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# EGR Combined with Particulate Trap for the Reduction of Oxides of Nitrogen and Smoke Emissions in a Small DI Diesel Engine

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***Abstract –*** *The increase in motorized transport has led to a simultaneous increase in oxides of nitrogen ($NO_x$) and smoke emissions. Though a wide range of reduction strategies have been explored, exhaust gas recirculation (EGR) combined with particulate trap technology has proved to be a more effective and economic choice. The effect of EGR on engine performance and emissions was studied on a single-cylinder, direct injection (DI) diesel engine run at a constant speed of 1500 rpm at various loads. The present work aims at studying the effect of hot and cool EGR on the formation of $NO_x$. The baseline readings were determined from the experimental results obtained from an engine without EGR run at various operating conditions. This would definitely form a healthy means of evaluation of the effect of EGR on engine performance and emissions. Comparison of the findings of hot and cool EGR at full load conditions corresponds to a proportion of 15% which amounts to be the maximum allowable one, has revealed the effectiveness of cool EGR on the reduction of $NO_x$ and smoke emissions as compared to hot EGR. Hence, a suitable particulate trap with a high trapping efficiency and cost effectiveness is strongly desired before the EGR cooler to reduce the smoke emissions to meet the emission standards. The present study uses a particulate trap with a substrate made of clay material, made into spheres coated with copper and zinc oxide catalyst material. Effective reduction in $NO_x$ and smoke emissions by 63% and 42% respectively have been observed by the combination of EGR and the particulate trap. A simultaneous increase in brake specific fuel consumption by 10% as compared to baseline operation has also been observed.*

***Keywords –*** EGR, metal oxide, $NO_x$, particulate trap, smoke.

## 1. INTRODUCTION

The inherent high thermal efficiency and low $CO_2$ emission of direct injection diesel engines has led to their usage in a wide range of applications in spite of them contributing a major percentage of air pollution as exhaust emissions. Improvement of combustion and development of after-treatment techniques are some of the approaches used in order to reduce exhaust emissions. Exhaust Gas Recirculation (EGR), though being the most effective technique currently available for reducing $NO_x$ emissions, its application has proved to lead to higher specific fuel consumption and particulate emissions [1,2]. The use of EGR is also known to aggravate the trade-off between $NO_x$ and particulate emissions especially at high loads [3,4]. Until recently, the reduction in flame temperature owing to the increased heat capacity of the recirculated charge was strongly regarded as the reason for reduction in $NO_x$ by EGR in a diesel engine [5]. It has been studied that $NO_x$ emissions are largely influenced by reduction in oxygen concentration [6]. Of all the methods, which aim at particulate emission reduction in diesel engines, particulate trap plays a vital role [7]. A reduction in power output and an increase in fuel consumption are attributed to the accumulation of particles on the surface of the filter material [8]. Regeneration, which the removal of the particles accumulated in the particulate trap, is used to reduce back-pressure [9]. Polat Oser and Ulrich Thomas [10] investigated the use of a catalyst coated on the particulate trap intending to reduce the ignition temperature of the particulates on the surface of the filter material. This paper aims to achieve simultaneous reduction in $NO_x$ and smoke emission by using a suitable EGR method combined with particulate trap.

## 2. EXPERIMENTAL SYSTEM

The test was conducted on a 4-stroke single cylinder, air-cooled, DI diesel engine running at a maximum load of 4.4 kW at a constant speed of 1500rpm coupled with an electrical generator. Figure 1 shows the arrangement of the experimental set-up. Table 1 gives detailed specifications of the engine. A U-Tube manometer was used to measure the back-pressure across the filter. The inlet/exhaust water temperatures of the EGR cooler, exhaust gas and bed temperature of the filter were measured by using thermocouples. An MRU emission monitoring analyzer was used to measure Hydrocarbon (HC), carbon dioxide ($CO_2$), carbon monoxide (CO) and oxygen present in the exhaust gas. Oxides of nitrogen ($NO_x$) and smoke intensity (SI) were measured with Kane May analyzer and Bosch smoke meter respectively.

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**Table 1. Engine specifications**

| | |
|---|---|
| Engine Type | Four-stroke cycle, high speed, Air cooled, Naturally aspirated, Compressed ignition diesel engine |
| No. of cylinder | Single |
| Bore and Stroke | 87.5 X 110 mm |
| Compression ratio | 17.5 |
| Rated speed, rpm | 1500 |
| Injection timing | 23$^o$CA BTDC |
| Fuel injection pressure | 200 bar |
| Rated output | 4.4 kW |

## 3. EXHAUST GAS RECIRCULATION (EGR)

EGR is the method by which a portion of engine's exhaust is returned to its combustion chamber via its inlet system (Figure 1). This method is designed to extract heat from combustion process, thus lowering its temperature and reducing $NO_x$ [11]. This method also involves displacing some of the oxygen inducted into the engine with its fresh charge air, thus reducing the rate of $NO_x$ formation. The study of the effect of EGR on $NO_x$ emission required the performance and emission tests to be performed in a DI diesel engine using both hot and cool EGR. The cool EGR system was found to stop the rise in the inlet charge temperature by using a shell and tube exchanger before mixing with the inlet air. The flow of exhaust gas was controlled by a flow control valve at the inlet and outlet of the cooler. The EGR ratio is defined as the percentage of $CO_2$ concentration in the intake and the exhaust by volume. The EGR percentage was varied in steps of 5. The maximum limit was 50% in low loads and 15% in high loads beyond which the engine will misfire. The present experimental results are constrained to full load for EGR rates of 0 to 15%. An increase in smoke emissions as compared to baseline operation has been observed by the usage of EGR in diesel engine. Hence, cool EGR method was selected for the combination of EGR with particulate trap for further analysis.

## 4. PELLET TYPE PARTICULATE TRAP (PTPT)

The present study uses a pellet type particulate trap (PTPT), which consists of a pellet type substrate with a coating of transition metal catalyst. Small pellets made of clay, providing catalyst support and thermal stability from the converter. The exhaust gases emanating from the engine get converted owing to their contact with the pellets and hence the catalyst as they flow up and down through the gap between them. This pellet type was found to create low back-pressure and hence is more efficient than other types of oxidizers. Clay balls replaced noble metals as catalyst substrates owing to high cost efficiency. The catalysts used for this study are given in Table 2. The catalyst was selected based on the following parameters: high conversion efficiency, suitability for wide range of temperatures, ability to withstand thermal shock, must convert into harmless products, cheap and available. They easily mix with other catalyst materials making it possible to have bimetallic coating.

**Table 2. Properties of metal oxides**

| Metal oxide | Molecular weight (g/gmol) | Melting point (K) | Boiling point (K) | Density (kg/m$^3$) |
|---|---|---|---|---|
| CuO | 79.54 | 1599 | - | 6400 |
| $TiO_2$ | 7990 | 2098 | 409 | 11280 |
| ZnO | 81.37 | 2100 | 1005 | 2910 |
| $La_2O_3$ | 325.81 | 2590 | 4500 | 6510 |

### *Selection of Metal Oxide*

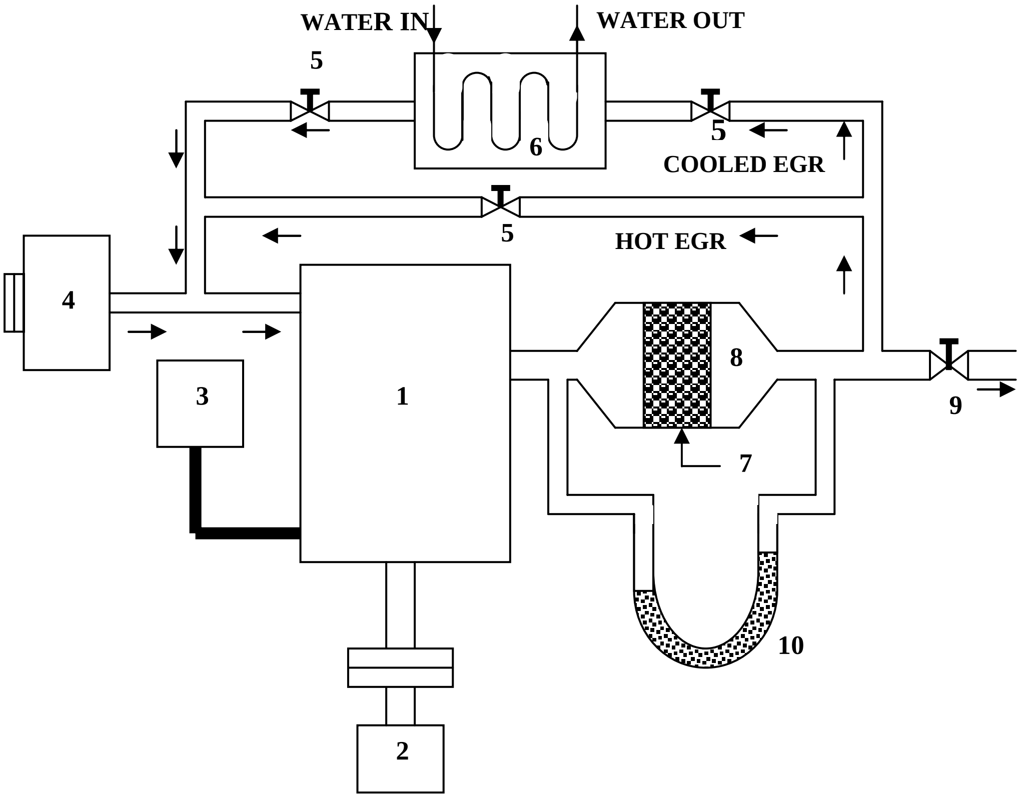
The effect of metal oxides on the trapping efficiency and pressure drop was studied for various catalysts including mainly copper oxide/Zinc oxide (CuO/ZnO), copper oxide/Titanium oxide ($CuO/TiO_2$), and copper oxide/Lanthanum oxide ($CuO/La_2O_3$). At full load conditions, the bed temperatures for the CuO/ZnO, $CuO/TiO_2$ and $CuO/La_2O_3$ were recorded as 385$^o$C, 438$^0$C and 470$^o$C respectively. The higher pressure drop of 17.6 cm of water column recorded for $CuO/La_2O_3$ as compared to CuO/ZnO and $CuO/TiO_2$ catalysts has proved the latter to be more active in trapping and hence oxidizing the partial combustion products namely smoke and soot, thus providing less back pressure of 15.4 cm of water column. CuO/ZnO, on the other hand shows high trapping efficiency of 86%, which is higher than $CuO/TiO_2$ by 5%. The experiment has revealed the fact that filters coated with bimetal catalysts namely copper oxide and zinc oxide give the maximum trapping efficiency. The catalyst material was coated on the clay substrate using impregnation or doping technique. The catalyst was packed inside the converter and fitted in the exhaust pipe.

### *Reduction of NOx and Smoke from Metal Oxide*

Carbon monoxide and organic fragments, forming a portion of the combustion products, reduce copper oxide and zinc oxide to their lower valence states, which then are able to hold together CO and $NO_x$ in their coordination sphere, thus converting them into $CO_2$ and $N_2$. Moreover, when these metal oxides are supported on inert materials like clay, in the form of pellets, chemisorption properties for $NO_x$ and CO are enhanced owing to an increase in the surface area. Although the binary copper oxide and zinc oxide may not have the synthetic effect on $NO_x$ reduction, one oxide could help the other oxide to attain the nano dimensions less than 1 atom size for each. This study was also found to have an additional advantage of adsorption of organic fragments on their rough surface.

### *Monitoring of the PTPT*

The exhaust gas was made to enter the converter axially by suitably connecting the catalytic converter attachment to the engine exhaust line. Pellets made of clay were packed in a cylindrical container with both ends fixed with stainless steel wire mesh. The container was fitted inside a cylindrical, insulated catalytic converter by means of flanges. Proper sealing was ensured to avoid exhaust gas leakage. The engine was run for about 10 minutes until steady state was attained. The experiment was repeated for a finite number of times to ensure consistency of results.




1- DI diesel engine 2- Electrical Generator 3- Fuel Tank 4- Surge Tank
5- Flow control valve 6- EGR cooler(Heat Exchanger) 7- Pellets 8- Pellet Type Particulate Trap
9- Back pressure valve 10- U-Tube Manometer

**Fig. 1. Schematic diagram of experimental set-up**

The pellet filter prepared was placed in a mild steel housing 5 mm thick and was fitted very close to the exhaust manifold of the engine as shown in Figure 1 in order to obtain the advantages of light off properties of the oxidizer after cold start of the engine. The pellet filter requires flexible intermediate layer having high absorption of radial and axial high frequency vibration and shock as it is subjected to high frequency vibrations, mechanical and thermal stress. The filter was closed on all sides to ensure that the exhaust gases do not escape. The housing has a short converging conical inlet and a short diverging conical outlet. The inlet is 10cm long and the cone angle is $30^o$.The thermocouple used to measure bed temperature was inserted into a 3mm diameter hole provided at the centre of the housing.

## 5. RESULTS AND DISCUSSIONS

Figures 2 to 5 discuss the test results to select suitable EGR type for maximum $NO_x$ reduction at the expense of smoke emissions with respect to intake oxygen concentration and intake gas temperature. The present work enables a better understanding of EGR characteristics combined with pellet type particulate trap (PTPT) at full load conditions for simultaneous reduction of $NO_x$ and smoke emissions and performance characteristics (Figures 6 to 9).

Figure 2 shows oxygen concentration in intake gas with two different EGR concepts, namely cool EGR and hot EGR against EGR rate. The intake charge temperatures indicated were measured in the intake manifold after mixing with exhaust gas. It is seen that for both hot and cool EGR, oxygen concentration decreases with increase in EGR rate. At a given EGR percentage, cool EGR contains more oxygen when compared to hot EGR. The EGR rate was almost kept constant in this series of tests. Hence it may be concluded that the inducted fresh air in the case of cool EGR is larger than that of hot EGR. Cool EGR will displace less of the fresh air volume, thus maintaining an adequate overall A/F ratio to sustain good combustion efficiency. Similar results were reported by [12].

The effect of both types of EGR on $NO_x$ under different EGR rates at full load condition is shown in Figure 3. It is evident from the Figure that $NO_x$ emission decreases with increase in EGR rates and that $NO_x$ reduction has a strong correlation with oxygen concentration in the intake gas and intake gas temperatures for both hot and cool EGR. At a given level of EGR rate, the cool EGR reduces more $NO_x$, which in turn indicates that, to achieve certain $NO_x$ reduction, cool EGR can achieve the goal with less EGR rate compared to hot EGR. The results show that with cool and hot EGR, for 15% EGR rate, $NO_x$ emission was reduced by 60 and 40 percent respectively. This is due to the reduction in oxygen concentration levels at higher loads. For cool EGR, the $NO_x$ reduction is more than that of hot EGR due to the reduction both in oxygen concentration and the temperature of the intake gas. Heat absorbed by EGR is directly proportional to the product of EGR flow rate, the specific heat at constant pressure and the temperature differential between combustion temperature and that of EGR. In addition, it can be concluded that EGR cooling would increase the temperature differential term thus increasing the EGR heat absorbing capacity and further reducing $NO_x$.

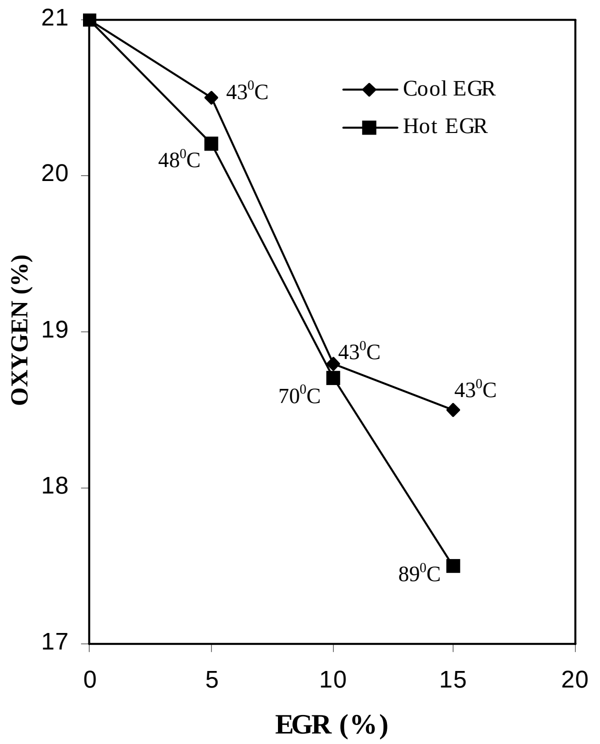



**Fig. 2. Effect of intake temperature on oxygen concentration**

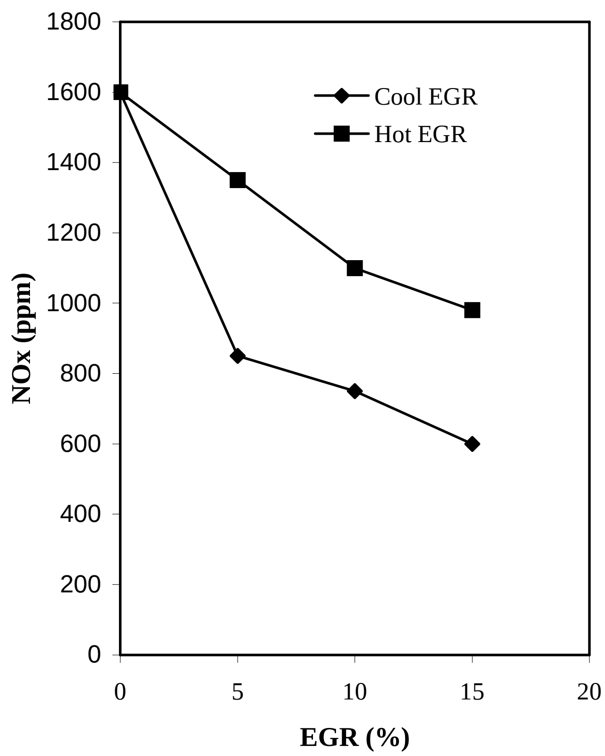



**Fig. 3. Effect of cool and hot EGR on NOx emission**

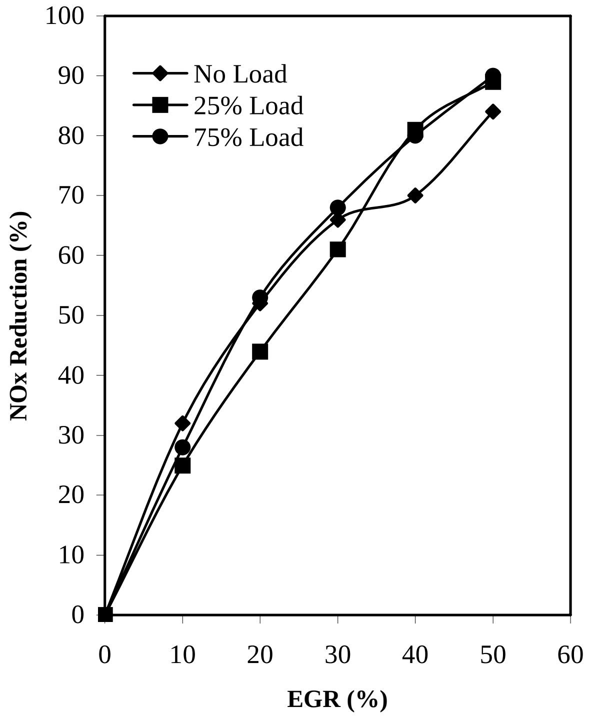



**Fig. 4. Effect of EGR rate on $NO_x$ reduction at various engine loads.**

The effect of EGR rate on $NO_x$ reduction at various engine load conditions is illustrated in Figure 4. EGR in diesel engine has real advantages at low engine load conditions where high air to fuel (A/F) ratios (50:1 to 100:1) dominate. At high engine load conditions, A/F ratios were greatly reduced and reached values as low as 20:1. These low A/F ratios usually lead to excessive smoke formation.

Smoke emission in both hot and cool EGR is indicated in Figure 5. The Figure signifies higher smoke level on both hot and cool EGR as compared to baseline operation. At full load conditions, the smoke intensity was found to increase by 10% and 20% respectively for hot and cool EGR from the baseline for 15% EGR rate. The variation of $NO_x$ emission with EGR rate for cool EGR and a combination of cool EGR with PTPT is sketched in Figure 6. In both the above-mentioned cases, $NO_x$ emission was found to decrease with EGR rate. At full load for 15% EGR rate, cool EGR with PTPT shows a reduction of $NO_x$ emission by 60 ppm as compared to cool EGR. A reduction of 63% $NO_x$ emission was obtained when compared to the baseline. This is attributed to the reduction in temperature due to the reduction in oxygen concentration. There is a significant reduction of $NO_x$ at 5% and 10% EGR on the introduction of a trap in combination with EGR. Hence, this study concludes that the adsorption of $NO_x$ by metal oxide coating leads to a proven suppression of $NO_x$ on the application of cool EGR in combination with trap.

Figure 7 shows the variation of smoke level with EGR rate for cool EGR and cool EGR combined with PTPT at full load. No drop in smoke intensity was observed with cool EGR rather an increase at 15% EGR, whereas, a significant drop in smoke intensity was recorded on the introduction of trap in addition to cool EGR. This illustrates the importance of the trap in diesel exhaust. At full load conditions, smoke level for cool EGR with PTPT filter was lower than that of the baseline by 0.8 Bosch Smoke Units (BSU), while that for cool EGR increased by 1.6 BSU from the default value of 4 BSU. The presence of a catalyst, which aids the regeneration of soot in the exhaust gases, causes the filter to effectively reduce the smoke level up to 42%.

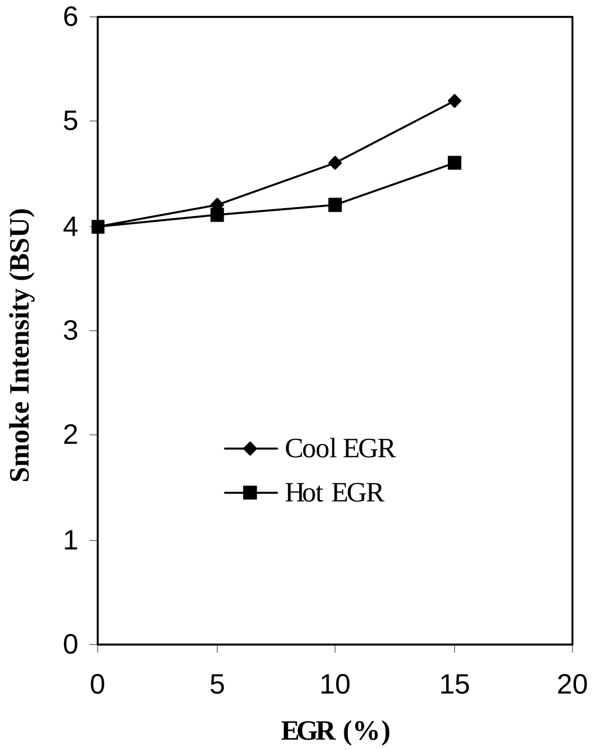



**Fig. 5. Effect of cooled and hot EGR on smoke emission with EGR rate at full load.**

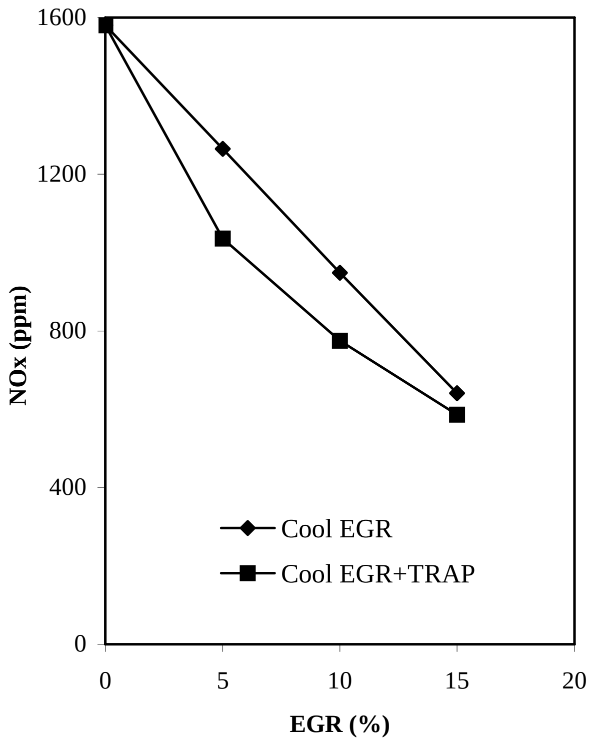



**Fig. 6. Effect of cool EGR and combination of cool EGR with PTPT on $NO_x$ emission with EGR rate at full load.**

The variation of brake thermal efficiency with EGR rate at full load condition is indicated in Figure 8. Brake thermal efficiency was observed to decrease with cool EGR and cool EGR combined with PTPT as compared with baseline operation. The presence of a trap is known to decrease the brake thermal efficiency. Cool EGR with PTPT at 15% EGR rate was observed to cause reduction in brake thermal efficiency by 23.20%, which is 2.10% lower than cool EGR and 3.40%, lower that of baseline mode engine at full load. Reduction in inlet oxygen concentration in the case of cool EGR and higher fuel consumption due to the development of back-pressure with PTPT serve as the reasons for the above observed trend.

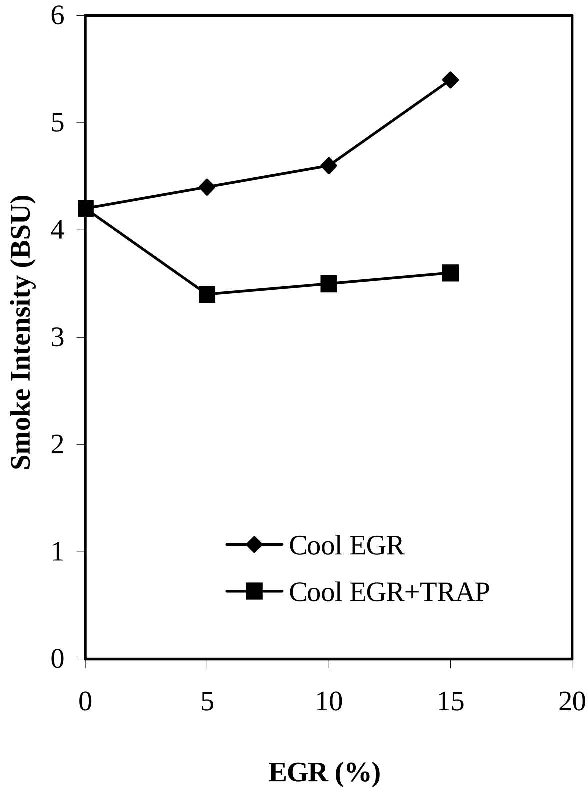



**Fig. 7. Effect of cool EGR and combination of cool EGR with PTPT on smoke emission with EGR rate at full load.**

The variation of specific fuel consumption with EGR at full load condition is sketched in Figure 9. The development of back-pressure in the presence of particulate trap has turned out to be the reason for the higher specific fuel consumption for cool EGR combined with PTPT as against that for cool EGR and baseline operation. The specific fuel consumption of cool EGR with PTPT is 0.36 kg/kWh, which is 0.05 kg/kWh, and 0.02 kg/kWh higher than that of baseline and cool EGR mode respectively.

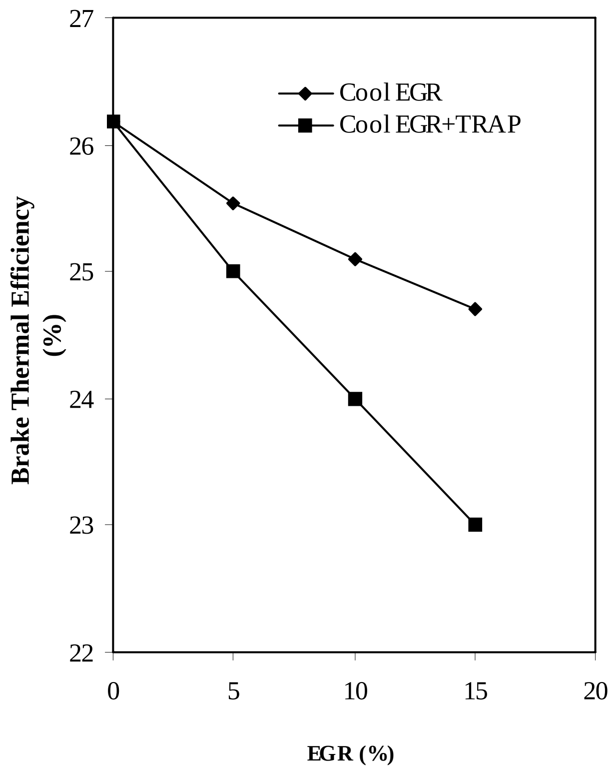



**Fig. 8. Effect of cool EGR and combination of cool EGR with PTPT on Brake thermal efficiency with EGR rate at full load.**

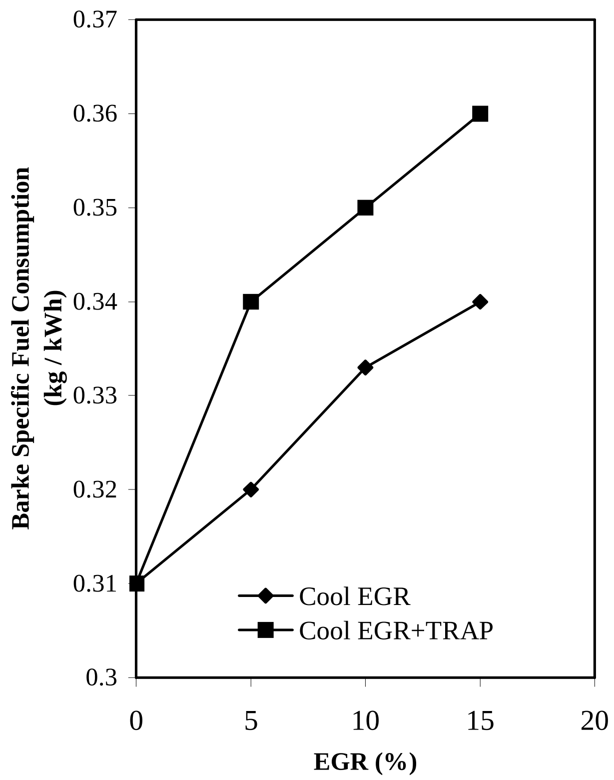



**Fig. 9. Effect of cool EGR and combination of cool EGR with PTPT on Brake Specific fuel consumption with EGR rate at full load.**

## 6. CONCLUSION

Experiments were conducted with a single cylinder, direct injection, naturally aspirated, four-stroke cycle diesel engine to determine how cool and hot EGR affect exhaust emission characteristics. From the present investigations on emission control from direct injection diesel engine using cool EGR and cool EGR combined with after treatment of exhaust gas by using different metal oxide catalysts coating on silica pellets, the following conclusions are drawn:

1. At a given level of oxygen concentration and intake gas temperature corresponding to EGR rate, the cool EGR reduces more $NO_x$, which indicates that, to achieve certain $NO_x$ reduction, cool EGR can achieve the goal with less EGR rate than hot EGR does.
2. At a given $NO_x$ level, the cool EGR results in lower smoke emission than hot EGR. It was observed that at full load for 15% EGR rate, the smoke level increases for the hot EGR and cool EGR by 4.4 BSU and 4.8 BSU respectively from baseline of 4 BSU.
3. The combination of cool EGR and PTPT was found to be an effective device for the reduction of $NO_x$ and smoke emissions.
4. Cool EGR with PTPT at 15% EGR rate cause reduction in brake thermal efficiency.
5. The engine, when operated with 15% cooled EGR combined with bimetal catalyst (CuO/ZnO) will result in simultaneous reduction of $NO_x$ and smoke intensity. It was found that in $NO_x$ and smoke emission, reductions achieved were as much as 63 % and 42% respectively.

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