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Intake Manifold Material Selection and Fluid Flow Analysis for Formula Society of Automotive Engineers (FSAE) Race Car

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ABSTRACT

The Formula SAE competition is organised for students who want to design and build a Formula-style race car. To limit the car's performance for safety and to encourage problem-solving skills, a 20mm restrictor was installed between the carburetor and the intake manifold to reduce air intake. When airflow is restricted, a bottleneck effect occurs, and less air is supplied to the engine for combustion, lowering engine efficiency. The goal of this project is to find a solution to this problem within the rules' limitations. This is accomplished by selecting an intake manifold that provides the best uniform distribution through each outlet and selecting a material that can withstand engine stress and vibrations while maintaining a relatively low temperature to ensure consistent velocity and pressure. Computational Fluid Dynamics (CFD) software is used to analyse the design's fluid flow, static, and thermal analysis, and the results are compared for each design. The best design and material will be used on the Universiti Malaysia Perlis Automotive Racing Team (UniART) race car.

1. Introduction

A Formula Society of Automotive Engineers (FSAE) car is a lightweight, low-velocity racing car that is used during an SAE competition that evaluate the car's performance along with technical inspections, among other criteria [1]. Students build and analyse the chassis [2, 3], as well as construct a crash attenuator to reduce impact during a collision [4]. Engine performance was also improved by changing the operative inlet for a better air-fuel mixture in the engine [5] and employing Internet of Things (IoT) to do diagnostics remotely [6 - 12]. Judging criteria varies through a series of events, which also includes cost and presentation, among other technical criteria such as time, maneuverability, and fuel consumption [13].

Intake manifold is a part of the engine located between the engine cylinder and throttle body. Its primary function is to provide a uniform air and fuel mixture distribution to all the cylinder runners

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by splitting the amount of air sucked into the engine cylinder. Essentially, uniform distribution is crucial to provide a better performance and optimum efficiency of the engine [14]. The analysis of fluid and aerodynamics are usually conducted through simulations as economical yet extensive alternative [15].

The input air given by the intake manifold to the engine is important since the engine output power mainly depends on the input. The size, shape, material, and manufacturing method are the parameters to be studied for a higher intake. The thermal conductivity of the intake manifold material shows a vital character in the engine performance since it increases the temperature of the intake manifold [16]. When the temperature of the manifold rises, it decreases the density and in turn the volumetric efficiency decreases.

Based on the findings, this serves as the foundation for the investigation of material properties for the application of an intake manifold for an FSAE car.

2. Methodology

This section describes the method utilized in the present investigation. The study consists of analysis using Computational Fluid Dynamics (CFD) software to simulate the fluid flow, static and thermal load towards the modelled intake manifold design.

2.1 Intake Manifold Design

The considered intake manifold designs follow the previous design selections, which include five designs, as shown in Figure 1. The designs were created using CATIA Stude nt Edition.

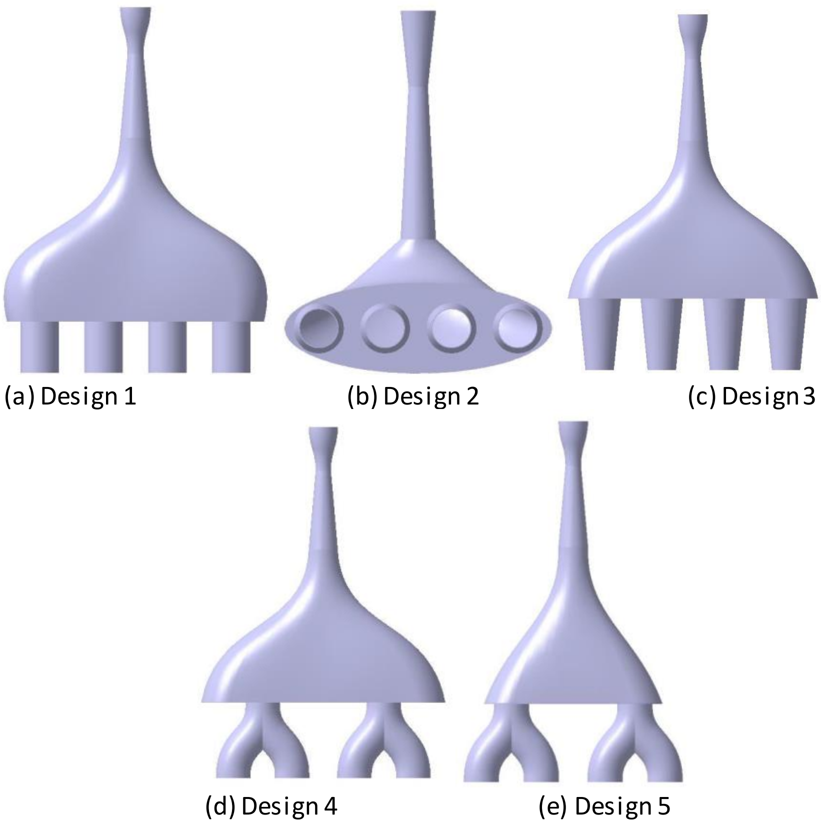

Fig. 1. Intake manifold designs

2.2 Fluid Flow Analysis

ANSYS CFX fluid flow analysis system from Ansys 2021 R2 was used for this analysis. The model that was previously designed is imported and mesh is generated using the settings shown in Table 1. Table 2 shows the domain and boundary condition settings. The values used for the relative pressure of input and output is taken from our previous research regarding the intake manifold design [17].

Table 1
Mesh settings

Inflation settings	
Boundary	Whole outer surface
Inflation option	First layer thickness
First layer height	0.0004
Maximum layers	7

Table 2
Fluid flow boundary conditions

Boundary conditions		
Domain	Turbulence Option	k-epsilon
	Wall Function	Scalable
	Boundary Type	Inlet
inlet	Mass and Momentum Option	Total Pressure (Stable)
	Relative Pressure	101325 Pa
Outlet 1	Boundary Type	Outlet
	Mass and Momentum Option	Static Pressure
	Relative Pressure	59025 Pa
Outlet 2-4, Body	Boundary Type	Wall

The data that was recorded from this analysis are the velocity and mass flowrate of the open outlet. The analysis is then repeated for all considered designs

2.3 Materials Properties

Further analysis requires the material to be defined and the materials that will be tested are aluminium alloy 6063, carbon fibre, and stainless steel. The considered material and their properties are listed down in Table 3.

Table 3
Mechanical properties of materials tested

Material	Mechanical Properties
Fiberglass	Density, ρ: 1850 kg/cm^3 Tensile X Direction: 0.78 GPa Tensile Y Direction: 0.031 GPa Tensile Z Direction: 0.031 GPa Thermal conductivity, λ: 0.4306 W/(m·K) Specific heat, Cp: 700 J/kg K
Aluminium alloy 6063	Density, ρ: 2770 kg/m^3 Tensile Yield Strength: 280 MPa Tensile Ultimate Strength: 310 MPa Thermal Conductivity, λ: 200 W/(m·K)) Specific heat, Cp: 875 J/kg K
Gray Cast Iron	Density, ρ: 7220 kg/m^3 Tensile Yield Strength: 3220 MPa Tensile Ultimate Strength: 2440 MPa Thermal Conductivity, λ: 52 W/(m·K) Specific heat, Cp: 447 J/g K
Carbon fibre	Density, ρ: 1800 kg/m^3 Tensile Yield Strength: 3220 MPa Tensile Ultimate Strength: 3584 MPa Thermal Conductivity, λ: 6 W/(m·K) Specific heat, Cp: 800 J/g K

2.4 Thermal Analysis

Referring to Table 4, the geometry of the selected intake manifold design is linked to the transient thermal analysis in Ansys. This step is done to import the mesh generation from previous analysis so that the remaining steps are to assign the material and thermal load. The considered material is applied to the intake manifold while the fluid inside the manifold is air. The generated data from this analysis are heat flux and air temperature.

Table 4
Transient thermal settings

Initial Temperature	Initial Temperature Value	26 ˚C
Analysis Settings	Number of Steps	50˚C
	Current Step Number	1
	Step End Time	300s
Convection	Geometry	Body
	Film Coefficient	15 W/m^2˚C
	Ambient Temperature	50˚C
Heat Flux	Geometry	Outlet
	Magnitude	3.e^{-005}W/mm^2
Temperature	Geometry	Inlet
	Magnitude	45˚C
Temperature 2	Geometry	Outlet
	Magnitude	90˚C

2.5 Static and Modal Analysis

The solution of transient thermal analysis is linked to the static structural analysis as a thermal load for the static analysis. Fixed supports were attached to both ends of the intake manifold for supporting the manifold between the engine and throttle. Pressure is applied to the inlet and an outlet to simulate the airflow. The total deformation, Von-Mises stress and strain results are generated for further discussion.

Modal analysis is performed to determine whether the self-excitation frequency of the intake manifold would be less than the natural frequency. The solution from the previous analysis is linked as the setup for the modal analysis. The solution linked from the static structural analysis serves as the pre-stress for the modal analysis. A total of 5 modes is set in the analysis settings. No further settings are required as the load was linked and imported, and the analysis can now be performed.

3. Results

This section is divided into two main subsections according to the purpose of the analysis: Design selection and Material selection.

3.1 Design Selection

The first subsection presents the results that will determine the new design for the intake manifold to be further tested on materials. The intake manifold is judged based on the criteria of flow velocity, mass flowrate and pressure.

3.1.1 Velocity

The average velocity of each design in each outlet is graphically presented in Figure 2. It can be observed that Design 1 has the best distribution of air velocity where each outlet has a minimal difference of 2m/s at most. Design 2 and 4 can be disqualified under the criterion of speed due to low and stark imbalance velocity egressing from each outlet. Design 3 has dispersed the highest speed among other designs while having a relatively balanced dispersion, albeit having a higher amount in the first outlet than the rest. The high velocity is due to the application of Bernoulli's equation, where increasing the diameter of outlet opening then gradually reducing it. Design 5 has an average velocity compared to other designs but has an unsatisfactory distribution as the value greatly decreases before increasing significantly. According to Kang *et al.,* [18] a lower velocity indicates a laminar flow which increases power loss

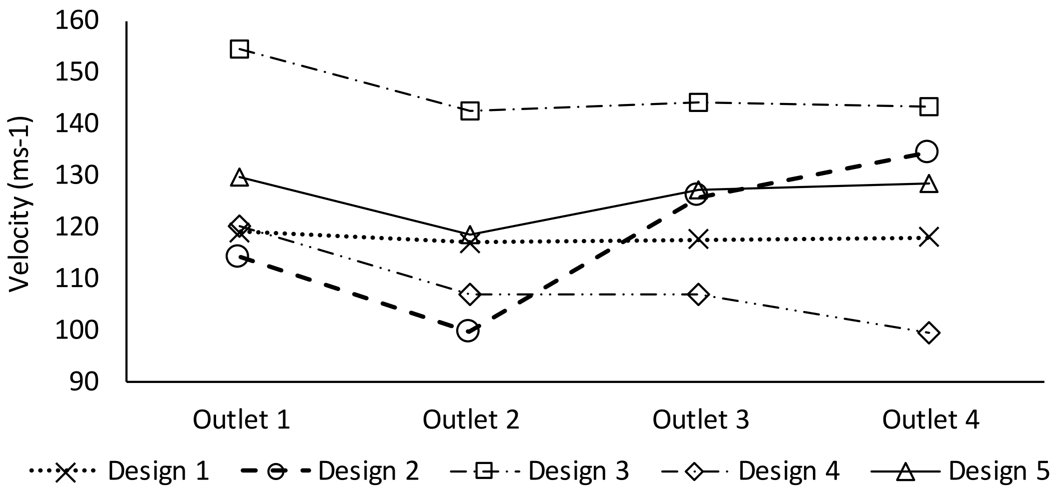

Fig. 2. Average Velocity for Each Design in Each Outlet

3.1.2 Mass flowrate

From Figure 3, design 1 is shown to have the highest average mass flowrate while having minimal deviation in distribution. However, the highest flowrate is achieved by Design 2 which shows an increasing trend in each outlet. Despite having the highest velocity, Design 3 had obtained the lowest flowrates along with Design 4. This may be due to the decreasing outlet diameter creating a minor bottleneck effect which limits the cross-section area and ultimately reduces the flowrate. The results have shown that the velocity of the incoming flow towards the outlet does not affect the mass flowrate.

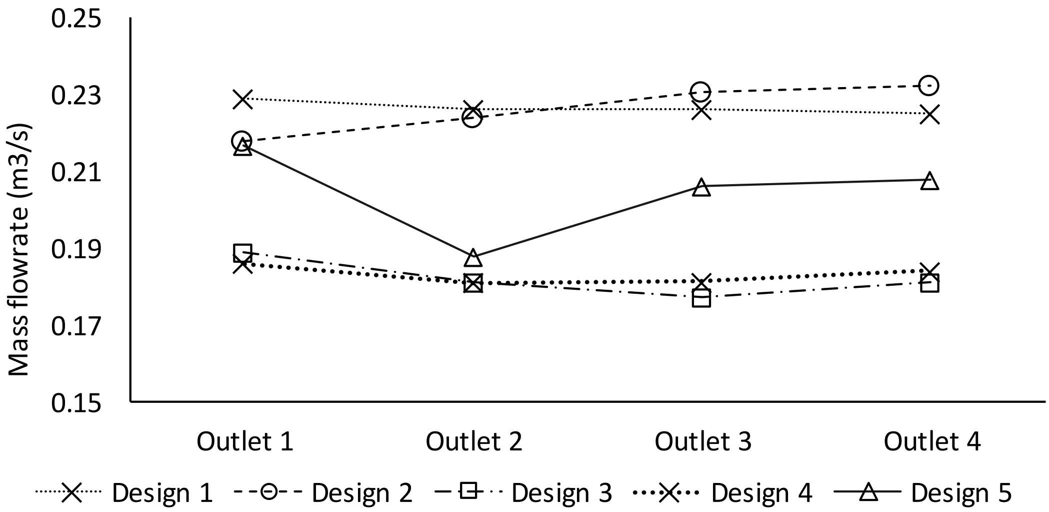

Fig. 3. Mass Flowrate for Each Design in Each Outlet

In conclusion, the decision of selecting Design 1 as the intake manifold design remains as it truly provides a high and balanced mass flowrate towards each outlet while providing a turbulent flow for a better air-fuel mixture for the combustion.

3.2 Material Selection

This section describes the simulation results to analyse a material through three categories, which consists of thermal, static and modal analysis.

3.2.1 Thermal analysis

Table 5 summarizes all the data from the thermal analysis. Inlet velocity influence on the temperature was neglected although results shown inlet velocity speed affects the cooling [19]. While epoxy is supposedly thermally resilient, grey cast iron had shown better results than carbon fibre in terms of the manifold and air temperature. A similar result was presented by Rautrao [20] where cast iron had surpassed carbon fibre in thermal properties by a large margin. A higher carbon content had increased the heat capacity of the material. Since cast iron has a relatively lower carbon content, it became a poor conductor of heat, which is why the manifold temperature did not exceed 90˚C despite having a higher air temperature inside.

However, fibreglass had remained as the superior choice for withstanding thermal loads. While epoxy itself has poor thermal conductivity, fibreglass is well known for its heat insulation purposes that reduces convection due to air trapped within the fibres structure alignment, restricting airflows [16]. Meanwhile, carbon fibres are conductive materials, which, despite being coated by epoxy, still can conduct heat throughout the fibres which reduce the insulating properties [17].

Table 5
Thermal analysis results

Material	Manifold Temperature (˚C)		Air Temperature (˚C)		Heat Flux (W/mm^2)	
	Min	Max	Min	Max	Min [$x10^{-6}$]	Max [$x10^{-2}$]
Aluminium Alloy	44	90	44	99	7.5061	11.88
Gray Cast Iron	38	90	38	95	6.9823	6.3142
Carbon Fibre	39	90	39	90	0.2047	1.7951
Fibreglass	32	90	36	90	0.0552	0.4206

3.2.2 Static analysis

Table 6 summarizes all the data from the static analysis. Aluminium experienced the highest stress, almost by twofold of grey cast iron, it was also stated by Nunez *et al.,* [21] that the material was shown to have lower performance than cast iron. Aluminium alloys are known to lose their strength when exposed to high temperatures, lowering the resistance against the load, causing it to obtain the highest deformation against other materials by a large margin.

Grey cast iron performed better than aluminium alloy, as expected by observing the results of experiments conducted by Chandan *et al.,* [22] and Jolly *et al.,* [23] and had also outdone fibreglass in withstanding strain and deformation, despite experiencing a large amount of stress that is almost 8 times larger than fibreglass. This is due to the grey cast iron microstructure and compositions that contain carbon which causes the material to become brittle which consequently performs better under compressive loads [24].

Composite materials such as carbon fibre and fibreglass epoxy have shown to have high resistance against stress. However, the largest strain occurred in fibreglass, both in minimum and maximum. This poses a potential failure during operation since composite materials are most susceptible to it when strained, even by a small amount. Despite experiencing a significantly low stress, fibreglass performed poorly in maintaining its shape as the deformation obtained was high.

Carbon fibres were repeatedly demonstrated to have significant strength and the results have proven it is the most superior material among the considered materials. Its exceptional mechanical properties are due to the fibre's stiffer nature and relatively great strength compared to glass fibre, as stated by Tang *et al.,* [24].

Table 6
Static analysis results

Material	**Total Deformation (mm)**		**Stress (MPa)**		**Strain (mm/mm)**	
	Min	Max	Min	Max	Min [x10^{-6}]	Max [x10^{-3}]
Aluminium Alloy	0	0.1530	0.1390	252.451	7.332	3.556
Gray Cast Iron	0	0.0582	0.1241	175.630	3.237	1.609
Carbon Fibre	0	0.0007	0.0031	5.728	0.0225	0.0255
Fibreglass	0	0.1066	0.0341	22.033	12.164	3.621

3.2.3 Modal analysis

Figure 4 shows the Maximum deformation for intake manifold. The deformation that occurs is more sensitive towards energy dissipation rather than stiffness degradation, regardless of the mode order but the sensitivity increases as the mode order increases [25]. This is due to the strain energy increasing along with the mode order increment which consequently causes large deformation in composite materials despite having a lower frequency.

Figure 5 shows the Natural frequency for intake manifold. Aluminium achieved a higher natural frequency than grey cast iron, a result that was verified by Surendra *et al.,* [26] that concludes aluminium as the superior choice for that reason. This is because the alloying element of copper in the material had increased the strength and hardness [27]. Cast iron was repeatedly demonstrated as an inferior choice from its low natural frequency but high deformation [22].

A higher value of vibration mode does not necessarily mean higher maximum deformation. This is proven by all the compared materials, excluding grey cast iron, where mode 3 produces a higher deformation compared to mode 4. According to Kudus *et al.,* [28], higher natural frequencies are vital to avoid resonance which may result in the structure experiencing fatal destruction.

Carbon fibre obtained an exceptionally high difference in natural frequencies compared to all the other materials due to its high stiffness. However, the drawback was that the high stiffness had consequently caused a high deformation. Meanwhile, fibreglass had obtained the largest deformation despite having the lowest natural frequencies. The performance differences between these two composite materials are due to their strength and stiffness, which was previously explained by Khalid *et al.,* [29] where carbon fibre has significant strength and stiffness compared to fibreglass.

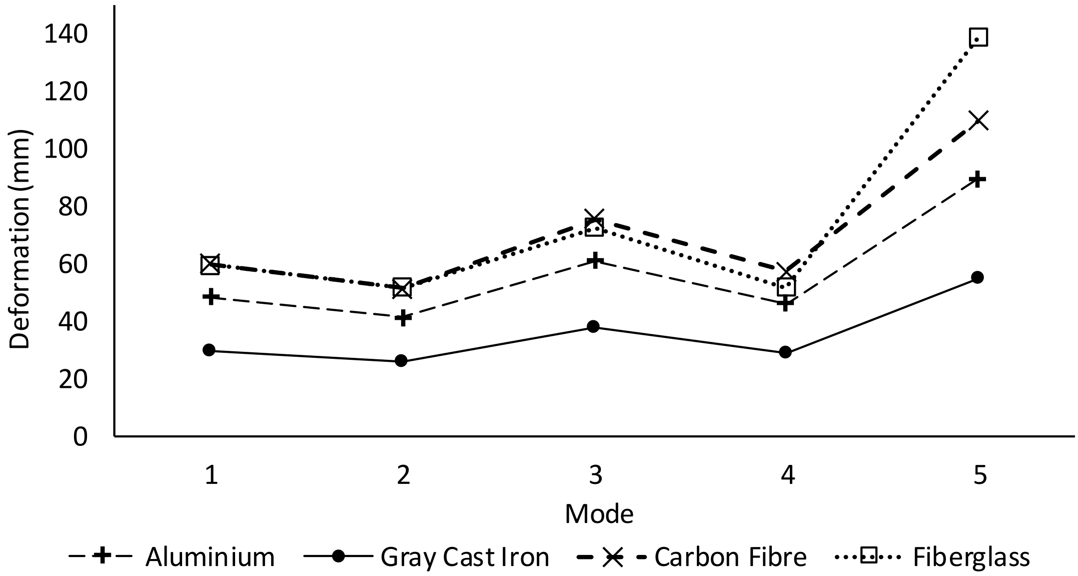

Fig. 4. Maximum deformation for intake manifold

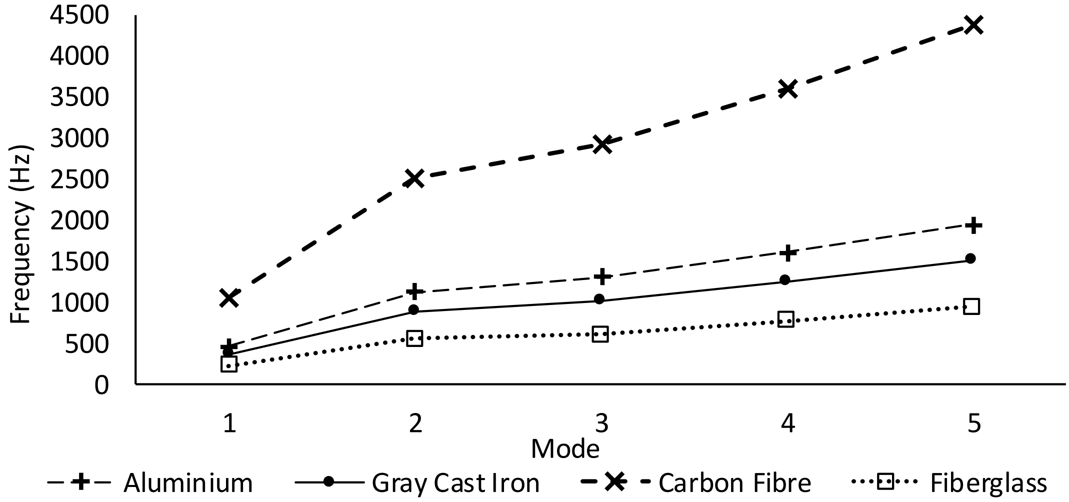

Fig. 5. Natural Frequency for Intake Manifold

4. Conclusions

Five intake manifold models are studied and analyzed under the criterion of velocity and mass flowrate in each outlet. The design with the highest yet balanced results is selected as the new design and will be proceeded to be the model for material testing. The considered materials, aluminium alloy, gray cast iron, carbon fibre, and fibreglass, are applied to the new intake manifold design and thermal, static and modal analysis are conducted. The material which can best withstand the thermal and structural load is chosen as the new material for the intake manifold.

Design 1 was selected for the intake manifold design for having a high yet balanced airflow in each outlet. Although it did not have the highest velocity at the outlet, it has the highest mass flowrate along with a turbulent flow that will assist the air-fuel mixture. Carbon fibre was selected to be assigned as the new material for the intake manifold. The material was proven to be strong enough to undergo high levels of vibration and stress. Having superior performance in static and modal analysis proves its suitability for the application. If the need arises for a better thermal property, the type of epoxy used could be changed to a more suitable one. Although the fabrication process may be complicated and delicate, its endurance will ensure the material will provide longer service life and save cost in the long run.

In conclusion, Design 1 was selected as the intake manifold design with carbon fibre as the material. Both the design and material had shown superior performance in the category that they were tested on. Future studies may broaden the scope regarding material properties and include material roughness for the analysis which may affect the temperature and fluid flow through friction and obstruction.

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