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Design, Development and Optimization of Exhaust System

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Abstract*— Main focus of this dissertation is to Design and Develop integrated catalytic converter and muffler, which is low costing, using CAD Modeling Software & fabrication of the same. Catalytic Converter is developed from metal oxides which are readily available in the local market. Modern cars are equipped with three way catalytic converters which are made from Platinum Group Metals (PGM) and Cerium Oxide (CeO_2) [1,2]. These days platinum is used as a lead catalyst in the catalytic converter which is both costly and it agglomerates at working temperature of catalytic converter [3]. Aim of this work is to use metal oxides in place of the Platinum Group Metals (PGM) and oxides which are required to import such as CeO_2 and use honeycomb structure formed by stacking hollow tubes made of stainless steel one over another so as to increase the contact area through which the exhaust gases pass and also causing laminar flow of exhaust gases to take place through the hollow tubes [4] in compare to conventional muffler in which resonating chambers are used which are harmonically tuned to cause destructive interference wherein opposite sound waves cancel each other out. In this work catalytic converter is developed based on catalyst material consisting of metal oxide namely kaolin (Al_2O_3•$2SiO_2$) and Urea ($CO(NH_2)_2$), in Wire Mesh substrate type. Here Urea is used for reduction and Kaolin for oxidation of flue gases, in which Urea replaces PGM.

Keywords - Catalytic Converter; CatCon; Muffler; Emission Control; Exhaust System.

I. INTRODUCTION

A Catalytic Converter is a cylindrical unit about the size of a small silencer and is installed into the exhaust system a vehicle such as a car, scooter, moped, motorcycle or auto-rickshaw. It is placed between the exhaust manifold and the silencer. Inside the converter there is a honeycomb structure of a ceramic or metal, which is coated with alumina base materials and thereafter a second coating of precious metals platinum, palladium or rhodium or combinations of the same. This second coating serves as a catalyst. A catalyst is a substance which causes a chemical reaction that normally does not happen in the given conditions. As a result of catalytic reaction, as the exhaust gases pass over the converter substrate, toxic gases such as CO, HC and NO_x are converted into harmless CO_2, H_2 and N_2. There are two types of catalytic converters: 1) A two-way converter, which is used to control only CO and HC emissions by oxidation. 2) A three-way converter, which is used almost in all petrol cars. It controls CO and HC by oxidation as well as NO_x by reduction. Three-way converters (TWC) are now commonly being used for petrol engines and operate in two stages. The first converter stage uses rhodium to reduce the NO_x in the exhaust into nitrogen and oxygen. In the second converter stage, platinum or palladium acts as a oxidation catalyst to change HC and CO into harmless water and CO_2. For supplying the oxygen required in the second stage, air is fed into the exhaust after the first stage. The catalyst allows oxidation of the exhaust gases at a much lower temperature than in the combustion chamber [5]. The main components of catalytic converter are A) Oxidation catalytic substrate B) Reduction catalytic substrate C) Intumescent Mat Insulation Packaging D) Stainless Steel Catalytic Converter body E) Lambda Sensor F) Heat Shield.

When the exhaust valve opens, high-pressure exhaust gas is released, which causes a pressure wave in the air causing an explosion. Since high pressure gases are released rapidly one after the other in an engine, the explosion occurring very fast combine together to form a steady noise. This noise consists of different notes of various frequencies. The predominant notes out of these have been found in two groups, viz., low frequency notes from 50 to 500 Hz and high frequency notes from 3,000 to 10,000 Hz. Thus any ideal silencer for absorbing this noise must effectively reduce both the low and high frequency notes. To reduce the noise, the engine exhaust is connected via exhaust pie to silencer, which is also called muffler. A tail pipe carries the exhaust gases from the muffler to the rear or side of the vehicle near the rear wheel. Mufflers used are of different types [6]. Muffler is engineered as an acoustic soundproofing device designed to reduce the loudness of the sound pressure created by the engine by way of acoustic quieting.

II. DESIGN AND OPTIMIZATION

- In here, *Fig. 1*, shows the integral structure of the catalytic converter and muffler which we fabricated. On the left side is the catalytic converter with the stainless steel wire mesh monolith structure on which catalysts will be doped.
- On the right hand side is the muffler, having honeycomb structure made from hollow pipes to provide laminar flow to flue gases and also have fins to give more air resistance to flow of flue gases.
- The Designing (Modeling) of the model has been carried out in PTC Creo 2.0 Parametric CAD Software developed by Parametric Technology Corporation, USA and Solidworks 2014 edition developed by Dassault Systèmes SolidWorks Corp.

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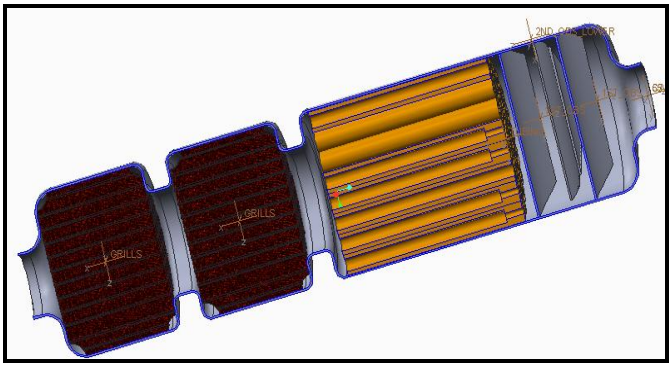
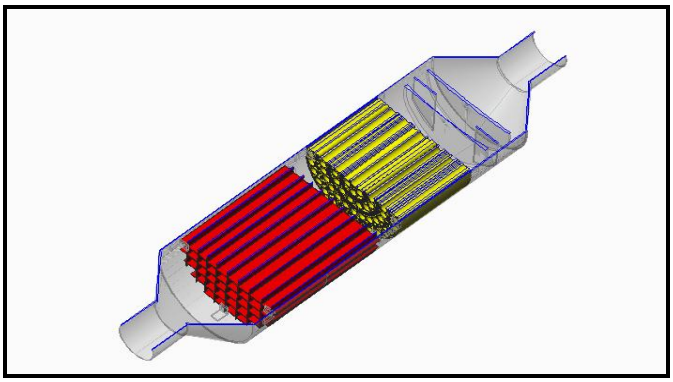


(A) Initial Design



(B) Final Design

Fig. 1: Design of Model

Brief Construction Details

Outer Casing:-

- The outer casing is in cylindrical shape and has diameter of 140 mm and is made of stainless steel sheet of 304 Grade having thickness of 1.5 mm.
- The cylinder is made of a stainless steel sheet of dimension 400*140 mm which is rolled into a cylinder by some industrial help.
- Once the cylinder is prepared as shown in *Fig. 2* both ends were welded to make a closed cylinder. *Fig. 3* shows the actual rolled cylinder with the help of sheet roller.

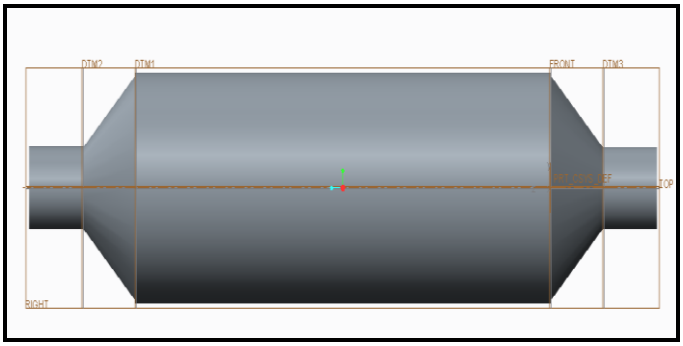
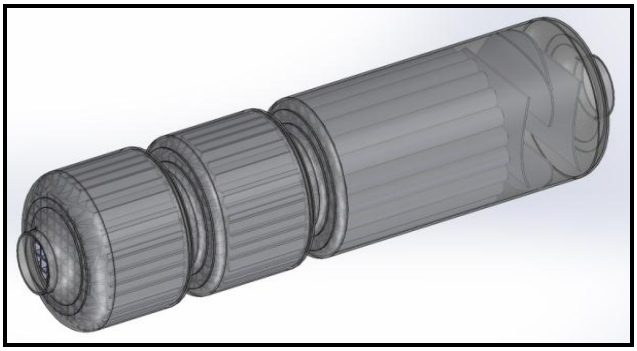


Fig. 2: CAD Model of Outer Casing

Fig. 3: Rolled Outer Casing

- Initially, as shown in *Fig. 4* there were 3 sections, 2 for catalytic converter and 1 for the muffler but while fabrication process only 2 sections were installed 1 for catalytic converter and 1 for muffler. In order to departmentalize them L clamps were welded and a single wire mesh was placed upon them so that catalytic converter and muffler can be differentiated.



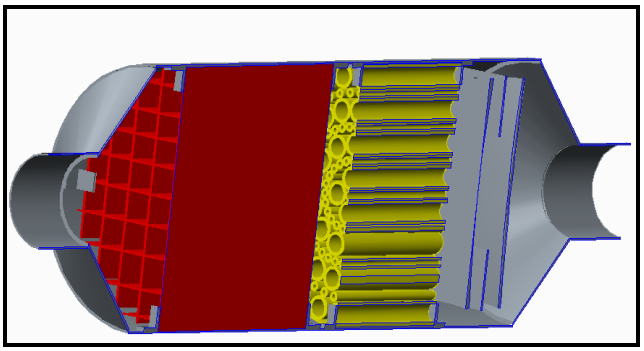


Fig. 4: Change In Design

Honeycomb Structure of Catalytic Converter:-

- Generally a honeycomb structure of ceramic material is used in the catalytic converters, which is prepared by casting process. Such structure helps in holding the material/chemical inside of it easily.
- In order to reduce the cost we have used S.S. Wire Meshes which can hold the material pasted upon it, very well. The S.S. Wire meshes which we have used are as shown in *Fig. 5.* A bunch of Wire Meshes was placed inside the catalytic converter in a group.

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- Wire Meshes served as dual function one for oxidation purpose and the second one for reduction purpose.

Fig. 5: Wire Meshes acting as Catalyst Substrate

Muffler:-

- Once the gases pass through the catalytic converter in the given design it will enter in the muffler.
- Now as shown in *Fig. 6* muffler also consists of two sections first one being tubular structure to create a laminar flow of the gases passing through it. Second being the obstructions to create the turbulent flow of gases.
- Such kind of design creates an optimum amount of back pressure which results in sound waves having shorter magnitudes, thus noise level is reduced.

➢ *Laminar Flow Tubes For Muffler:*

- Stainless Steel tubes having OD 5 mm and ID 2.5mm and 12.7 mm OD and 9.7 mm are placed parallel to each other for steady distribution of exhaust and forming a laminar flow. At the rear end, tubes have opening of 2.5 mm creates maximum backpressure and increasing the flow velocity at the outlet side. The length of the tubes is 100 mm.

➢ *Turbulence by Obstructions:*

- Exhaust coming from the tubular pipes collides with the primary curved section and pushes it away from the centre and the secondary curve towards the centre. This construction creates turbulence which decreases the sound energy of exhaust gases.

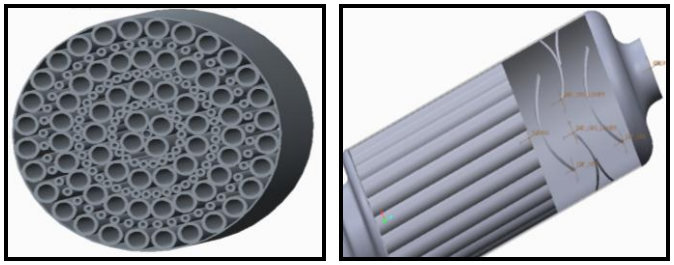

Fig. 6: Cross section Of Muffler

III. FABRICATION

Welding the outer casing:

Tungsten Inert Gas (TIG) welding is preferred for welding the Flat Stainless sheet which is rolled into circular shape with the help of sheet roller to form the circular shape of the Outer Casing, in which the wire mesh substrate of catalytic converter, hollow tubes made of stainless steel are stacked to form a honeycomb structure, and obstructions for increasing back pressure will be placed and welded to inner side of the casing.

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, is an arc welding process that uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by an inert shielding gas (argon or helium), and a filler metal is normally used, though some welds, known as autogenous welds, do not require it. A constant-current welding power supply produces electrical energy, which is conducted across the arc through a column of highly ionized gas and metal vapors known as a plasma. GTAW is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys [7].

In this research the base metal to weld is Stainless Steel 304 Grade Sheet metal of 1.5 mm thickness (Used to make, the outer Casing, L-Clamps to hold the wire Mesh Substrate, Obstructions), the filler material used is ER 304L as per AWS Numbering System, and the shielding gas used is a combination of C_2 or 2% Carbon Dioxide and 98% Argon. Argon/CO_2 mix is used as it gives smooth finish as compared to Argon/O_2 mix. The Electrode used is Thoriated tungsten, most common type of tungsten electrode for use on carbon and stainless steel. The Thoriated tungsten starts readily and maintains a stable arc. It has a greater resistance to contamination and will maintain a sharp point and will not break down as readily as pure tungsten [8]. All the figures, *Fig. 7* to *Fig. 10* below shows the TIG welding process carried out to make the prototype consisting of catalytic converter and muffler enclosed in a single casing.

Fig. 7: Rolled S.S Sheet, Edges Welded to form Outer Casing

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Fig. 8: Obstructions, (A) Obstructions Cut Outs (B) Welded Obstructions

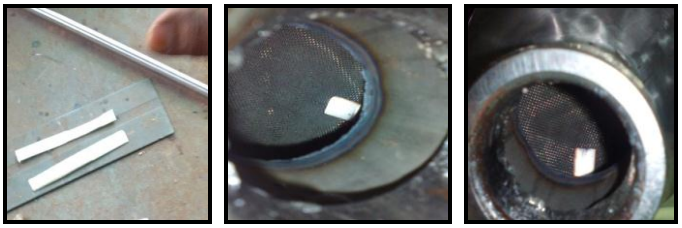

Fig. 9: L-Clamps, (A) Strips to make Clamps (B) & (C) Welded L-clamps to Support wire Mesh Substrate

Fig. 10: Welding, (A) Spot Welding done to form Tapping (B) Completely Spot Welded Prototype (C) Finished Prototype with Weight

Catalyst preparation And fabrication:

The experimental methodology consists of two different parts: 1) Catalyst and substrate preparation and fabrication of Catalytic converter, 2) Emission test. In this work only single type of configuration is chosen for the work *viz* Wire mesh substrate type. Method of preparation of above mentioned configuration is disused below.

- *Wire mesh substrate catalyst*

Material selection: Kaolin ($Al_2O_3 \cdot 2SiO_2$-Anhydrous) was used as metal oxide catalyst. Pure urea (CH_4N_2O or $CO(NH_2)_2$) was used as reducing agent. With above listed oxidizing metal oxide, urea was paired for the catalyst.

Catalyst slurry preparation: Sodium silicate (Na_2O_3Si) solution was used in wash coat material to increase the coating strength to surface of woven stainless steel substrate. And carbide methyl cellulose (CMC) was added as a pore former. 80.0 grams of sodium silicate solution was added into 20·0 gm. of metal oxide ($Al_2O_3 \cdot 2SiO_2$) to get 20% metal oxide slurry. The slurry then was stirred well. 8.0 grams of $CO(NH_2)_2$ and 10·0 gm. of carbide methyl cellulose (CMC) was gradually added. To ensure homogenization, it was milled for around 6·0 hours by using ball mill. *Fig. 11(A)* shows the prepared catalyst slurry. The slurry reactor preparation was carried out in accordance with Nijhuis et al. [9], and compared with preparations for monolithic reactors described by Avila et al. [10] and Haber [11]

Material selection for substrate: The substrate material is stainless steel, as it is widely used in the automotive exhaust system not only due to its advantages in mechanical and physical properties but also low-cost [12]. The stainless steel wire mesh of 20*20 size is selected for the economic purpose was cut to Circular shape of Diameter 14 cm. prior to catalyst coating. *Fig. 11(B)* shows the wire mesh substrates.

Wash coat material: Metal oxide (Kaolin), served dual functions: an oxidation reduction catalyst and for the wash coat. Kaolin has higher thermal stability and high durability. This property is suitable for catalyst embedment or catalyst [13].

Substrate coating: The stainless steel wire mesh will then coated with the metal catalyst via dipping technique. *Fig. 11(C)* shows coated wire meshes that are to be calcinated. In this process stainless steel wire mesh was immersed into prepared catalyst slurry for duration of 5 minutes. Then the coated wire mesh was removed from catalyst slurry to be blown using air blower. Until the unwanted residual catalyst was evaded from the surface of the stainless steel wire mesh. After blow process, coated stainless steel wire mesh was dried in sunlight for two days before being calcinated in an open air furnace [14].

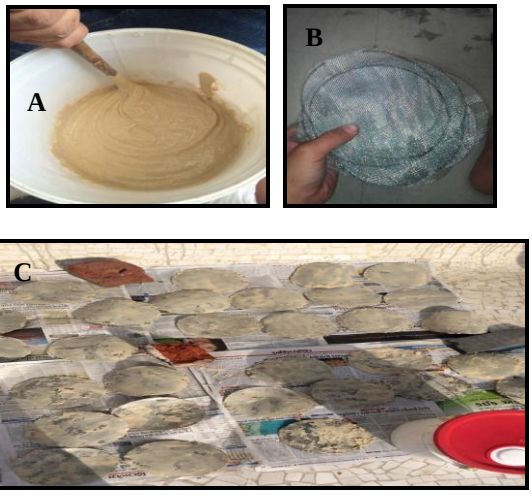

Fig. 11: Wire mesh substrate catalyst, (A) Slurry Preparation (B) Wire mesh Substrate (C) Slurry coated wire meshes

Calcination is a process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled [15]. Calcinations take 6·0 hours at a temperature of 550˚C with temperature ramping upon 10·0˚C/min and holding time of a 300 minutes [16]. *Fig. 12* shows the Calcination

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process carried out of wire mesh catalyst substrate. After the Calcination process the stainless steel wire mesh were arranged into straight bar to become a substrate for using as a catalytic convert.

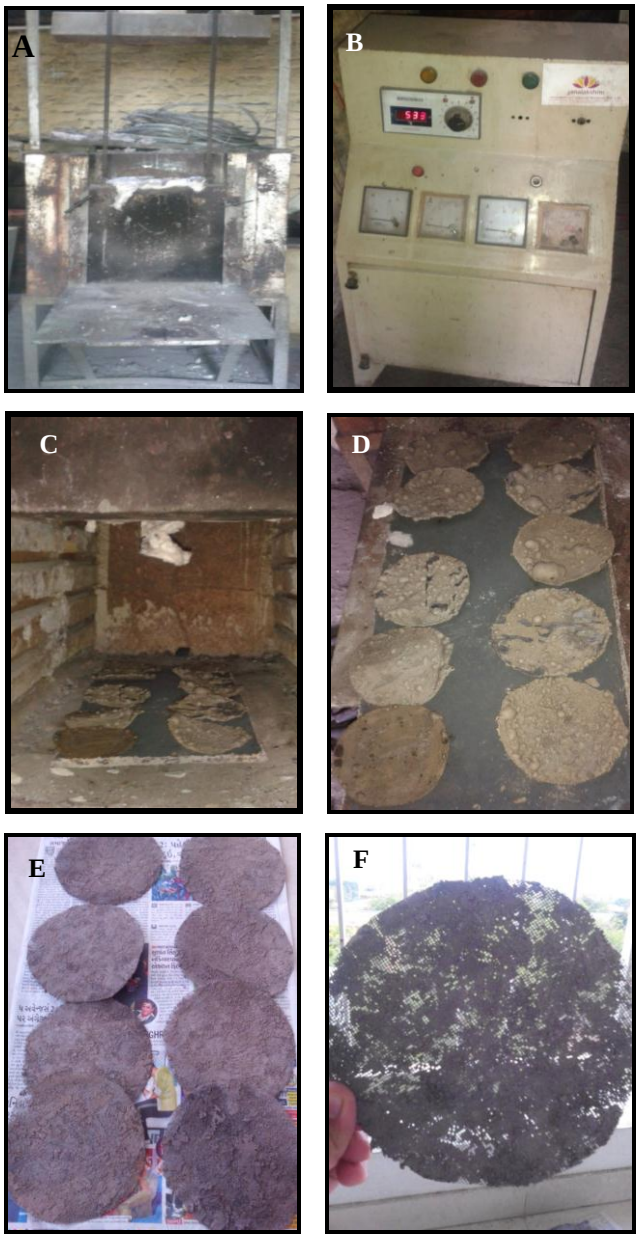

Fig. 12: Calcination Process, (A) Induction Heating Furnace For Calcination (B) Control Panel of Furnace (C) Wire Meshes being Calcinated (D) Calcinated Wire Meshes (E) & (F) Wire Meshes after Removing excess Catalytic Powder

➢ *Catalytic converter fabrication*

Catalytic converter chamber: The fabrication catalytic converter consist of few components, namely the converter chamber, substrate. To avoid thermal optimization and design validation, converter was made from Stainless Steel 304 Grade Sheet Metal. The Catalytic Converter chamber was made by rolling the S.S sheet and joining the edges by wielding. The S.S wire mesh were placed inside the chamber and from both the sides of Chamber L- Clamps were welded so as to support the wire mesh substrate. Tapping's at both the sides of chamber were provided. One tapping was provided at the inlet of the chamber so as to couple the chamber with the exhaust manifold of the engine were as the Other tapping at the outlet of chamber was made for the inserting the probe of the gas analyzer. Coupler is provided at the inlet of the chamber, and is glued with industrial Adhesive to inlet. This is shown in *Fig. 13.*

Fig. 13: Tapping's, (A) Inlet Tapping (B) Coupler glued at Inlet & L- clamp to support wire Meshes (C) Exhaust Tapping

Substrate: The stainless steel wire mesh pieces were then coated with metal catalyst before arranged into a straight bar. The length of stainless steel wire mesh arrangement was around 15·0 cm. A total of 50 pieces were used in an arrangement for 15·0 cm length. The stainless steel wire mesh substrate configuration is shown as in *Fig 14.*

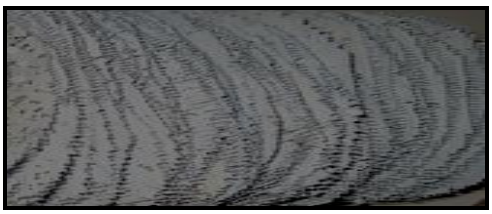

Fig. 14: Stainless Steel Wire Mesh Substrate

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Costing:

Table 1 Cost/Price of Materials used in Research

Item	Specifications		Rate (Rs/-)		Amount (Rs/-)
Stainless Steel Hollow Tubes (SS 304 & 202 Grade)	5 mm OD, 2.5 mm ID 40 Ft. Length	12.7 mm OD, 9.5 mm ID, 16.7 Ft. Length	35Rs/Ft.	30Rs/Ft.	1400+502 = 1902/-
S.S Sheet + S.S Tube (SS 304 Grade)	1.5mm thickness (Weight -4.4Kg), 2" Tube Diameter		260Rs/Kg		1144+300 = 1444/-
S.S Wire Mesh	20*20 MeshSize (20 Foot Length)		50Rs./ft		1000/-
Carboxy Methyl Cellulose (CMC)	-		250Rs./500g		250/-
Urea	-		200Rs/500gm		Free
Kaolin	Anhydrous		40Rs/400g		40/-
Sodium Silicate Gel	-		30Rs/kg		Free
Araldite Klear Epoxy	Industrial Adhesive		45Rs/10g		45/-
Fabrication Cost	Sheet Rolling, Pipe Cutting, Grinding, TIG Welding		-		200+290+200+420 = 1110/-
Labour Cost	-		-		200/-
Induction Heating	Calcination Process		175Rs/Hour		Free
Total					5991/-

IV. TESTING

The testing of the catalytic converter was done on Briggs and Stratton engine used for BAJA Vehicles. It's a 305cc, 10 HP, OHV, 4 stroke, single cylinder, air cooled engine and runs on petrol, shown in *Fig. 15(A).* Its petrol tank capacity is 2.5 liters. The experimental setup is shown in the *Fig. 15(B)* below. As shown in *Fig. 15(B),* catalytic converter was attached at the exhaust outlet of the engine through the coupler so as to prevent the leakage of the exhaust gases. At the outlet of muffler, probe was inserted to detect the exhaust gases and readings were taken, as seen in *Fig. 15(D),(F),(G).* The testing for the emissions emitted from the engine is done its idling condition. The engine is cranked and with the help of tachometer the RPM in the idling condition is measured i.e. 1900 rpm in no load condition, as seen in *Fig. 15(C).* The testing has be done in two ways: 1) Without attaching the catalytic converter, *Fig. 15* and 2) With attaching catalytic converter to the exhaust outlet of the engine, *Fig. 16*. The testing has been done in the college lab and as well as at a certified PUC Center.

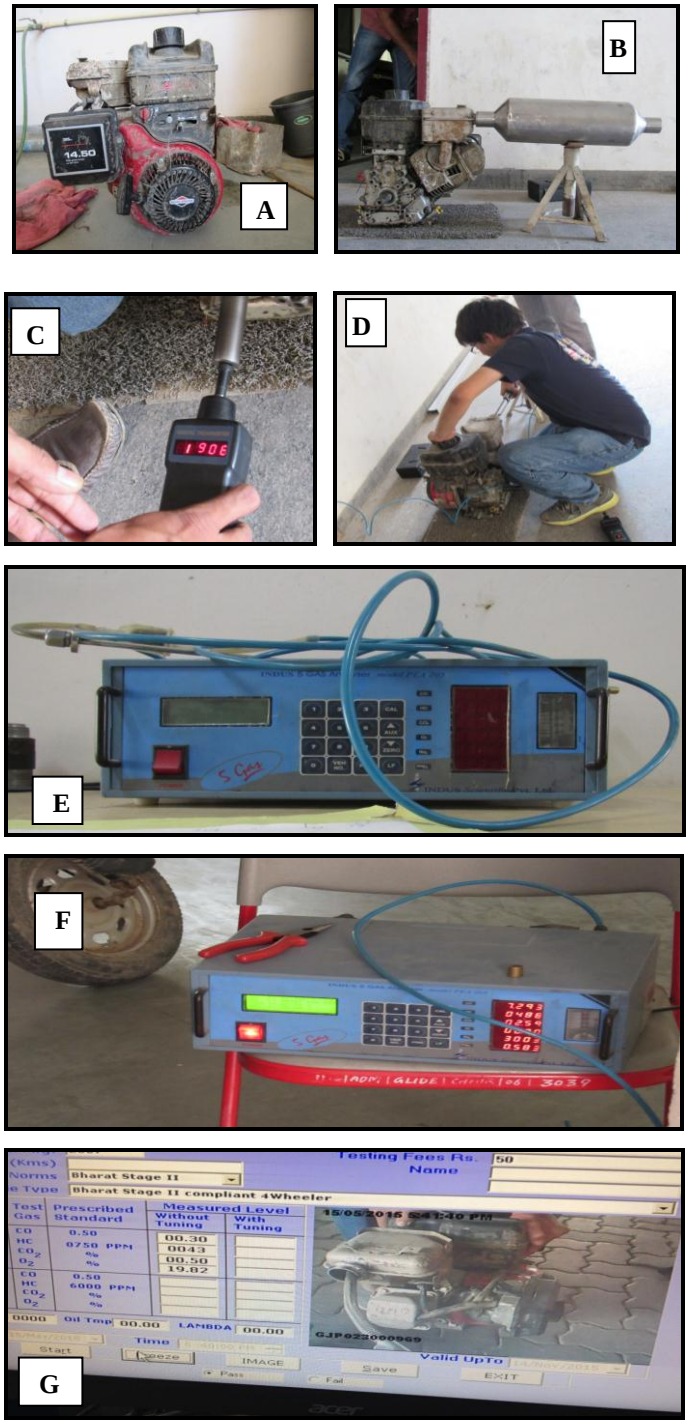

Fig. 15: Testing without Attaching Catalytic converter, (A) Test Engine (B) Experimental Setup (C) Idling RPM measurement (D) Inserting probe in the exhaust outlet of engine (E) Exhaust Gas Analyzer Machine (F) Reading Of Exhaust Gases without attaching Catalytic converter (G) Readings without attaching Catalytic converter at PUC Center

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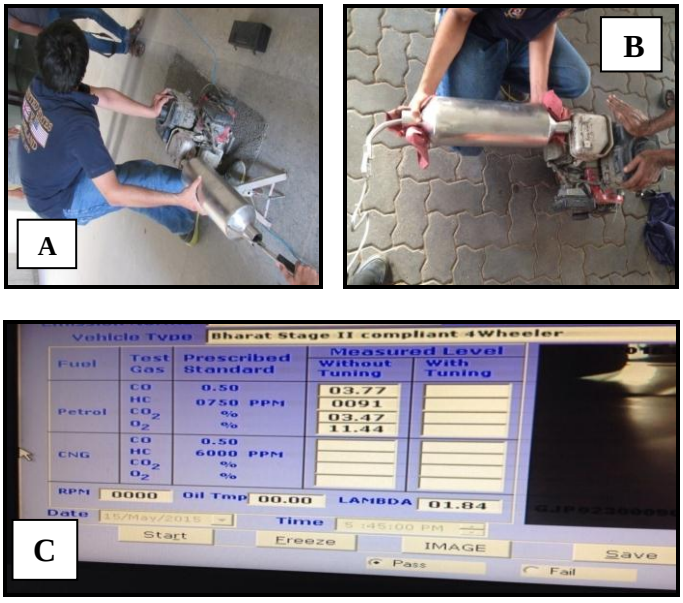

Fig. 16: Testing with Attaching Catalytic converter, (A) Probe inserted in Muffler outlet in college lab (B) Probe inserted in muffler outlet at PUC Center (C) Readings after attaching catalytic converter at PUC Center.

Since the oxygen sensor of exhaust gas analyzer failed in the college lab, the readings after attaching the catalytic converter couldn't be obtained. Seeing the results obtained after attaching the catalytic converter at PUC Center, inferences were made that the chemical combination of metal oxide (Kaolin) and Urea, failed in reducing the exhaust gases emissions, and very steep rise was found in the values of HC, CO and CO_2 emissions, whereas decrease in the value of O_2 emissions. Hence it can be deduced that the combination of Kaolin and Urea fails in reducing the emissions of the engine.

V. RESULT

Based on the present experimental study, use of metal oxides as catalyst in the catalytic converter for gasoline fuelled engine were investigated as shown in Table 1 and following conclusion were drawn:

Table 2 Experiment test result

As Per Bharat Stage 2 Complaint 4 Wheeler				
Test Gas	Unit	Prescribed Standard	Without Converter	With Converter
CO	% Vol.	0.5	0.3	3.77
HC	PPM	750	43	91
CO_2	% Vol.	NA	0.5	3.47
O_2	% Vol.	NA	19.82	11.44

- Steep increase in CO emission volume by 3.47%, HC PPM increase by 48 PPM and CO_2 emissions by 2.97% and reduction in O_2 volume by 8.38% were observed at ideal working temperature with the fabricated Catalytic converter, Hence it can be deduced that above chemical combination of metal oxide (Kaolin/Urea) used in this research was a failure.
- Engine Noise Reduction by 25-30 db.

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