysis helps to evaluate the velocity outlet and pressure when the fluid (air) flows in the exhaust manifold.

3.1 Exhaust Manifold Design

First of all, the existing design is created in order to generate ideas for new designs as displayed in Figure 1. Few parts of the existing design are used to develop new exhaust manifold designs. Three new designs (a,b,c) of the exhaust manifold had been created as shown in Figure 1. Every design of the manifold is assembled together with the help of mating in SOLIDWORKS.



(a) Existing Design (b) Design 1

(c) Design 2 (d) Design 3

Fig. 1. Exhaust manifold design

3.2 Steady-State Thermal

Two materials namely Cast Iron and Stainless steel, 304 were chosen as an alternative to mild steel which is the current type of material for the exhaust manifold. The material properties in Table 2 were gathered in order to run the steady-state thermal analysis.

Table 2
Material properties which were used in the Steady-state thermal analysis [21-22]

	Mild Steel (MI)	Cast Iron (CI)	Stainless steel, 304 (SS)
Specific heat, C_p (J/kg. K)	510.7896	460.548	502.416
Thermal conductivity, k (W/m.K)	50	55	25
Density,*p* (kg/m^3)	7850	7300	7982
Melting point (°C)	1530	1204	1450

The exhaust gases flow inside the exhaust manifold at a temperature of approximately 800 °C [17]. The inner surface of the exhaust manifold is exposed to exhaust gases. In order to apply the temperature of 800 °C to the inner surface of the geometry, the inner surface of the geometry is selected and named as Inner wall. Figure 2 illustrates the inner wall being applied at an 800 °C temperature. In addition, the convection occurs at the outer surface of the exhaust manifold. As shown in Figure 3, the outer surface of the geometry is subjected to convection of air at a temperature of 100 W/m^2 °C. The ambient temperature under convection is set to be 25 °C which is the initial temperature [18]. The settings for all materials are the same.

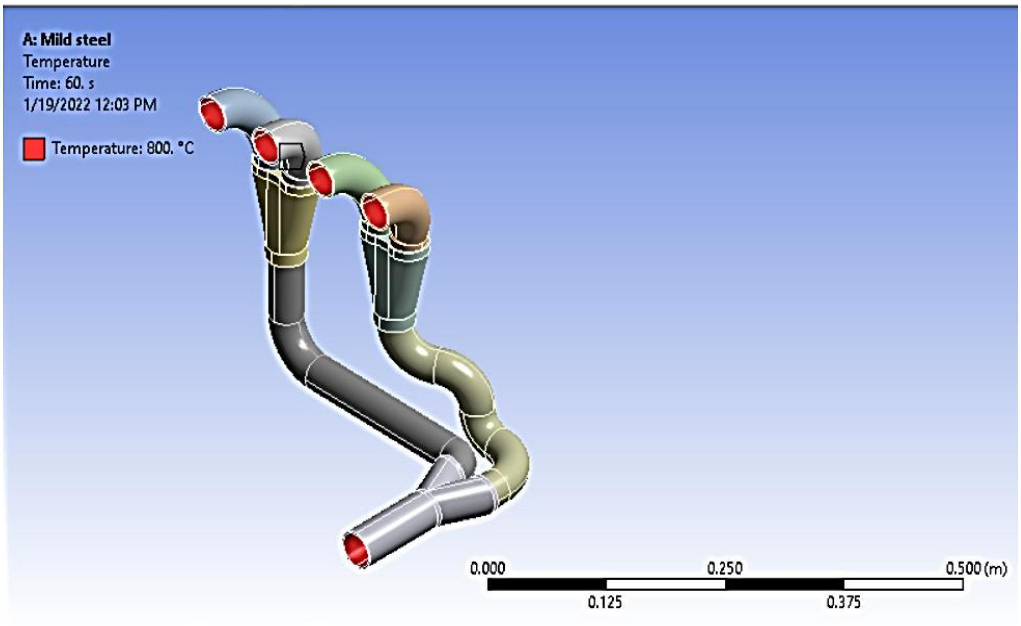


Fig. 2. Temperature was applied to the Inner wall

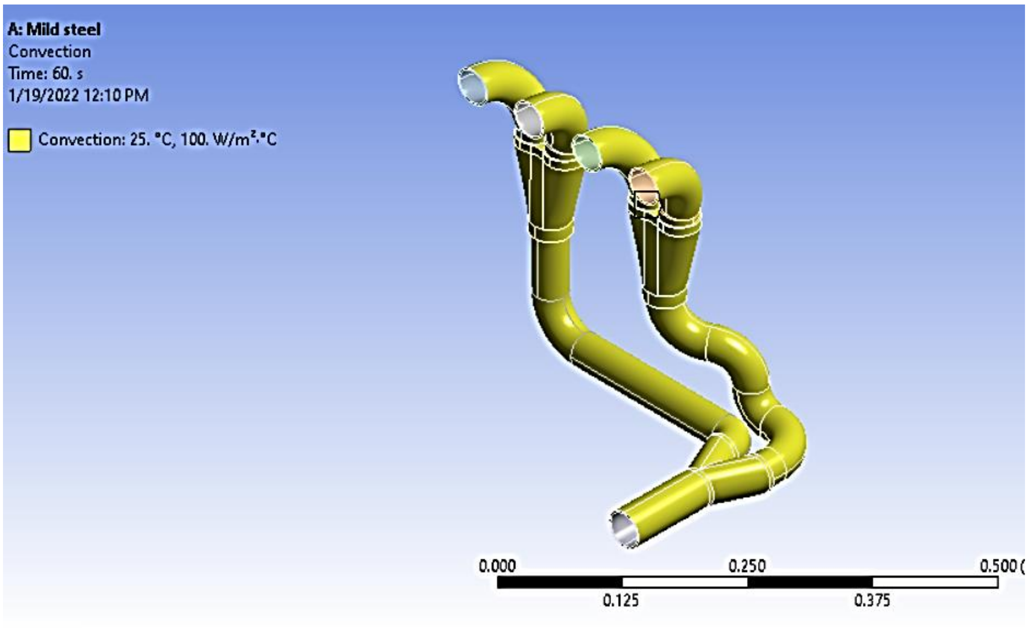


Fig. 3. Convection was applied on the outer surface of the geometry

3.3 Fluid-Flow (Fluent)

As the exhaust gases flow inside the exhaust manifold, it is important to study the flow at the inner surface of the exhaust manifold. In order to create the inner surface geometry, a tool named Fill is used and it fills the spaces by caps inside the exhaust manifold. Figure 4 shows the inner geometry which was created using DesignModeler in ANSYS.

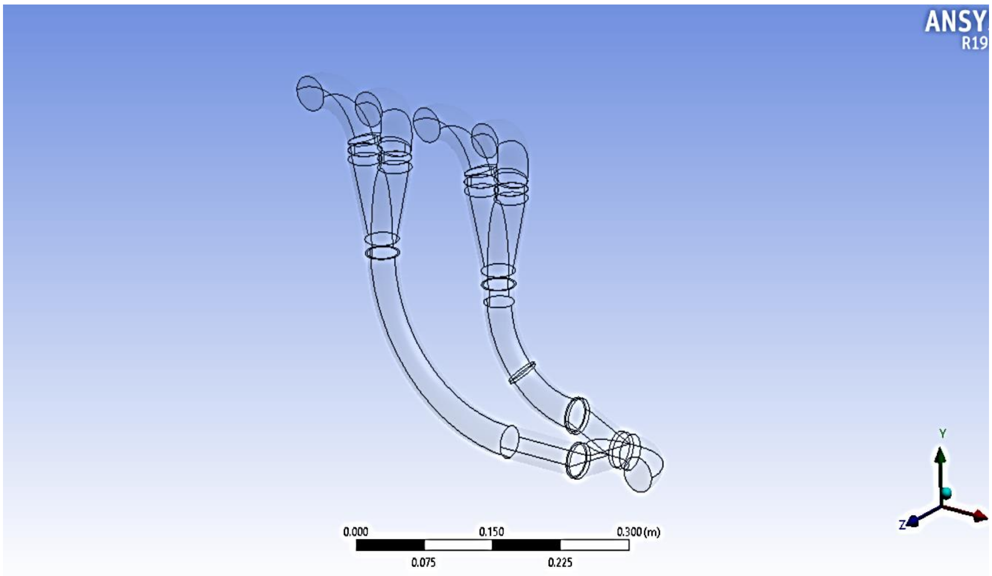


Fig. 4. The view of inner geometry after all other solid parts are suppressed

The general setting is as follows

i. Solver type is Pressure-Based
ii. Velocity Formulation is set to be Absolute
iii. Time is steady.

The model of the analysis was set in the following way

i. Viscous model
ii. Realizable k-epsilon (two-equation) which is used for turbulent flow conditions. Realizable is preferred because it provides accurate predictions and superior performance for flows
iii. Near Wall Treatment is set to Standard Wall Function.

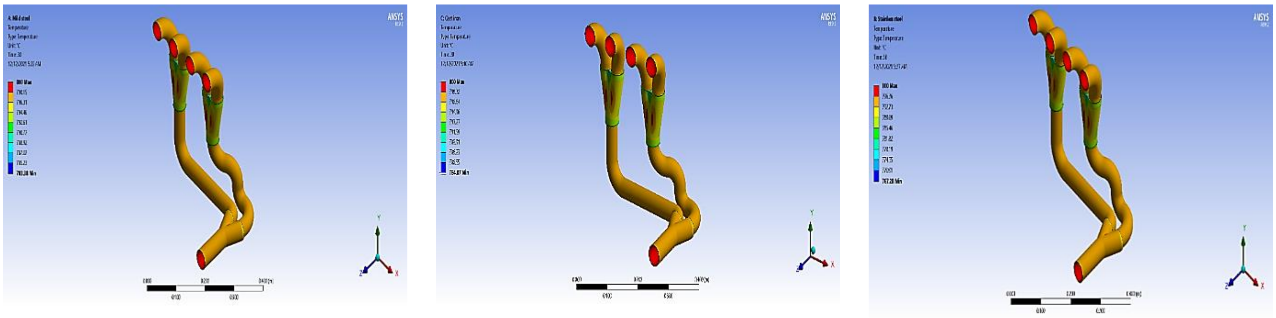
The material of the fluid is air. The boundary conditions were taken from the previous study [10]. All the inlets are set to be velocity-inlet and the outlet is set to be a pressure outlet. The velocity magnitude at every inlet is about 20 m/s and the pressure at the outlet is zero. In addition, the turbulence intensity remained the same as its original parameter which is 5%.

4. Material and Design Analysis Results

The results for two analyses had been obtained as follows.

4.1 Steady-State Thermal Analysis
4.1.1 Temperature distribution

Figure 5 illustrates the temperature distribution of the three materials which are mild steel, cast iron and stainless steel. Based on the appearances, the effect of 800 °C on the exhaust manifold is almost the same for all materials. Therefore, the data of temperature distribution over 30 seconds until the temperature reaches 800 °C is obtained. Figure 6 was plotted using the temperature distribution data. The lines represent the difference between the maximum value and minimum value of the temperature. From the line graph, stainless steel has the highest temperature difference compared to the other two materials, while mild steel is slightly better than cast iron.



(a) Mild steel (b) Cast Iron (c) Stainless steel

Fig. 5. Temperature distribution of three materials on the exhaust manifold

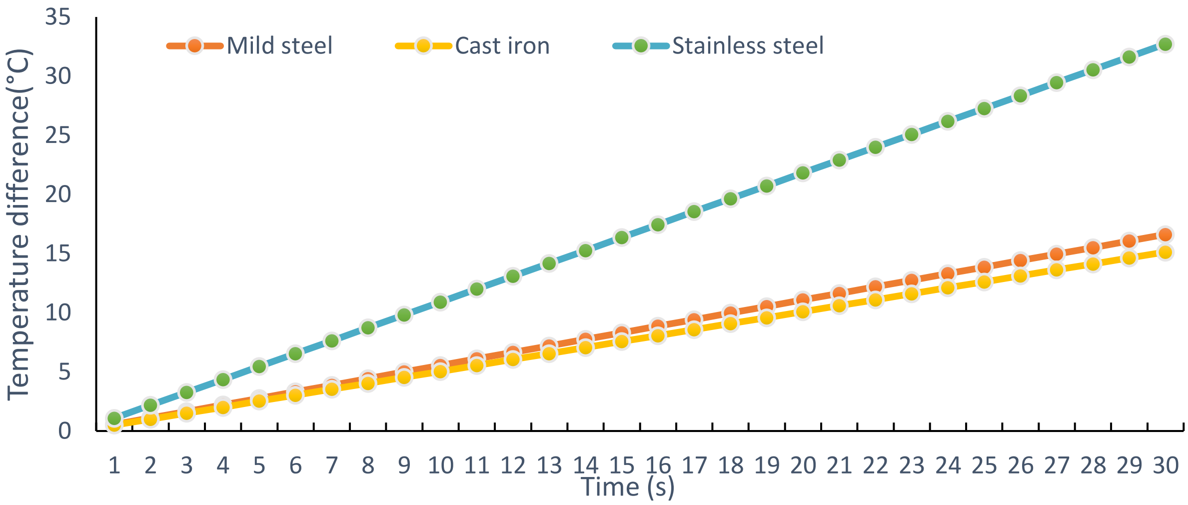
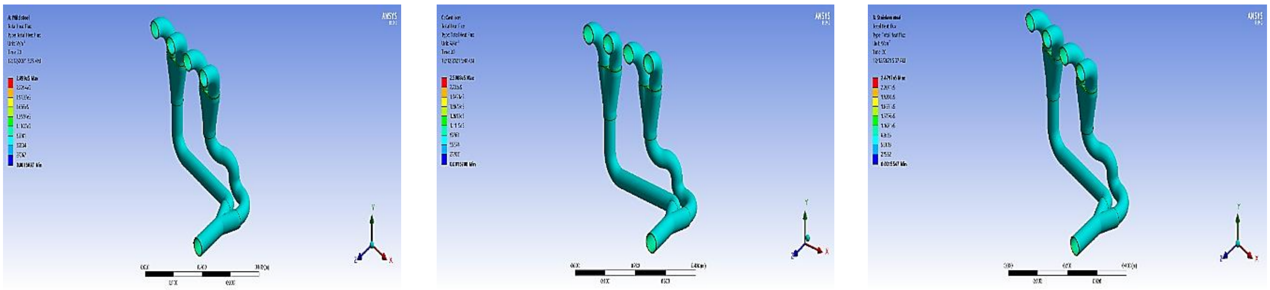


Fig. 6. Graph of comparison on temperature difference between materials

4.1.2 Total heat flux

Figure 7 shows the total heat flux of the three materials; Mild steel, Cast iron and Stainless steel. Based on the appearances, the effect of heat flux on the exhaust manifold is almost similar for all materials. To differentiate the heat flux between materials, the data is analysed separately. Table 3 tabulates the maximum and minimum values at the end of the time period which were taken to demonstrate the difference between materials. Figure 8 and Figure 9 illustrate the differences in maximum and minimum heat flux between materials. stainless steel has the lowest heat flux compared to other materials based on the maximum and minimum values.



(a) Mild steel (b) Cast Iron (c) Stainless steel

Fig. 7. Temperature distribution of three materials on the exhaust manifold

Table 3
Maximum and minimum value of Total Heat Flux at the end of the time

Material	Mild Steel (MI)	Cast Iron (CI)	Stainless Steel (SS)
Maximum value of Heat flux	24.99 x 10^4 W/m^2	25.008 x 10^4 W/m^2	24.797 x 10^4 W/m^2
Minimum value of Heat flux	15.697 x 10^{-4} W/m^2	15.708 x 10^{-4} W/m^2	15.547 x 10^{-4} W/m^2

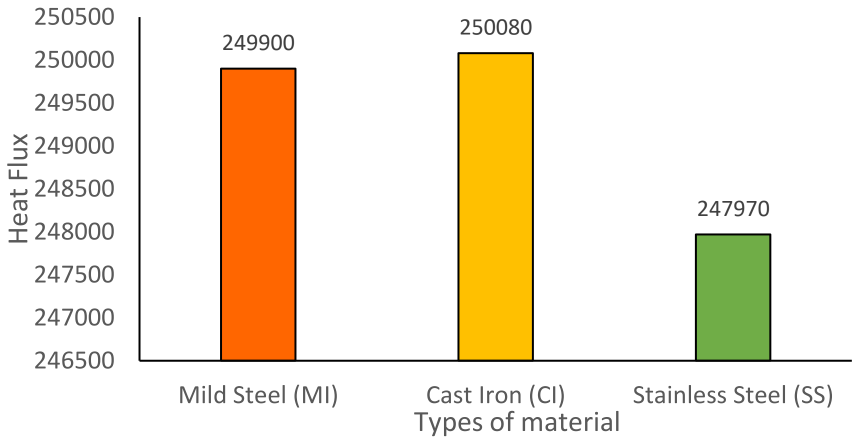


Fig. 8. Maximum heat flux at time period of 30 seconds

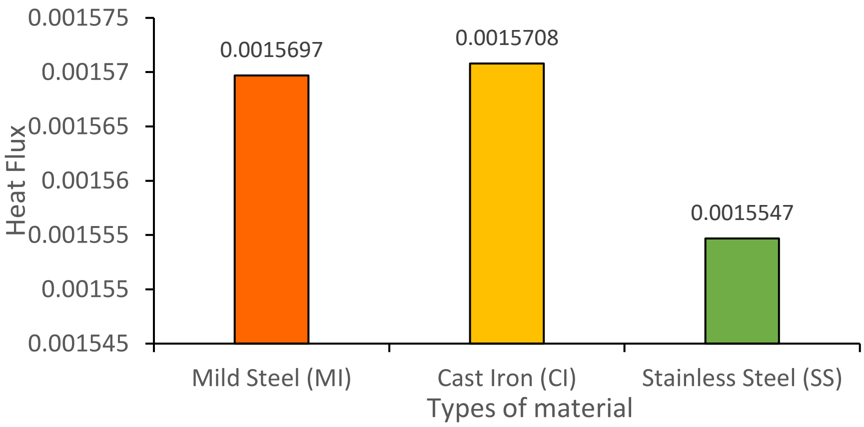


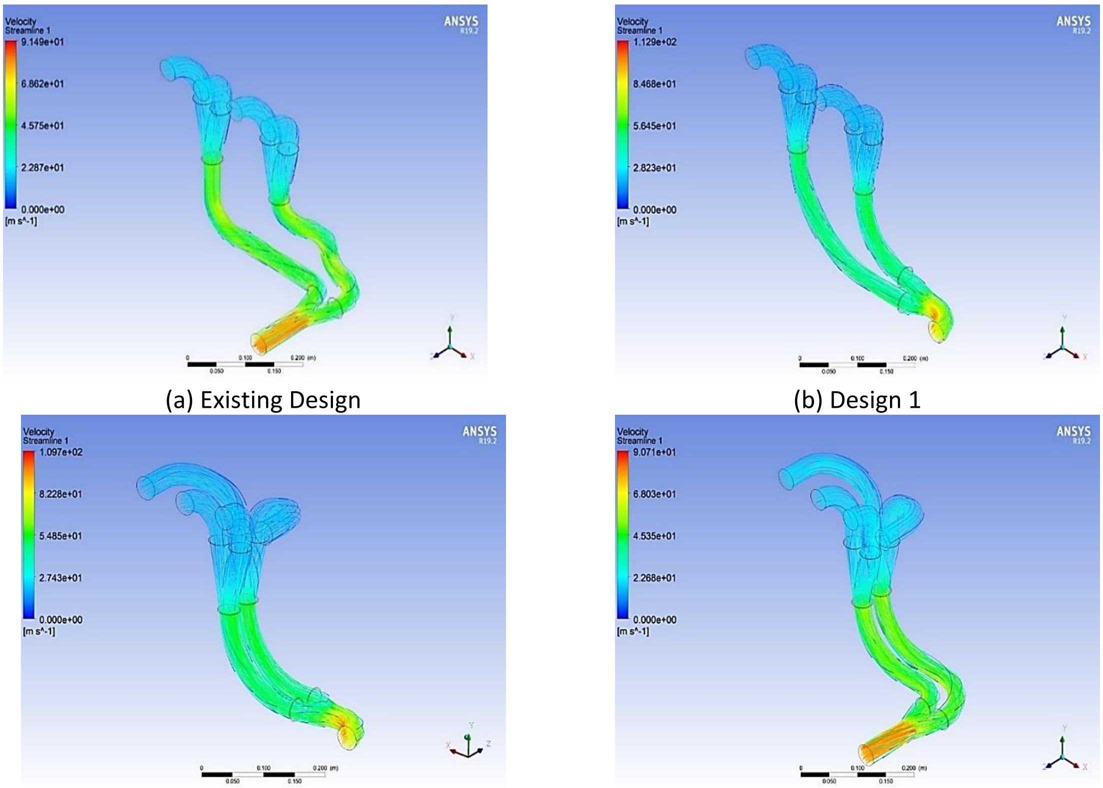
Fig. 9. Minimum heat flux at time period of 30 seconds

4.1.3 Discussion

According to the temperature distribution result, Stainless steel (SS) has a greater temperature difference compared to Mild steel (MI) and Cast Iron (CI). The larger the temperature difference, the greater the heat transfer rates will be. This proves that the heat transfer from the exhaust gases to the exhaust manifold is slower when Stainless steel is used. From the results of the heat flux, Stainless steel has lower heat flux when comparing the maximum and minimum values with Mild steel (MI) and Cast Iron (CI). Usually, materials with high heat flux conduct heat easily, as proved by Hassan experiment data [23]. Therefore, Mild steel and Cast Iron conduct the heat from the exhaust gas easier than Stainless steel. To conclude, stainless steel is superior in both temperature difference and heat flux. As previously stated, the current exhaust manifold is made of mild steel, and the results have shown that stainless steel is far superior to the current material.

4.2 Fluid Flow Analysis
4.2.1 Velocity streamlines

Based on Figure 10, the red colour lines represent the highest value in the streamlines. As determined by velocity streamlines, Design 1 has the highest value in velocity which is 112.9 m/s and then followed by Design 2 which has 109.7 m/s.



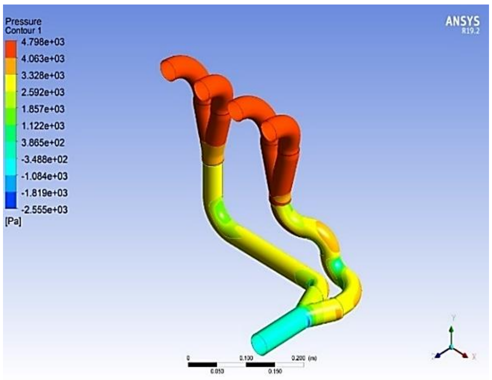
(a) Existing Design (b) Design 1

(c) Design 2 (d) Design 3

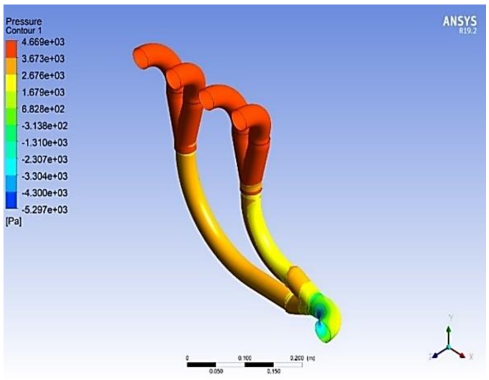
Fig. 10. Velocity streamlines of each design of the exhaust manifold

4.2.2 Pressure contour

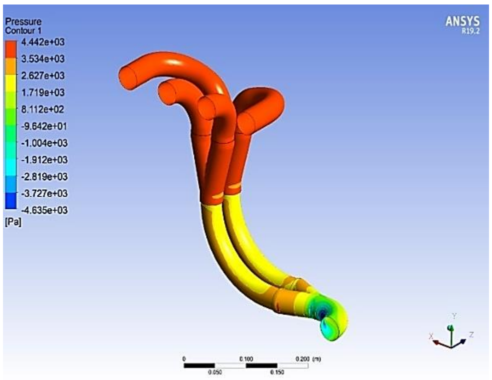
According to the pressure contour of each design of the exhaust manifold as shown in Figure 11, Design 2 has the lowest amount of pressure (about 4.442 kPa) at the top of the exhaust manifold. Besides that, Design 3 has the second-lowest pressure of 4.597 kPa among the other designs.



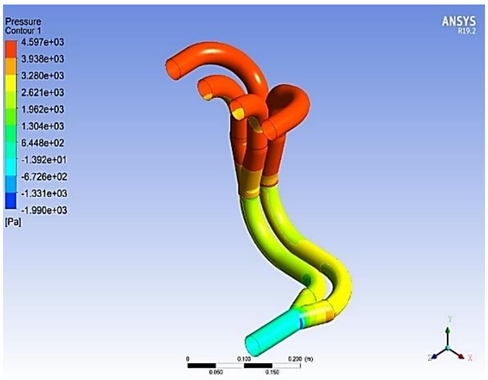
(a) Existing Design



(b) Design 1



(c) Design 2



(d) Design 3

Fig. 11. Pressure Contour of each design of the exhaust manifold

4.2.3 Velocity at outlet

Figure 12 depicts the maximum value of the velocity at the outlet for every manifold design. Referring to the bar chart below, Design 2 has the highest value of outlet velocity and the existing design has the lowest among others. The second highest is Design 1 which has a velocity of 84.52 m/s.

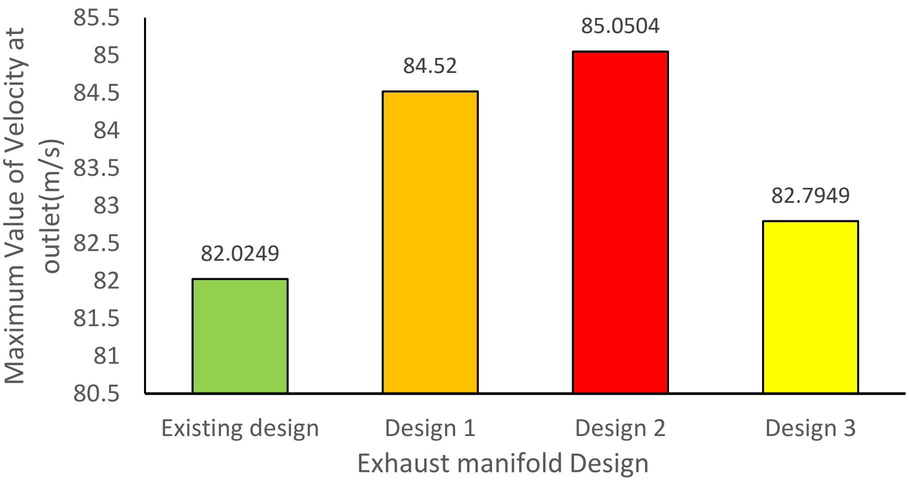


Fig. 12. Graph of comparison in velocity at outlet

4.2.4 Discussion

From all perspectives, Design 2 is better in terms of velocity and pressure when compared with other designs. Design 2 has higher velocity and lower pressure than the existing design where the flow can be improved if the existing design is replaced with Design 2. This is due to the fact that as the velocity approaching the exhaust outlet rises, the pressure drops to atmospheric pressure [14,24].

5. Conclusion

This study examines the material of the exhaust manifold by analysing the temperature distribution and heat flux. The materials were evaluated using Steady-State Thermal analysis in ANSYS software. This paper focused on the effects of exhaust gas temperature on different exhaust materials. To sum up, the results clearly show that Stainless steel has a higher temperature difference and has 24.797 x 10^4 W/m^2 heat flux which is lower than other materials. Hence, Stainless steel was chosen as a replacement for the current material.

Additionally, the fluid flow behaviour in the exhaust manifold with geometrical changes has been discussed in this study by analysing the air velocity and pressure. The exhaust manifold was improved by modifying and redesigning it in an effort to improve the engine performance. The fluid flow behaviour is simulated and evaluated using CFD software called ANSYS. Design 2 was selected based on the criteria of having high velocity at the outlet and low pressure at the inlets. By comparing the results, Design 2 has an outlet velocity of 85.0504 m/s and 4.442 kPa of pressure at the top part of the manifold which is better than the current design.

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