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Academic @ Paper
ISSN 2146-9067
International Journal of Automotive Engineering and Technologies
Vol. 2, Issue 1, pp. 1 – 9, 2013

International Journal of Automotive Engineering and Technologies

http://www.academicpaper.org/index.php/IJAET

Original Research Article

Investigations on Performance and Emissions of a Stationary DI Diesel Engine with Different Exhaust Gas Recirculation Temperatures

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Received 07 January 2013; Accepted 04 April 2013

Abstract

This paper addresses the application of Exhaust Gas Recirculation (EGR) for reduced oxides of nitrogen (NOx) emissions from naturally aspirated direct injection stationary diesel engine. Prevailing and future emission norms compel engine manufacturers to incorporate techniques to reduce engine out emissions especially NO_X and particulate matter NOx formation predominantly depends on high combustion temperature and literature indicates EGR is an attractive method to reduce combustion temperature. EGR temperature is an important factor while admitting higher percentage of EGR. Higher EGR temperatures caused due to increased loads limit the conduct of higher EGR ratios. EGR cooling can be advantageous when higher ratios of EGR need to be employed. The effect EGR temperature on engine thermal efficiency, NOx, smoke and HC emissions at different load conditions for different EGR percentage are discussed in this paper. NOx reductions and thermal efficiency were found to be better for hot EGR up to about 30% EGR and thereafter EGR cooling shows better results. Smoke and HC emissions increase for both cooled and hot EGR as compared to no EGR case but EGR cooling reduces HC emission as compared to hot EGR.

Key words: Diesel Engine, Emission, Oxides of Nitrogen, Exhaust Gas Recirculation, Thermal Effect, Dilution Effect.

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1. INTRODUCTION

Oxides of nitrogen (NOx) are one of the major hazardous pollutants from diesel engine emission. Exhaust Gas Recirculation (EGR) is an established and effective technique in controlling oxides of nitrogen in diesel engines. Literatures indicate that combustion temperature is a critical factor in NOx formation and EGR reduces combustion temperature considerably resulting in to reduced amount of NOx. EGR temperature influences the inlet charge temperature and alters the combustion process consequently effecting engine performance and pollutants. The effect of EGR temperature on performance and pollution parameters are investigated on a single cylinder naturally aspirated stationary DI diesel engine are carried out and results are presented in this paper.

2. LITERATURE REVIEW

2.1 Background

India, being second largely populated country in the world and 70% of its population largely depends on agriculture, stationary CI engines find wide applications in agricultural area for pumping water, power generation and other crop processing works. Diesel engines are widely used for stationary applications like captive power generation especially in remote locations or during electrical power failures or as prime movers like for pumps, harvesters, threshers, expellers, flour mills etc (Table 1). Diesel engines with power less than 20 hp used primarily for agricultural machinery, irrigation purposes and more than 20 hp mainly used for power generation. Even though emission regulations for such engine applications do not come under stringent norms in India, their contribution on air quality cannot be overlooked.

Table 1. Applications of stationary diesel engines

Segment	Capacity	Application Areas
Small range	2-20 HP	Pump sets, agricultural machinery, water pump sets, threshers, harvesters, and oil expellers
Medium range	20-25 HP	Tractors, power gen-sets, industrial applications
	25-140 HP	Power generation, industrial applications and others.
Large range	140-400 HP	Power generation, industrial application
	400-750 HP	Power generation and marine applications
Very large range	750-1200 HP	Power generation
	1200-7200 HP	Power generation (base load) and marine applications.

2.2 Diesel Emissions

During the combustion process of a diesel engine, chemical energy is converted into mechanical energy at high temperatures and under high pressure. A variety of combustion products are formed when diesel fuel is burnt. These are typically carbon monoxide, hydrocarbons, oxides of nitrogen, carbon dioxide, and fine particles. For diesel combustion the most important engine out emissions are oxides of nitrogen (NO_X), particulates and smoke. NO (Nitric Oxide) and NO_2 (nitrogen dioxide) are lumped together as NOx. NO is a colorless and odorless gas, while NO_2 is a reddish-brown gas with pungent odour. Both gases are toxic, but NO_2 is 5 times greater toxic than that of NO. Although NO_2 is largely formed from oxidation of NO, attention has been given on how NO can be controlled before and after combustion. Mechanism of formation and control of NOx in diesel engine is very complex owing to heterogeneous and transient combustion nature of diesel fuel combustion [1]. Although NO_2 is largely formed from oxidation of NO, attention has been given on how NO can be controlled before and after combustion [1]. NOx can cause severe health problems like irritations in the respiratory system mainly a cause for asthma, lung cancer and cardiovascular diseases. NOx has detrimental environmental impacts like ground-level ozone, acid aerosols, acid rain, toxic chemicals and deterioration of water quality [2, 3, and 4].

2.3 NOx Formation Parameters

Diesel combustion is characterized by heterogeneous air-fuel mixture but there exist local stoichiometric air–fuel ratios resulting in to high flame temperatures [5, 6, and 7]. The formation of NOx is dependent on temperature, local oxygen concentration and duration of combustion. The most critical parameters contributing to the formation of NOx is local combustion temperature, which is directly a function of several hardware and operating parameters such as; load, compression ratio, boost level, charge temperature, injection timing, mixture formation (nozzle configuration) cylinder peak pressure, Cetane number, etc. The higher the combustion temperature (above 1800 K) inside the cylinder during combustion, the more energy is available to split the strong triple-bonding between the atoms of the molecular nitrogen of the combustion air to generate atomic nitrogen chain carriers resulting in NO formation [8].

The second most critical parameter is availability of oxygen. Diesel combustion requires excess percentage of oxygen for better and complete combustion. Due to the heterogeneous air fuel mixture during combustion in CI engines, local air/fuel ratio (λ) influences the NOx formation and not the overall λ value.

The third most important parameter is time. Only a short period of time is available to the NO formation process, since the most critical gas temperatures are achieved between the start of combustion and shortly after the occurrence of peak cylinder pressure. However, investigations have shown that the formation process of NO takes place in both flame as well as the post-flame area, providing a sufficient amount of time for the NO formation reaction [9]. Of all three factors local reaction temperature and Oxygen concentration has greater influence in the formation of NOx. Therefore any factor that can reduce the maximum combustion temperature along with reduced availability of oxygen can reduce the emission of NOx [10, 11].

Exhaust gas recirculation is gaining importance in the recent past as a measure to control NOx emissions. In this technique a measured volume of engine out exhaust is recirculated along with fresh intake air [9, 10 and 12]. EGR application modifies the normal combustion process as it reduces the amount of oxygen and presents combusted products like CO_2 and H_2O, principle constituents of EGR, during combustion. Reductions in oxygen entry into the cylinder due to EGR is referred to as dilution effect and where as high specific heat gases CO_2 and H_2O contained in EGR absorbing more heat during combustion is thermal effect [13]. The net result of both these effects is to reduce combustion temperature leading to reduced NOx emissions. Literatures indicate the adverse effects of EGR at higher load and higher percentage of EGR in terms of fuel penalty and particulate emissions [14, 15].

3. METHODOLOGY of EXPERIMENT

3.1 Test Engine

The test engine is a Kirloskar AV1® engine with data acquisition systems (DAS) for recording engine performance parameters. Modifications were made to cool the exhaust gas being recirculated by using two heat exchangers. An orifice meter was used to determine the flow rate of recirculated exhaust gas. Percentage of exhaust gas was taken as ratio of amount of exhaust gas recirculated to total engine exhaust gas. AVL®smoke meter was used to measure the smoke level and INDUS®5 gas analyzer for O_2, CO, CO_2, HC and NOx measurements. Specification of the test engine is mentioned in table 2.

Table 2. Test Engine Specification

Type	4-Stroke, Single Cylinder Diesel Engine
Make	Kirloskar AV – 1
Loading	Electrical, Resistive Air Heaters
Rated Power	3.7KW, 1500 RPM
Bore & Stroke	85mm x 110mm
Cylinder Capacity	624.19 cc
Compression Ratio	16.5 : 1
Pressure Transducer	Piezo Sensor, Range: 140 kg/cm^2
Starting	Auto Start

3.2 Experimentation Procedure

Even though rated power of the engine was 3.7 kW, at electrical dynamometer a maximum of 2.5 kW power was possible to attain. Test was conducted in three steps. First the engine was run without EGR (only diesel) for load from 0.5 kW to 2.5 kW in steps of 0.5 kW. Exhaust gas cooling was achieved by passing it through one heat exchanger and further cooling is done by passing it through second heat exchanger. This case is referred to as cold EGR. Finally the exhaust gas was directly mixed with fresh air without passing through any heat exchangers and pipe lines carrying the exhaust gas were insulated using glass wools. This case is referred to as hot EGR in the discussion. Exhaust gas is recirculated in percentage of total exhaust gas (volume basis) in steps of 10% up to 50% (further increases led to rough running of the engine). The percentage volume is measured using a rotameter specially designed for diesel engine exhaust. For every load the exhaust gas volume was measured by fully closing the exhaust gas valve and fully opening the exhaust by pass valve (diverting the entire exhaust gas as EGR) for a short period and then completely closing the bypass valve (no EGR). These two values serve as reference as 0% and 100% EGR and with these two reference values, in-between values like 10%, 20%, 30%, 40% and 50% are marked. A settling tank to minimize gas vibrations and a filter with wire mesh filled with glass wool (to arrest soot particles entering in to the engine) were used in the EGR pipe line as indicated in fig.1. A pressure transducer is mounted centrally on the engine cylinder head for pressure value tapping. Results of the experiment are compared for different cooling of the EGR in the following section.

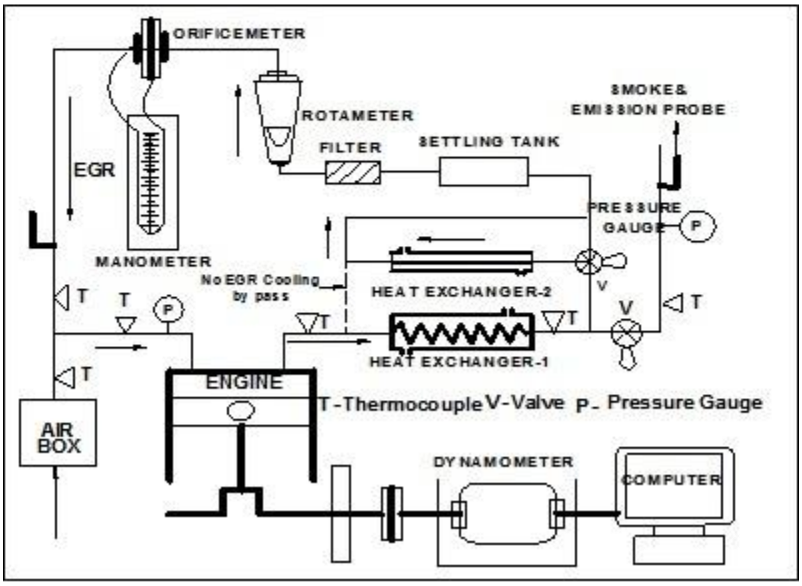

Fig.1. Layout of experimental set up

4. RESULTS and DISCUSSION

4.1 EGR and Air Fuel Ratio

Effect of hot and cold EGR on air fuel ratio (AFR) for different loads at 40% EGR is plotted in the fig.2. As the test engine runs at constant speed, the time available for inducting air at all loads remains same. AFR change due to increased fuel quantity when the engine runs with only diesel. The application of EGR reduces the amount of air intake due to the increased temperature. This is called as thermal throttling leading to dilution effect. Higher the temperature of EGR lesser is the AFR. Reduced AFR results into reduced oxygen percentage at all loads and for all percentage of EGR rates.

Lower temperature of EGR admits more oxygen as compared to higher temperatures. CO_2 percentage for hot and cold EGR do not show appreciable difference up to 30% EGR rate but difference is noticeable thereafter. Increased mixing time between fuel spray and air and deteriorated combustion quality at higher EGR rate produce more amount of CO_2 in the exhaust. Increase in EGR percentage Increases EGR temperature which accelerate oxidation rate of carbon resulting into higher amount of CO_2. These results are plotted in fig.3, for the maximum load of 2.5kW.

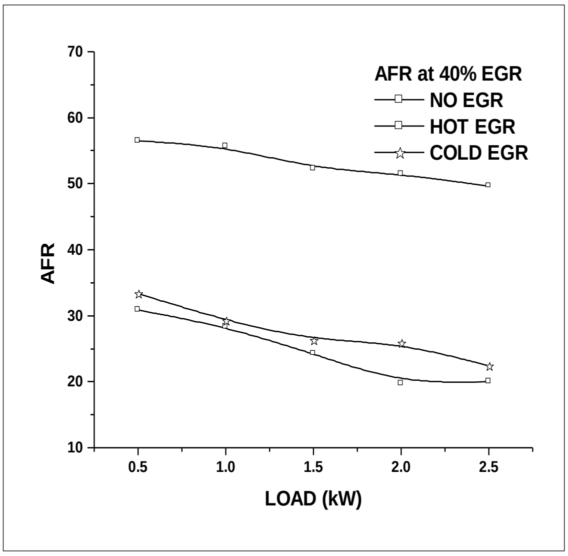

Fig.2. Effect of EGR on AFR for different loads for three EGR temperatures at 40% EGR

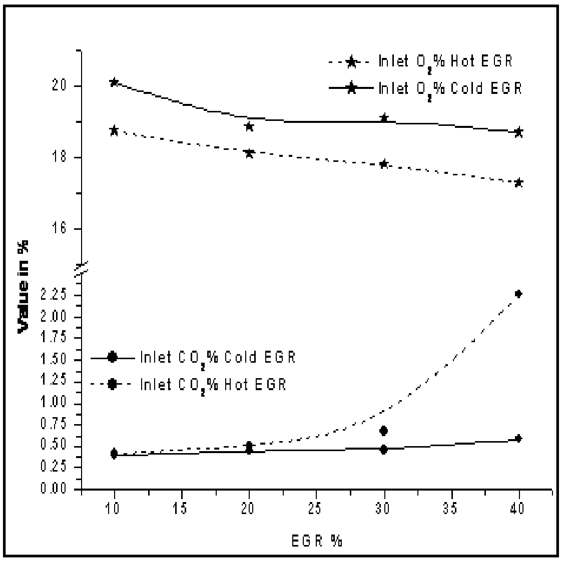

Fig.3. Effect of EGR on percentage CO_2 and O_2 concentrations for hot and cold EGR modes for different EGR at full load (2.5kW)

4.2 EGR and Exhaust Gas Temperature

Exhaust gas temperature show a decreasing trend as the percentage of EGR increases for all cases of EGR temperatures. This is mainly due to reduced oxygen and increased CO_2 with increased EGR rates. Increased cycle temperature is expected for hot EGR and lower cycle temperatures with cooling the EGR. Increased availability of oxygen during the combustion is also an important parameter contributing to combustion temperature. During the experiment it is observed that more oxygen is admitted in to the engine cylinder when EGR is cooled. Availability of excess oxygen with cooled EGR as compared to hot EGR may be the reason for increased cycle temperature with EGR cooling during lower EGR rates (about 30%). As the EGR dose increase beyond about 35% combustion temperature increases for hot EGR **(fig.4).**

4.3 EGR and Oxides of Nitrogen

Emission of NOx largely depends upon the combustion temperature. Due the reduced amount of oxygen in the combustion chamber, injected diesel fuel has to diffuse wider to prepare local stoichiometric mixture. This increases ignition delay [16, 17] and also auto-ignition locations to be shifted towards the wall of the combustion chamber.

This results in increases in volume of the combustion flame. Enlargement of flame volume happens to enclose H_2O and CO_2 also which absorb more energy released by combustion, leading to lower combustion temperatures and, ultimately, to reduced NO_X emissions [18]. Hot EGR is found effective at lower EGR rates (up to 30%) in reducing combustion temperature (**fig.4**) as compared to cooled EGR. Similar trends are recorded for NOx emissions **(fig.5).** At higher percentage of EGR cooled EGR is found to result in to lower NOx emissions as compared to hot EGR.

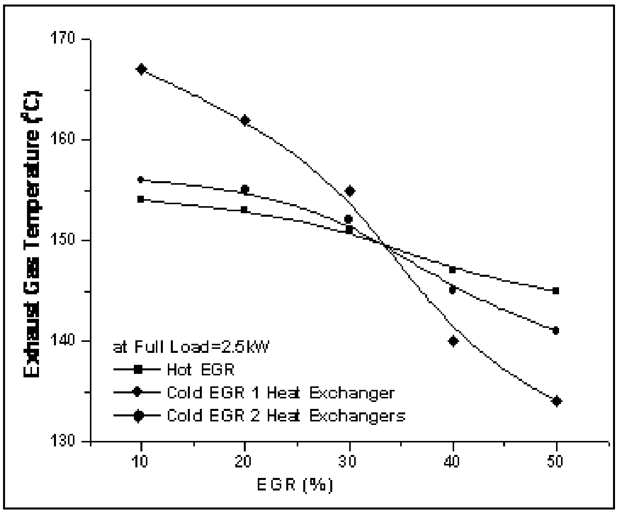

Fig.4. Effect of EGR cooling on exhaust gas temperature at full load of 2.5 kW for different EGR rates

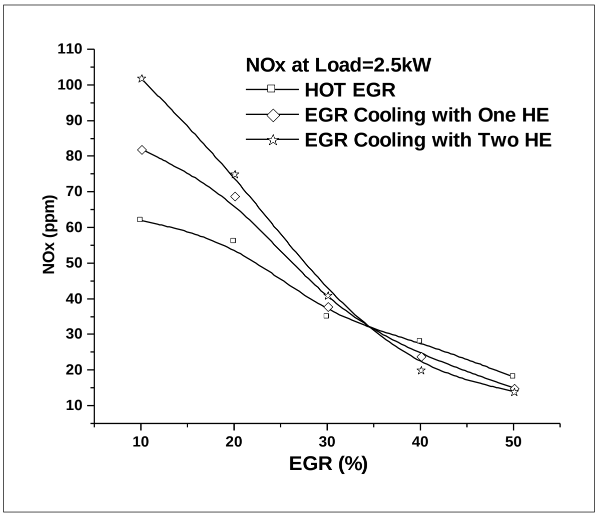

Fig.5. Effect of EGR on NOx emission for three cases of EGR cooling at 2.5 kW load

4.4 EGR and Oxides of Nitrogen, Hydrocarbon, Smoke

EGR is cooled using two heat exchangers to vary the temperature of EGR gas before it was mixed with fresh air. It was possible to attain the EGR temperatures of 37, 46, 56 and 75 degree centigrade. At these temperatures values recorded for NOx, UBHC and smoke are plotted in fig.6 at 40% EGR. It is clear from the plot that smoke percentage tends to decrease with increased EGR temperature. Reduced oxygen availability and presence of exhaust gas constituents during combustion modifies the normal combustion. Combustion tends to be incomplete and further deteriorates as the percentage of EGR increases.

Percentage of oxygen reduces as the inlet EGR temperature increases tending the combustion to be incomplete emitting more HC in the exhaust. Even though EGR reduces the engine out NOx emission, it is clear from the plot that NOx amount increase as the temperature increase for the same percentage of EGR. This result vindicate that NOx is temperature sensitive.

4.5 EGR and Thermal Efficiency

Thermal efficiency decreases as EGR percentage increase for all cases of EGR cooling. It is observed that cooling of EGR slightly improves the efficiency after 30% EGR. Engine torque and brake power slightly reduces as percentage EGR increase for all cases of EGR cooling. For hot EGR this is more pronounced as more compression work is required to compress expanding hot gas. Fuel consumption also increases to govern the constant engine speed. With lower torque and increased fuel consumption tend to reduce the thermal efficiency. Increased temperature of EGR reduces availability of oxygen due to increased thermal throttling. The lack of oxygen effects mixing time and normal combustion as well. The difference in thermal efficiency becomes noticeable after 30% EGR. It was shown in the previous figure that amount of oxygen reduce as percentage of EGR increase Increased amount of burnt gases (EGR), increased mixing time and poor combustion as a consequence of reduced availability of oxygen with higher percentage of EGR make thermal efficiency to slightly reduce after 30% EGR. This is shown in fig.7.

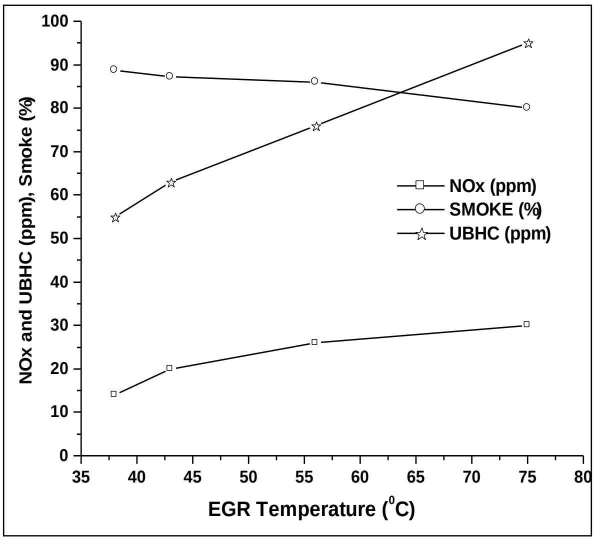

Fig.6. Effect of EGR temperature on NOx, HC and smoke emission at 2.5 kW load and 40% EGR

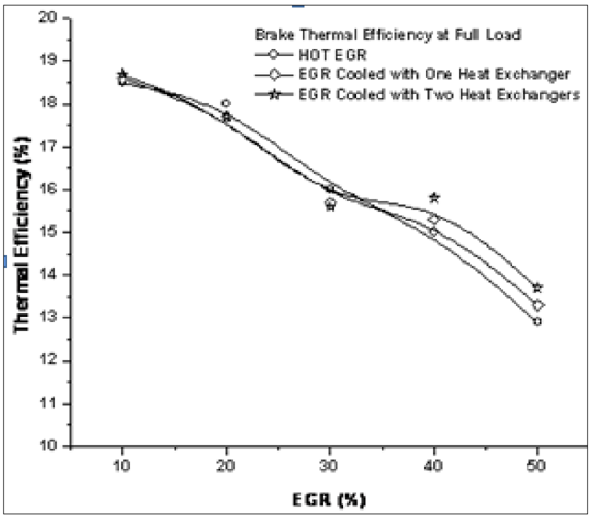

Fig.7. Effect of EGR on Thermal Efficiency for Three Cases of EGR Cooling at 2.5 kW load

4.6 EGR and Thermal Efficiency, NOx, Air Fuel Ratio

In the fig.8, thermal efficiency, NOx and AFR are compared between no EGR and three cases of EGR cooling.

Reductions in NOx emissions are remarkable at all loads amounting up to 88% at full load and 40% EGR. NOx reductions are more for hot EGR as compared to cooled EGR due reduced O_2 concentrations (Dilution Effect) up to around 35%. But after that this reductions slightly reverse. This may be because of the steep rise inlet charge temperature for hot EGR after 35% EGR. This increased charge temperature favors the formation of NOx as compared to cooled EGR. 88% reduction in NOx results in to a loss of 18% in thermal efficiency.

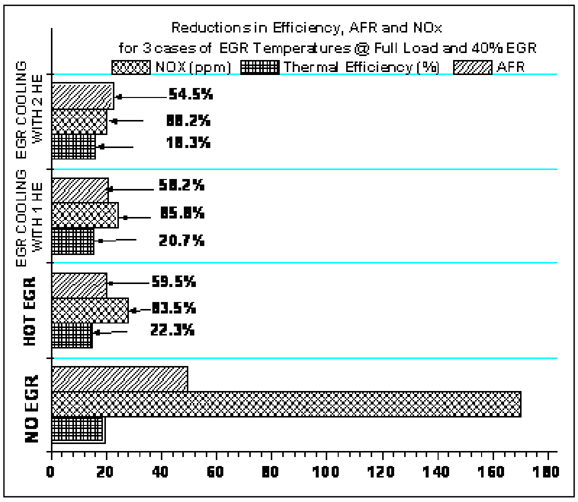

Fig.8. Comparison of efficiency, NOx and AFR for three cases of EGR cooling at 2.5 kW load

5. CONCLUSION

The results demonstrated are for the DI Diesel engine running at constant speed which is a common feature of stationary engine applications. The objective of the study was intended to study the effect of EGR temperature on emission and performance. The main emphasis was on NOx and thermal efficiency. EGR cooling results in to a remarkable overall reduction of dangerous NOx emission up to 88.2%. Up to around 35% of EGR, cooling of EGR does not show appreciable results in terms of NOx and thermal efficiency but cooling become significant thereafter. Results plotted in fig.8 indicate an improvement in thermal efficiency and increased percentage of NOx reductions for 40% EGR and at full load. Beyond 35% EGR a sharp increase in gas temperature takes place, higher gas temperature with reduced availability of oxygen amount together tend to deteriorate the combustion quality resulting in to reduced thermal efficiency and increased NOx emission for hot EGR. When higher percentage of EGR required to be admitted (above 35%), EGR cooling becomes more effective when compared to hot EGR.

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