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Flow in Catalytic Converter of Spark Ignition Engine with Air Box

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Abstract— The paper deals with the fundamental understanding of complex processes taking place involving fluid flow, pressure, velocity profiles in the catalytic converter. The study of pressure contours and velocity vectors of fluid flow inside the catalytic converter are explained using numerical model. ANSYS Workbench 14.5 is been used for geometric modelling of catalytic converter. Domain discretization and analysis was carried out in Fluid Flow (Fluent). The substrate is modelled as porous. The pressure, velocity, mass flow and temperature fields in the converter with respect to inlet conditions are studied. In CFD analysis, fluid properties are specified with suitable assumptions. Parameters are taken from an experiment[1] on a four stroke single cylinder spark ignition engine running at a speed of 3000rpm.Catalytic converter plays an important role in reducing harmful gases without changing the design of an engine, but the presence of catalytic converter increases the exhaust back pressure which results in the volumetric efficiency decrease and higher fuel consumption. Therefore studies on simulation of flow through the catalytic converter are very important.

Keywords— Flow, Fluent, Catalytic Converter, Spark Ignition

I. Introduction

The spark ignition engine exhaust gases contains oxides of nitrogen (NO_x) 20g/kg of fuel, carbon monoxide (CO) 200g/kg of fuel, and organic compounds which are unburned or partially burned hydrocarbons (UHC) 25g/kg of fuel [2]. Catalytic converter is a stainless steel container mounted along the exhaust pipe of engine and inside the container is a porous ceramic structure through which the exhaust gas flows [3]. In most of the converters, the ceramic is a single honey comb structure with many flow passages. The passages comprises of many shapes, including square, triangular, hexagonal and sinusoidal. Early converters used loose granular ceramic with the gas passing between the packed spheres. Since it is difficult to keep the sphere in place, many converter developers opted for ceramic monolith which offers various advantages. Among these advantages are smaller volumes, lower mass and greater ease of packaging (Heck & Farrauto, 1995), [4]. The active catalyst layer is applied on the monolith walls. The coating, called washcoat, is composed of porous, high surface area inorganic oxides such as γ-Al_2O_3(gamma alumina), CeO_2 (Ceria) and ZrO_2 (Zirconia). Noble metal catalyst, such as Platinum (Pt), Palladium (Pd) and Rhodium (Rh), are deposited on the surface and within the pores of the washcoat (Pontikakis, 2003) . Exhaust gas flowing in a catalytic converter diffuses through the washcoat pore structure to the catalytic sites where heterogeneous catalytic reactions occur. The specific reactions vary with the type of catalyst installed. Most present-day vehicles that run on gasoline are fitted with a “three way” converter, so named because it converts the three main pollutants in automobile exhaust: carbon monoxide, unburned hydrocarbon and oxides of nitrogen. The first two undergo catalytic combustion and the last is reduced back to nitrogen [5]. The nature of the exhaust gas flow is very important factor in determining the performance of catalytic converter. The pressure gradient and velocity distribution through the substrate are important in particular. Therefore CFD analysis is used to design efficient catalytic converters by modeling the exhaust gas flow, the pressure drop and the uniformity of flow through the substrate can be determined. In this paper ANSYS FLUENT (ANSYS Work Bench 14.5, Fluid Flow-Fluent) is used to model the flow of exhaust gas through catalytic converter, so that the flow field may be analyzed. Catalyst substrates coated with the active catalyst washcoat are packaged in steel housings to form catalytic converters. Emission performance durability and mechanical durability are the two key aspects of the overall durability of an emission control system. The emission durability depends on the quality of the catalyst coating and on the operating conditions such as temperature or levels of catalyst poisons in the exhaust gas. In CFD, the system consumes less memory space and less response time, if the rectangular cross section is assumed. However, in actual practice, the rectangular corners are suitably rounded off which ensures the smooth flow of exhaust gas with less turbulence near the wall sides [6]. On the other hand, the flow characteristics of the exhaust gas such as flow velocity, temperature, composition of raw emissions and flow distribution play an important role for the conversion rate and light-off behavior of catalytic converter [Michael G. Campbell (1995), Chandler.G.R (2000)] [8].

II. Material and Methodology

Exhaust gas is used as working fluid media, which is assumed to be steady and compressible. High Reynolds number k- ε turbulence model is used in the ANSYS Fluent model. This turbulence model is widely used in industrial applications. The equations of mass and momentum are solved using SIMPLE algorithm to get velocity and pressure in the fluid domain. The assumption of an isotropic turbulence field used in this turbulence model is valid for the current application. Other fluid properties are taken as constants. Filter media of catalytic converter is modeled as porous media. For porous media, it is assumed that, within the surfacearea containing the distributed resistance there exists a local balance everywhere between pressure and resistance forces. The emission conversion efficiency and light-off of a catalytic converter depends on various factors. On one hand, there are the properties of the monolith such as cross section, length, cell density, wall thickness, wash coat formulation and loading.

Governing Equations:

Mass :

$$\frac{\partial}{\partial t}(\rho) + \nabla \circ (\rho \mathbf{U}) = 0$$

Momentum :

$$\frac{\partial}{\partial t}(\rho \mathbf{U}) + \nabla \circ (\rho \mathbf{U}\mathbf{U}) = -\nabla p + \nabla \circ \boldsymbol{\tau} + \rho \mathbf{B}$$

Energy :

$$\frac{\partial}{\partial t}(\rho h) + \nabla \circ (\rho \mathbf{U} h) = -\nabla \circ \mathbf{q} + \dot{S}_h$$

Species Mass :

$$\frac{\partial}{\partial t}(\rho Y_k) + \nabla \circ (\rho \mathbf{U} Y_k) = -\nabla \circ \mathbf{J}_k + \dot{S}_k \qquad \forall\, k = 1, 2, \ldots, N$$

Boundary Conditions

1. Turbulence Model : k-epsilon
2. Working fluid : Exhaust gas
3. Inlet conditions :

Exhaust Gas:

Mass flowrate 3.05kg/s @ Pressure 3.57 bar

Air:

Mass flow rate 120 lit/hr (0.0051kg/s) @ atmospheric Pressure 1.0 bar, 27 deg Centigrade

4. Outlet conditions : 1.1 bar
5. Catalytic Converter : Porous Media

IV. Results and Discussion

The behaviour of the fluid inside the catalytic converter is discussed here. A good flow is observed at inlet and out let of catalytic converter because of straightness. It is found that the flow is very uniform in the substrate. The maximum pressure drop occurs due to porous media. The total pressure drop of catalytic converter is about $2.5e^5$ Pa, of which 71% is from the substrate itself.

The geometry construction, meshing, cell zone conditions, boundary conditions and results in CFD post is given in following figures.

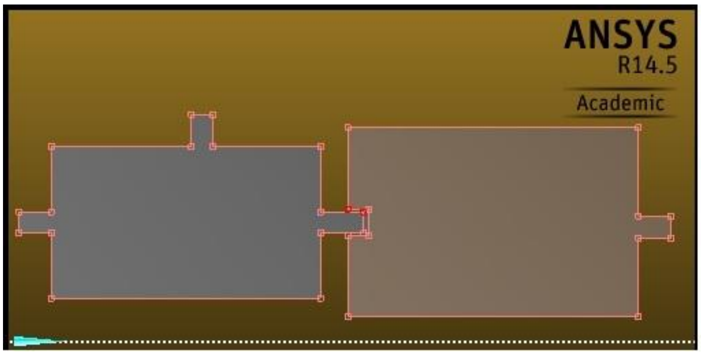

Figure1: Geometric Modelling

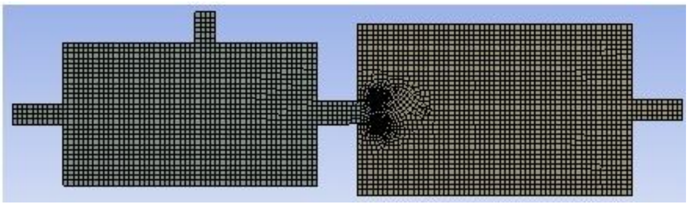

Figure2: Mesh Model

Table1. Mesh information

Domain	Nodes	Element
Airbox	8978	4304
Substratewall	11412	5529
All Domains	20390	9833

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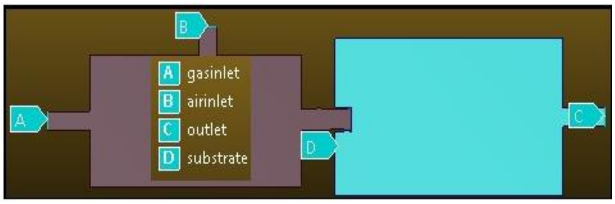

Figure3: Named selections assigned to catalytic converter with air box arrangement to reduce the back pressure

Table 2. Boundary Physics for simulation

Domain	Boundaries	
airbox	Boundary - airbox symmetry 1	
	Type	SYMMETRY
	Boundary - airbox symmetry 2	
	Type	SYMMETRY
	Boundary - airinlet	
	Type	MASS-FLOW-INLET
	Boundary - contact_region src	
	Type	INTERFACE
	Boundary - gasinlet	
	Type	MASS-FLOW-INLET
	Boundary - wall airbox	
	Type	WALL
substratewall	Boundary - contact_region trg	
	Type	INTERFACE
	Boundary - outlet	
	Type	PRESSURE-OUTLET
	Boundary - substratewall symmetry 1	
	Type	SYMMETRY
	Boundary - substratewall symmetry 2	
	Type	SYMMETRY
	Boundary - wall substratewall	
	Type	WALL

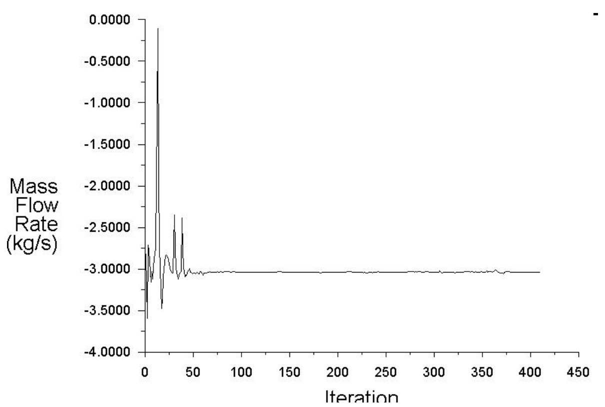

Figure4: Simulation Conversion

Convergence is done using absolute criterion of 1e-6. Solution methods - spatial discretization, Gradient-Least square cell based, Pressure- standard, Momentum, Turbulent Kinetic energy and turbulent dissipation rate are taken at second order upwind, Surface monitors report with respect to massflowrate at outlet and solution is initialized & computed from exhaust gas inlet Solution is run for 500 iterations as shown in Fig.4.

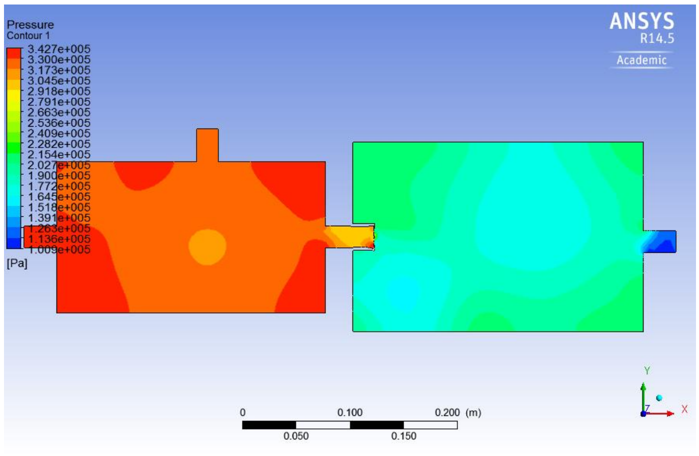

Figure 5: Pressure Contours for mass flow rate of 3.05 kg/s Exhaust gas from the exhaust pipe and 0.0051 kg/s of air from air box

Pressure is important factor in catalytic converter. Back pressure is observed at out let of catalytic converter as shown in Fig.5. It is also observed converter with air box minimizes backpressure compared to without air box. As the inlets of air box and out let at converter are flattened, the complete setup is placed slightly angular in experimentation to minimize the backpressure which has a negative effect on engine efficiency resulting in a decrease of power output.

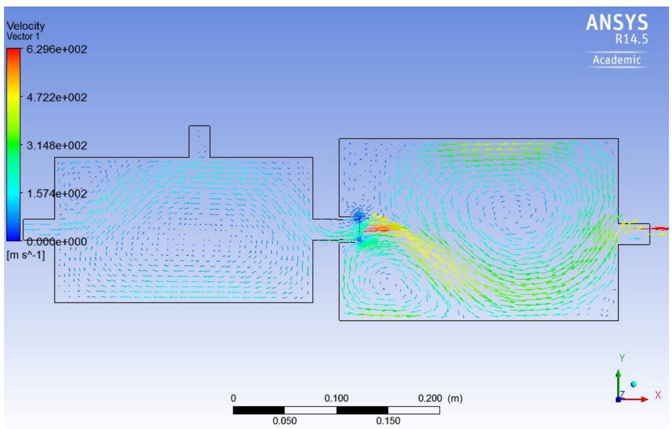

Figure 6: Velocity Vectors for mass flow rate of 3.05 kg/s Exhaust gas from the exhaust pipe and 0.0051 kg/s of air from air box

The X-velocity component distribution of the fluid flow in Fig.6 shows how the fluid decelerates rapidly when it passes through the porous media. It has taken reverse path in catalyst region due to the resistance exerted by the substrate.

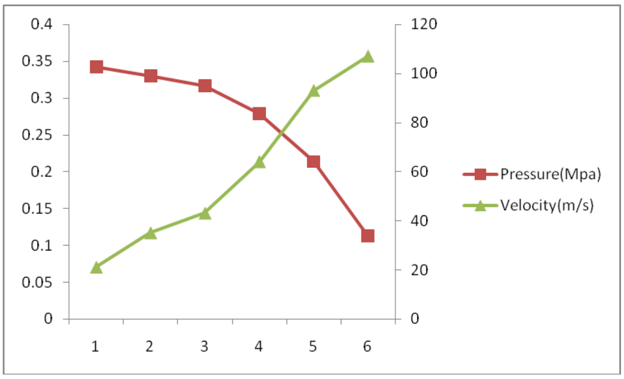

Figure 6: Pressure and Velocity relation for Isothermal & constant Exhaust mass flow

V. Conclusion and future work

The following conclusions are made from the Fluid Flow (Fluent) simulation.

- At constant mass flow rate of exhaust gas and air the pressure is dropped drastically in substrate wall surface.
- The velocity is increased with respect to pressure and at given mass flow rates of exhaust gas and air.

Future work

- Flow simulation can be done for different massflowrates at different temperature conditions
- FEA can be done for different catalysts for thermal stress and can be discovered efficient & economic catalytic converter.

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