International Journal of Applied Science and Engineering

Design and analysis of exhaust manifold for multi-cylinder diesel engine with monolith catalytic converter using CFD

P. Thangapandian

Department of Mechanical Engineering, Karpagam Institute of Technology, Coimbatore, Tamilnadu 641105, India

ABSTRACT

This paper discusses the challenges in converting the existing multi-cylinder diesel ventilation system into an innovative model of the manifold with monolithic. Reactant gases after treatment of car engines are increasingly being used for the benefit of environmental quality, especially in the large metropolitan region of the country, through the use of exhaust systems to bring an end to their main pollutants. A well-conditioned exhaust system increases the performance of the engine. The performance of the manifold has a significant impact on engine efficiency. With the accelerated growth of modern technology and numerical methods, computer simulation has become a valuable method for research and development of fluid flow systems. The industrial CFD (Computational Fluid Dynamics) software was used to analyze the exhaust manifold system. In order to enhance the fundamental understanding of manifold operations, extensive knowledge was obtained on the flow property distribution and heat transfer. Various calculations were performed to research the parametric impacts of working conditions and math on the exhibition of manifolds. Proposals were made to improve complex plan and execution.

Keywords: Exhaust manifold, Catalytic converter, Monolythic, Computational fluid dynamics.

OPEN ACCESS

Received: February 3, 2021
Revised: May 3, 2021
Accepted: July 1, 2021

Corresponding Author:
P.Thangapandian
thangapandian.mech@karpagamtech.ac.in

Publisher:
Chaoyang University of Technology
ISSN: 1727-2394 (Print)
ISSN: 1727-7841 (Online)

1. INTRODUCTION

These days, as the outflow guidelines become more rigid, there are numerous examinations which search the efficiency and better discharge execution. The exhaust system has been embraced since certain years back as an extremely viable gadget which permits the transformation from unsafe mixes to less damageable ones, mostly the change from Nitrogen oxides, hydrocarbons also, carbon monoxide to nitrogen, water and carbon dioxide. Such a component, for the most part, utilized for gas motors, is called Three-Way Catalyst because of the treatment of these three mixes.

A catalyst exhaust gas flow is basically 3D and for each channel has varying conversion rates and temperatures. Therefore, a 3D simulation with complete exhaust system configuration and intake border condiments is the best way to consider the transient output of an exhaust system during the cold start time Benjamin et al. (2006). An exhaust system extracts exhaust gases from many cylinders in a single tube in every multi-cylinder I.C. engine. This header is related by bends with these cylinders. The engine is mounted to downstream and is primarily used in multi-cylinder engines where multiple exhaust streams have to be collected into one channel Deger et al. (2004). As of late with the presentation of the more severe discharge guidelines, numerous enhancements have been concentrated to accomplish better efficiencies in the decrease of contamination emanations Fontanesi and Giacopini (2013). The light-off season of the exhaust system, for instance, reduces the time it takes to increase the temperature of the monolith to minimize the infection start- outflows, contributing to an important way of raising the fumes discharge framework (Jeong and Kim, 2000). One measure achieve that is by warming the substrate either electrically or by methods for post chamber ignition, yet a disadvantage of this is the extra energy flexibly which is required (Kim and Lee, 2015). Another impressive way to deal with increment the converter temperature rapidly is to mount it legitimately to the ventilation system with the principle limitations being the absence of room around the motor and the difficult and generous need of having a very much appropriated liquid stream at the impetus entrance, in any case the change productivity and toughness of the exhaust system might be undermined (Koltsakis and Stamatelos, 1997). Many researchers modified the design of exhaust manifold and evaluated the results in experimentally or analytically (Kresovic et al., 2002; Masood et al., 2007; Milanovic et al., 2003; Mu et al., 2019; Rakopoulos et al., 2009; Scheeringa et al., 2002; Shaikh et al., 2020; Umesh and Rajagopal, 2013).

The industrial software of CFD in this review using to study the exhaust manifold with a monolith catalytic converter. The goals were twofold, the first was to reveal the potential to CFD as a modelling tool of this nature multiples. The second was to provide specific details, Flow distribution and heat information shift to provide insight and simple multiple process awareness.

2. EXPERIMENTAL SETUP

The weight contrast in each fumes port must be found from the reproduction when the silencer ways out to climate pressure. Noticed if any chocking in the ports. Locate the more focused on the spot on the mass of the complex by temperature and tension on it study the impacts of the stone monument regarding pressure drop across it and laminarization of move through it.

There are a few boundaries we ought to have as a main priority when planning a ventilation system. The math of the complex which incorporates boundaries, for example, length, measurement, and shape fundamental for an effective plan. Numerous shapes include the utilization of oval lines or round lines in the complex plan. The way that round lines have a bigger cross-sectional territory than oval lines and give superior stream dissemination is the principle advantage. The lines can be planned with a tendency point or as a blend of straight and rakish lines. High tendency points of lines in a complex will expand the stream obstruction which is an undesired impact. The line widths can also be treated as pipes with higher steps are more suited for engines at higher rates as more fumes are dropped at higher speeds. Then again, lower-width pipes are used best at lower engine speeds.

When constructing a complex, the length of the lines is a vital consideration. This is important to use the space available for designing and selecting the length of the fitting rows. Too long queues cause gases to expand, which decreases the pace of smoking. This marvel is not desired and as the fumes of gas are limited, more gases remain in the chamber that decreases the engine's power and competence. That is why a good duration for the lines is selected to minimize the concentration of gases in the chamber to a foundation.

Temperature is another critical limit which needs to be addressed when preparing a complex due to high fumes and the warmth movement. Often the complex is provided with some kind of protection to reduce the warmth movement by radiation to the engine narrows. In most instances, the complex is coated with earthenware to preserve it warmly. The thicker the creative mix, the stronger the shield. The covering for the ventilation system is another form of protection used. In fact, this technique is less costly than the covering of steel goods but it provides less security and much lower restaurant performance.

The backpressure boundary must have an outstanding interest. Backpressure has an undesirable effect when the amount of residues left in the head increases as the back Weight increases. Residual weight expansion will decrease the amount of the incoming charge, which therefore extends the temperature until the strain starts. A few experiments demonstrate how the back weight expansion affects warm performance for different complex acceptance weights.

For any instance of enlistment complex weight, there is abatement in warm effectiveness when the back weight increments. It is additionally critical to take note of that for the most elevated enlistment complex weight we get the least warm productivity decrease, and for the most minimal worth appeared of acceptance complex weight we get the most elevated decrease in warm effectiveness. By and large, the most minimal acceptance complex weight esteem and the most noteworthy back weight worth will decrease impressively the net yield.

3. METHODOLOGY

The piston climbs up the bore in exhaust stroke to reduce the entire volume of the chamber. The valve of smoke will open sooner or later. The high-pressure gas gases drain through the headers of ash and smoke. The heavyweight head is due to the distinction between high pressure and gases in the ignition chamber and barometric weight. When gases level out between the burning chamber and the climatic weight outside the smokes frame, the pressure differential decreases and the exhaust speed decreases. Therefore the gases beat a portion of medium weight 'bone' is created. The residual gases are fumed in the tail area. At first, the tail segment will balance the environmental segment. The effect of syphoning by the power of high and medium weight segments is further decreased. This results in less weight than environmental weight in the low finish of the smokes.

This makes a high-pressure contrast between the admission complex and burning chamber, which expands the speed where air is brought into the motor. This expansion in admission air speed prompts an increment in the measure of air in the ignition chamber which permits the motor to add more fuel and accordingly make more force. Headers help to expand exhaust speed.

3.1 Evaluation Based on NIST Statistical Test Suites

The chamber volume of the remaining gas at the admitting pressure vary as weight proportion and pressure proportion are adjusted. As the volumetric efficiency increases, it decreases. The effect on a volumetric efficiency of the ideal cycle is defined by the term. The findings of the evaluation are used for familiar clearance as info load conditions. The characteristics are evaluated in map form. The visual appreciation is more attractive and the current complex is familiar.

3.2 Pressure Form for the Current Complex and New Design

The high weight at the head is because of high-pressure distinction from the fumes in the ignition chamber and climatic weight. In the current complex, the weight was not consistently conveyed and the impact of non-consistently circulated pressure gives an effect on the speed of the progression of pollutant gases. The weight move through the source of the ventilation system should be consistently conveyed thus the new complex plan is drawn.

The ventilation system goes through a uniform weight conveyance alongside the stream. The weight dispersion is normal along the way thus the source speed will be high for the stream. The pollutant gases even out between the ignition chamber and the climatic weight outside of the fumes framework. The distinction in pressure increments and the speed of leaving exhaust increments. Hence the extent of fumes rummaging impact is an immediate capacity of the speed of high and medium weight segments of fumes beat.

4. DESIGN OF EXHAUST SYSTEM

The exhaust system was divided into subcomponents and designed individually. The proposed design of some main different pieces of the exhaust systems is described below.

4.1 Catalytic Converter

An exhaust system is a mechanism used by an internal ignition engine to diminish the harmfulness of emanations. In addition, exhaust systems are used in generator systems, forklifts, mining vehicles, trucks, transport systems, trains and other engine prepared devices. An exhaust system offers a plastic reaction environment, where negative inflammatory effects are converted into less toxic. Fig. 1 displays the catalytic converter used in the study.

4.2 Monolith

Monoliths are structures that contain different sorts of interconnected or isolated channels (straight, wavy or pleated) in a solitary square of material. The channels of the most widely recognized honeycomb monoliths regularly have roundabout, square or three-sided cross areas. Solid reactors are those loaded up with monolith that are either made of permeable synergist material or the synergist material is saved in the channels of an inactive solid help. In the two courses of action, the channel dividers work as an impetus and the channels give space to the stream of gas and additionally fluid.

Currently, the two important monolith monuments of industry and discovery are clay and metallic stone. Usually, fired monoliths are formed by expulsion, while metal monoliths are produced through layers. The Monolith converter requires the number of cells or ducts from which gas fumes flow. The configuration of the monolith is represented in Fig. 2 and the cross-section view is depicted in Fig. 3. It has three elements.

- A laminar stream area
- Porous synergist layer
- Relatively non-permeable substrate

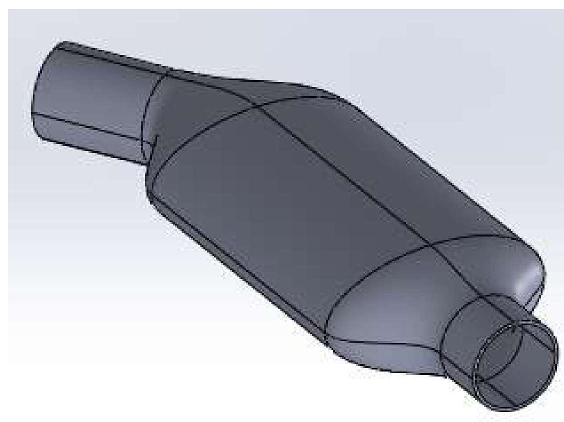


Fig. 1. Design of catalytic converter in exhaust system

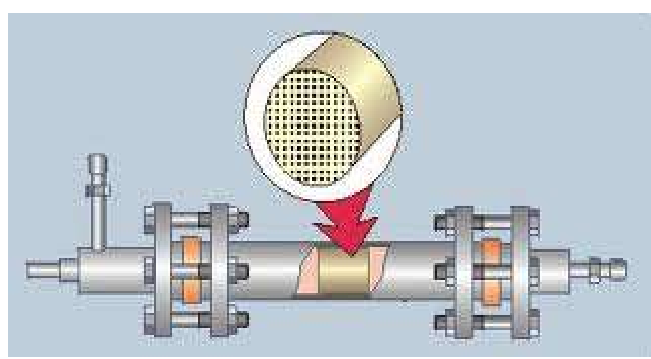


Fig. 2. Monolith

In order to minimise the vehicle discharges of carbon monoxide and hydrocarbons best or worse the instance of exhaust systems is now practical. Due to the square-channel stone monument, the monolith measurement is entirely defined by a combination of two borders: the size of the channel (DH) and either the thickness (tw) of the divider or the space of the cell (n) (CPSI). In the case of a synergistic expulsion of the monolith, the measuring of impulses in the reactor volume unit can be entirely determined by the measurement of stone monuments. In this application, pressed beds and Monolith are used for two types of exhaust systems.

The Monolith converter comprises the number of cells or pipes through which the pollutant gas streams. In this venture, the monolith has been joined inside the exhaust system. This stone monument gives the laminarization stream and lessens the ventilation system pressure. The elements of the complex are length 1m, oval in cross-sectional territory having measurements of width 466.16mm and stature 300mm.

4.3 Exhaust Manifold

A ventilation system, a key impulse, a front silencer and a back quilting system are used in the pollutants setting. A pollutants port in the chamber head is used in the ventilation system. The degree of machining surface in the chamber head on this complex matches a coordinated surface on the gases port region. This optional plan is based on a uniform model. It's just this model. The collective calls straight that the spine on which the turbo is mounted opposite the uniform hub. There are four lines in this scheme, in which two lines are parallel, and two other lines twist. The old and modern design of the exhaust distributor can be seen in Fig. 4 and Fig. 5.

This system is limited in scale but it is low compared to a modern scheme. This plan has pipes with an inside diameter and thickness of 52.8 mm, of 4 mm (OD: 60 mm). The way that line points are circulated in the model is what makes this turbo exhaust header a measured option for this company. The external lines have 3.57 crawls with a circular section width of 110 mm and a smooth output end. The two lines at the middle of the channel measure 235 mm and 103 mm circular. Open curves produce the less tightening effect and more streaming and lower temperatures coincidence, thus erosion is minimised.

Fig. 3. Cross-sectional perspective of Monolith

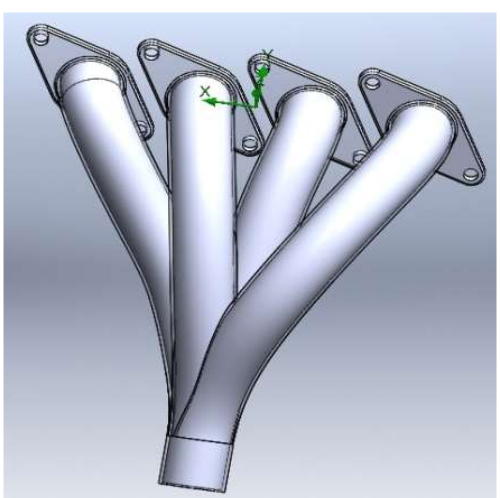


Fig. 4. Old design of exhaust manifold

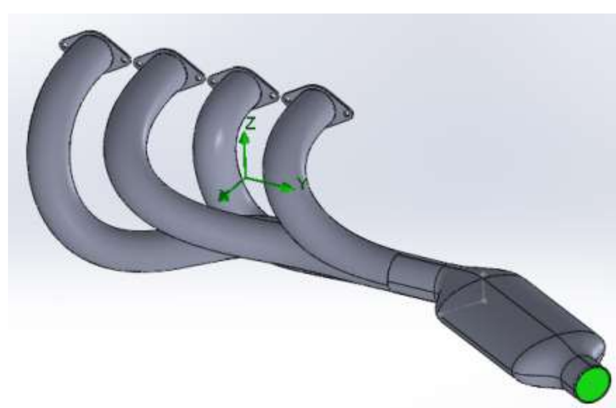


Fig. 5. New design of exhaust manifold

This is another plan of ventilation system for four-chamber motor. The new plan of ventilation system changes from straightforward plans to plans with a more elevated level of multifaceted nature. It is like that of the old plan yet the mathematical highlights and specialized angles are differs from others. In this plan, all the four lines are bowed fit as a fiddle however different point. In our venture, we are presenting an idea of the monolith. The fundamental capacity of monolith is to give laminarization stream and limit the reverse of weight. This plan is a viable fit as a fiddle and size and it gives a significant level of weight contrast. In this plan, all cylindrical lines have a few tendency points before they meet at the gatherer, and the length of the lines likewise changes in contrast with the length of lines.

For the new version of the exhaust collector, the operating concept is identical to the old design. The only difference is that there are few modifications to the design feature and we introduce a monolith concept implementation into the catalytic converter. The monolith function is to achieve laminarization and to achieve the greatest difference in pressure.

In the four cylinder engine, each cylinder contains an exhaust port. Exhaust gases coming out from the engine to respective exhaust port according to their firing order. The flow of exhaust gas from inlet to outlet of the exhaust manifold is similar to that old design except that the monolith. High pressure (2 bar) exhaust gas coming out from the engine is flows through the exhaust manifold and freely released to the atmosphere, most important part of the exhaust manifold is catalytic convertor and monolith. The main function of catalytic is to convert harmful gases into harmless gases (i.e.) conversion CO, NOx into harmless. When the exhaust gases are flowing through the monolith, the flow gets laminarized and the exit pressure also gets decreased. This result would show the maximum level of pressure difference. Whereas an absence of monolith the back pressure built up was much greater, due to this large amount of residual gases remains in the combustion chamber and, as a consequence, the temperature increases. The exit velocity, the pressure and pressure difference without monolith were calculated using the following relation (1) and (2).

Pressure Calculation:

$$200000/(0.3 \times 9.81) + [\![37.674]\!]^2/(2 \times 9.81) + 1.34 = P_2/(0.3 \times 9.81) + [\![142.85]\!]^2/(2 \times 9.81) + 0 \quad (1)$$

$P2 = 197615.04$ Pa

Where,

Mass flow rate (m) = 700 kg/hr, density of air (ρ) = 0.3 kg/m3, total discharge (Q) = 0.648 m3/s, discharge at each port = 0.648/4 = 0.162 m3/s, Area at inlet (A1) = π/4*(0.074)2 = 4.3*10-3 m2, Velocity at inlet (V1) = 0.162/4.3*10-3 = 37.674 m/s, Area at outlet (A2) = π/4*(0.076)2 = 4.536*10-3 m2, Velocity at outlet (V2) = 0.648/4.536*10-3 = 142.857 m/s, P1 is pressure at inlet in N/m2 = 200Kpa, Z1 is the datum height of inlet in m, P2 is pressure at inlet in N/m2, Z2 is the datum height of inlet in m, ρ is the density of the hot air in kg/m3, g is the acceleration due to gravity in m/s2.

Pressure difference without monolith

$$(P1 \sim P2) = 200000 \sim 197615.04 \quad (2)$$

$$(P1 \sim P2) = 2384.96 \text{ Pa}$$

5. SIMULATION

In two examples, the exhaust manifold simulation was conducted in the programme computational fluid dynamics (CFD), firstly without the monolith in view, and in the second case the monolith simulation was performed. The findings of the simulation were presented below for both cases.

5.1 Flow Simulation without Monolith

During exhaust stroke, the exhaust gases are entered into the exhaust manifold at high pressure and temperature exist at low pressure. In this exhaust manifold design of four cylinders, the important factors of monolith design were absent. Due to the absence of monolith, the exhaust gas was not properly removed from the exhaust manifold. Due to the absence of monolith, backflow with occur, which cause the exhaust gas to flow inside the exhaust manifold itself, which reduces the efficiency of the system. However, CFD software is used to scan input and exit for various values, which can't be achieved with other software, which only values are available at inlet and outlet. The different simulations such as the temperature and the pressure distributions were conducted. The simulation results were shown in Fig. 6 to Fig. 8.

5.2 Flow Simulation with Monolith

This is the flow simulation of exhaust manifold with the monolith. The presence of monolith gives laminarization inflow and it restricts backflow. This figure clearly shows that the pressure is too high at the beginning of manifold and the pressure too low at the exit. This is due to the presence of monolith. Fig. 9, Fig. 10 and Fig. 11 were illustrated the pressure flow and temperature analysis of exhaust manifold with the monolith.

CFD software has been used to simulate exhaust manifold with monolithic catalytic converters. The simulation was done in two ways; the catalytic converter without a monolith was conducted first. Then the catalytic converter with monolith conducted the simulation. Where the CAD is split into 43 orders of nodes and elements of the catalytic converter. In Fig. 12 illustrated the specific heat capacity and thermal conductivity of exhaust manifold with and without monolith are shown. The results are taken from the simulations, which were different temperatures were investigated.

Thangapandian, International Journal of Applied Science and Engineering, 19(1), 2021012

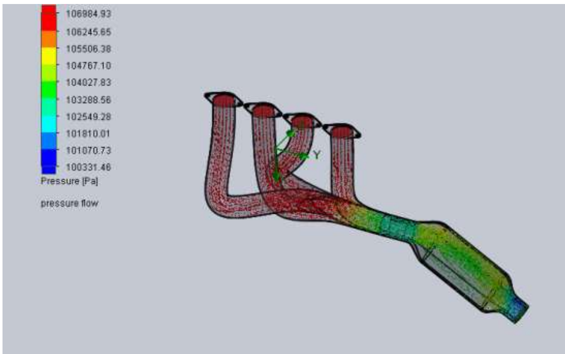


Fig. 6. Pressure flow analysis of manifold without monolith

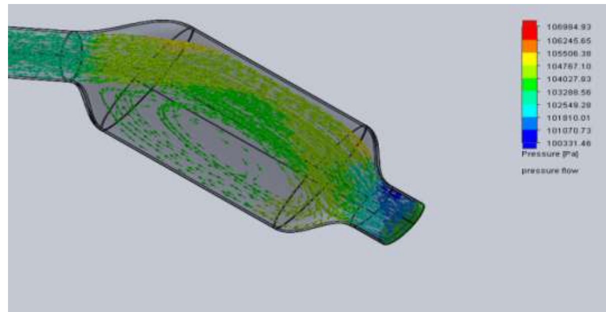


Fig. 7. Pressure flow analysis of catalytic converter

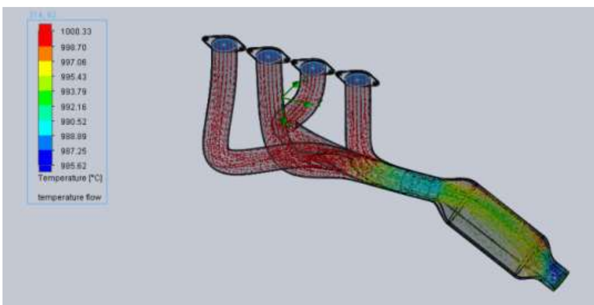


Fig. 8. Temperature analysis of catalytic converte

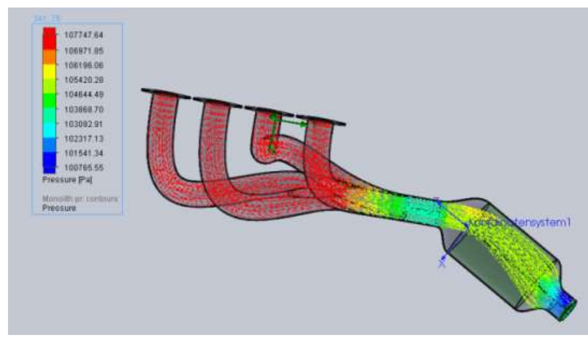


Fig. 9. Pressure flow analysis of manifold with monolith

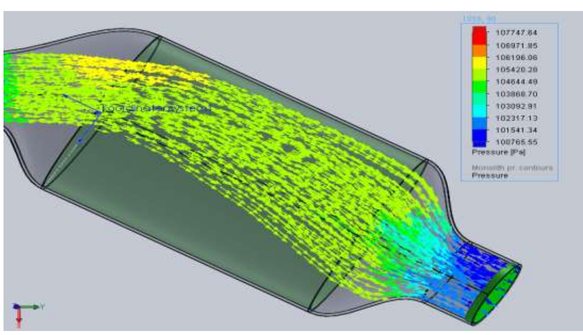


Fig. 10. Pressure flow analysis of catalytic converter with monolith

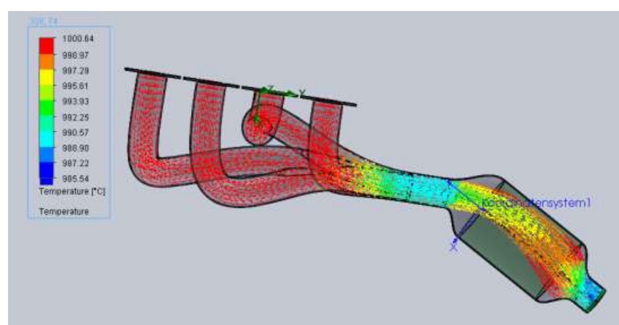
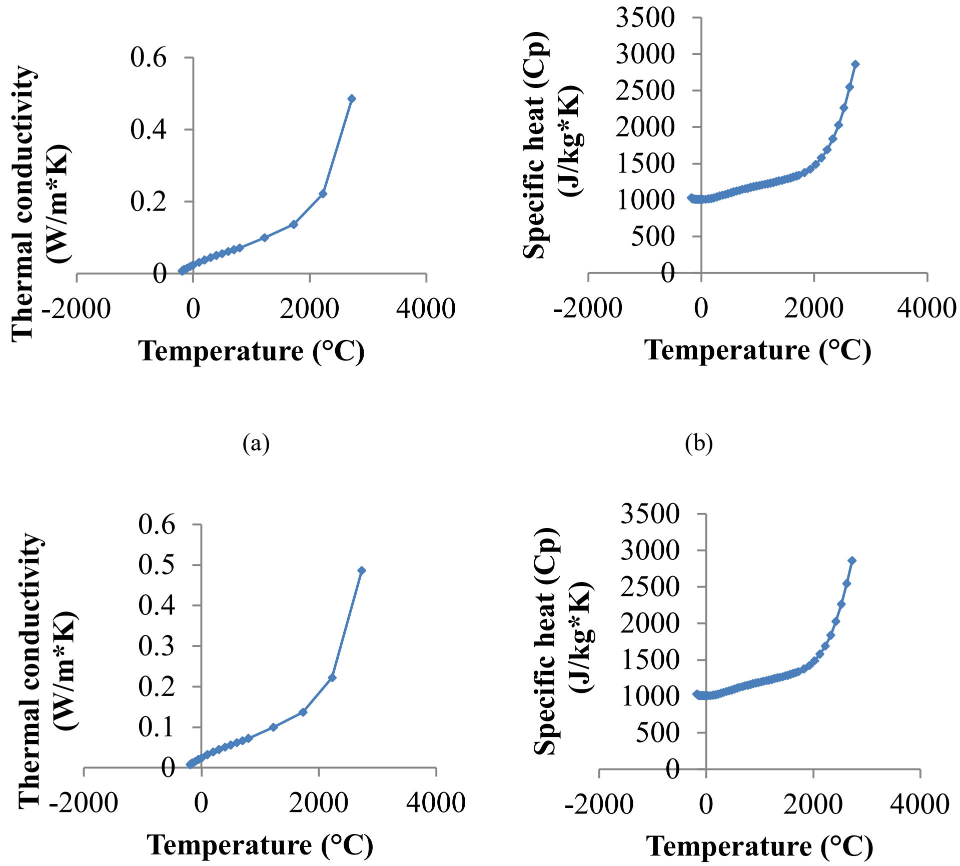


Fig. 11. Temperature analysis of catalytic converter with monolith



(c) (d)

Fig. 12. Simulation results of thermal conductivity and specific heat of exhaust manifold with and without monolith

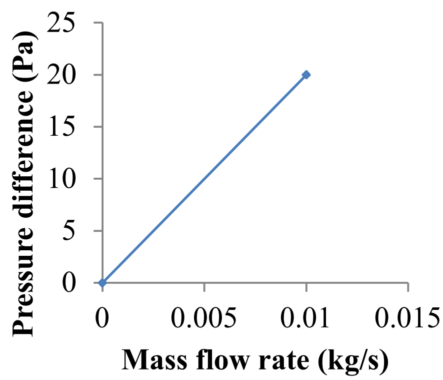


Fig. 13. Pressure drop increased with the mass flow rate

The simulation results show that the values are increasing with increased temperature. The pressure difference versus the mass flow rate is presented in Fig. 13, the pressure drop increased with the increase in mass flow rate. However, the exhaust flow rate has affected the temperature, The operating parameters are tabulated in Table 1 and the simulation properties of exhaust manifold with and without monolith are clearly represented in Table 2.

Table 1. Design and simulation parameters

Properties	Without Monolith	With Monolith
Thermodynamic parameters	Static Pressure: 101325.00Pa Temperature: 30.00°C	Static Pressure: 101325.00Pa Temperature: 30.00°C
Velocity parameters	Velocity vector Velocity in X direction: 0m/s Velocity in Y direction: 0m/s Velocity in Z direction: 0m/s	Velocity vector Velocity in X direction: 0m/s Velocity in Y direction: 0m/s Velocity in Z direction: 0m/s
Solid parameters	Default material: Iron Initial solid temperature: 30.00°C	Default material: Iron Initial solid temperature: 30.00°C
Turbulence parameters	Turbulence intensity and length Intensity: 2.00% Length: 0.004m	Turbulence intensity and length Intensity: 2.00% Length: 0.004m
Mesh Dimensions	Total cells: 24633, Solid cells: 8500, Partial cells: 9850, Fluid cells: 6283	Total cells: 24633, Solid cells: 8500, Partial cells: 9850, Fluid cells: 6283

Table 2. Simulation properties

Simulation Properties	Without Monolith	With Monolith
Pressure (Pa)	107007.51	107772.87
Temperature (°C)	1000.65	1000.64
Density (kg/m^3)	0.29	0.29
Velocity (m/s)	196.685	264.871
Velocity (X) (m/s)	160.475	153.521
Velocity (Y) (m/s)	168.606	261.570
Velocity (Z) (m/s)	71.977	77.602
Temperature(Fluid) (°C)	1000.65	1000.64

7. CONCLUSION

The exhaust collector's flow was measured and the flow problem studied. The problem was corrected in the new configuration and the flow was made effective to minimise exhaust gas pressure, thus improving the engine's combustion efficiency and volumetric quality. Sonic with chokes and even supersonic flows in regions will easily occur in a rear exhaust port. The extremely high temperature allows the gas to increase viscosity, which greatly increases the Reynolds number. Furthermore, the profound influence on the exhaust port flow of downstream elements is much stronger than the upstream elements found on the intake side. This is why the most published knowledge regarding the movement of exhaust ports is unclear. Particularly when it comes to how much flow in any given situation is needed. It is often cited that 60 percent of the intake flow should be drained but it is just a crude variation.

REFERENCES

Benjamin, S.F., Disdale, W., Liu, Z., Roberts, C.A., Zhao, H. 2006. Velocity predictions from a coupled one-dimensional/three-dimensional computational fluid dynamics simulation compared with measurements in the catalyst system of a firing engine. International Journal of Engine Research, 7, 29–40.

Deger, Y., Simperl, B., Jimenez, L.P. 2004. Coupled CFD-FE-analysis for the exhaust manifold of a diesel engine. In ABAQUS Users' Conference, 199–208.

Fontanesi, S., Giacopini, M. 2013. Multiphase CFD–CHT optimization of the cooling jacket and FEM analysis of the engine head of a V6 diesel engine. Applied Thermal Engineering, 52, 293–303.

Jeong, S.J., Kim, W.S. 2000. Numerical analysis of light-off performance and thermo-fluid characteristics in a three-way monolithic catalytic converter. SAE Technical Paper.

Kim, T.Y., Lee, S.H. 2015. Combustion and emission characteristics of wood pyrolysis oil-butanol blended fuels in a DI diesel engine. International Journal of Automotive Technology, 16, 903–912.

Koltsakis, G.C., Stamatelos, A.M. 1997. Catalytic automotive exhaust aftertreatment. Progress in Energy and Combustion Science, 23, 1–39.

Kresovic, U., Hussein, W., Zhou, C.Q., Majdak, J., Cantwell, R. 2002, January. CFD Analysis of Liquid-Cooled Exhaust Manifolds in a Real Time Engine Cycle. In ASME International Mechanical Engineering Congress and Exposition, 36355, 39–46.

Masood, M., Ishrat, M.M., Reddy, A.S. 2007. Computational combustion and emission analysis of hydrogen–diesel blends with experimental verification. International Journal of Hydrogen Energy, 32, 2539–2547.

Milanovic, R., Zhou, C.Q., Majdak, J., Cantwell, R. 2003. January. CFD modeling of flow and heat transfer inside a liquid-cooled exhaust manifold. In Heat Transfer Summer Conference, 36959, 785–792.

Mu, M., Sjöblom, J., Ström, H., Li, X. 2019. Analysis of the flow field from connection cones to monolith reactors. Energies, 12, 455.

Rakopoulos, C.D., Kosmadakis, G.M., Pariotis, E.G. 2009. Evaluation of a new computational fluid dynamics model for internal combustion engines using hydrogen under motoring conditions. Energy, 34, 2158–2166.

Scheeringa, K., Schwerin, D., Groves, B., Zhou, C., Majdak, J., Cantwell, R. 2002. CFD Analysis of a Liquid Cooled Exhaust Manifold. In 8th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, 2878.

Shaikh, S.K., Pathan, K.A., Chaudhary, Z.I., Khan, S.A., 2020. CFD Analysis of an Automobile Catalytic Converter to Obtain Flow Uniformity and to Minimize Pressure Drop Across the Monolith. CFD Letters, 12, 116–128.

Umesh, K.S., Rajagopal, V.P.K. 2013. Cfd Analysis Of Exhaust Manifold Of Multi-Cylinder Si Engine Todetermine Optimal Geometry For Reducing Emissions. International Journal of Automobile Engineering Research and Development, 45–56.