

Experimental Analysis on Catalytic Converter Using CFD

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ABSTRACT: The catalytic converter is a device which converts harmful exhaust gases from internal combustion engine into harmless gases. Harmful gases like NO_x, CO, unburned HC etc. are converted into N₂, CO₂, H₂O respectively. Internal Combustion engines generate undesirable emissions during the combustion process, which include, NO_x, CO, unburned HC, smoke etc. Apart from these unwanted gases, it produces Particulate Matter (PM) such as lead, soot. All these pollutants are harmful to environment and human health. They are the main causes for greenhouse effect, acid rain, global warming.

KEYWORDS: CFD, Catalytic Converter, Particulate Matter (PM), Wire Mesh.

I. INTRODUCTION

The simplest and the most effective way to reduce NO_x and PM, is to go for the after treatment of exhaust. Devices developed for after treatment of exhaust emissions includes thermal converters or reactors, traps or filters for particulate matters and catalytic converters. The most effective after treatment for reducing engine emission is the catalytic converter found on most automobiles and other modern engines of medium or large size. The catalyst and filter materials placed inside the catalytic converter increase back pressure. This increase in back pressure causes more fuel consumption, and in most cases, engine stalling might happen. The presence of catalytic converter increase back pressure in engine.

In Internal combustion Engines loose a small amount of work due to exhausting of burnt gases from the cylinder and the admission of fresh charge into the cylinder. This loss of power due to gas exchange process is due to pumping gas from lower inlet pressure to higher exhaust pressure. The gas exchange processes affects the volumetric efficiency of the engine. The performance of the engine, to a great deal, depends on the volumetric efficiency. During the exhaust stroke when the piston moves from bottom dead centre to top dead centre, pressure rises and gases are pushed into exhaust pipe. Thus the power required to drive the exhaust gases is called the exhaust stroke loss and increase in speed increases the exhaust stroke loss.

Therefore it is clear from the above discussion that the net work output per cycle from the engine is dependent on the pumping work consumed, which is directly proportional to the backpressure. To minimize the pumping work, the backpressure must be as low as possible for obtaining the maximum output from the engine. The backpressure is directly proportional to the pressure drop across the catalytic converter or design of complete exhaust system components causing the back pressure. Therefore exhaust system components and devices such as catalytic converter, in this case must be designed for minimum backpressure so that it should not disturb the engine as well as other subsystems operation. The present work therefore is an attempt to reduce exhaust emissions using copper as a catalyst without affecting engine performance.

The concept of Catalytic Converters in A.k.M Mohoddin et al is to present the results of an experimental study of the performance and conversion efficiencies of ceramic monolith three-way catalytic converters (TWCC) employed in automotive exhaust lines for the reduction of gasoline emissions. Two ceramic converters of different cell density,

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substrate length, and hydraulic channel diameter and wall thickness were studied to investigate the effect of varying key parameters on conversion efficiencies and pressure drop [2]. In this paper improvements of converter channels fluid-dynamics aiming to enhance pollutant conversion in all the engine operating conditions are investigated with respect to the role of channel cross-section shape on mass and heat transfer processes by L. Andreassi, S. Cordiner and V. Mulone [3].

The primary requirements of exhaust after treatment systems are low back pressure, low system weight, better emission performance and lower cost. Combinations of these properties provide better engine performance and higher system value. Knitted wire mesh substrates with different geometry and channels are used as carriers of diesel oxidation catalyst, three way catalyst and selective catalytic reduction (SCR) NO_x catalyst. Wiremesh materials are chosen not only to withstand corrosion and erosion environments but also durable at maximum continuous operating temperature and peak thermal spikes by S. Rajadurai, S. Jacob, C. Serrell, R. Morin and Z. Kircanski [4]. The pressure drop behaviour of catalytic converters has been investigated for a number of different substrates, suitable for high performance IC-engines, regarding cell density, wall thickness and coating. The measurements have been performed on an experimental rig with room-air flow and hot-air flow by F. Ekstrom and B. Andersson [5].

II. RELATED WORK

The presence of catalytic converter in exhaust system of diesel engine increases the back pressure in engine. It is due to catalyst and filter materials placed inside the catalytic converter. Due to increase in back pressure, the fuel consumption is higher in engine. Hence the flow phenomenon inside the catalytic converter should be fully understood in order to consider the current requirement of higher engine efficiency and lower emission. . CFD can perform the base of virtual simulation of the experimental tests. By significantly lowering the need for costly and time-consuming tests, CFD has the potential in reducing the overall time. Based on this approach, the flow behaviour in catalytic converter was carried out.

Number of simulation

A single phase single species incompressible flow simulation with Air as the working fluid will be carried out in two stages:

Stage1: The mesh configuration will be chosen as MC - 1 and three geometrical variants will be considered, with inlet and outlet conical portion length as:

- 70 mm
- 80 mm
- 90 mm

Qualitative objectives

The flow field will be described by plotting the following for all the 5 cases.

- a) Velocity and pressure contour plots on the symmetry plane
- b) Vector plots and Path lines originating from inlets
- c) The pressure variation along the centre- line will be plotted for all the 5 cases.

Quantitative objectives: The pressure drop is calculated for all the 5 cases.

Assumptions:

The following assumptions are carried out in order to simplify the problem

- The Working fluid considered is air.
- The assumed vehicle speed is 60 m/s. This gives the necessary inlet speed to the catalytic converter with inlet cross-section of 58 mm x 36 mm as approximately 28.87 cm/s.
- The flow is steady and incompressible.

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- A high turbulence intensity of 10% flow was assumed for the inlet, while the hydraulic diameter at the inlet will be considered to close the turbulence model equations.

Geometric Modelling

The catalytic converter consist of

- Inlet duct
- Inlet conical portion
- First compartment
- Second compartment
- Outlet conical portion
- Outlet duct

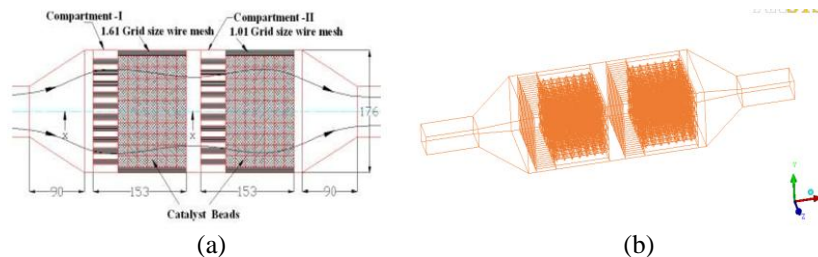


Fig.1 (a) Two dimensional geometry of catalytic converter (b) Three dimensional model of catalytic converter.

The inlet duct and outlet duct both having rectangular cross section and they are 110 mm long. The rectangular cross section is 58 mm × 36 mm. the both inlet and outlet conical section length of the device is varied for obtaining minimum back pressure. The conical section length may be 70 mm, 80 mm and 90 mm. the length of the catalytic converter (excluding inlet & outlet duct and conical section) is 374 mm, to meet the less ground clearance available in present vehicles the height of the catalytic converter is restricted to 110 mm. which is having constant rectangular cross section of size 176 mm × 110 mm. the catalytic converter consist of two compartments. The gap between the compartments is 34 mm, the compartment is being placed 17 mm from the conical section.

The both compartments consist of filter and catalyst domain. The filter length is 41 mm and consists of 10 vertically placed 8 mm thick wire meshes. Which are equally spaced with their surfaces being parallel to the flow of gas. The first meshes are placed 12mm from either side walls of the device. The catalyst domain consists of catalyst beads and steel wire meshes, these are arranged in alternate layers. The beads are arranged horizontally in a single layer so that the gas can enter at one end of the bead and come out in the opposite end. Altogether, there are 5 layers of beads stacked in between 4 steel meshes (3.75 mm thick), with the top and bottom bead layers having a double layer of steel mesh from the top and bottom wall of the device, respectively. During its travel, the gas follows the up and down movement and meets the entire inner surface area of the catalyst. Each bead is of 16 mm (length) x 32 mm (width) x 16 mm (height) dimension. There are altogether 315 catalyst beads {7(along the length) x 9 (top view) x 5 (layers)}.

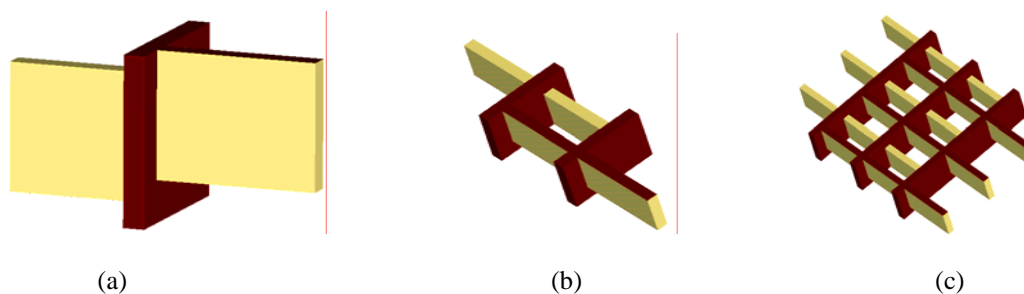


Fig 2. (a) Single bead (b) two beads (c) Array of beads

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The bead is 2 mm thick consisting of a 16 mm x 16 mm square plate with two flanges of 15 mm x 12 mm cross section and 2 mm thickness. The two flanges on either side are arranged at 4 mm from either end of the plate and alternately leave a gap of 4 mm from the bottom and top of the square plate, for the flow to pass through. The beads are designed so that the top and bottom portions are open and the gas can go up and down to the next layer of beads through the steel wire mesh layers which are also horizontally placed.

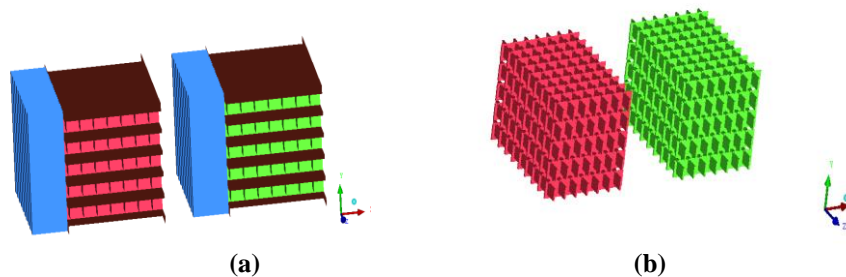


Fig. 3 (a) catalytic converter showing 1st and 2nd compartment (b) catalyst beads showing in 1st and 2nd compartment

III. WIRE MESH SPECIFICATIONS

In this analysis, the selected steel wire mesh grid sizes are 1.96, 1.61, 1.01 and 0.65 mm. The specifications of these wire meshes are shown in Table 1. Three models are made, each using two different grid size wire meshes placed in two separate compartments. The details of wire mesh grid sizes used in different models are shown in Table 2.

Table 1: Wire Mesh Specifications

Sl. No.	Wire mesh/gap size (mm)	Wire diameter (mm)	Open Area / porosity (%)	Weight (kg/m ³)	Mesh per inch	Cells per square inch	Viscous resistance [x 10 ⁷](1/m ²)	
							Normal	Transverse
1	1.96	0.58	59.3	1.71	10	100	3.846	3846
2	1.61	0.51	57.7	1.56	12	144	4.286	4286
3	1.01	0.41	50.8	1.51	18	324	6.086	6086
4	0.65	0.25	51.8	0.92	28	576	8.606	8606

Table 2: Wire Mesh Grid Sizes

Model Name	Wire mesh grid size in compartment 1 (mm)	Wire mesh grid size in compartment 2 (mm)
MC - 1	1.96	1.61
MC - 2	1.61	1.01
MC - 3	1.01	0.65

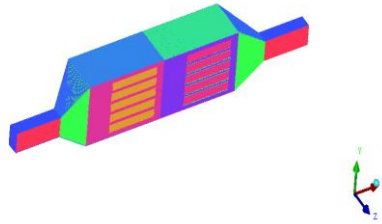
Grid Generation

The geometrical model of catalytic converter is meshed in ICFM CFD. The complete geometry is very big because of the modeling of the catalyst bead surfaces. Therefore, only a half-section across a vertical plane cutting through the geometry will be modeled. This is required to reduce the total cell count and hence the computational effort.

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(a)

Fig.4 (a) Computational Meshed Model

Domain Conditions

The continuity and 3 - dimensional momentum equations will be solved for the isothermal flow modelling. Turbulence will be modelled by $k-\epsilon$ RNG turbulence model appropriate to account for high velocities and strong streamline curvature in the flow domain. The reference pressure will be set at 1.33 atm and all pressure inputs and outputs will be obtained as gauge values with respect to this.

Material

Air will be the working fluid considered to be operating at 350⁰ C and 1.35 bar. The material properties under these conditions are

Table 3: Material Property

Property	Air
Density (kg/m ³)	0.7534
Viscosity (Pa.s)	3.0927×10^{-5}
Specific heat (J/kg-K) (not used)	1056.6434
Thermal conductivity (W/m-K) (not used)	0.0242

Boundary conditions

Boundary conditions are a set of properties or conditions on surfaces of domains, and are required to fully define the flow simulation.

The types of boundary condition used are:

- Inlet
- Outlet
- Wall

Inlet

An inlet boundary condition is used where the flow is predominantly directed into the domain. The inlet boundary condition is velocity inlet. The engine selected for this study is a four stroke twin cylinder (80mm bore and 110mm stroke length) water cooled diesel engine. The engine displacement is calculated as 603 cm³/s for the assumed vehicle speed of 60 m/s. This gives the necessary inlet speed to the catalytic converter with inlet cross - section of 58 mm x 36 mm as approximately 28.87 cm/s. Therefore, inlet velocity will be maintained at a slightly higher value of 0.3 m/s. Fluid used – for simplicity of analysis a single gas entity is considered having air ideal gas.

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Turbulence – A high turbulence intensity of 10% will be flow will be assumed for the inlet while the hydraulic diameter at the inlet will be considered to close the turbulence model equations.

Outlet

An outlet boundary condition is used where the flow is predominantly directed out of the domain. The outlet will be considered as a pressure outlet at zero gauge pressure.

Wall

Walls are solid (impermeable) boundaries to fluid flow. A zero velocity, no slip condition would be applied to all walls.

Table 4: Wall Boundary Condition

Location	Type
Catalyst beads compartment	Wall
Surfaces filter side compartment	Wall
top compartment	Wall

Governing Equation

For flow calculations the differential conservation equations are integrated over a given control volume.

Continuity equation

$$\frac{d}{dt} \int_{V(t)} \rho dV + \int_s \rho(U - W) dn = 0$$

Momentum equation

$$\frac{d}{dt} \int_{V(t)} \rho U dV + \int_s \rho(U - W) U dn = \int_s \tau dn - \int_s \rho \overline{U * U} dn + \int_V S_m dV$$

The Turbulence model used in this project work is *k-ε* RNG turbulence model. It is appropriate to account for high velocities and strong streamline curvature in the flow domain. The differential transport equation for the turbulence kinetic energy and turbulence dissipation are given below.

Turbulence kinetic energy

$$\frac{\partial(\rho k)}{\partial \tau} + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \epsilon$$

Turbulence dissipation

$$\frac{\partial(\rho \epsilon)}{\partial \tau} + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \frac{\epsilon}{k} (C_{1\epsilon} P_k - C_{2\epsilon} \rho \epsilon)$$

Numerical Scheme

Fluent allows us to choose either of two numerical methods:

- Segregated Solver
- Coupled Solver

Using either method, Fluent will solve the governing integral equations for the conservation of mass, momentum and (when appropriate) for energy and other scalars such as turbulence and chemical species. In both cases a control – volume based technique is used that consists of:

1. Division of the domain into discrete control volumes using a computational grid.

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2. Integration of the governing equations for the discrete dependent variables such as velocities, pressure, temperature, and conserved scalars.
3. Linearization of the discretized equations and solution of the resultant linear equation system to yield updated values of the dependent variables.

The two numerical methods employ a similar discretization process (finite - volume), but the approach used to linearize and solve the discretized equations is different.

Linearization: Implicit v/s Explicit

In both the segregated and coupled solution methods the discrete, non-linear governing equations are linearized to produce a system of equations for the dependent variables in every computational cell. The resultant linear system is then solved to yield an updated flow-field solution. The manner in which the governing equations are linearized may take an “implicit” or “explicit” form with respect to the dependent variable of interest. By implicit or explicit we meant the following.

Implicit

For a given variable, the unknown value in each cell is computed using a relation that includes both existing and unknown values from neighboring cells. Therefore each unknown will appear in more than one equation in the system, and these equations must be solved simultaneously to give the unknown quantities.

Explicit

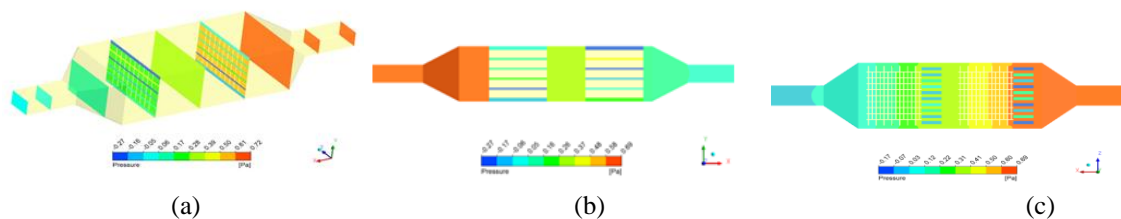
For a given variable, the unknown value in each cell is computed using a relation that includes only existing values. Therefore each unknown will appear in only one equation in the system and the equations for the unknown value in each cell can be solved one at a time to give the unknown quantities.

IV. EXPERIMENTAL RESULTS

Stage – 1

In 1st stage we have consider the steel wire mesh configuration as MC-1 for all three models of catalytic converter having conical portion length as 70 mm, 80 mm and 90 mm respectively. In this section Velocity and pressure contour plots on the symmetry plane, Vector plots and Path lines originating from inlets, is plotted for all the 3 cases, pressure drop is also calculated for each catalytic converter.

Catalytic converter - 70 mm - MC - 1



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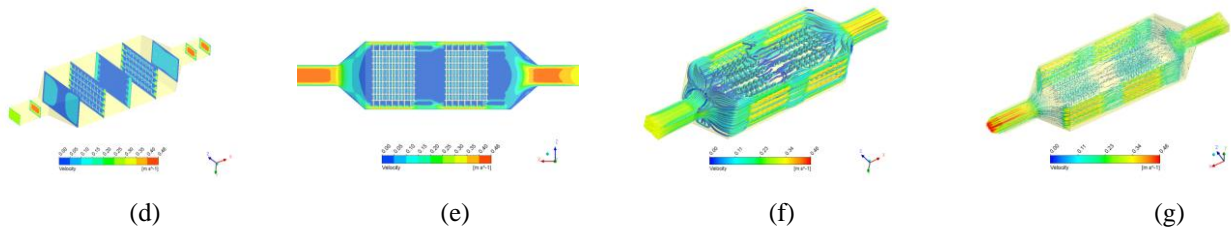


Fig. 5 (a) Pressure Contour (b) Pressure Symmetry (c) Pressure at Y=0 (X-Z Plane) (d) Velocity Contour (e) Velocity Symmetry (f) Path lines (g) Velocity Vector

Table 4: Pressure drop for catalytic converter 70mm - MC – 1

Position	Pressure Drop
0	0
100	0.04542
200	0.03409
300	0.3127
400	0.3189
500	0.5298
600	0.5943
700	0.6649
734	0.6792

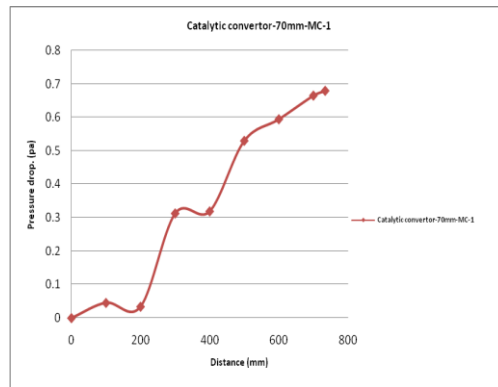
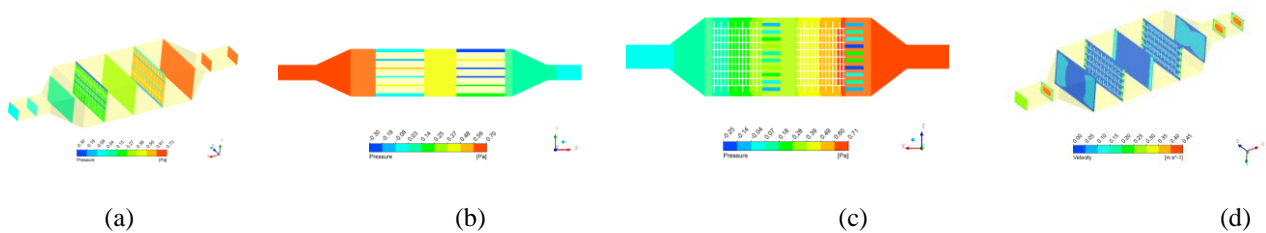


Fig.6 Pressure Drop Vs Distance of Catalytic Converter

Fig. 6 shows the variation of pressure drop along the distance of catalytic converter 70mm – MC – 1. As we see in the graph there is less pressure drop up to 200mm. after 200 mm there is sudden increase in the pressure drop. The sudden increase in pressure drop takes place due to presence of catalyst beads and steel wire mesh. The catalyst beads and steel wire mesh, they resist the motion of the air due to that there is sudden decrease in pressure drop takes place and again there is decrease in pressure drop after 400mm this is happen due to the air enters the second compartment and in second compartment again there is a presence of catalyst beads and steel wire mesh.

Catalytic Converter - 80mm - MC - 1



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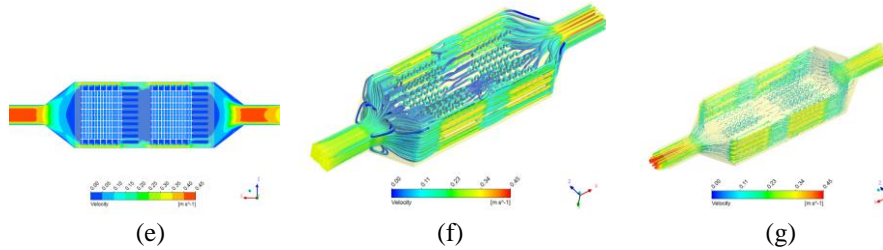


Fig.7 (a) Pressure Contour (b) Pressure Symmetry (c) Pressure at Y=0 (X-Z Plane) (d) Velocity Contour (e) Velocity Symmetry (f) Path Lines (g) Velocity Vector

Table 5: Pressure Drop of Catalytic Converter 80mm - MC - 1

Position	Pressure Drop
0	0
100	0.04852
200	0.03058
300	0.2847
400	0.3168
500	0.5384
600	0.6002
700	0.6707
754	0.6903

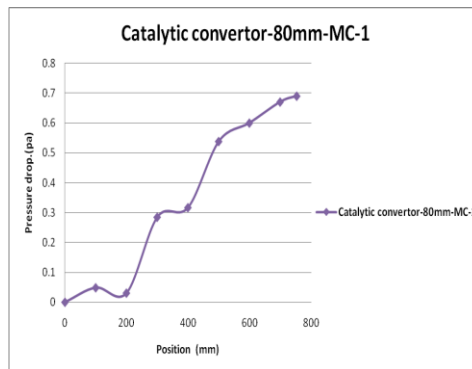
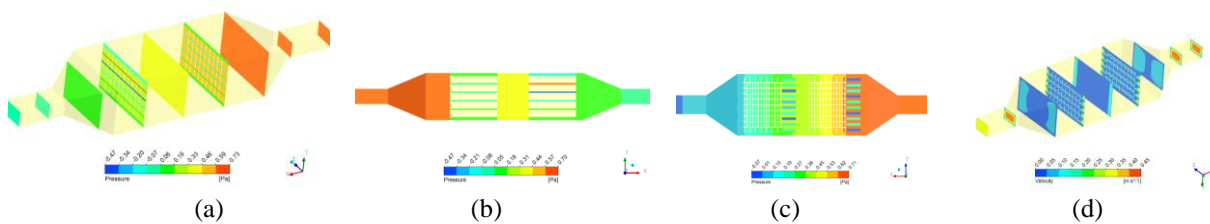


Fig.8 Pressure Drop Vs Distance of Catalytic Converter

Fig. 8 shows the velocity contour of catalytic converter 80mm - MC - 1. As we see from the fig that the velocity of fluid is maximum during inlet and outlet position of catalytic converter. As it passes through the first compartment and second compartment the velocity of fluid is minimum. Fig. 7 shows the variation of pressure drop along the distance of catalytic converter. The pressure drop is less at the inlet and outlet duct each having length of 110mm. the fluid can easily pass through in the inlet and outlet duct because these are not having any obstruction to the fluid.

Catalytic Converter - 90mm - MC - 1



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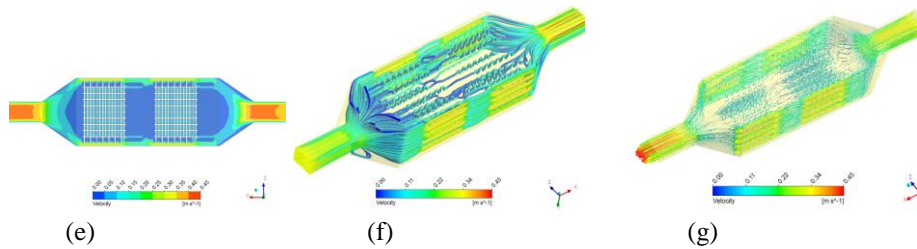


Fig. 9 (a) Pressure Contour (b) Pressure Symmetry (c) 25 Pressure at Y=0 (X-Z Plane) (d) Velocity Contour (e) Velocity Symmetry (f)Path lines (g) Velocity Vector

Table 6: Pressure drop for catalytic converter 90mm – MC – 1

Position	Pressure Drop
0	0
100	0.05115
200	0.02887
300	0.2866
400	0.3156
500	0.5298
600	0.5997
700	0.6677
774	0.6906

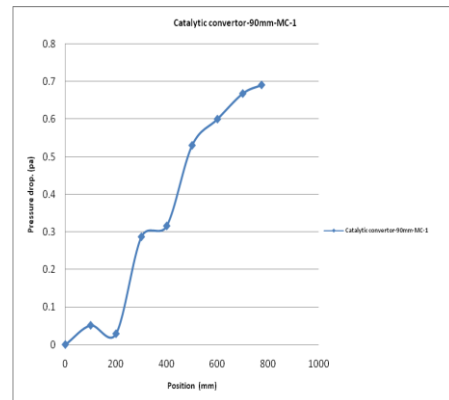


Fig.10 Pressure Drop Vs Distance of Catalytic Converter

Fig.10 shows the variation of pressure drop along the distance of the catalytic converter model 90mm - Mc - 1. It can be seen from the fig. 10 that there is a less pressure drop in between 300 mm to 400 mm. the reason for less pressure drop is that there is gap between the first compartment and second compartment of catalytic converter during that the fluid can easily flow so due to that the pressure drop is less.

Comparison of Pressure Drop of Catalytic Converter 70 mm - MC - 1, 80 mm - MC - 1, 90 mm - MC - 1 Respectively

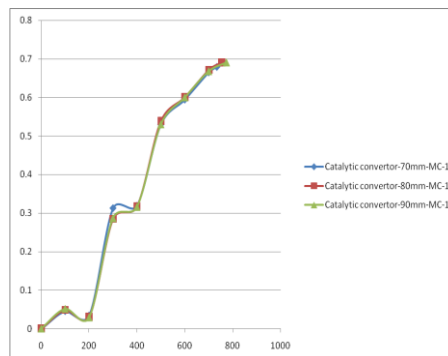


Fig.11 Pressure Drop Vs Distance of Catalytic Converter of Three Models

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Fig. 1 shows the comparison of pressure drop of catalytic converter 70 mm – MC – 1, 80 mm – MC – 1 and 90 mm – MC – 1 respectively. We can see from graph that the catalytic converter model 70 mm – MC – 1 has the lowest pressure drop, except during length between 300 to 400 mm so the total pressure drop of catalytic converter model 70 mm – MC – 1 is less, so it is considered for further study. We can see from graphs that as the conical portion length increasing the pressure drop also increasing.

V. CONCLUSION

It is concluded that the catalytic converter 70mm-MC-1 has the lowest pressure drop among the catalytic converter with different conical portion length such as 80 mm and 90mm for same boundary condition. Again we have compared the catalytic converter model 70mm – MC – 1 with different wire mesh grid sizes such as MC – 2 and MC – 3, in that also it has the lowest pressure drop, due to lower pressure drop the fuel consumption become lower and volumetric efficiency becomes higher. The special shaped catalytic beads allow the exhaust gas to flow freely without making any obstruction or blocking, so it helps to limit the pressure drop to the minimum level resulting in better engine performance. The catalytic beads are very hard, no wear and tear of catalyst can take place, and hence long life of catalyst is assured.

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