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# An experimental study on the effect of EGR on performance and emission on four stroke SI engine with various catalytic coatings

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ABSTRACT

In this study effect of exhaust gas recirculation (EGR) on performance, emission and combustion of a single cylinder, four stroke spark ignition are investigated. EGR is one of the most effective means of reducing NOx emissions from IC engines and is widely used in order to meet the emission standards. In the present work, experimental investigation has been carried out to study the performance, emission and combustion characteristics by exhaust gas recirculation in a SI engine using various catalytic coatings and different EGR flow rate. Experimental results show that $NO_x$ emissions were reduced when the engine was operated with cooled EGR. The maximum $NO_x$ reduction for copper coated engine with 10% EGR is about 45 % lower than standard engine. The other catalytic coatings like chromium and nickel shown the NOx reduction of 7 % and 4 % lower than standard engine.



## Introduction

Due to the world-wide air pollution and strict upcoming emission regulations, a new concept of combustion technology that can improve the emission characteristics is registered. Technologically advanced countries are exerting efforts to develop environmentally friendly engines for vehicles through improvement of combustion [1]. In exhaust gas recirculation two methods are available. One is replacement EGR and other one is additional EGR [2]. The first method implies that some of the air entering the engine is replaced by exhaust gases. This means that the air/fuel ratio and the exhaust flow leaving the engine are both reduced. The second method denotes that exhaust gases are added to the air mass flow entering the engine. By this procedure the air/fuel ratio and the exhaust mass flow are kept constant [3]. Normally replacement EGR is used in CI engine and additional EGR is used in SI engine. Both methods could be utilized with cooled or hot exhaust gases. Thus cooling the EGR can be seen as an alternative to additional EGR.

The application of EGR will reduce the NOx formation by three effects, namely dilution effect, thermal effect and chemical effect [4]. Out of these dilution plays a major role in NOx reduction. EGR reduces NOx because it dilutes the intake charge and lowers the combustion temperature (Ladommatos et al 1997). A practical problem in fully exploiting EGR is that, at very high levels, EGR suppresses the flame speed sufficiently that combustion becomes incomplete and unacceptable levels of particulate matter (PM) and hydrocarbons (HC) are released in the exhaust. This transition to incomplete combustion is characteristically very abrupt due to the highly nonlinear effect of EGR on flame speed (Cenk Sayin et al 2008). In a transient operating environment, it is particularly difficult to reliably approach this instability limit without occasionally producing undesirable bursts of HC and PM emissions. The result is that petrol engines must be typically operated significantly below their maximum EGR potential, thus penalising NOx emissions.

The above problems can be effectively solved by using catalytic coatings, which improves lean limit and hence better combustion. In the present investigation various low cost catalytic coatings were used along with different EGR flow rate to identify the best combination of EGR flow rate and the desired flow catalytic coating.

**Exhaust Gas Recirculation System**

Exhaust gas recirculation (EGR) is used for controlling the NOx emissions.EGR is an effective technique of reducing NOx emissions from the SI engine exhaust. EGR involves replacement of oxygen and nitrogen of fresh air entering in the combustion chamber with the carbon dioxide and water vapor from the engine exhaust. The recirculation of exhaust gases raises the total heat capacity of the working gases in the engine cylinder and thus lowers the peak gas temperature. Throughout the experimental investigation, cooled EGR was used. A custom designed EGR cooler was used to cool the exhaust gases. Exhaust gases were drawn from the exhaust pipe and passed to the inlet airflow passage. The exhaust gases recirculated were regulated by a valve and directly sent to the inlet manifold. The manifold was designed with sufficient length to ensure thorough mixing of fresh air with exhaust gases. The temperature of the exhaust gas-fresh air mixture was measured just before its entry into the combustion chamber using a thermocouple. EGR quantity was determined using the expression

$$EGR\ \% = \frac{[M_a]\text{ without EGR --- }[M_a]\text{ with EGR}}{[M_a]\text{ without EGR}}$$

Where = $[M_a]$-Mass flow rate of air, kg/s

Two EGR percentages, 5% and 10 % were adopted .The engine was operated in the entire load spectrum with 0 %, 5 % and10 % EGR to study the combustion, emission characteristics and performance of the engine using various catalytic coatings.

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Figure 1 shows the Schematic diagram of the EGR unit and experimental setup.

**Selection Of Catalysts**

From the review of literature, it has been found that many noble and non-noble metals act as catalysts for hydrocarbon oxidation [11],[12]. As the aim of the present work is to develop a catalytic combustion system, with least modifications and low cost, without the usage of the noble metal catalysts such as platinum, palladium etc. Upon inquiry, it was found that, a single set of platinum coating alone costs very high compare to the engine cost .Although the noble metal catalysts were well proved for their catalytic activity, the high cost of coating prohibits them in practical systems. Rytcher et al. [12] identified some non-noble metals with comparable performance with noble metal catalysts in hydrocarbon oxidation. Their results showed that the non-noble metals such as copper, nickel showed catalytic activity. Hence, the catalysts such as copper, nickel and chromium are selected for in-cylinder coating for the present work.

Although these catalysts were already studied by different researchers under certain conditions, detailed study involving heat release rates, combustion phenomena are not carried out. The catalysts performance depends upon the coated surface temperature. Metal catalysts used in the present study are Copper, Chromium, Nickel.

**Catalytic Coating Details**

The catalysts are coated by plasma coating technique. Earlier study Dhandapani, [10] conducted with electroplating technique indicates shorter coating life. The plasma coating of catalysts are applied on the inside surface of cylinder head and on piston crown. As the cylinder wall surface is subjected to rubbing action and at the time of combustion, only a small portion of the cylinder wall is exposed to hot gases, the cylinder wall is not coated with catalysts.

The surface to be coated was first cleaned and degreased with a chemical solvent. A special bonding material was first coated, before the catalysts are coated. The material to be coated, which is either in the form of wire, rod or fine powder, was fed to a melting zone. The molten metal was further heated to a very high temperature leading to plasma stage. The hot plasma is accelerated along with carrier gas in the form of a jet towards the substrate. When the plasma jet impinges on the surface to be coated, the coating material flattens and sticks to the surface. It forms a hard surface when it is cooled and coalesced. The plasma coating equipment consists of a spray gun, feed hopper, carrier gas supply unit and power supply unit. The spray gun is used to coat the material of the surface. The coating was applied in layers until the desired thickness was obtained.

**Experimental Setup**

The experiments were conducted on a single cylinder, four stroke, air-cooled engine, which is commonly used in electrical generator. The engine is coupled with an eddy current dynamometer (20 kW) for loading. The fuel flow rate was measured using gravimetric system. The exhaust emissions such as hydrocarbon, oxides of nitrogen, carbon monoxide and carbon dioxide were measured using AVL make gas analyzer. The in-cylinder pressure was measured with the help of pressure transducer, which was flush mounted into cylinder head and the corresponding crank angle position was obtained by crank angle encoder. The pressure and crank angle positions

were conditioned and amplified using four channel charge amplifier (AVL indimeter 619). The combustion parameters were analyzed with the help of Indicom mobile software. The Schematic diagram of the experimental setup is shown in figure 1 and the specification of the engine is given in table1.

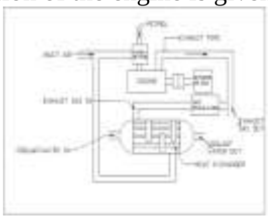

**Figure 1 Schematic diagram of the EGR unit**

**Results And Discussion**

The experiments were conducted on the single cylinder four stroke engines using various catalytic coating like Nickel, Chromium and copper with different EGR flow rate at constant speed (2500 rpm) with varying loads. The performance and emission data were analyzed for thermal efficiency, BSFC, exhaust gas temperature, HC, CO, $CO_2$and NOx emissions. The characteristic curves were drawn and the detailed results are discussed in the following sections.

**Performance analysis**

**Brake Thermal efficiency**

The effect of exhaust gas recirculation on brake thermal efficiency is shown in Figure 2. The brake thermal efficiency decreases marginally with increase in EGR flow rate for all the

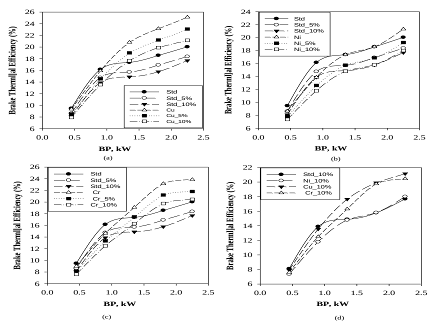


**Figure 2 Variation of brake thermal efficiency with brake power for different EGR flow rate and coatings**

catalytic coating. The decrease in thermal efficiency could be due to combustion deterioration when the EGR is increased and the gaseous fuel–air mixture is more diluted with exhaust gases. The reduction in efficiency may also be due to the decrease in oxygen concentration in the combustion chamber and replacement of air by EGR. The higher flow rate of EGR reduces the average combustion temperature inside the combustion chamber resulting in decrease in brake thermal efficiency at all loads. But when catalytic coatings were used the thermal efficiency higher than the base engine.

**Specific fuel consumption**

The variation of specific fuel consumption with load is shown in Figure 3 for various catalytic coatings with and without EGR. It is observed that SFC decreases with increase load and increases with increase in flow rate. For copper coating at full load the SFC for without EGR is found to be 0.299 kg/kW-hr with 10% EGR it is 0.355 kg/kW-hr compared to standard engine SFC of 0.374 kg/kW-hr and 0.424 kg/kW-hr were observed.

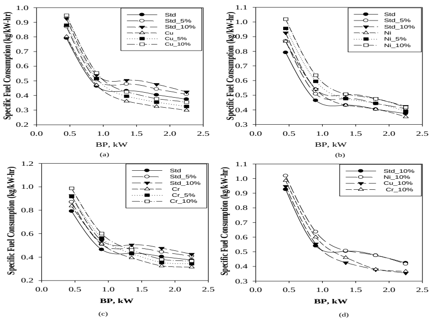

**Figure 3 Variation of specific fuel consumption with brake power for different EGR flow rate and coatings**

In the case of Nichel and Chromium were used at full load the SFC for without EGR is found to be 0.352 kg/kW-hr and 0.0.314 kg/kW-hr with 10% EGR it is 0.4167kg/kW-hr  and 0.0.366 kg/kW-hr at full load due to the deficiency in oxygen concentration results in increased fuel consumption to produce the rated power. Hence increase in EGR flow rate at full load results in the increase in SFC.

**Exhaust gas temperature**

Figure 4 shows the variation of exhaust gas temperature with brake power for different EGR flow rate and coatings. The exhaust gas temperature decreases marginally with increase in EGR flow rates. In general due to the EGR there is a reduction in peak combustion temperature hence the exhaust gas temperature drops down which is also due to lower availability of oxygen for combustion and higher specific heat of intake exhaust gas air mixture.

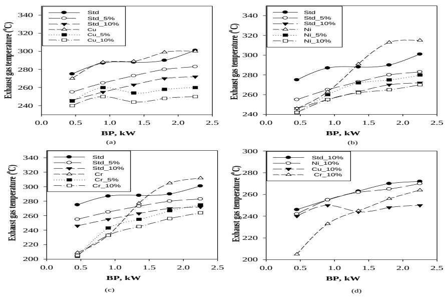

**Figure 4 Variation of exhaust gas temperature with brake power for different EGR flow rate and coatings**

**Emission Characteristics**

**Carbon monoxide emission (CO)**

The variation of CO with brake power is shown in Figure 5 with different catalytic coating and varied flow rate of EGR percentage. It is an intermediate product in the combustion of a hydrocarbon fuel, so its emission results from incomplete combustion. CO emission

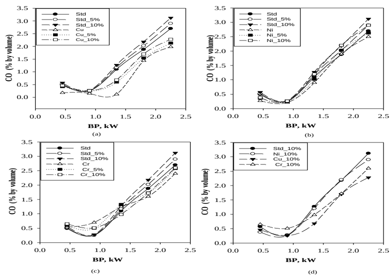

**Figure 5 Variation of carbon monoxide with brake power for different EGR flow rate and coatings**

increases with an increase in EGR rate. This may be due to the fact that recirculated exhaust gases replace some of the oxygen present in the inlet air that causes incomplete combustion and this dominates over the effect of an increase in inlet temperature

**Carbon dioxide emission ($CO_2$)**

The variation of carbon dioxide with brake power for different EGR flow rate and different coating is shown in Figure 6 Carbon dioxide is a principal constituent of products of combustion. The nature of $CO_2$ is higher heat capacity and it serves as a heat absorbing agent during the combustion, which reduces the peak temperature in the combustion chamber. The $CO_2$ concentration decreases in general for various EGR percentages. Due to the instability in combustion and deficiency in oxygen it makes the CO concentration to increase and $CO_2$ concentration to decrease with an increase in EGR rate.

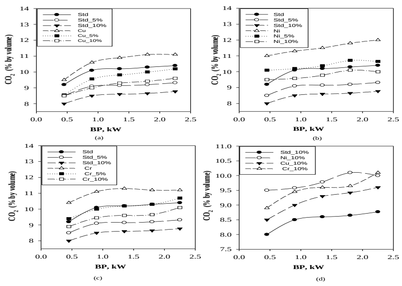

**Figure 6 Variation of carbon dioxide with brake power for different EGR flow rate and different coatings**

Hydrocarbon emission

The variation of hydrocarbon (HC) with brake power for different EGR flow rate and various coatings depicted in Figure 7. The hydrocarbon variation increase in EGR resulting in increase in HC emission. The increase in hydrocarbon with increase in EGR rate is due to the

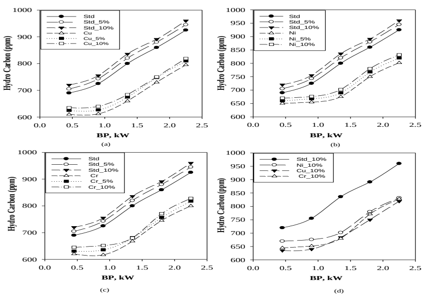

**Figure 7 Variation of Hydro Carbon (ppm) with brake powerfor different EGR flow rate and coatings**

reduction of oxygen in the inlet charge by the recirculated exhaust gases in the cylinder. The lack of oxygen is responsible for reduced oxidation rate, which may be lead to incomplete combustion and hence higher hydrocarbon emissions. The result shows that copper coated engine has the lowest HC emission when compare to standard and other catalysts for 10 % EGR. For the entire catalytic coated engine shows better performance than the standard engine at 10 % EGR.

**Oxides of nitrogen emission**

The oxides of nitrogen in the emissions contain nitric oxide (NO) and nitrogen dioxide ($NO_2$). The formation of NOx is highly dependent on in-cylinder temperature, the oxygen concentration and residence time for the reactions to take place. Implementation of EGR technique in petrol engines results in increased soot emission and formation of particulate matter in the engine cylinders. When the engine components are exposed to high velocity soot particulates, particulate abrasion may occur. Sulphuric acid and  condensed water in EGR also cause corrosion (Ho Teng 2006)   Figure 4.27 shows the variation of oxides of nitrogen emission with brake power at various catalytic coating with different EGR flow percentages. Generally, the $NO_x$ emission tends to reduce significantly with increase in EGR flow rate.

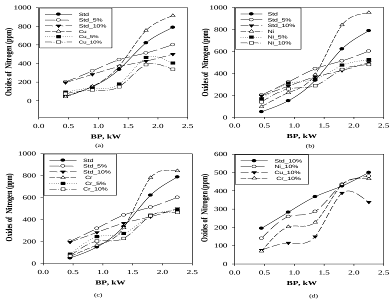


**Figure 5.24 Variation of oxides of nitrogen with brake power for different EGR flow rate and coatings**

## Conclusion

The brake thermal efficiency decreases marginally with increase in EGR flow rate that result in larger replacement of air for all the catalytic coating

- The NOx emission reduces with increase in EGR flow rate, due to the presence of higher heat capacity gases that reduces the peak combustion temperature and exhaust gas temperature. Among the catalysts, the best NOx emission reduction is achieved for copper coating with 10% EGR
- The maximum $NO_x$ reduction for copper coated engine with 10% EGR is about 45 % lower than standard engine. The other catalytic coatings like chromium and nickel shown the NOx reduction of 7 % and 4 % lower than standard engine
- Increasing EGR rate dilutes the intake charge and reduces its oxygen. Dilution also decreases combustion temperature, which results in reduction of the amount of burnt fuel thus HC emission increases in comparison with no EGR.
- Due to the instability in combustion and deficiency in oxygen it makes the CO concentration to increase and $CO_2$ concentration to decrease with an increase in EGR rate.
- Engine operation with copper catalytic coating with 10 % EGR were able to reduce NOx, and reduction in brake thermal efficiency and $CO_2$ also increase in CO and Hydrocarbon were observed compared to standard and other catalytic coatings.
- The catalysts can be rated based on the performance as copper > chromium > nickel > standard

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**Table 1. Engine Specification**

| | |
|---|---|
| Make | Honda Side valve |
| Type | 4 stroke, air cooled, horizontal shaft, single |
| Displacement | 197 cc cylinder |
| Bore x stroke | 67 mm X 56 mm |
| Compression ratio | 4.5:1 |
| Rated brake power | 2.28 kW at 3000 rpm |
| Max. Torque | 0.8 kg-m at 2500 rpm |