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Design and CFD Analysis of Exhaust Manifold for the Four - Cylinder SI Engine using Alternate Fuels

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Abstract
One of the most crucial components of the engine is the exhaust manifold which incorporates the exhaust gases from the various different cylinders and sends it to the final exhaust pipe. The exhaust manifold is an important component of the automotive engine and hence it directly impacts the engine performance. The way of functioning of exhaust manifold is very intricate and the working efficiency of the exhaust manifold is dependent on various parameters like exit velocity of the exhaust gases, back pressure etc. This project emphasizes on the study of the thermal and flow characteristics of the exhaust manifold as well as the study of the backpressure effect onto the exhaust manifold. The exhaust manifold is analyzed using the distinct fuels namely alcohol, gasoline as well as LPG. The exhaust manifold chosen for the study is generic manifold used in the four-stroke gasoline engine. The project encompasses the design modelling which is performed in the CATIA software along with the theoretical analysis of the exhaust manifold thereby using ANSYS software. After the execution of the simulations, the conclusions are drawn regarding the effect of the various parameters on the efficiency of the exhaust manifold. Along with that, the fuels are also compared to determine the most suitable fuel used for the higher efficiency of the exhaust manifold.

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I. Introduction

The exhaust manifold is the crucial part of an IC engine and it accumulates the exhaust gases and transfers the exhaust gases produced from the engine cylinder to the outlet or the exhaust section. It is located at the end of the engine block and it might be connected either at the front or at the backside of the car. The exhaust manifolds are constructed by either the cast iron or the stainless steel. The efficiency of the exhaust manifold depends on the distribution of the temperature and heat dissipation within the manifold which in turn causes the deformations and the thermally induced stresses. The exhaust manifold has a direct impact on the working performance of an IC engine. The efficiency of the IC engine improves if the exhaust velocity of the outlet gases can be increased.

The exhaust manifold also impacts engine performance in other aspects as well. The outlet manifold impacts other characteristics such as fresh charge intake, piston movement during the outlet stroke as well as the cylinder filling up of cylinder. The pressure existing in the valve affects the movement of the gases. Hence the pressure can be identified as the parameter which significantly affects the working of the exhaust

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manifold which in turn affects the functioning of an IC engine.

Another parameter which has a major impact on the engine performance is known as backpressure. The backpressure is the resistive force which prevents the fluid flow and results in the pressure drop. It is a known fact that the back pressure building up on the exhaust of an IC engine is also responsible for the lesser efficiency of an engine. This results in the reduction of the power output of the engine. The backpressure in the exhaust is integrally caused by the muffler, exhaust manifold, catalytic converter as well as the various pipes interconnected in the system. The backpressure can be the result of the obstruction which can accumulate the residual in the cylinder head. This can prevent the intake of the fresh charge and can ultimately lead to unnecessary temperature rise during the compression. Hence the back pressure has to be reviewed carefully.

1.1 History of the exhaust manifold

The development of the exhaust manifold has come a long way since the early times. The traditional manifolds used in the automotive industry were the traditional original equipment manufacturers supplied cast-iron modules. They were used in order to reduce the cost as well as the saving of the space. Nowadays the new type of exhaust manifolds also known as the headers are installed keeping in mind for the optimization of the power production. The exhaust manifold designs back in the days were highly inefficient compared to nowadays. Older manifolds were solely designed for the exit of the gases out of the engine cylinder without keeping in mind about the flow optimization, back pressure and several other aspects. The back pressure used to be a lot higher and along with that, there was no smooth flow of the gases. This resulted in the higher work done by the piston at the final stroke of the engine. The inefficient design resulted in the accumulation of the exhaust gases at the outlet and due to this, the temperature inside the engine used to higher. Nowadays a lot of research has been carried out regarding the exhaust manifold configurations and the various aspects of the design and the performance have been improved.

The testing and optimization of the manifolds can be done either by the trial and error method as well as the advanced CFD analysis method. The trial and error method is pretty accurate but it is very cost-inefficient and takes a lot of time to complete. However, the CFD analysis can obtain critical details regarding the flow structure and thermal parameters.

1.2 Aim of the Project

The project aims to understand and outline the parameters affecting the working of the exhaust manifold. The main of the project is to determine the most suitable alternative fuel to be used in the engine so that the fluid flow of exhaust gas on the exhaust manifold could be optimized. The objectives of the project are stated as follows.

- To conduct the CFD analysis on the multi-cylinder engine exhaust manifold
- To understand the mechanism of the gas flow in the exhaust manifold
- To determine the effect of the backpressure on working of the exhaust manifold
- To optimize the working of the exhaust manifold

1.3 Problem Definition

Nowadays, traditional fuels such as gasoline and petrol are being replaced with the non-conventional fuels made up of different constituents. The advanced fuel used for the automobile has to perform comparatively similar to the traditional fuels whereas the harmful gas emissions have to controlled and prohibited. Hence there is a growing need to carry research on alternative fuels. The effectiveness and viability of

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the fuel exist in the efficiency of the fuel and the power obtained by the vehicle when using alternative fuels.

The exhaust system is one area where the effectiveness of the fuels can be visualized. The exhaust system transmits the gases from inside of the engine to the outside of the engine and vehicle. The pressure existing in the exhaust manifold is an important parameter for the IC engine efficiency. The exhaust flow is rather pulsating than the smooth transmission. Due to which the backpressure is generated. It can be defined as the pressure of the gas originated by the engine for nullifying the hydraulic resistance for the exhaust of the gases. The backpressure is rather an undesirable phenomenon since it results in the lesser power output and the failure of the vehicle parts such as turbocharger seals. So this project is aimed at the determination of the backpressure at the exhaust for the different alternative fuels. The fuels considered for this project are LPG gas and the ethanol or more commonly known as alcohol. The traditional analysis is very inefficient and complex. It is also difficult to analyze and find the exact solution because of the complexity of the manifold design. Hence the analysis will be carried out using the advanced CFD analysis. The CFD analysis will determine the exhaust flow parameters and as a result, the best fuel for exhaust manifold can be determined.

II. Literature Review

The literature study is conducted by reviewing various documents, journals as well as the articles regarding the exhaust manifold and its analysis. Some of the reviewed journals and their findings are summarized below.

K. S. Umesh Et Al. (2013) performed the CFD analysis of the exhaust manifold for the multi-cylinder spark-ignition engine. They made the consideration of using the 8 different models of the exhaust manifold regarding the project. They evaluated the mass flow rate of the exhaust gases and found out the pressure and the velocity contours for the six various loading conditions at 2, 4, 6,8,10 and 12 Kg. respectively. Finally, they found out the performance results of the exhaust manifold models in terms of back pressure and exhaust velocity. They found out that the higher the loading of the models, higher would be the backpressure of the exhaust manifolds. The value of the backpressure was found to be generally higher for the short bend side exit with the reducer model. The highest back pressure occurred at 12 kg loading and the back pressure was found to be lowest at 2 Kg. loading. The lowest backpressure was produced in a long bend centre exit model. However, the exhaust velocity was found to be highest in the long bend centre exit model at 12 kg loading and the lowest exit velocity was produced in the short bend centre exit model at 2 Kg. loading. They concluded that the long bend centre exit model was the most efficient design for the exhaust emission in the exhaust manifold.

Mohd. Sajid Ahmed Et al. (2015) executed the design and analysis of the multi-cylinder four-stroke engine. The analysis was performed using the CFD technique. They designed the five different models and made a comprehensive analysis of the models in terms of velocity and the pressure contours. They modified the shape of the different models by converging or diverging the inlet and the outlet section of the exhaust manifold. They analyzed the results by using the CFD post-processing. Through the analysis, they found out that the fifth model having equal divergent and the convergent area of the manifold outlet had the smooth outlet flow. Along with that the fifth model had the lowest backpressure without the recirculation and had a higher exhaust velocity. They concluded that the 5^{th} model was the optimized model. They also realized that the integration of the exhaust manifolds with the reducers could reduce the emissions.

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Kelbessa Kenea Deressa Et al. (2016) designed and analyzed the rear spoiler of the SU vehicle using the CFD analysis process. They designed the spoiler using the CATIA software at 3 degrees and 28 degrees respectively and performed the analysis of the spoiler using the ANSYS fluent software. They found out the drag coefficient of the vehicle when using the different spoilers. They found out that the coefficient of the drag was lowest when 3° spoiler was used and when the 28° spoiler was tested, it had the highest coefficient of drag. They also found that the 3° spoiler had the maximum streamline velocity and the fuel economy of the vehicle was found to be increased by 3.2% with the use of the spoiler. Hence the 3° spoiler was further selected for the fabrication process. They used the mild steel sheet and used the bending and welding process to complete the fabrication process.

Barhm Mohamad Et al. (2017) conducted the modelling and analysis of the four-stroke gasoline engine exhaust gas systems. They investigated the exhaust gas flow by using CFD analysis on the parameters such as manifold pressure and temperature as well as the exhaust piping systems and the gas velocity. They determined the result of the CFD simulation in terms of streamline as well as the pressure and velocity contours. They used the three fuels like LPG, gasoline and alcohol for the study. They noted that the flue gas temperature and pressure went on decreasing when the gases moved forward to the exhaust manifold outlet. Through the mathematical model, they realized that the highest velocity of exhaust gases was found to be near the outlet of exhaust manifold since the pressure at that position was low. They confirmed that the variation of the exhaust piping length, as well as the variation of the bend pipes numbers, made a direct impact on the backpressure rise as well as the power output of the engine.

Yasar Deger Et al. (2004) executed the couple FE and CFD analysis for the diesel engine exhaust manifold. They performed the CFD analysis for the fixed operation conditions with the variation only with the cooling flow. First, they prepared the numerical model and generated the mesh of the manifold. They applied the boundary condition regarding the thermal property and selected the particular surface and ambient temperature of the model. Through the CFD analysis, they found out that the maximum temperature in the manifold occurred near the exhaust gas outlet. They also conducted the FE analysis of the manifold using ABAQUS. Using the FE analysis they found out that the yield stress and the maximum thermal stress were almost the same. The stress values were found to be higher near the water cooling and the vapour cooling points.

III. Process Methodology

This section deals with all the processes and methods involved in executing the project. During the initial phase of the project, the design review and brief study are carried out. And in the next phase, the engine and the manifold selection will be carried out. After the selection of the manifold, the design process is carried out. The design of the manifold is performed in the CATIA v5 software. After the overall modelling of the manifold, the design calculation is carried out. And later on, the design is subjected to the analysis. The analysis is carried out in ANSYS software. For the analysis process, the designed model is meshed into minute elements and the boundary conditions are established. Later on, the meshed model is subjected to analysis after inputting all the required data. Finally, the results are drawn out. The processes are outlined in the diagram below.

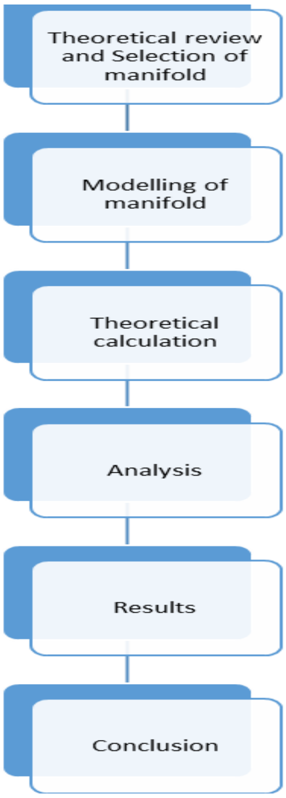

Figure 1: Project methodology

IV. Theoretical Review And Selection of The Manifold

This section deals with the theoretical aspects and appropriate selection of the manifold. Initially, the exhaust manifold is reviewed and overall information regarding the manifold is obtained.

As stated earlier in the introduction section, the exhaust manifold is the part of the engine which helps to transmit the gases inside the engine cylinder to the outside of the engine. The exhaust manifold also plays an important role in the prevention of the transmission of the exhaust gases inside the automobile. The exhaust manifolds use two or multiple pipes for funnelling the exhaust gases out of the engine.

The construction of the exhaust manifolds is made from either the cast iron or the tubular steel. The cast iron manifolds are generally heavier manifolds which are cheaper for construction. They also can cast longer time compared to the tubular steel exhaust manifolds. However, the cast iron manifolds are brittle and the risk of the crack is prominent which can cause noise problems in the engine. On the contrary, the tubular steel manifolds are lighter in weight and are designed to be fit in the tight and small spaces. Moreover, being the lighter manifolds, tubular steel manifolds can be used where there is a high demand for higher power such as in race cars.

The process of exhaust gas transmission yields a lot of thermal stress and fatigue on the exhaust manifold. The backpressure causes the internal pressure on the exhaust manifold. The loadings of the mechanical and thermal nature are the factors responsible for the exhaust manifold failure. And hence the thermal analysis and the structural analysis is carried out with the inclusion of the backpressure, stresses, heat transfer coefficient as well as other related input parameters.

V. Modelling of the Manifold

This section deals with the designing of the exhaust manifold which can be later imported to the ANSYS software for the analysis. The exhaust manifold modelling has been done using the AutoCAD software.

The initial stage of the designing of the manifold is to find out the dimensions of the manifold. The dimensions are measured manually and they are noted. The bends on the pipes are carefully reviewed.

After the measurement of the dimensions, the modelling stage is started. The modelling is made on the AutoCAD software which can be imported to the ANSYS easily for the analysis process. The manifold model of this project consists of the four pipes which are used to draw the gases from the engine cylinder. The pipes are connected to one single pipe which transports the gases outside of the engine. Thus the 3d model of the manifold is successfully designed and the 2D drawing of the manifold is sketched stating the different views of the manifold. The 3D model of the exhaust manifold is shown in the figure below.

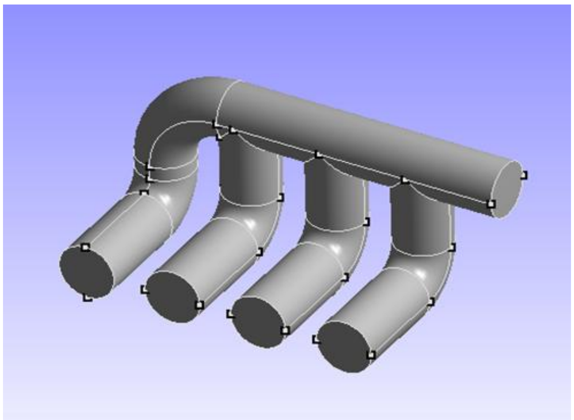

Figure 2:3D design of the exhaust manifold

The 2D sketches of the exhaust manifold are represented on the different views with the inclusion of the dimensions which can be shown as follows.

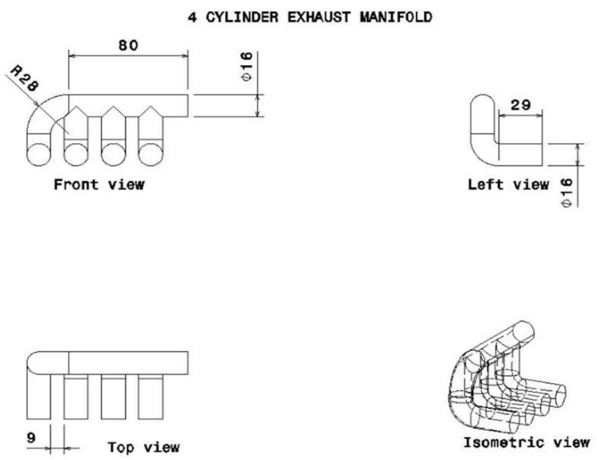

Figure 3: Different views of exhaust manifold design

VI. Theoretical Calculation

The design calculation is performed after the selection of the vehicle and the consideration of overall parameters. At first, the selected engine is specified and after that, the thermal and flow calculations are performed. The engine selected in this case is the VVT engine of the k series and the number of cylinders is 4. The maximum power produced by the engine is known to be around 83 brake horsepower. The camshaft valve configuration of the engine is a double overhead camshaft engine. The compression ratio is known to be 11:1.

The engine specification is stated below which is taken from the internet source.

Max Power	83 bhp @ 6000 RPM
Max Torque	115 Nm @ 4000 RPM
Mileage (ARAI)	20.4
Transmission Type	Manual
No of gears	5 Gears
Drivetrain	Front-Wheel Drive
Cylinders	4, Inline
Turbocharger/Supercharger	No
Valve/Cylinder (Configuration)	4, DOHC
Engine Start-Stop Function	No
Engine Type	K Series VVT Engine
Engine Description	1.2-litre 83.11bhp 16V K Series VVT Engine
No. of Cylinders	4
Valve Configuration	DOHC
Fuel Supply System	MPFI
Bore x Stroke	73 X 71.5 mm
Compression Ratio	11.0:1

Table 1: Specification of engine

After reviewing the engine specification and other related parameters, the calculation is made for determining the heat transfer coefficient and the engine exhaust flow which are discussed further below.

We know that the Heat transfer coefficient (H) = $q/\Delta T$

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Where, q = Heat flux (w/m^2)
And ΔT = change in Temperature (k)
Also, q = -k dT/dx
dT/ dx = -250 c/m (x) + 27 c/m (x2) {c/m= calorie/meter}
q11 = {-250 c/m + 27 c/m (2x)} -24
q = {-k dT/dx} 0.005 = {-250 + 0.27} -24
= 5993.42 w/m2
Hence, H = 5999.72/ (523-300)
H = 26.9 w/m^2 k

6.1 Calculation of the engine exhaust flow

The cubic feet per minute intake airflow data can be found in the manufacturers' manual. In the case of the non-availability of the CFM airflow data, the calculation regarding the volumetric efficiency can be utilized. The formulae of the intake airflow are given below.
Engine size (CID) x RPM}/3456} X volumetric efficiency = Intake airflow (CFM)
Intake airflow (CFM) = 73*4000/3456 X 0.7

Exhaust airflow (V) = 59.14 CFM (or) 34.4 m/s

VII. Analysis

This section deals with the analysis of the thermal and flow parameters of the exhaust flow of gases in the engine. The analysis is performed using ANSYS fluent software. The analysis is commenced after the overall calculation of the required parameters. The material properties required for the execution of analysis are found out and tabulated initially. The overall analysis of the exhaust manifold can be described as below.

7.1 Engineering data imported in the ANSYS

The first process for the simulation is to define the type of the simulation and after the definition, the material data and the boundary conditions have to be introduced. The simulation to be conducted in the ANSYS is selected as the fluid flow (fluent). Then the design model is imported into the ANSYS fluent software. The model is then subjected to meshing.

The material properties which are used for the analysis process are shown in the table below.

Material	Gasoline	Alcohol	LPG
Density	1.0685	1.255	1.8982
Viscosity(kg m-s)	$1.72*10^{-5}$	$9.26*10^{-6}$	$1.143*10^{-5}$
Specific heat (J/kg-k)	2220	2570	1680
Thermal conductivity (W/m-K)	0.0250	0.171	0.0508

Table 2: Material fluid properties used in the analysis

Also, the properties of the material used in the exhaust manifold are given in the table below.

Density(kg/m^3)	7800
Specific heat(j/kg k)	450
Thermal conductivity(w/m k)	24

Table 3: Material properties of the exhaust manifold

7.2 Meshing

After importing the model, the meshing has proceeded. For this, the mesh tab is clicked twice and the project can be viewed. The mesh method is also defined and the edge sizing is also reviewed. Finally, after editing the meshing according to the requirement, the finer mesh is produced which is shown in the figure below.

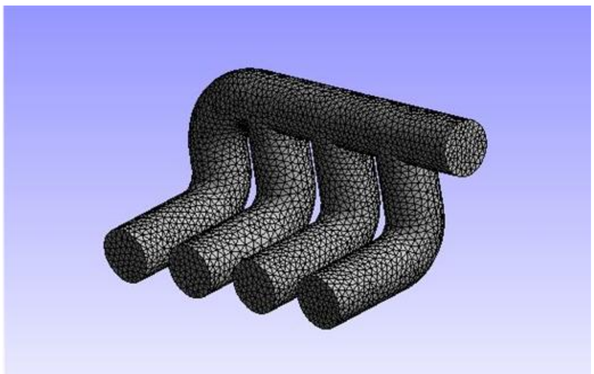

Figure 4: Meshing of the exhaust manifold

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The mesh details are given in the figure below.

Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Relevance	0
Sizing	
Use Advanced Size Function	On: Curvature
Relevance Center	Fine
Smoothing	High
Curvature Normal Angle	Default (18.0 °)
Min Size	Default (2.9361e-002 mm)
Max Size	Default (3.75830 mm)
Growth Rate	Default (1.20)
Minimum Edge Length	4.0 mm
Inflation	
Assembly Meshing	

Figure 5: Meshing details

After the meshing, it is determined that the number of nodes is 13536 and the number of elements is found to be 66419.

7.3 Boundary definition

After meshing the model the boundary conditions are defined. The velocity zones in the different regions are stated in different coordinates. The temperature at all the zones are also provided and the hydraulic diameter is also given. The inlet boundary conditions are given in the table below.

Table 4: Inlet boundary conditions of the manifold

Zone	X-velocity (m/s)	Y-velocity (m/s)	Z-velocity (m/s)	Mean Hydraulic diameter (mm)	Temperature (K)
Velocity Inlet 1	-34.4	0	0	0.00877	523
Velocity Inlet 2	-34.4	0	0	0.00877	523
Velocity Inlet 3	-34.4	0	0	0.00877	523
Velocity Inlet 4	-34.4	0	0	0.00877	523

The ANSYS model with the applied boundary conditions is shown below.

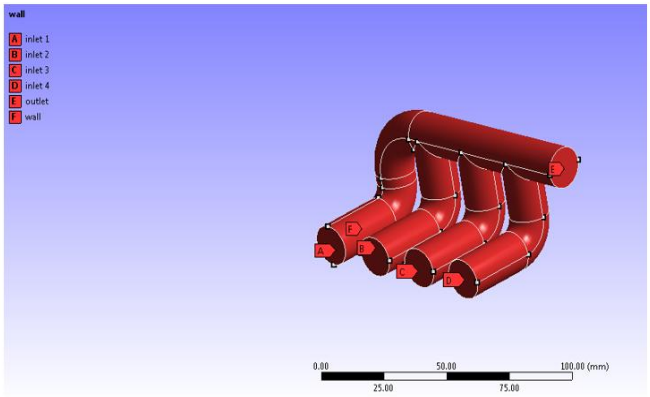

Figure 6: Exhaust manifold with boundary conditions

After boundary conditions set up for the project, the ANSYS solution is enunciated. Thus the ANSYS results can be viewed after applying the solution. The solution of the analysis can be viewed in terms of velocity, pressure and temperature contours.

VIII. Results

This section includes all the finding of the project using ANSYS. The results of the project are viewed in terms of the velocity, pressure and temperature contours. The findings of the project are elaborated down below.

8.1 Velocity contour

From the ANSYS fluent, the velocity profiles can be determined. The exhaust manifold, in this case, is visualized in terms of the velocity profiles of the gas flows. From the results, it can be found out that the inlet velocity of all the gases is the same. The exhaust gases of all the three fuels are found to be slowed down after moving forward in the Z direction. The inlet velocity of the gases in all the manifold pipes is found to be 34.4m/s.

As the LPG gas moves forward, the velocity of the gas is reduced and the velocity range is confined between 8.81 m/s to 17.6 m/s, for gasoline 8.43 – 16.6 m/s and for alcohol 8.71 to 17.4 m/s until it reaches to the bent section of pipe. It is noticed that for all the three cases, the inlet 1 exhaust pipe has no differing exhaust velocity until it is connected to the main pipe. But the rest of the inlet pipes have a slight backflow. It is observed in all the three cases that the velocity of the exhaust gases from the inlet pipes keeps increasing and the increase is only halted after the pressure outlet. The velocity range of the LPG gas is found to be the widest but only by a small margin. Since the gasoline is more commonly used in this manifold than the other two fuels namely LPG and alcohol, hence the theoretical exhaust outlet velocity of the manifold is closer to the Gasoline compared to the rest of the fuels.

The results regarding the velocity profiles of the fuels are shown below.

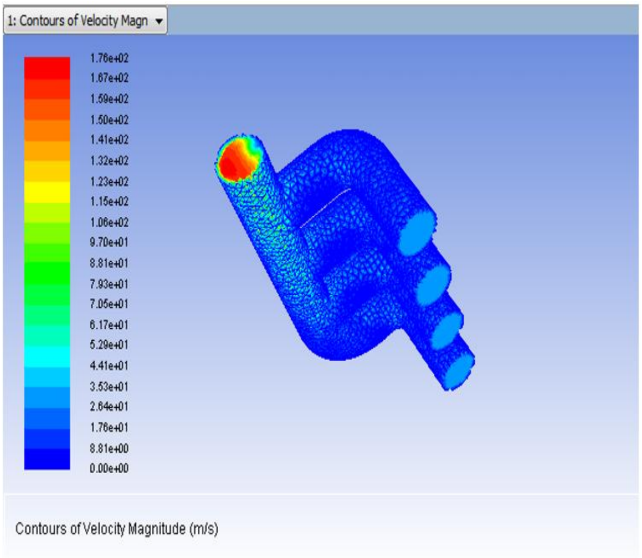

Figure 7: Velocity contour of LPG gas

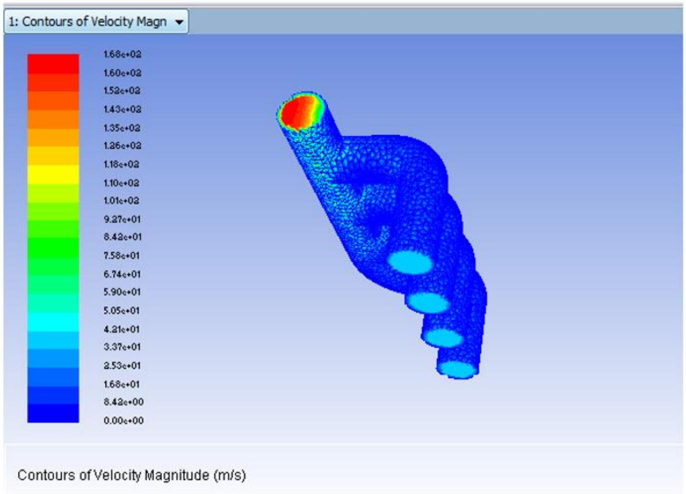

Figure 8: Velocity contour of gasoline

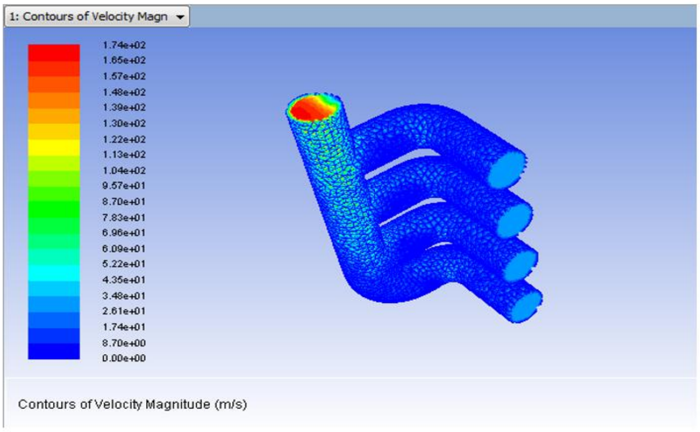

Figure 9: Velocity contour of Alcohol

8.2 Pressure contour

After reviewing the results of the pressure contours, is can be noted that the manifold pressure continues to reduce. Due to which, the flow from the inlet section to the outlet section is possible. For the gasoline operated engine, two of the inlet pipes in the exhaust manifold have the same pressure but rest of the pipes of the exhaust manifold have lesser pressure. The small amount of the backpressure can be observed at the joints section of the 3rd manifold inlet pipe.

For the alcohol-fueled engine manifold, the pressure continues getting reduced from the first inlet pipe bend section. The back pressure region

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can be visualized. The backpressure can be found higher in case of the alcohol operated manifold compared to the other fuels. The backpressure in the LPG fuel manifold exists near to the 2nd and 3rd pipe end. It is determined that alcohol fuel provides the maximum exit pressure of about 1490 Pa at the outlet. Whereas LPG provides slightly lesser pressure at 1160 Pa and gasoline only provides about 345 Pa at the outlet.

The diagrams illustrating the pressure contours of the different fuels are shown below.

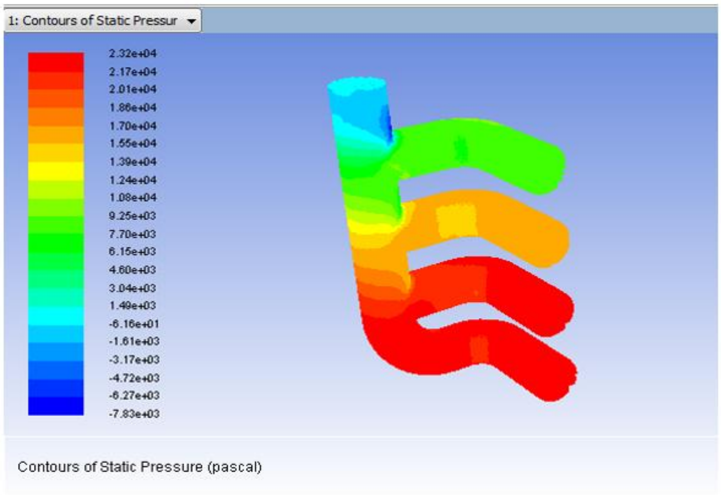


Figure13: Pressure contour of alcohol

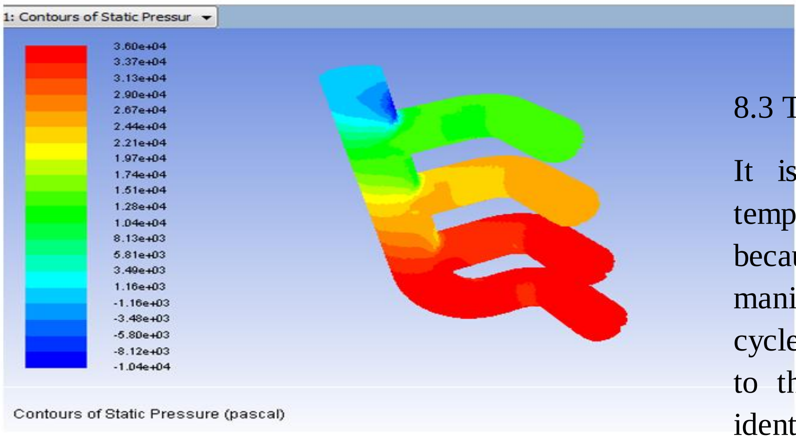


Figure 10: Pressure contour of LPG gas

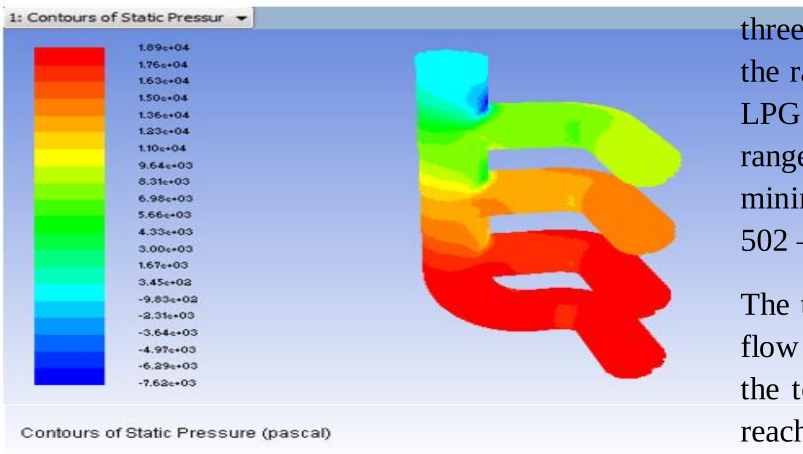


Figure 11: Pressure Contour of gasoline

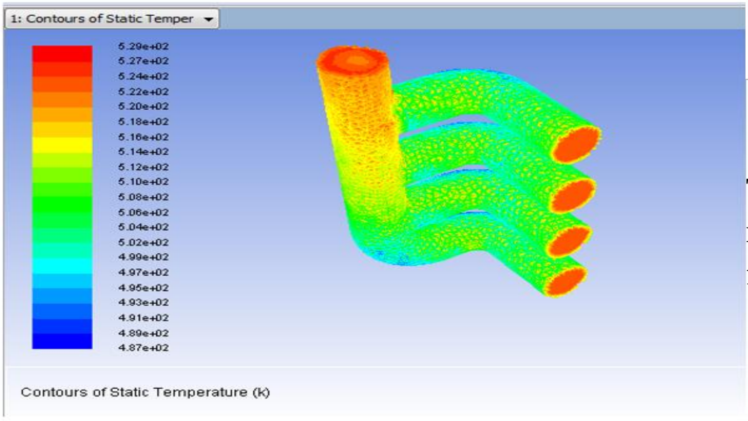
8.3 Temperature contour

It is obvious from the result that the inlet temperature of all the four input pipes is identical because the inlet temperature of the exhaust manifold is the outlet temperature of the otto cycle. The variation of temperature from the inlet to the exhaust manifold outlet is found to be identical but the variation is mostly significant only at the pressure outlet region.

The maximum outlet temperature range among the three fuels is produced by the alcohol which is in the range of 517-521 K, which is followed by the LPG gas fuel and the outlet temperature is in the range of 506-518 K and the gasoline gives the minimum temperature range which is around the 502 – 515 K at the exhaust manifold outlet.

The temperature is found to be reduced when the flow of exhaust gas is in the forward direction but the temperature suddenly increases when the gas reaches the pipe bend. The temperature variation in case of the gasoline manifold is in the range 523 K to 488 K but the temperature is seen to suddenly rise to 506 K at the pipe bend section. In LPG gas the temperature reduction occurs in the range of 523 K to 488 K and the sudden increase in temperature is visualized at the section of the pipe bend at 510 K. In the case of alcohol, the temperature reduction is observed to decrease from 523 K to 510 K and the sudden increase is observed to be 516 K at the pipe bend.

The below-given pictures illustrate the temperature contour of all three fuels when passed into the exhaust manifold.



Alternative fuels	Range of Velocity (m/s)	Range of Pressure (pa)	Range of Temperature (k)
LPG	8.81 – 17.6	- 1.04 e4 to 3.60 e4	506 -518
Gasoline	8.42 – 16.8	- 7.62 e3 to 1.89 e4	502 -515
Alcohol	8.70 – 17.4	- 7.83 e3 to 2.32 e4	517 – 521

Figure14: Temperature contour of LPG

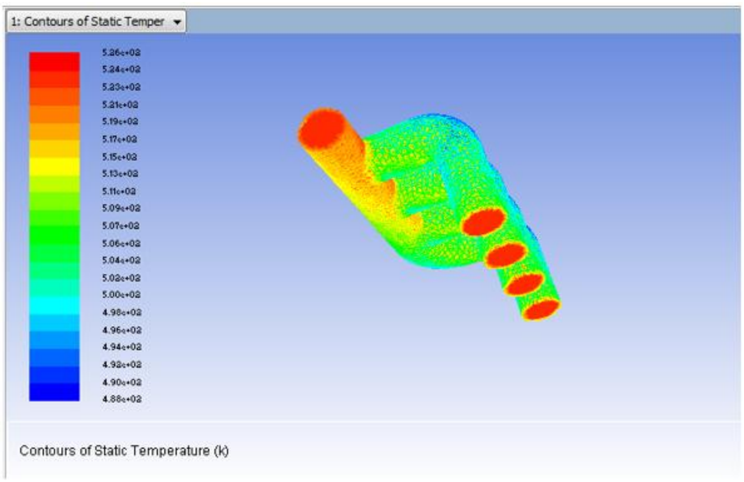


Figure 12: Temperature contour of Gasoline

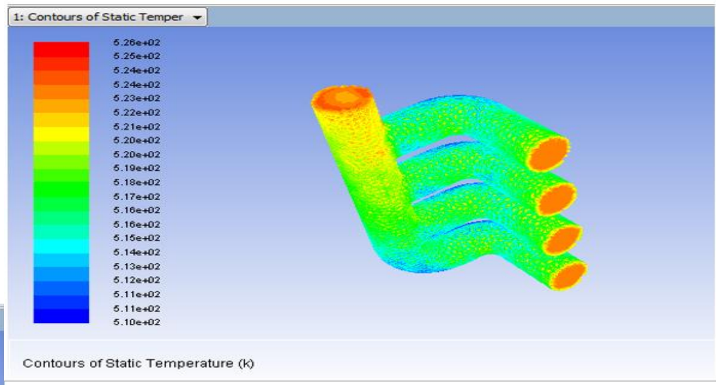


Figure 13: Temperature contour of Alcohol

The results containing the velocity range, pressure range and the temperature range of the alternative fuels are tabulated as below.

Table 5: Alternate fuel Results of ANSYS

IX. Conclusion

The efficiency of the IC engine depends on the effectiveness of the exhaust manifold. The high back pressure of the exhaust manifold is very undesirable for the exhaust manifold. From the above-mentioned result, it can be inferred that the LPG fuel had the maximum range of the exhaust velocity and the pressure difference was also lesser compared to the other fuels. Through the analysis, it has been found out that the negative pressure existed at the common section between the primary duct and the individual duct inlets. The highest back pressure occurred with the alcohol-fueled manifold. The gasoline fuel exhibits the intermediate pressure difference as well as the temperature range and the least working pressure. Through the research, it is determined that the highest exhaust velocity of the gases are found nearby the exhaust manifold outlet. The temperature of the exhaust gases is found to be reduced when the exhaust gas flow occurs toward the outlet of the manifold. But the temperature is suddenly found to be increased at the pipe bend section. Hence LPG is chosen as the most efficient fuel for the optimized flow of the flue gas in the exhaust manifold.

X. References

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