IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 3 Issue 4, April 2016.
www.ijiset.com
ISSN 2348 – 7968

Effects of Exhaust System Pressure Measurement Probes in Cold Flow Bench and Validation with CFD

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Abstract
A study on the probe profiles used in back pressure measurement was performed to estimate the measurement performance of each probe profile. The exhaust catalytic converter assembly along with adapters is adopted for virtual analysis and experimentation. Four different pressure measurement probe profile types such as straight, 25º tapered end, 45º tapered end and 90º bend are involved in the field of study to measure back pressure of chosen assembly. Back pressure of the catalytic converter assembly obtained from Computational Fluid Dynamics (CFD) is then correlated with the test result obtained from flow bench measurement using different pressure measurement probes as explained. The difference of back pressure gap between the CFD results and measurement result incurred using straight profile probe in flow bench is very close with the maximum deviation less than 5%. While the other pressure measurement probes has the maximum deviation of 53%, 46% and 58% respectively. The paper will discuss in detail the experimental procedures, data acquisition and data handling.
Keywords: *Back pressure, CFD, Probes, Cold flow bench.*

1. Introduction

Engine exhaust pollution and noise are controlled through the use of Catalytic converter, Muffler and Resonator. Well-designed exhaust systems collect exhaust gases from engine cylinders and discharge them as less polluting and silently as possible [4,5]. In order to reduce harmful gasses like the CO, NOx and CO2 from exhaust gas the DOC, PFF, DPF and SCR are used in converters based on emission norms. Those components are increasing the back pressure on the exhaust system.

The backpressure usually refers to the pressure exerted on a moving fluid by obstructions against its direction of flow. The average pressure in the exhaust pipe during the exhaust stroke is called the mean exhaust pressure and the atmospheric pressure is called the ambient pressure. The difference between these two pressures is defined as backpressure [3].

Excessive back pressure in the exhaust system creates excessive heat, lower engine power and fuel penalty in the engine [1]. To avoid that, the back pressure limit fixed based on engine power. The amount of power loss depends on many factors, but a good rule-of-thumb for exhaust system is that one inch (25.4 mm) of mercury backpressure causes about 1% loss of maximum engine power [2].

The probe profiles are majorly contributed in back pressure measurement of exhaust systems. To validate that, four different probe profiles are selected at random, straight probe, 25º tapered end probe, 45º tapered end probe and 90º bend probe respectively. Those probes are used in cold flow bench to measure the back pressure of converter assembly [6]. The same sample (Converter) models are analyzed with CFD (STAR CCM+ 9.04) [7].

Those CFD results are compared with test results. The straight end probe results are very closer to the CFD results with the maximum deviation of 5%. The other probes test results are having more than 40% deviation compared with CFD result. These kind of difference accrued by velocity contribution on back pressure measurement. Based on the probe profile the velocities are takes place on measurement result. Here, the contributions of velocities are increasing the pressure level on measurements. Those impacts of pressure measurement while using different probes are validated in experimental and virtual analysis.

2. Problem Identification

Pressure drop measurement test of exhaust system has done by different methods in OEM's and Tier-1 supplier's ends. In this paper, how to set the proper instrumentation for exhaust system back pressure measurement in test bench and how it reacts with measurements, those things are measured and also validated with CFD.

3. Experimental Analysis

3.1 Test Setup

The cold flow bench is used to measure the back pressure of converter assembly. The cold flow bench maximum mass flow rate and temperature are 1200kg/h and 318K respectively. The simple model of converter assembly is selected for back pressure measurement test. The converter assembly is mounted on cold flow bench with proper setup. The test setup is shown in Fig:1. Backpressure across the systems are analyzed with the aid of two number of pressure sensors.

Pressure sensor one is placed 50mm before the inlet flange of the converter assembly. The pressure sensor two is placed open to the atmospheric pressure. The mass flow rate is increased from 100 to 600kg/h. The remaining air temperature is maintained with 303K and the measurements are acquired for two minutes time span at all stages. The outlet pressure of the converter assembly is kept at 1atm.

Fig. 1 Converter - Back pressure measurement test setup

3.2 Selection of Pressure Measurement Probes

Pressure measurement probe profiles are majorly contributing on back pressure measurement test. Here, four different types of probes selected at random and those are used to measure the back pressure across the converter assembly with cold flow bench.

Those probes are shown in Fig:2, straight, 25º tapered end, 45º tapered end, and 90º bend probe respectively. Compared with straight probes the inclined probes are mostly used by many automotive industries. Those inclined probes are very critical while measuring the back pressure of moving fluids like exhaust gas.

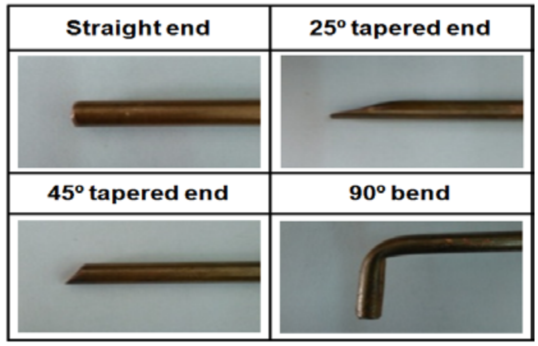

Fig. 2 Pressure measurement probe

Here, we can see the difference of probe contribution in back pressure measurement test results. The tapered end and bend probes are producing high pressure compared with straight probes. This kind of difference accrued by velocity contribution on back pressure measurement, based on the probe profiles the velocities are contributing on back pressure measurement result. Here, the contributions of velocities are increasing the pressure level on measurements. The cold flow bench test results are listed in Table:1.

Table 1: Cold flow test results

S.No	Mass flow rate (kg/h)	Back pressure (mbar)			
		Straight	25º tapered end	45º tapered end	90º bend probe
1	100	2.72	4.38	4.52	5.17
2	200	6.16	11.45	10.50	13.00
3	300	10.25	21.75	18.92	24.45
4	400	15.21	35.83	29.37	38.97
5	500	20.80	53.78	41.49	57.43
6	600	28.25	78.87	57.82	80.81

Those results are plotted in graph and it's shown in Fig:3. In this test result the straight probe results are slightly lower compared with other inclined probes. The 45º tapered end probe producing lower back pressure compared with remaining two inclined probes. The 45º tapered end probe is selected and those results are compared with straight probe test results. The minimum difference between the straight probe and inclined probe is 42% and maximum difference between the straight and inclined probe is 53% (45º tapered end probe).

ISSN 2348 – 7968

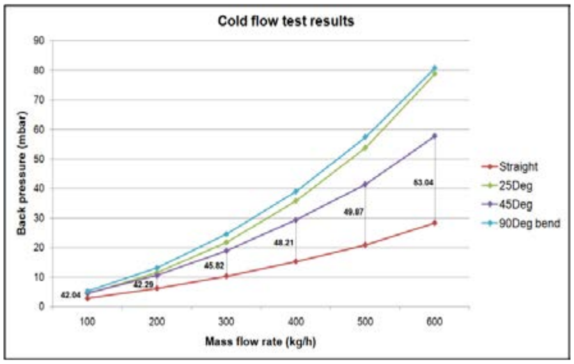

Fig. 3 Graphical representation for cold flow test results

4. Virtual Analysis

CAD model of the present converter which will be examined in the paper is shown in Fig.4. The converter consists of inlet and outlet pipes, two cones, substrate (Porous), support mat, and shell.

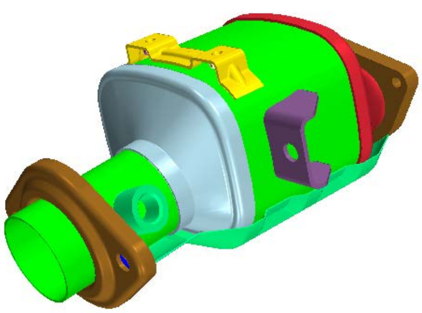

Fig. 4 Converter CAD Model

4.1 Three Dimensional Study

A three-dimensional model of converter is generated in CFD tool Star CCM+ v9.04 for the analysis.

4.2 Modeling and Meshing

The CAD model is imported in Star CCM+ and the surface preparation was carried out. The parts are merged to one another to create regions such as fluid or solid etc. The solid region was separated and deleted, the remaining fluid region is shown in Fig:5.

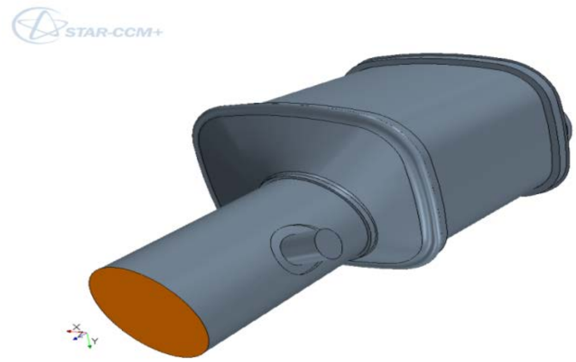

Fig. 5 Converter - Fluid region

The fluid region of the converter is surface meshed and then polyhedral mesh was performed, with a refined prism layer mesh near the wall. The k-ε turbulence model is used, with standard wall functions for near-wall treatment. The model has approximately 1 million cells with maximum skewness angle of 85 degree. The fluid region with mesh is shown in Fig: 6.

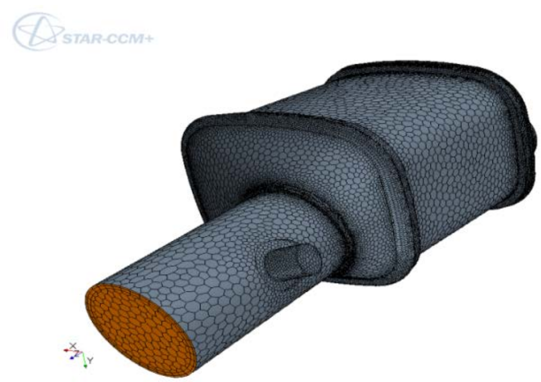

Fig. 6 Converter - Meshed fluid region

4.3 Governing Equations

CFD solver Star CCM+ is used for this analyze. It is a finite volume approach based solver which is widely used in industries. Governing equations solved by the software for these analyze in tensor Cartesian form are following:

Continuity:

$$\rho\left(\frac{\partial uj}{\partial xj}\right) = 0$$

Momentum:

$$\rho\frac{\partial}{\partial xj}(ujui) = -\frac{\partial p}{\partial xj} + \frac{\partial \tau ij}{\partial xj} + Scor + Scfg$$

Where ρ is density, uj is j^{th} Cartesian velocity, p is static pressure, τij is viscous stress tensor.

4.4 Boundary Conditions

Air is used as fluid media, which is assumed to be steady and comparable. High Reynolds number k-ε turbulence model is used in the CFD model. This turbulence model is widely used in industrial applications. The CFD analysis of this model would be passing air at fixed mass flow rate through the converter assembly. The time conditions implemented are steady state. Converter substrate is considered as porous region.

The inertial and viscous resistances are calculated with respected to the tested converter substrate dimensions. The inertial and viscous resistances are $10.321 kg/m^4$ and $621.8795 kg/m^3.s$ at 600kg/h respectively. The Pressure drop across the converter assembly is measured. The mass flow rates are 100 to 500kg/h. The air temperature is maintained with 300K. The outlet pressure of converter assembly is kept at 1atm.

4.5 Post Processing Results

The CFD flow analysis is conducted on converter assembly. The inputs of the converter assembly are mass flow rate 100 to 600kg/hr, and air temperature is 300K. At maximum mass flow rate (600kg/h) pressure, velocity and vector plots are shown in Fig:7&9 respectively.

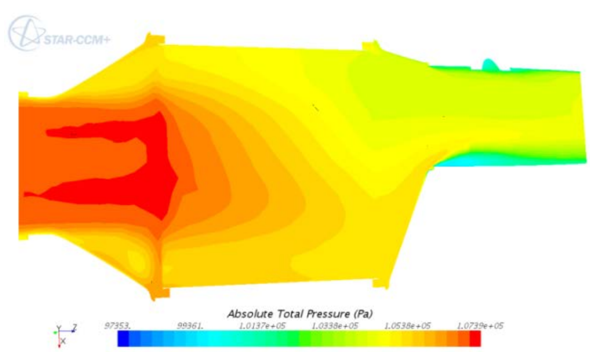

Fig 7 Pressure plot

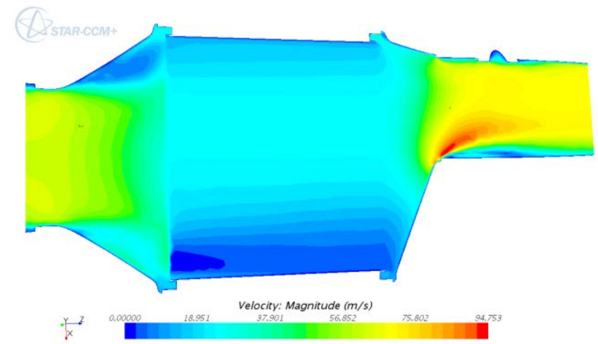

Fig 8 Velocity plot

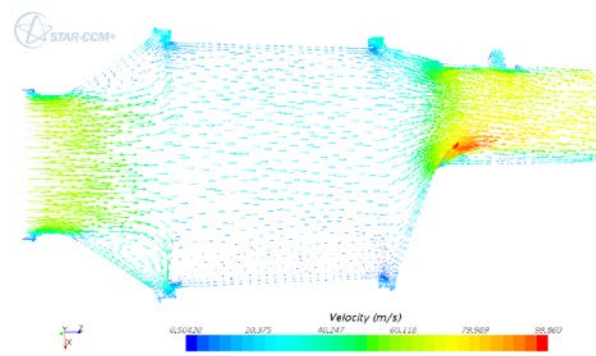

Figure 9 Velocity Vector

The pressure drop results of converter assembly are listed in Table:2

Table 2: CFD results

S.No	Mass flow rate (kg/h)	Back pressure (mbar)
1	100	2.4433
2	200	5.7244
3	300	9.8282
4	400	14.6415
5	500	20.2224
6	600	26.5792

5. Validation of Cold Flow Bench Test Results with CFD.

Case-1: The flow analysis results (CFD) of converter assembly are correlated with test results. Those are plotted in graph and it's shown in Fig:10. Here, the straight probe test results are very closer to the CFD results. The minimum difference between the straight probe and inclined probe is 2% and maximum difference between the straight and inclined probe is 7% (Straight probe test

ISSN 2348 – 7968

results vs CFD results).

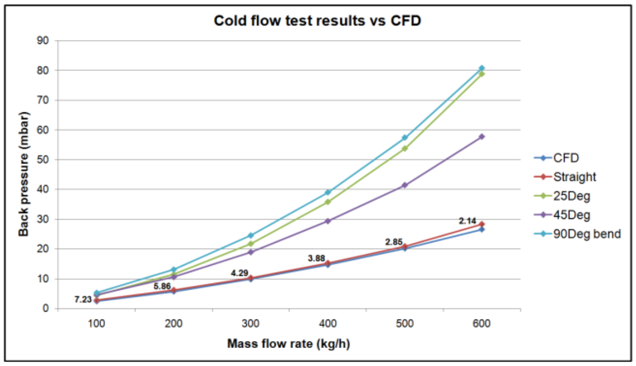

Fig 10 Graphical representation for cold flow test results vs CFD with converter assembly

Case-2: The same pressure measurement probes used in case 1 is used to measure the back pressure of muffler assembly in cold flow bench. In this case, the deviation obtained is similar to the previous case with respect to probe profiles. The straight probe test results are very closer to the CFD results in both cases. The minimum difference between the straight probe and inclined probe is 1% and maximum difference between the straight and inclined probe is 8% (Straight probe test results vs CFD results). The pressure difference is shown in Fig:11.

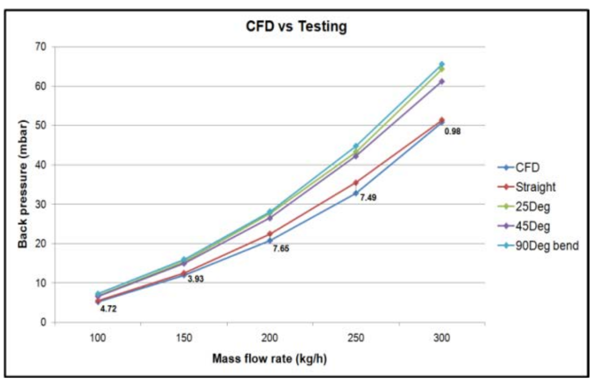

Fig 11 Graphical representation for cold flow test result vs CFD with muffler assembly

6. Conclusion

The following conclusions can be drawn from the experimental and virtual investigation.

1. The minimum difference of 42% was recorded, when compared with straight probe and inclined probes test results measured in cold flow test bench. If the same probes are using in hot flow bench like burner or engine bed, then the velocity becomes three times higher compared with cold flow bench test. This will increase the existing difference between the straight and inclined probe. Therefore, the straight probes are suitable for pressure measurement.

2. The virtual results of converter assembly are correlated with test results. It's having overall difference of 4%.

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Biographies

Dr. S Rajadurai, Ph. D. born in Mylaudy, Kanyakumari District, Tamil Nadu, India, received his Ph.D. in Chemistry from IIT Chennai in 1979. He has devoted nearly 35 years to scientific innovation, pioneering theory and application through the 20th century, and expanding strides of advancement into the 21st century. By authoring hundreds of published papers and reports and creating several patents, his research on solid oxide solutions, free radicals, catalyst structure sensitivity, and catalytic converter and exhaust system design has revolutionized the field of chemistry and automobile industry. Dr. Rajadurai had various leadership position such has the Director of Research at Cummins Engine Company, Director of Advanced Development at Tenneco Automotive, Director of Emissions at ArvinMeritor, Vice-President of ACS Industries and since 2009 he is the Head of R&D Sharda Motor Industries Ltd. He was a panelist of the Scientists and Technologists of Indian Origin, New Delhi 2004. He is a Fellow of the Society of Automotive Engineers. He was the UNESCO representative of India on low-cost analytical studies (1983-85). He is a Life Member of the North American Catalysis Society, North American Photo Chemical Society, Catalysis Society of

IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 3 Issue 4, April 2016.
www.ijiset.com
ISSN 2348 – 7968

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