International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.2, Issue.4, July-Aug. 2012 pp-1486-1491 ISSN: 2249-6645

Diesel Emission Control by Hot EGR and Ethanol Fumigation; an Experimental Investigation

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ABSTRACT: *Exhaust Gas Recirculation has emerged as one of the promising technique in abating oxides of Nitrogen but combustion quality deteriorates at higher loads and higher percentage of Exhaust Gas Recirculation do not become attractive owing to decreased efficiency and increased hydrocarbon and smoke. Another technology that offers promise of being able to reduce engine emissions is alcohol fumigation. An experimental investigation is carried to examine the performance and emission with alcohol fumigation in the presence of hot Exhaust Gas Recirculation on a single cylinder DI diesel engine. The main focus was on oxides of nitrogen, hydrocarbon and smoke emission and variations in thermal efficiency. Results pertaining to Exhaust Gas Recirculation showed greater reductions in NOx emission. The reductions in the efficiency were marginal (about 5%) up to 30% Exhaust Gas Recirculation but tend to increase amounting up to 30 to 40% at higher loads and higher percentage of Exhaust Recirculation (above 30%). Hydrocarbon concentrations and smoke percentage also simultaneously increased indicating poor combustion. Alcohol fumigation in presence of hot Exhaust Gas Recirculation comparatively improved the thermal efficiency with simultaneous reduction in concentrations of HC and smoke level. Results pertaining to only diesel, diesel with Exhaust Gas Recirculation and Exhaust Gas Recirculation combined with ethanol fumigation without reducing diesel injections are presented in this paper.*

***Key Words*:** EGR; Ethanol; Fumigation; NOx; Smoke; HC; Efficiency; Dilution effect

I. INTRODUCTION

Exhaust emissions from diesel engines are substantial source of air pollution. In recognition of this fact, the regulating authorities of all countries implemented strict regulations which are in effect since 1991. Unfortunately single technology is currently not available to meet these regulations without penalties in engine performance and efficiency. Application of various motor vehicle emission control technologies has established a history of success. This success, however, has largely been offset by the constantly growing numbers of vehicles and miles traveled. Heavy-duty diesel engine manufacturers have developed new technologies in response to increasingly stringent emission standards. The diesel engine has long been a champion of fuel economy, with advantages in reliability and durability over other power plants. Yet, controlling NOx, and particulate emissions has been a formidable challenge to the diesel industry because most traditional NOx, control approaches tend to increase particulate emissions, and vice versa. Many development programs carried out over the last five years have yielded remarkable results in laboratory demonstrations. Traditionally, design changes aimed at reducing one of exhaust species have led to an increase in the other. Exhaust Gas Recirculation, EGR, is one of the most effective means of reducing NOx emissions from diesel engines and is likely to be used in order to meet future emissions standards. The main difficulties with these techniques are to meet the requirement for NOx and at the same time minimize the fuel penalty.

I. 2. ETHANOL AS MOTOR FUEL

Historically ethanol and methanol have been used as automotive fuels for long time, both as neat fuels and as blend components chiefly in gasoline engine. Nikolaus Otto, the father of the Otto engine, regarded ethanol as an attractive fuel for combustion engines and in 1908 Henry Ford started the construction and production of an ethanol fuelled engine and claimed that alcohol could be an automotive fuel for the future. Although replacing diesel fuel entirely by alcohols is very difficult, an increased interest has emerged for the use of alcohols, and particularly lower alcohols (methanol and ethanol) with different amounts and different techniques in diesel engines as a dual fuel operation during recent years. Ethanol or ethyl alcohol was used as quality motor fuel in the first automobile, the original Ford Model-T and after that it is only recently that interest was shown in the use of ethanol and methanol as diesel fuels. It is reported that about 80% proof ethanol is optimum as higher proofs do not give as much reductions in oxides of nitrogen emissions [1-2].

II. DIESEL NO_X FORMATION AND EFFECT Of EGR

NOx is formed by an endothermic reaction in the burned gas regions of the cylinder. The formation of NOx is very sensitive to temperature. The higher flame temperatures accompanying early or rapid combustion greatly increase NOx formation [3]. Thus the amount of NOx in diesel exhaust is sensitive to flame temperature. Availability of oxygen and burn duration are the other two reasons for the formation of NOx[3]. Dilution of the charge by rerouting a part of the exhaust gas (EGR) reduces the availability of oxygen on one hand and reduces the flame temperature on the other, owing to higher specific heats of EGR lased constituents like H_2O and CO_2 [4-9]. Thus presence of exhaust gas during combustion helps in abating the formation of NOx but higher percentage of EGR deteriorates the combustion quality thereby causing incomplete combustion [7].

III. DIESEL COMBUSTION WITH ETHANOL

Local mixture formation, self-ignition and combustion needs time to be completed. Not-complete combustion of diesel fuel is a source of hydrocarbon emission and smoke. In order to avoid this inconvenient effect, injection of ethanol to inlet duct is considered [10]. Ethanol will quickly evaporate (but will not self-ignite), and will be ignited by burning diesel droplets resulting in very high combustion rate of both fuels, especially diesel fuel. With higher combustion rate higher thermal efficiency, higher power output and lower emission of HC and smoke are expected. Hence, the combined effect of ethanol fumigation (without reducing the amount of diesel being injected) and EGR is expected to reduce NOx with marginal loss of efficiency when compared to use of EGR alone.

IV. TEST ENGINE

Table.1. Specification of the test engine

Type	4-Stroke, Single Cylinder Diesel Engine(Water Cooled)
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: 2000 PSI.
Starting	Auto Start.
Orifice Diameter for air flow	15mm

The test engine is Kirloskar AV1 engine facilitated with data acquisition systems (DAS) for recording engine data measurement. External EGR is routed into the intake manifold through a one inch diameter GI pipe. The EGR line emerges right after the exhaust manifold from the engine and enters the in the intake manifold close to engine. Fresh air and EGR are made to mix before it enters into engine cylinder. An orifice meter is used to determine the flow rate of EGR. The reported percentage of EGR is defined as the volumetric ratio of the recirculated gas to the total charge induced in to the cylinder. AVL smoke meter is used to measure the smoke level and INDUS® 5 gas analyzer for O_2, CO, CO_2, HC and NOx measurements.

Details of the test engine are given in **table 1**. The ethanol fumigation is achieved through an additional injector attached just before the inlet manifold, inclined and in opposite direction to EGR flow.

The injection pump is driven by the cam shaft of the engine. Cam is so designed to inject the ethanol in 5, 10, 15 and 20% of total amount of diesel injected in a cycle for a given load. This arrangement is shown the **fig.1**.

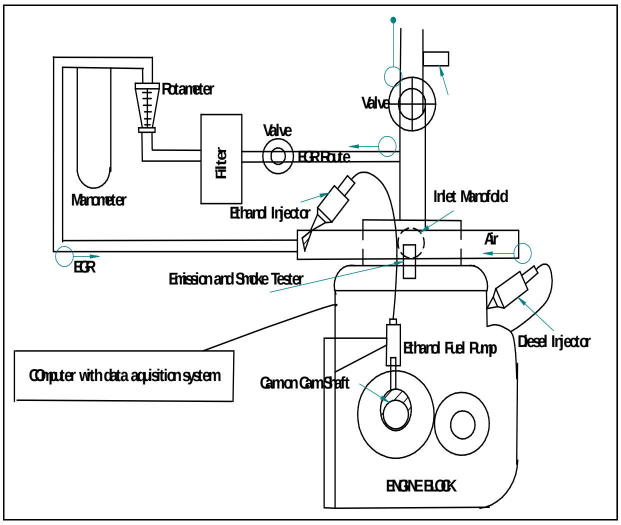


Fig.1 Test engine layout.

V. RESULTS AND DISCUSSIONS

5.1 Engine Torque

As expected injecting ethanol will increase the torque (adds energy) as amount of diesel injected is not reduced. In the **fig.2**, the trend of torque at part load of 1.5 kW and maximum load of 2.5kW for 5, 10, 15 and 20% ethanol fumigation are compared with those corresponding to only hot EGR. Torque values for 5%, 10% and 15% ethanol fumigation are higher as compared to hot EGR for both part and full load but for 20% values reduce. At full load torque is almost same for 5, 15 and 20% ethanol fumigation and hot EGR for all percentage of EGR. 10% fumigation gives the optimum results for all values of load and EGR percentage.

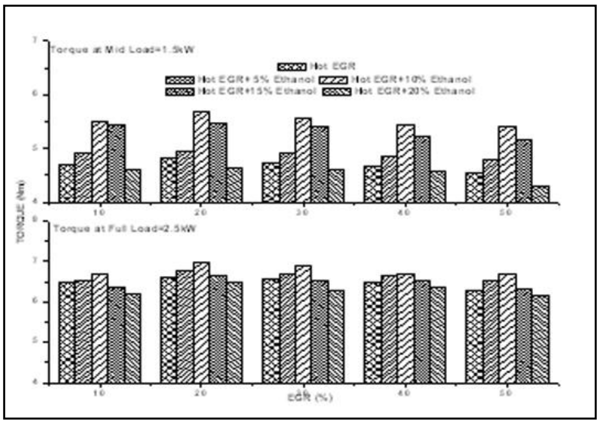


Fig.2; Comparison of engine torque for part load (1.5kW) and full load of (2.5kW) for increasing percentage of EGR

5.2 Thermal Efficiency

Thermal efficiency is a measure of engine output power and fuel consumption. For an engine operating at constant speed, the torque increase as the load increase. Ethanol fumigation improves the efficiency when compared to corresponding values of hot EGR for all loads.

The thermal efficiency values are comparatively better for 5% and 10% ethanol fumigation as compared to higher dose (fig.3). Fig (4) depicts the results of thermal efficiency for part load (1.5kW) and full load (2.5kW) for 10 to 50% EGR. The variation in thermal efficiency is negligible up to 30% EGR and tends to slightly decrease thereafter particularly for only hot EGR case. Ethanol fumigation along with hot EGR shows improved efficiency in this region.

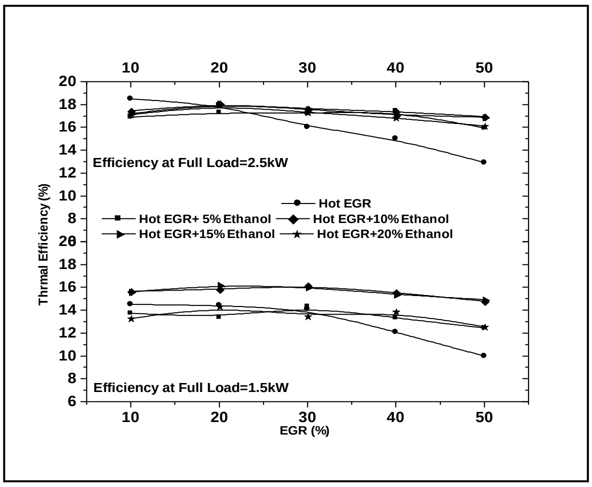


Fig.3. Engine thermal efficiency for 50% and40% EGR for increasing load.

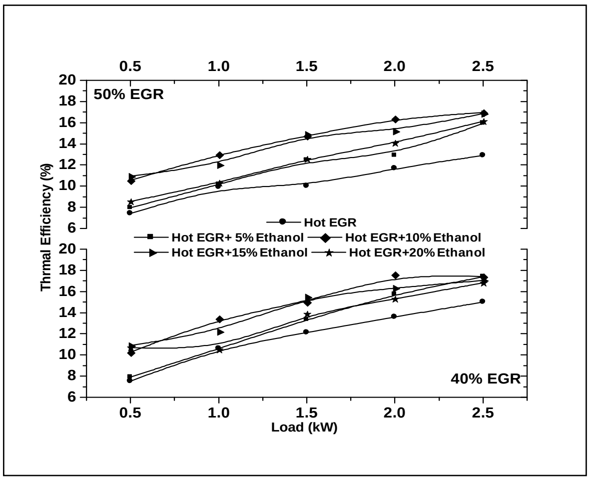
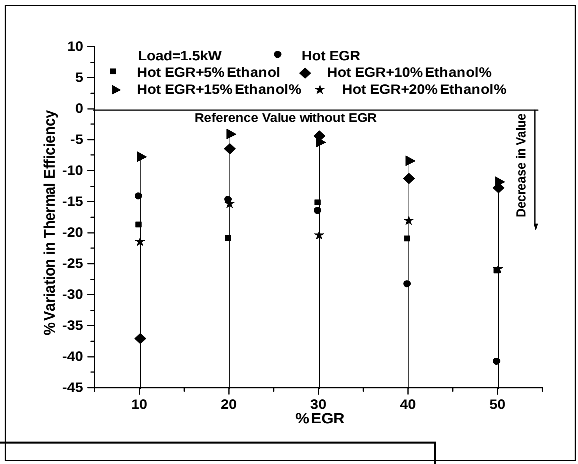
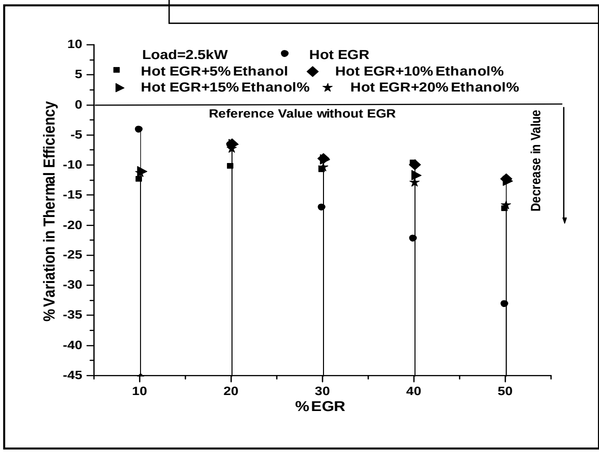


Fig.4; Engine thermal efficiency for different EGR percentage at part load (1.5kW) and full load(2.5 kW).

The fig(5) and Fig.(6) show the comparison of variation in thermal efficiency in percentage for three different cases; (i) Hot EGR. (ii) Hot EGR with different





percentage of ethanol fumigation and (iii) Only diesel, which is taken as reference. It is clear that thermal efficiency reduces for both ethanol fumigation with EGR and hot EGR when compared with only diesel case. However for ethanol fumigation with EGR, these percentage losses are less and values are more close to reference values. The loss in efficiency is limited to around 20% for fumigation case where as it is up to 40% for without fumigation case. Another observation is that loss of efficiency is very marginal (around 5%) for up to 10% ethanol fumigation and then it slightly increases (around 20%) as the fumigation percentage increases.

Fig.5; Percentage variation in engine thermal efficiency for different EGR percentage for part load of 1.5kW.

Fig.6; Percentage variation in engine thermal efficiency for different EGR percentage for full load of 2.5 kW.

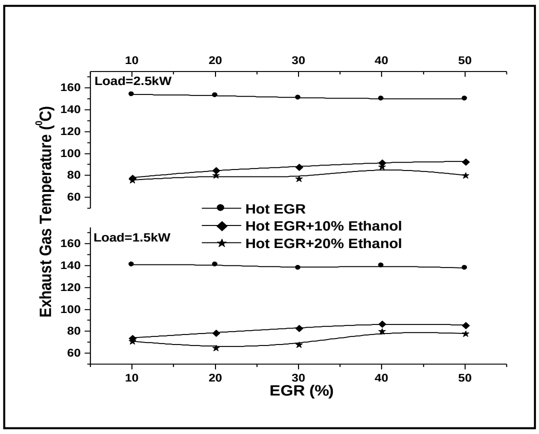


Fig.7; Engine exhaust gas temperature for part load of 1.5kW and full load of 2.5 kW against different percentage of EGR.

5.3 Flame temperature

Ethanol with their greater latent heat of vaporization gives a higher charge density; and their higher laminar flame speed allows them to be run with leaner, or more dilute, air/fuel mixtures [10].

In ethanol and air mix combustion more moles occur than in diesel combustion, therefore the torque increases (Fig.2). On the other hand, triatomic gas is more susceptive to the heat, which will be taken from the working fluid present in the cylinder, thus decreasing the temperature in the combustion chamber and exhaust gas as well. The engine exhaust temperature as an indicative of combustion temperature (Fig.7) for hot EGR and ethanol fumigation with EGR for part and full load vindicate this.

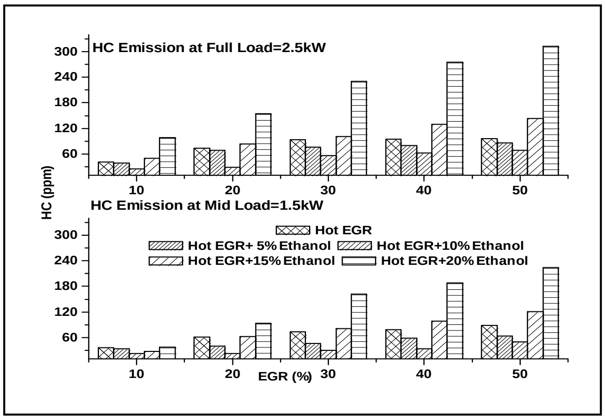
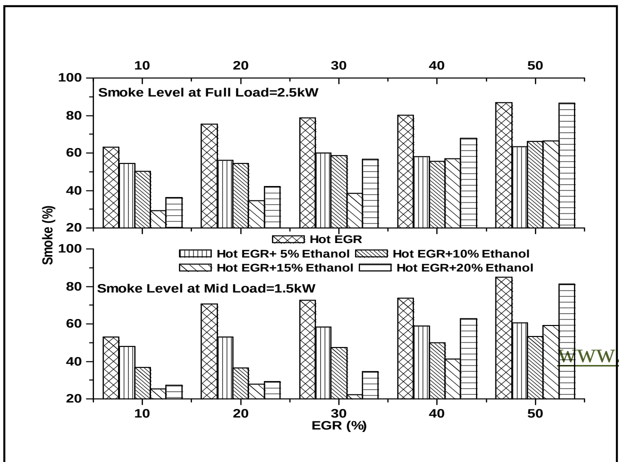


Fig.8; Emission of Unburnt Hydrocarbon emission



for part load of 1.5kW and full load of 2.5 kW against different percentage of EGR.

5.4 Hydrocarbon Emission

Emission of HC in the engine tail pipe is mainly a result of incomplete combustion. Presence of burnt gas (EGR) causes reduced availability of oxygen due to thermal throttling [5, 6, and 12].

Fig.9; Smoke emission for part load of 1.5kW and full load of 2.5 kW against different percentage of EGR.

Ethanol fumigation during intake is expected to supply oxygen as ethanol in comparison to diesel fuel contains some oxygen atoms. Ethanol molecules contain 35 percent oxygen, and serve as an "oxygenate" to raise the oxygen content and emission of HC and smoke are expected to be low with ethanol taking part in the combustion.

This is found true even in the presence of EGR during the combustion but only up to 10% fumigation and there after for 15% and 20% ethanol dose HC concentration increased even more than the values corresponding to only hot EGR. This indicates a poor combustion. Also high HC emissions due to higher dose of alcohol were probably caused by very strong quenching effect due to its high latent heat of evaporation and low centane number.

5.5 Smoke Emission

Smoke is a result of condensation of hydrocarbon and presence of soot. Soot, particulate (smoke) is formed mostly through incomplete combustion of fuel, with small contributions from the lubricating oil [11], more difficult pulverisation of the heavy diesel droplets and non-homogeneous distribution of the diesel fuel over the combustion chamber.

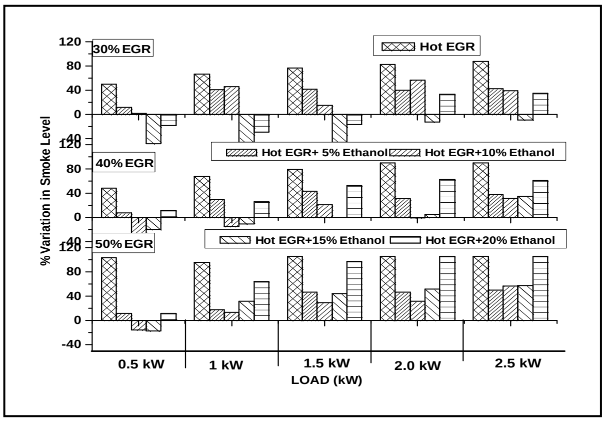


Fig.10; Percentage variation in smoke different engine load for 30%, 40% and 50% EGR

As the fuel in the advancing flame plume combusts, pyrolytic reactions crack the hydrocarbons that have yet to pass through the flame. As these reactions occur, particulate masses form. If the fuel mixing is poor within the cylinder, large quantities of particulates can form [2]. Typically, above temperatures of 500^0C, the particles are composed solely of clusters of carbon, while at temperatures below this; higher molecular weight hydrocarbons condense onto the clumps. As the particulates travel through the flame and into the more heavily oxygen populated areas, the clumps tend to oxidize and for this reason concentrations are reduced in the leaner regions of combustion. The presence of ethanol favors oxidation process and smoke level is expected to reduce and literatures suggest that ethanol is best fuel to minimize smoke and particulate matters.

Fig. (9&10) indicate Hot EGR emit more smoke as compared to EGR with ethanol fumigation. As fumigation quantity is increased from 5% to 15% the smoke level tend to decrease remarkably. But further increase in fumigation of ethanol records slightly higher values mainly due to reduced temperatures where soot oxidation is hampered and also due to deteriorated combustion. Smoke levels are found nearly same or even less for ethanol fumigation with EGR when compared to only diesel case (taken as reference) up to 30% EGR for both part load (1.5kW) and full load (2.5 kW) and thereafter its values start climbing for higher loads. This result is obvious as HC concentrations (Fig.8) show similar trend.

5.6 NOx Emission

Diesel NOx emissions result from the thermal fixation of atmospheric nitrogen and its oxidation in the presence of high combustion temperature. Control of these emissions can be achieved by reducing the peak flame temperatures

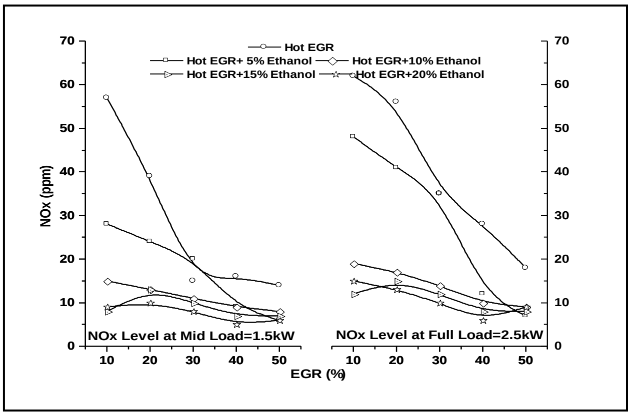


Fig.11; NOx emission for part load of 1.5kW and full load of 2.5 kW against different percentage of EGR.

EGR reduces the peak temperature by diluting the charge with burnt exhaust gas. Higher NOx emission reductions can be achieved through higher percentage of EGR but results into a loss in thermal efficiency and increased HC and CO emission especially at higher EGR values and higher loads. Alcohols generally give lower fuel heat release rates, resulting in lower NOx emissions. With fumigation of ethanol in the presence of EGR enables admit more percentage EGR with greater reductions in NOx along with comparatively lower emissions of HC and smoke. Fig. (11) show the reductions of NOx for part load and full load with and without ethanol fumigation. NOx concentration remains low for ethanol fumigation case as compared to without fumigation for entire range of EGR percentage.

VI. CONCLUSION

It can be concluded from the results obtained from the experiment that

1. EGR method to abate NOx emission is very effective. The disadvantage is decreased efficiency and increased HC and Smoke with higher percentage of EGR and at higher loads.
2. Ethanol fumigation without altering the diesel injection proves to be a better option in reducing HC, smoke and NOx apart from improving the engine thermal efficiency.
3. Ethanol fumigation above 10% tends to increase HC and smoke emissions when compared to corresponding values for 5 and 10% , however these values are very less as compared to use of EGR without ethanol fumigation.
4. 10% ethanol fumigation with HOT EGR is a better option for higher percentage of EGR to be used with maximum reductions in NOx emissions with marginal loss of efficiency.

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