CFD Analysis of Exhaust Manifold of SI Engine

Sumit Nichal[1], Dr. Sudhakar Umale[2]

[1] M.Tech Student, Dept. of Mechanical Engineering, Sardar Patel College of Engineering, Andheri, Mumbai, Andheri, India

[2]Head of Department, Dept. of Mechanical Engineering, Sardar Patel College of Engineering, Andheri, India

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Abstract: This paper describes how different parameters of the manifold, such as material type and geometric sizes, have an impact on the efficiency and performance of an automobile engine, and how they affect the efficiency and performance of the engine. Also this paper explains how back pressure are often reduced by certain change within the geometry of the manifold. At various points along the manifold, changes in pressure, velocity, and temperature were mathematically calculated. Generally speaking, engine exhaust backpressure refers to the force produced by engines to overcome hydraulic resistance in the exhaust system and release gases into the atmosphere.

KEYWORDS: *Exhaust Manifold, Back Pressure, Computational Fluid Dynamics.*

1. INTRODUCTION

In this paper A vehicle's exhaust manifold is very important part present in any vehicle exhaust system. This exhaust pipe is connected to all of the engine's exhaust ports, and it funnels the recently-exhausted air to the pipe. As a result of the manifold gaskets, toxic exhaust cannot creep into the vehicle and harm its occupants as well. It is unnecessary to say, it's crucial that do possess a mechanics of manifold in good condition. The first one corresponds to the first cylinder bank, and so the opposite is for cylinder bank two. The overwhelming engines that are inline typically have only 1 manifold. Rotary engines typically have just one manifold while turbocharged models are equipped with "down pipes" they do not have one manifold recent the turbo's right side also. There are, of course, exceptions to any or all of the above or any of these norms, however within the globe, there are relatively few exceptions to this rule. It is possible for exhaust gases to flow backwards beneath the valve overlap when the piston is moving upward because of: vacuum within the manifold, backpressure within the exhaust, and air mass within the manifold.

In terms of engine exhaust back pressure, it is the exhaust gas pressure generated by the engine to overcome the hydraulic resistance of the exhaust system and discharge the gases into the atmosphere. A fuel-injected natural aspirated engine's exhaust backpressure is the gage pressure at the exhaust exit of the exhaust turbine or the pressure at the exhaust manifold exit in turbocharged engines. Even though the word back suggests a pressure that is exerted against the direction of flow of a fluid, there are two reasons to object.

Sulzer Innotec [1] for Guascor performed series of coupled CFD-FE simulations, the heat transfer, fluid flow, and stress analysis are coupled in one direction for each case. The investigation looked at possible optimization measures for structural enhancement by plotting temperature, stress, and displacement distributions. In addition, the paper offers some design suggestions that are presumably effective in decreasing the temperature peaks and gradients and in ensuring a longer service life for exhaust manifolds an algorithm developed by Sulzer Innotec performs this interpolation.

Sweta and AlkaBani [2] investigated to determine the optimum element size, an analysis is performed with a tetrahedron element of first order on an off-road vehicle diesel exhaust manifold. A convergence test is run for structural load to determine the optimum element size. To determine the heat transfer characteristics overall, second-step thermal analysis is performed on temperature mapping, heat flow, and heat transfer characteristics overall. Some suggestions are presented below, which can serve as guide to improve thermal stress reduction by using the investigated FE model of off-road vehicle diesel manifolds. The geometry is often modified, and other materials and grades may be chosen as an alternative that provides adequate temperature resistance.

Omer Cihan, Mehmet Bulut [3] had studied a numerical study has been conducted to determine how flowing materials and manifold types behave in two different types of common automotive manifold designs. The following conclusions should be drawn from this study: Due to characteristics of gasoline fuel, gasoline fuel had significantly lower pressure and velocity as compared to both other fuels studied. CFD was used to analyse two different manifold designs, with three different points (1, 2 and 3) being considered for analyses of pressure, temperature, and velocity changes. A CFD procedure was used to analyse the changes in temperature, pressure, and velocity in two different manifold designs.

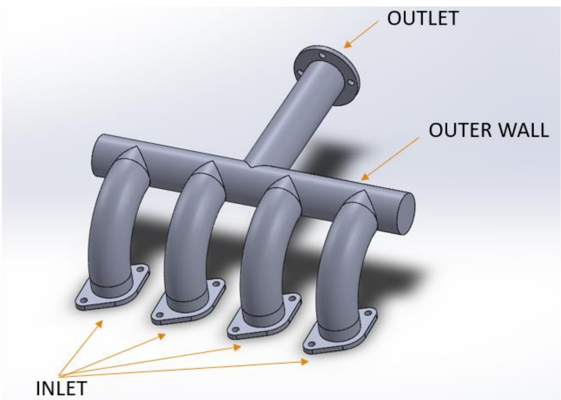
.Bin Zou, Yaqian Hu [4] has introduced Thermal Modal Analysis of Exhaust Manifolds - The Effect of Temperature. Using the exhaust manifold thermal modal analysis as an example, a basic analysis process is built in this work. And the temperature pre-stress is applied on exhaust manifold modal by the coupling of ABAQUS and STAR CCM+, By using bolt pre-tightening force, ABAQUS analyses the thermal mode of the exhaust manifold and concludes that heating causes the nonlinear change of material physical properties and generates thermal stress, both of which lead to a decline of structure's natural frequency. In the automotive exhaust system, the exhaust manifold is adjacent to the engine, and since the exhaust gas temperature of the exhaust cylinder can reach 800°C above, the tail gas heating effect is obvious.

S. Rajadurai, M. Guru Prasad [5] has investigated Modal Analysis for Exhaust Manifold in Hot Condition. . Due to the higher combustion temperature, exhaust systems tend to exhibit nonlinear material characteristics, complicating the design due to material weakness as temperature increases. Furthermore, the situation is further complicate by the fact that the customizing and servicing of the engine are conducted by different levels of expertise, resulting in a change in operating conditions and temperatures. The auto manufacturers are also working toward lower fuel consumption, which results in mass reduction. The traditional linear modal analysis ignores nonlinear inherent characteristics of materials, contacts, and geometry which can lead to qualitative errors in stiffness requirements on response analysis. In order to estimate the results of an analysis of the influence of linear and nonlinear material properties in hot conditions, a fixed stress level must be defined.

K. S. Umesh, V. K. Pravin & K. Rajagopal [6] has performed an Experimental analysis of optimal geometry for Performance-enhancing exhaust manifold of a multi-cylinder si engine. IC engines require a highly efficient exhaust manifold. In order to design an exhaust manifold, many parameters must be taken into consideration, including: back pressure, exhaust velocity, mechanical efficiency etc. This parameter varies depending on the particular needs of the designer. With increased back pressure, the exhaust gases must be compressed to a higher pressure, requiring additional mechanical work and/or a slowdown in energy extraction from the exhaust turbine, thereby affecting the intake manifold boost pressure.

Yunchao Wu, Pinaki Pal [7] has studied a skeletal chemical kinetic mechanism for gas and gasoline/ethanol mix surrogates for engine CFD applications. Process fluid dynamic (CFD) simulations square measure usually applied in engine style to realize higher understanding of fuel combustion that correct reaction mechanisms square measure a necessity. However, gas fuels derived from rock oil comprise thousands of individual hydrocarbons as well as linear and branched alkanes, olefins, cycloalkanes and aromatics that renders the determination of the precise composition impractical. Validations of the skeletal mechanism were performed against the careful mechanism and out there experimental knowledge for ignition delay times and stratified flame speeds.

2. THE GEOMETRIC MODEL OF EXHAUST MANIFOLD.



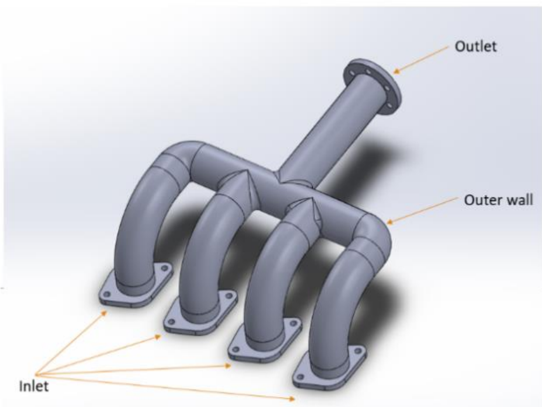


Fig -1: Exhaust manifold model from previous

Fig-2: Modified exhaust manifold model Literature.

The geometric model of **Exhaust Manifold** System was developed on the Solid works software. Exhaust is located in the center of the header, with a bend radius of 100 mm. A bend and the exhaust have a diameter of 52.48 mm and 60.3 mm, respectively. In order to connect it to exhaust muffler, flanges were attached to the manifold's outlet, which was 220mm long. The Geometry 3D model of Exhaust Manifold was shown in above figure. Engine specifications was taken from literature [6] for CFD Analysis. Geometrical model has four inlet ports which is directly connected to combustion chamber. All four inlet converges into single pipe which then connected to outlet port and further this port is connected to muffler, catalytic converter and finally exhaust pipe.

Based on literature review reversion (back Pressure) happens when exhaust gases flow backwards and contaminate the intake charge. (It is the opposite of The Scavenging Effect.) Reversion usually happens at low and mid rpm. Remember, Air will always try to move from high pressure to low pressure. So, at low rpm, during valve overlap, exhaust gases can flow backwards due to:

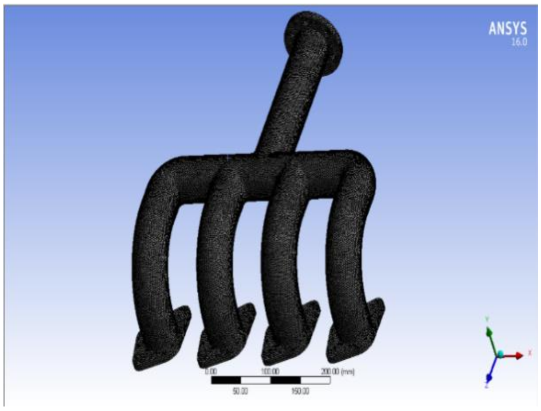
- Low pressure in the intake manifold (vacuum)
- High Exhaust system backpressure (backpressure)
- The upward motion of the piston.

So for improvement of engine performance and to reduce the back pressure at required level we need to do any one of these changes. 1) Change in the Material 2) Change in the length of header pipe as well as runners. 3) Changing the design geometry. 4) Changing no. of headers.

Table-1: Engine specification of exhaust manifold model.

Engine	4 Stroke 4 Cylinder SI engine
Make	Maruti-Suzuki Wagon-R
Calorific Value of Fuel (Gasoline)	45208 KJ/Kg-K
Specific Gravity of Fuel	0.7 gm/cc
Bore and Stroke	69.05 mm X 73.40 mm
Swept Volume	1100 cc
Compression Ratio	7.2 :1
Dynamometer Constant	2000
Diameter of Orifice	29 mm
Coefficient of Discharge of orifice	0.65

3. MESHING



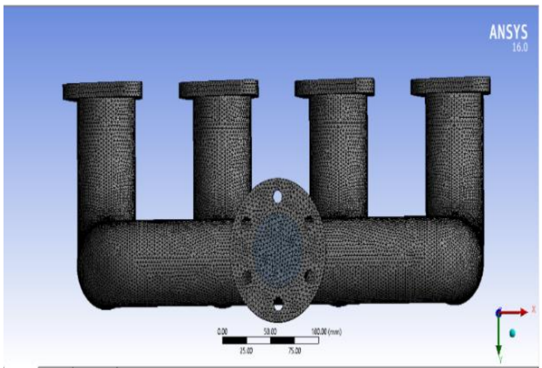


Fig-3: Detailed meshing of modified exhaust manifold model.

After 3D geometric modelling, the previous exhaust manifold model and modified manifold model were meshed by ANSYS Fluent 16.0 meshing modular. The automatic mesh was done in order to get desired meshed quality with smoothing was set to high to improve the accuracy of the simulation. Automatic meshing with high smoothing has done on geometric model of Modified model of exhaust manifold. Number of elements created by meshing is 10, 42,121.

4. MATHEMATICAL MODELLING

The numerical models used for the simulations are listed in the relevant section. Moreover, the boundary conditions and governing equations used for the calculation are provided.

Governing Equations

A mathematical model is created based on the conservation of mass, energy, and momentum in different physical phenomena. These governing equations used are given in following section:

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0$$

4.1 Conservation of momentum

X-momentum equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial u}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

Y-momentum equation:

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial u}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right)$$

Z-momentum equation:

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial u}{\partial x} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right)$$

4.2 Conservation of energy

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right)$$

4.3 Mathematical Models

Different models are required to do numerical study which are as follows,

1. Energy Model

2. k-ε Turbulent Model

4.4 Material Model

a) Material Fluid Properties

Table-2: Material Fluid Properties

Material	Air + Gasoline
Density (kg/m3)	1.0685
Viscosity (Pa-s)	3.0927 x 10-5
Specific heat (J/kg-K)	1056.6434
Thermal conductivity(W/mK)	0.0250

b) Material Solid Properties

Pipes were made from SA106 (grade B) material which is also called as carbon Steel.

Density:-7,663 kg/m3

Thermal Conductivity: - 45 W/mk

Specific heat: - 490 j/kg-k

4.5 Boundary Conditions

In this case, exhaust gas will be considered an incompressible fluid with a temperature range between 230 and 280 degrees Celsius.

For Inlet: - Mass Flow Rate for 2kg load at 1500 RPM is 0.424 kg/s.

Mass Flow Rate for 4kg load at 1500 RPM is 0.626 kg/s.

Inlet Temperature:-400-500°C.

Mean Hydraulic Diameter: - 0.00877m.

Outlet: - Gauge pressure: - 0 pa

Outlet hydraulic diameter: - 0.01302m

Outer wall: - Convection

Heat transfer Coefficient= 50 W/m^{2}K

Wall with constant heat flux.

No slip condition for all directions on the wall.

5. RESULTS

The CFD analysis of Exhaust Manifold is carried on ANSYS Fluent 19.0. The resulted values of Back Pressure at different loading conditions at the same RPM were compared with the experimentally observed values [6] from the literature survey.

For mass flow rate of 0.424 kg/s for 2 kg of loading back pressure in the exhaust manifold is 895 pa.

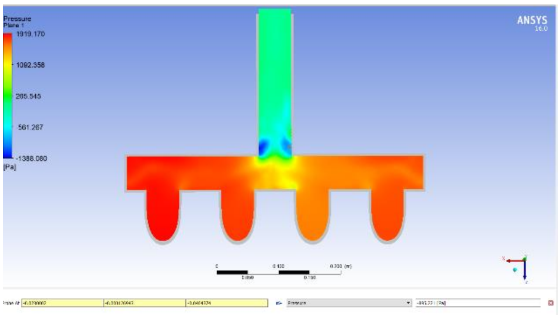


Fig-4: Pressure contour of 2kg loading

For mass flow rate of 0.626 kg/s for 4 kg of loading back pressure in the exhaust manifold is 984 pa.

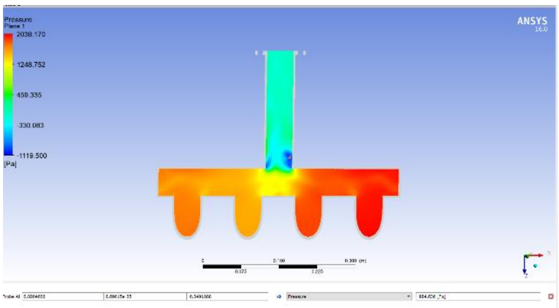


Fig-5: Pressure contour of 6kg loading

Based on experimental values, CFD simulations yielded promising results. In the following back pressure distribution section, you can view the graph of comparison between simulation and experimental.

Table-3: Simulation Results comparison with experimental research paper results.

Load on Engine	Mass flow Rate (kg/s)	RPM	Experimental value of Back Pressure (Pa)	CFD value Back Pressure (Pa)
2 kg	0.424	1500	882.57	895.221
4 kg	0.626	1500	1049.28	984.636

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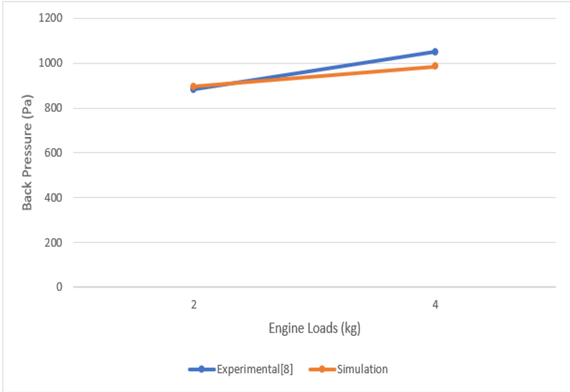


Fig-6: Variation of back pressure in exhaust manifold.

Fig. 6 showed the resulted values of back pressure Simulated values from simulation were compared with experimentally obtained values [8] reported in the literature. The back pressure plots for both CFD Simulation and observations from experimentation show that variations are similar. The back pressure simulation resulted in the following values near about close to the experimental results, because of assumption made in meshing. The maximum variation of back pressure a simulation of the experimental results yielded values around 20.2 %.

5.1 Analysis of Modified Exhaust Manifold system.

Reversion (back Pressure) happens when exhaust gases flow backward and contaminate the intake charge. (It is that the opposite of The Scavenging Effect.) Reversion usually happens at low and mid-rpm. Remember, air will always attempt to move from high to low. So, during valve overlap, at low rpm, exhaust gases can flow backward due to:
Low pressure in the intake manifold (vacuum) There is a high level of backpressure in the exhaust system.

Upward movement of the piston.

So for improvement of engine performance and to reduce the backpressure at the required level we need to do any one of these changes.

1) Change in the Material

2) Change in the length of header pipe as well as runners.

3) Changing the design geometry.

4) Changing no of headers.

As a result of changing the exhaust manifold geometry and pressure and velocity contours are generated at the same boundary conditions and same engine loading.

5.1.1 2kg loading at 1500 rpm

Following are the CFD simulation results obtained with a loading of 2 KG. Mass flow rate from inlet is 0.424 kg/s. The pressure and velocity contours have been shown below.

5.2.1 Pressure Distribution

For Mass flow rate of 0.424 kg/s for 2 kg loading maximum pressure in the exhaust manifold is 572 Pa.

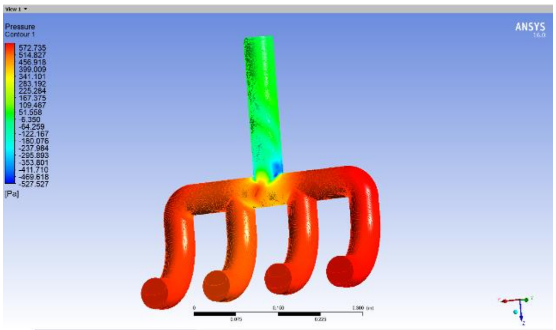


Fig-7: Pressure distribution in modified exhaust manifold at mass flow rate 0.424 kg/s for 2kg loading

For Back Pressure calculation, plane need to be created along with pressure distribution contour. By using Probe parameter present in Ansys Fluent 16.0, back pressure at particular point can be calculated. Generally inside exhaust manifold, reversed flow occurs due to sharp edges or uneven geometry. For that instance plane is required to generate at particular point or area from where reversed flow occurred as shown is below fig 7.

For mass flow rate of 0.424 kg/s for 2 kg of loading back pressure in the modified exhaust manifold is 402 pa.

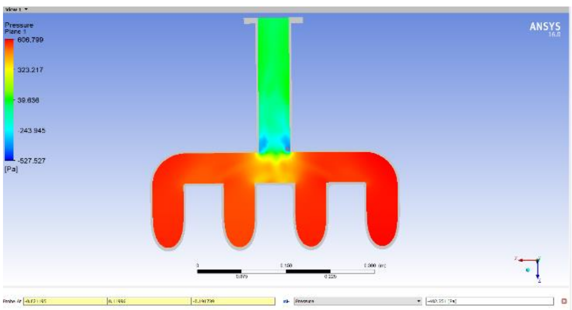


Fig-8: Pressure plane distribution in exhaust manifold at mass flow rate 0.424 kg/s for 2 kg of loading (back pressure flow).

5.1.2 Velocity Distribution

For Mass flow rate of 0.424 kg/s for 2 kg loading maximum velocity in the exhaust manifold is 45 m/s.

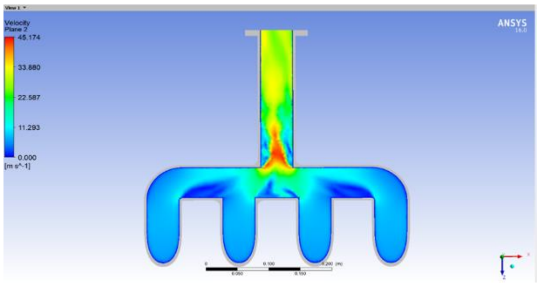


Fig-9: Velocity distribution in exhaust manifold atmass flow rate 0.424 kg/s for 2kg loading.

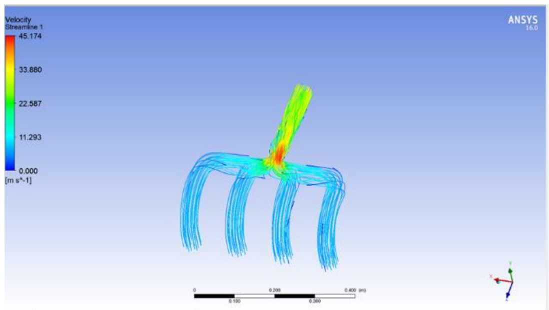
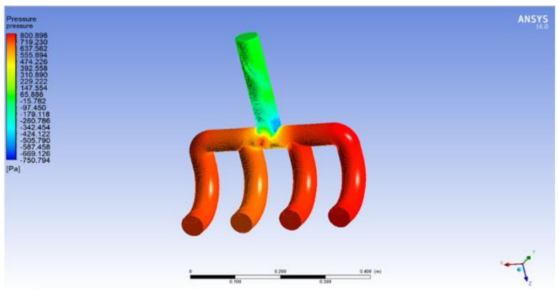


Fig-10: Velocity Streamlines in exhaust manifold at mass flow rate 0.424 kg/s for 2kg of loading.

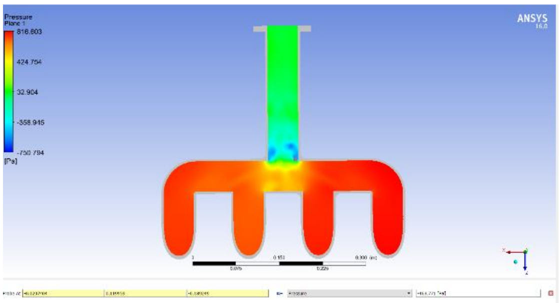
5.2 4kg loading at 1500 rpm

Following are the CFD simulation results obtained with a loading of 2 KG. Mass flow rate from inlet is 0.626 kg/s. The pressure and velocity contours have been shown below.



5.2.1 Pressure Distribution

Fig-11: Pressure distribution in modified exhaust manifold at mass flow rate 0.424 kg/s for 2kg loading.



5.2.2. Velocity Distribution

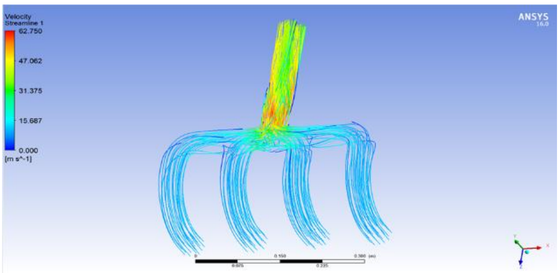
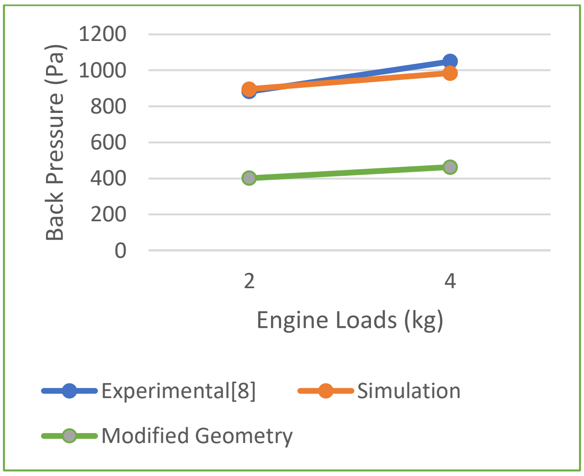


Fig-12: Velocity Streamlines in exhaust manifold at mass flow rate 0.626 kg/s for 4kg of loading.

Table-4: Results Table comparing previous model and modified model (Back Pressure)

Load on Engine	CFD Simulation value (Validation Result) Backpressure(Pa)	Modified Exhaust Manifold Backpressure (Pa)
2 kg	895.221	402
4 kg	984.636	463



Above fig shows a graphical presentation of the backpressure generated in the previous literature model [8] and modified geometry model. Blue line indicates the experimental value of backpressure of exhaust manifold which was calculated using Morse test apparatus. The orange line indicates CFD simulation values of the same literature model for validation purposes. Green line represents the value of back pressure generated in modified exhaust manifold model. All results are calculated at 2kg and 4 kg engine loading at 1500 pm. As we can see that in modified geometry of exhaust manifold back pressure reduced to almost half of the previous literature model. At 2 kg loading backpressure generated is 402 Pa which was 895.221 Pa. Also at 4 kg of engine loading backpressure generated is near about 463 Pa which was 984.636 Pa in the previous exhaust manifold model [6].

6. CONCLUSIONS

Designed the 3D model of Exhaust manifold using Solid works software. Performed the CFD Analysis of Exhaust Manifold Using ansys Workbench (Fluent). Different types of flow Patterns observed in Post Processor of exhaust gases flowing through Exhaust Manifold using ansys fluent post processor. Determined and studied the different contours generated like Pressure, Velocity and Temperature according to different loading condition at 1500 rpm. From this analysis it is observed that at 2kg of loading back pressure generated of about 402 Pa. Use of smooth corners and fillets lowers the returning pressure to the engine. It is possible to reduce back pressure of almost 4% only by removing sharp corners. It is observed that at 2 kg loading backpressure generated is 402 Pa compared to 10 kg loading which about 1029 Pa. So 2 kg loading is more suitable than10 kg engine loading which at lower back pressure level. From above study it is observed that it is possible to reduce back pressure by doing geometry modifications like removing sharp corners and adding fillets.

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