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EXPERIMENTAL INVESTIGATION ON LOW TEMPERATURE GLOW PLASMA BASED EXHAUST SEPARATION AND PURIFICATION FOR STATIC AND DYNAMIC APPLICATIONS OF INTERNAL COMBUSTION ENGINE

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ABSTRACT

Continuous increase in air pollution has become one of the major challenges to balance the earth's biosphere. Exhaust emissions from automobile contributes significantly to air pollution, thus there is a need to control the pollutants of these emissions. To solve this problem, Low temperature glow plasma setup is installed in the filtration of exhaust gas of CI diesel engine and car for separating and removing hydrocarbons (HC) and nitrogen oxide (NOx) molecules. The system consists of diesel particulate filter mounted with sets of plasma reactor to generate low temperature glow plasma and activated carbon molecules on the sides of the reactor to absorb soot and hydrocarbons. Thus at the end of he gas purification process, the harmful polluting gases such as NOx, soot and carbon monoxide (CO) have been efficiently cleaned.

KEY WORDS: Exhaust Emission, Low temperature glow plasma reactor, Gas purification.

INTRODUCTION

Basic fundamental studies have reported that the gases such as carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC) etc. with particulates which are emitted by combustion of fuels in internal combustion engines are the main cause of increase in global warming (Environmental and social impact assessment guidelines, 2005). Emission standards for light-duty diesel vehicles (GVW ≤ 3,500 kg) are summarized in Table 1. Ranges of emission limits refer to different classes (by reference mass) of light commercial gen set/ vehicles. The lowest limit in each range applies to passenger cars/ Gen set (GVW ≤ 2,500 kg). Hence use of CI engines or diesel engines is safer from environmental protection point of view. Besides, diesel engine has higher thermal efficiency.

NO_x has harmful effects on both human beings and ecosystem. NO_x has consequential impact on human respiratory system resulting in inflammation of the airways and also affects the functions of lungs. On the other hand it causes leaf damage and reduces growth in vegetation. NO_x is also responsible for occurrence of photochemical smog, acid rain and ozone (O_3) which can damage vegetation severely.

Over and above, soot and various hydrocarbons that are emitted from diesel engine are dangerous for environment. Soot combines with various other pollutants and form acid rain which results in poor water quality, crops and soil damage. Besides, inhaling these particulates causes coronary heart diseases, asthma, bronchitis and many other respiratory problems.

For maintaining emission standards for light duty diesel vehicles in the reference norms euro 4, various modification implies in engine and exhaust section of the vehicles, i.e. advanced fuel injection system, combustion chamber modification, charge shaping and increase of air motion in engine. Catalytic converter and hybrid metal matrix composites filter introduced in exhaust system in order to maintain euro 4 standards. Apart from these modifications various studies and experiments have been performed for the filtration of exhaust gases emitted

Table 1. Emission standards for light-Duty Diesel Vehicles, g/Km

Year	Reference	CO	HC	HC+NOx	NOx	PM
1992	-	17.3-32.6	2.7-3.7	-	-	-
1996	-	5.0-9.0	-	2.0-4.0	-	-
2000	Euro 1	2.72-6.90	-	0.97-1.70	0.14-0.25	-
2005	Euro 2	1.0-1.5	-	0.7-1.2	0.08-0.17	-
2010	Euro 3	0.640.800.95	-	0.560.720.86	0.500.650.78	0.050.070.10
2015	Euro 4	0.500.630.74	-	0.300.390.46	0.250.330.39	0.0250.040.06

from diesel engine. Yamamoto T. *et al.*, 2003; performed the experiment for conversion of NO to NO_2 without reducing NO_X concentration with ac packed –bed reactor and pellet less pulsed corona reactor in exhaust gas of diesel engine. Which shows minimum reaction products for given power of 26 KeV, when NO concentration was low (~100 ppm). In this experiment it was found that when loaded condition of engine exceeds 50% (NO>300PPM) there was not much decrease in NO concentration and more or less the reactor performed equally. M. Okubo *et al.*, (2004), demonstrated an experiment set-up in which pulse barrier discharge is used to produce non-thermal plasma for incineration of diesel particulate, as results by injecting activated oxygen species into the exhaust pipe in oxidation of No to NO_2. Takaki *et al.*, (2007), demonstrated the influence of streamer to glow transition on NO removal from a simulated diesel exhaust gas in non-thermal plasma reactor through pulsed power generator supplies at 30kV pulse with rate 300 pps repetition and efficiency for NO removal obtain at 25g/kWh with 30% of elimination rate of energy efficient. T. Kuwahara *et al.*, (2013), performed a pilot scale experiment for emission control of marine diesel engine by the use of non-thermal plasma reduction and ozone injection with efficiencies on NOX removal of 143g NO_2/kWh. Balachandran *et al.* (2014), studied the effects of temperature on performance of emission control by non-thermal plasma and 2.45 GHz microwave system for 200 kW marine diesel engines, after simulation of non-thermal plasma kinetics in below 3.2 eV show complete removal of NO_X and SO_2 is possible. Dam *et al.*, (2016), demonstrated the experimental setup to control the emissions from diesel engine using cold plasma on applied current and treatment get reduction rate on CO 96% vol, CO2 95% vol, NOX 93% PPM and CXHY 58% respectively.Other methods such as physically separating the soot particles from exhaust gases by passing it through a filter have also been developed.

It is evident from the brief review that many efforts have already been made in the past to control the emissions from exhaust gases of CI engines. But in these methods gases like CO, NO_x and hydrocarbons are not easily filtered. Besides, these methods were less efficient, costly and have complex operation mechanisms. In the present experimental set-up, low temperature glow plasma is used in a simple design operation to purify the exhaust gases efficiently. By the use of this method NO molecules present in the exhaust gases gets oxidizes to NO_2 molecules and is filtered later. Further, the remaining soot and hydrocarbon compounds present in the exhaust gases get adsorbed in the activated carbon molecules present inside the particulate separate unit.

METHODOLOGY

The mechanism of DC plasma formation in field is the ionization of gas atoms, after negative element having gained sufficient energy between collisions to come over ionization threshold. This process requires a pre electron generation, which could be produced by either a field emission structure or a heated filament

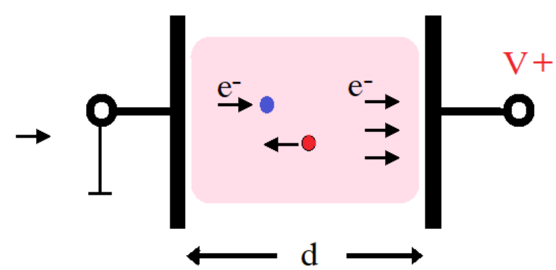

Fig. 1. DC discharge by ionizing collisions

The discharge formation depends upon the multiplication of the initially generated electrons. Town send coefficient α, denotes the relevant excess of electron flux per unit follow length,

$$dj_e = \alpha\, j_e dx \qquad .. (1)$$

α can also be interpreted as the number of ionization eventsof electron per unit length and j_e is electron flux. Under action of the electric field, the electrons are accelerated between the collisions, as shown Figure 1. This results in Maxwellian shift by the directed kinetic energy E_e

Accordingly,

$$\alpha = \frac{1}{\lambda c} exp(-\frac{Vi}{Ee}) \quad .. (2)$$

With λc denoting the mean free path length for gas-kinetic collisions and Vi denoteionization potential

The energy gain of the electrons along the mean free path length is given by the electric field E

$$E_e = \lambda_c eE \quad .. (3)$$

Then, with $\lambda c \approx$ p-1 where p is the gas pressure, with constants A and B

$$\alpha = Ap\, exp(-B\frac{pd}{V}) \quad .. (4)$$

Where, the electric field has been replaced by the applied V (voltage) and the d (distance) between two electrodes.

Without a continuous generation of primary electrons, the electron avalanche will stop after reaching the anode of the discharge. Such a discharge is called un-sustained. Examples are corona discharges for paper charging in copy machines or for exhaust cleaning in power-plants or for chemical reactors.

Using the above method, a low temperature glow plasma reactor is designed and various experiments have been performed.

Figure 2(a) and Figure 2(b) show the complete assembly of the exhaust gas filtration system starting from exhaust gases of diesel engine containing contaminants and particulate matter entering at exhaust manifold and clean gases rejected out to atmosphere. This process follows the following steps.

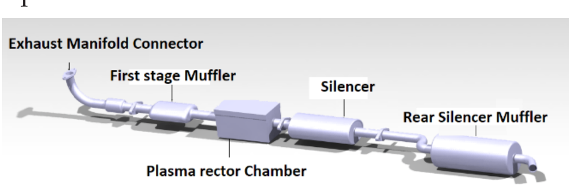

Fig. 2 (a). Design of exhaust gas filtration setup

First of all the exhaust gases from engine containing pollutants gets into the exhaust manifold connector. Then these gases get in to the first stage muffler which helps to expand the gas volume and

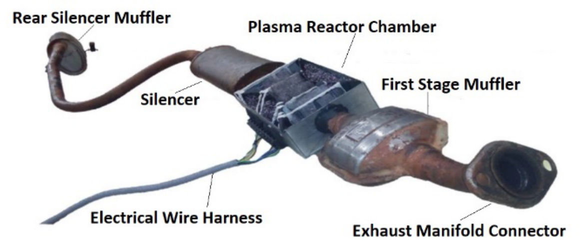

Fig. 2 (b). EAPS (Exhaust air purification system) setup

thereby decreases the pressure, then these gases directly pass through low thermal glow plasma reactor chamber. In this chamber the nitrogen oxides present in the exhaust gases are oxidized in the presence of low thermal glow plasma and results in formation of NO_2 molecules (reaction 5). Further, this nitrogen dioxide reacts with soot present in the gas to form carbon monoxides (CO), carbon dioxides (CO_2), nitrogen monoxide (NO) and nitrogen gas (N_2) (reaction 6). Nitrogen dioxide also reacts with hydrocarbons to form Nitrogen gas (N_2), carbon dioxide (CO_2) and water (H_2O) molecules (reaction 7). The remaining soot and hydrocarbon present in the exhaust gas gets adsorbed by the activated carbon present on sides of the plasma reactor.

Following reaction takes place inside the plasma reactor chamber-

$$NO + \tfrac{1}{2}O_2 \rightarrow NO_2 \quad .. (5)$$

$$C(soot) + NO_2 \rightarrow CO + NO \text{ or } CO_2 + \tfrac{1}{2}N_2 \quad .. (6)$$

$$NO_2 + \text{Hydrocarbon} \rightarrow N_2 + CO_2 + H_2O \quad .. (7)$$

Now the gases have been cleaned and these gases will pass through silencer, the main function of this silencer is to minimize the pressure and noise intensity developed by engine gases and plasma reactor chamber. Then these gases will pass throughthe rear silencer muffler and will exit the system leniently. Thus at the end of these process the harmful polluting gases are cleaned efficiently under normal pressure condition.

The plasma chamber (Figure 3) is made from galvanized iron sheet. Exhaust gases get in to the plasma chamber from intake port. The V-shaped plasma reactor coil plates, where low temperature glow plasma is generated, are placed in such a way that the vertex is pointed towards the gas intake side and the open end is towards the exhaust gas outlet. The coil plates are made up of aluminum and iron plate with diamond pattern net. The plasma coil plates have been separated with thick layers of porcelain which acts as insulator. The activated carbon and steel mesh is placed at sides of plasma reactor plates whose function is to absorb remaining soot and hydro compounds, besides it also prevents the deposition of particulate matters over meshed coils of plasma reactor plates.

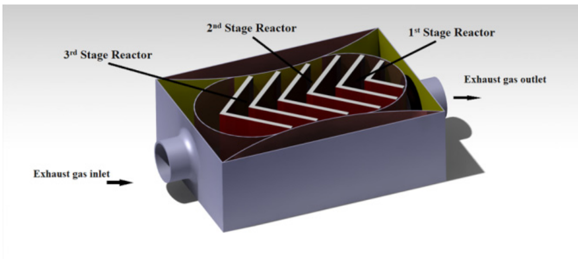

Fig. 3. Assembled view of low thermal glow plasma reactor chamber

DESCRIPTION OF EXPERIMENTAL SET UP

Figure 4 shows the experimental setup layout. A single cylinder four stroke diesel engine with water cooled system is used for the experiment. Engine foundation bed consists of electrical eddy current dynamometer with orifice in conjoint with U shaped tube manometer. Actual experimental setup is shown in Figure 5 and detailed specification is described in Table 2. The consumption rate of fuel with measuring tube and Engine emission analysis is carried out with NETEL-24 exhaust gas analyzer and AVL437 smoke meter tester sensor.

The basic setup parameters as shown in the above

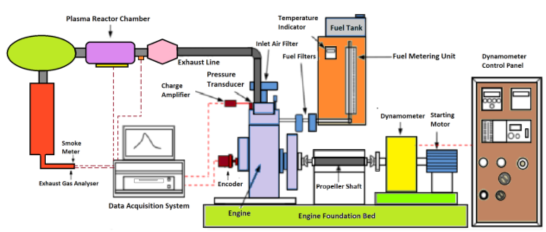

Fig. 4. Experimental setup Layout diagram

Fig. 5. Static Experimental setup

Table 2. Engine Specification

Make	Kirloskar oil engines
Model Number	TV1
Engine type	Single cylinder 4S diesel engine
Bore	86.50mm
Stroke length	115mm
Compression Ratio	16:1
Displacement	661.5 cm^3
Fuel Injection Pressure	240 bars
BHP	3.50Kw at 1500RPM
Rated speed	1500 RPM
Dynamometer	Eddy current dynamometer

Table 2 were put into the computer program for the configuration. Electric supply was given to the battery charger. The diesel engine connected to eddy current dynamometer was set into computerized mode.

In order to study the performance of Exhaust air purification system in dynamic condition, Exhaust air purification system is installed in a test vehicle. Test vehicle description shown in Table 3.

Table 3. Test Vehicle Specification

Make	Tata
Model Number	Indica V2 Dle
Engine type	Four cylinder diesel engine
Valves	4 Nos.
Camshaft	Single overhead camshaft (SOHC)
Compression Ratio	22:1
Fuel Injection	Direct injection
Maximum Power	48.2 bhp @ 5000 rpm
Maximum Torque	85 Nm @ 2500 rpm

The experimental setup of low thermal glow plasma reactor shown in figure 2 (b) was installed in experimental car. Test performedfor emission of soot and HSU (Hartridge Smoke Unit) in order to checkemission standard prescribe under Rule 115(2) of central motor vehicle Rules 1989.

RESULTS AND OBSERVATION

Diesel exhaust emissions naturally occurring from the experimental engine present various components into air in the following proportions (approximate volume %): $N_2$70-74, $O_2$5-17, CO_2 2-12 and H_2O 2-10. Regulated harmful components present are CO 100-10000PPM, HC50-500PPM, NO_X 30-600 PPM, SO_X is proportional to fuel Sulphur content and PM is 20-200 mg/m^3. Un-regulated harmful components present, in mg/km, are:

ammonia25, Cyanides 0.625, Benzene 3.75, Toluene 1.25 and Aldehydes 0.0. This analysis of actual emission rate for static condition with specific loads are compared with those analyses obtained from the operation of the experimental engine designed with low temperature glow plasma attachments of three power ranges of 50KeV, sum of 100KeV, and sum of 150KeV.

Emission Characteristics

Figure 6 shows volume percentage of oxygen emitted during operation of the static engine system with and without the thermal glow plasma reactors attachment. In each case the loadvariation was from 0 to 8Kg. These results help us to identify the variation in emissions. The first observation is that oxygen emission decreases with increase in load in 50KeV, 100KeV and 150KeV cases which justified the reaction of emission exhaust with Oxygen shown in equation number (5). With incorporation of low thermal glow plasma reactor of 50KeV power it is observed that the emission level is lower in comparison to the emissions occurred from the static engine without the plasma reactor attachment. At no load condition, the emissions were 17.48 and 14.9 Vol% for the engines without and with plasma reactor attachment, respectively, which changed to 9.046 and 5.47 Vol%, at a load of 8 Kg. Further decrease in oxygen emission levels were observed when a low thermal glow plasma reactor of 100KeV power was attached; the resultant oxygen emissions were 15.2 and 11.2Vol%, respectively, at no load condition and at a load of 8 Kg. An attachment of a plasma reactor of 150KeV power brought the oxygen level further down to and 6.8Vol% at zero load and full load, respectively. These variations indicate that some inter-gas reactions occur inside the reactor.

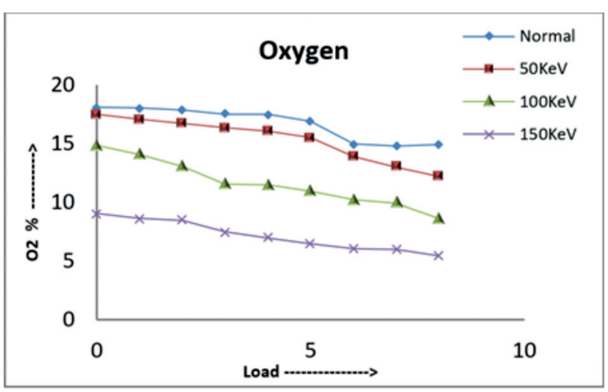

Fig. 6. Change of Oxygen percentage emission with engine load

Figure 7 presents volume percentage of HC in the emitted gas from the engine with and without plasma reactor attachment at various loads. The results show a trend of variation of volume percent of HC similar to that of oxygen, i.e., and the volume percent of HC decreases with increase in load in all the cases; and it also decreases with attachment of plasma reactor and its power. Without plasma reactor attachment HC emission is 70 ppm at 0 load which decreases to 20 ppm at full load of 8 Kg. When a plasma reactor of 50KeV is attached to the engine, hydrocarbon emission started around 53.2 PPM at 0 load and decreased to around 19.4 ppm at full load Similar pattern is observed with attachments of plasma reactors of 100 and 150KeV, HC content at full load was 9.12 ppm in case of the former and 12.32 ppm in case of the later. Higher value of oxygen results in formation of less HC.

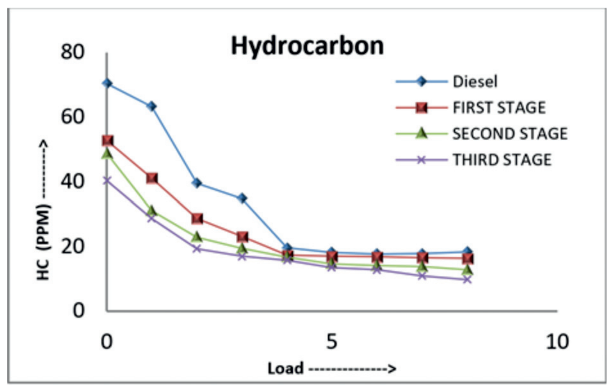

Fig. 7. Change of Hydrocarbon (PPM) emission with engine load

Atmospheric air contains larger oxygen amount, so they emit less hydrocarbon. Lower level of HC in the emission from the engine with plasma reactor means purification capacity of the reactor is better which increases with increase of its power.

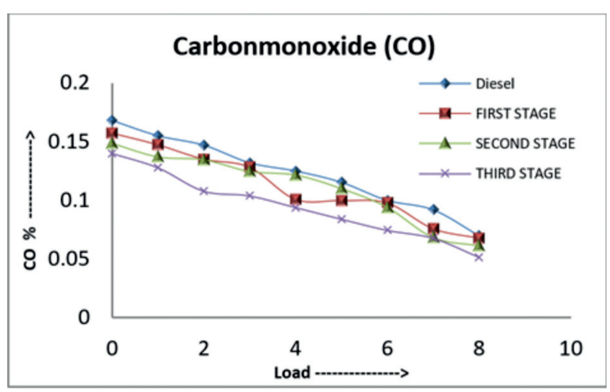

Fig. 8. Change of Carbon monoxide percentage emission with engine load

The CO emission variation for different conditions of filtration in reactor chamber is indicated in Figure 8. It is observed that, in all the cases the percentage of CO decreases with increase in load as well as the power of the plasma reactor attachment.

Figure 9 shows the CO_2 emission pattern during operation of the engine with and without the plasma reactor attachment. Not with standing some

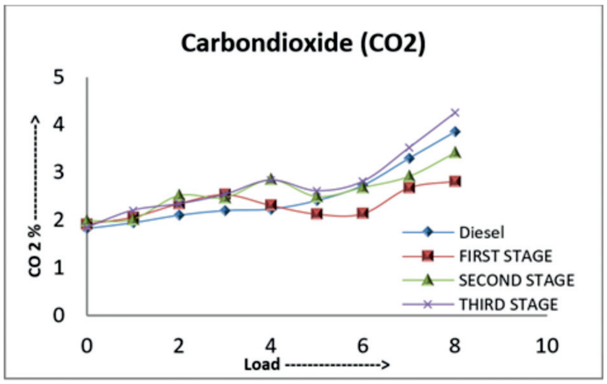

Fig. 9. Change of Carbon dioxide percentage emission with engine load

discrepancies, a trend of increase in CO_2 emission with plasma reactor attachments as well as its power is observed. Since the gas mixture contains CO and O_2, under favorable thermodynamic and kinetic conditions prevailing inside the plasma reactor, they react to form CO_2 resulting in a rise in CO_2 and fall in CO and O_2 in the emission.

Emissions of NO_x are recorded at different loads with and without the attachment of low thermal glow plasma reactor. Attachment of a reactor of 50KeV power, NO_x reduced about 40% volumetrically, which went down by 65 Vol% with an attachment of a reactor of 100KeV power. Attachment of a reactor of 150KeV power shows almost a constant NOx emission at a rate of 52 PPMas shown in Figure 10. Thus this reactor

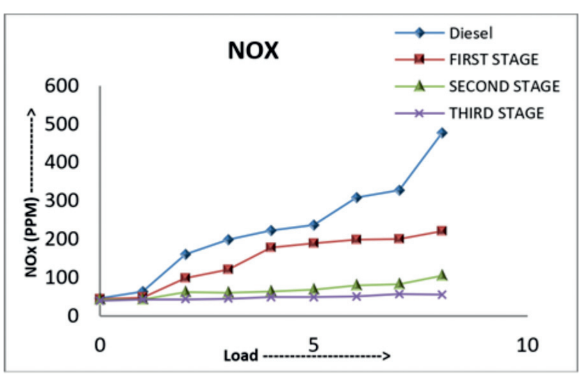

Fig. 10. Change of NO_X (PPM) emission with engine load

eliminates NOx emission almost completely through chemical reactions (5) – (7).

Figure 11 shows the exhaust emission in terms of Hsu gas particle with different RPM of car engine without low thermal glow plasma reactor on

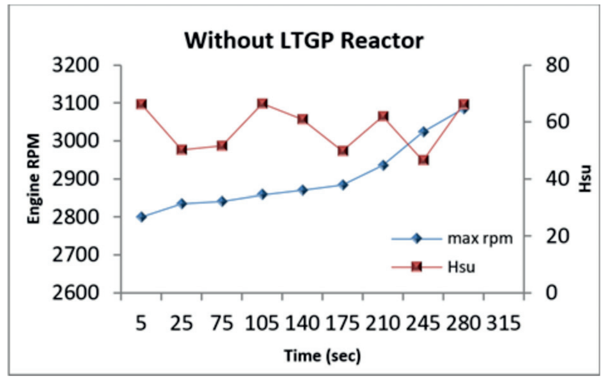

Fig. 11. Effect of Hartridge Smoke Unit with respect to engine RPM without Reactor Off in position

deactivate state. The average 58.2PPM Hsu is recorded during the experiment.

Figure 12 shows the exhaust emission in terms of Hsu gas particle with different RPM of car engine with 1st stage low thermal glow plasma reactor at 50KeV on active state. The average 50.8PPM Hsu is recorded during the experiment.

Figure 13 shows the exhaust emission in terms of Hsu gas particle with different RPM of car engine with 1st stage and 2nd stage of low thermal glow

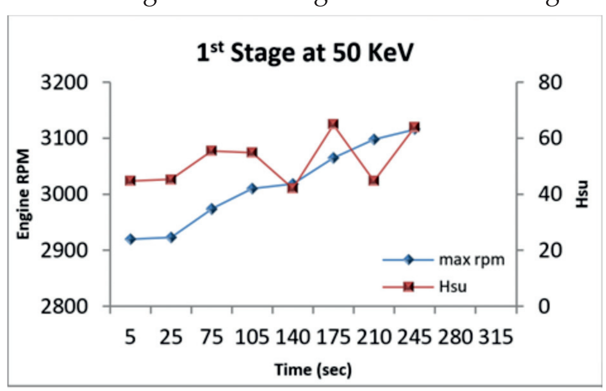

Fig. 12. Effect of Hartridge Smoke Unit with respect to engine RPM without Reactor at 50 KeV

plasma reactor at 100KeV on active state. The average 48.9 PPM Hsu is recorded during the experiment.

Above Figure 14, show the exhaust emission in terms of Hsu gas particle with different RPM of car engine with 1st stage, 2nd stage and 3rd stage of low thermal glow plasma reactor at 150KeV on active state. The average 47.12 PPM Hsu is recorded

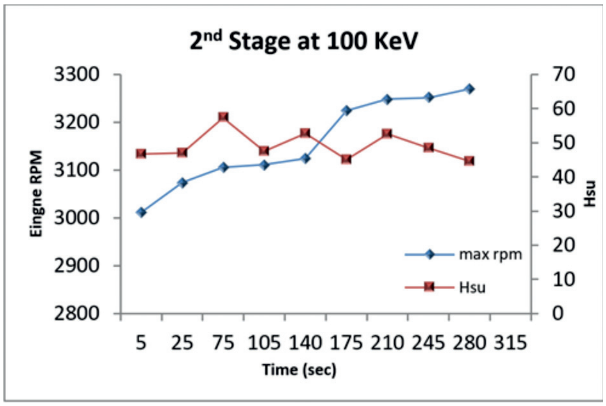

Fig. 13. Effect of Hartridge Smoke Unit with respect to engine RPM without Reactor at 100 KeV

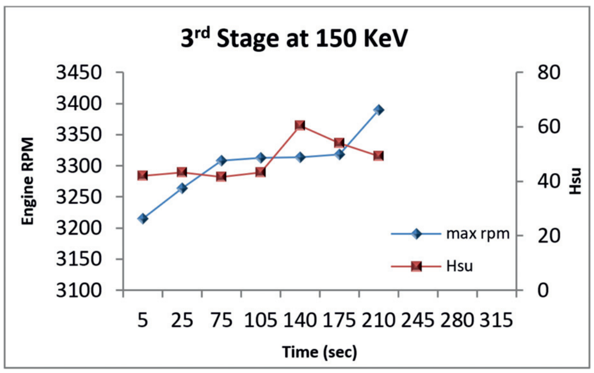

Fig. 14. Effect of Hartridge Smoke Unit with respect to engine RPM without Reactor at 150 KeV

during experimental.

CONCLUSION

Present experimental investigation shows the stability of gases reaction that take place inside low thermal glow plasma reactor for the diesel engine exhaust gas filtration and replacement of catalyst converter in conventional exhaust system. Hence we found that single stage 50KeV activation of reactor is not enough for separation of harmful exhaust gas i.e. NOX and CO emission. On 2nd stage and 3rd stage i.e. 100-150KeV activation of reactor, satisfying reduction in emission of harmful gases of diesel exhaust are obtained.

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