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Reduction of Nitrogen Oxides Emissions in a Single Cylinder Compression Ignition Engine Using Cool Exhaust Gas Recirculation System

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ABSTRACT

In various countries around the world, the emissions of NO_X from petrol/gasoline and diesel engine vehicles are restricted by legislation. NO_X is produced in the combustion chamber of engines at high temperatures and high pressure. One of the most promising technology for effective control of NO_X emissions is Exhaust Gas Recirculation (EGR) and now most modern engines require exhaust gas recirculation to meet emission standards. EGR lowers the presence of oxygen concentration and burn temperature in the combustion chamber and hence controls the NO_x. The experimentation was carried out on a 5.2 kW of single cylinder four stroke direct injection diesel engines in computerized mode to investigate the performance, emissions and combustion parameters at different EGR ratios (10, 20 and 30%). From the results, O_2, NO_X and exhaust temperatures are found to be reduced whereas HC and CO emissions are increased as the EGR concentration increases.

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NOMENCLATURE

EGR	Exhaust Gas Recirculation
DI	Direct Injection
ppm	parts per million
H_2O	Water Vapor
NO_X	Oxides of Nitrogen
O_2	Oxygen
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
PM	Particulate Matter
HC	Hydrocarbon
N_2	Nitrogen
NO	Nitric oxide
CO	Carbon Monoxide
NHRR	Net Heat Release Rate
CO_2	Carbon dioxide
CA	Crank Angle
CI	Compression ignition

INTRODUCTION

One of the crux in development of internal combustion engines is the reduction in engine out emissions. As the individual mobility in the earth is growing and the transportation sector is increasing, it is significant to limit the impact of traffic on the environment and the health of the population. Diesel fueled engines are considered as much reliable remote production of power in areas where centralized power transmission is difficult, and as well as for operating the farm equipment because of their cheaper cost of fuel, simplified operations and ruggedness in production. These engines are good viable alternate to gasoline fueled engines because recently they turn out lesser amount of emissions [1, 2].

The major critical products of diesel exhaust includes oxides of nitrogen (NO_X), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter (PM) are harmful while products like oxygen and water vapor are harmless [3, 4]. NO_X causes a broad

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variety of health and environmental impacts because of assorted compounds and derivatives in the relation of nitrogen oxides, including nitric acid, nitrogen dioxide, nitrous oxide, nitric oxide and nitrates [5]. Nitrogen dioxide is an irritant, which at high concentrations causes inflammation of the respiratory tract. When nitrogen is combusted inside the engine it mixes with oxygen atoms to form nitric oxide (NO) and nitrogen dioxide (NO_2). At ambient conditions NO_2 is much harmful than NO. Nitric oxide and nitrogen dioxide are together called as oxides of nitrogen (NO_X) [6]. NO_X gases are responsible for the formation of smog and acid rain as well it became a central core for the formation of ground level ozone and fine particles, both of which are related with adverse health effects.

Exhaust gas recirculation (EGR) in diesel engines

To avoid harmful emission of NO_X, there are different techniques that are proposed to reduce oxides of nitrogen (NO_X) from diesel engines; EGR, fuel denitrogenation, retarded injection timing, water injection, staged injection of fuel, decrease of pre-mixed burn by reducing ignition delay and exhaust catalysts. Out of all these proposals, the most effective and easily practicable technique for internal combustion engines is EGR [7]. In general, by increasing the EGR rate influences the internal combustion engine in different ways like thermal effect, chemical effect and dilution effect. *Thermal effect*: Results into decrease in the combustion gas temperature due to increase of inlet specific heat capacity of EGR gases of carbon dioxide CO_2 and water vapor (H_2O) compared to O_2 and N_2.

Dilution effect

The outcome is the reduction of the oxygen gas and its effects on kinetics of the elementary nitric oxide formation reactions. *Chemical effect*: The recirculation of carbon dioxide (CO_2) and water vapor (H_2O) are separated during combustion and then it modifies the combustion process and the NO_X formation. The endothermic dissociation of water vapor (H_2O) results in decreasing the flame temperature, increase the soot formation, increase the ignition delay and lower the combustion temperatures.

Because of cylinder liner and piston ring wear, the implementation of EGR is difficult in heavy duty diesel engines [8].It is majorly identified that sulfur oxide in the exhaust gas causes the wear. The results shows that the sulfur oxide concentrations in the oil layer is more powerful to the EGR rate, inverse with engine speed and under light load conditions. It was also known that as the carbon dioxide levels are increases with the EGR, the combustion noise levels also increases [9]. The use of EGR can also badly effects on lubrication and engine robustness.

Experimental setup

The engine setup consists of single cylinder, four strokes, diesel engine connected to eddy current type dynamometer for loading is shown in the Fig. 1. It is provided with necessary instruments for crank-angle measurements and combustion pressure. The signals are interfaced to computer through engine indicator for P – theta, and P - V diagrams. Provisions are also made for interfacing fuel flow, airflow, load measurement and temperatures. The setup has stand-alone control panel box consisting of fuel tank, manometer, air - box, fuel measuring unit, fuel flow measurements and transmitters for air, engine indicator and process indicator. Rotameters are provided for cooling water and calorimeter water flow measurement. This setup enables to study the engine performance. The technical specifications of the computerized engine, eddy current and pressure sensors are given in Table 1.

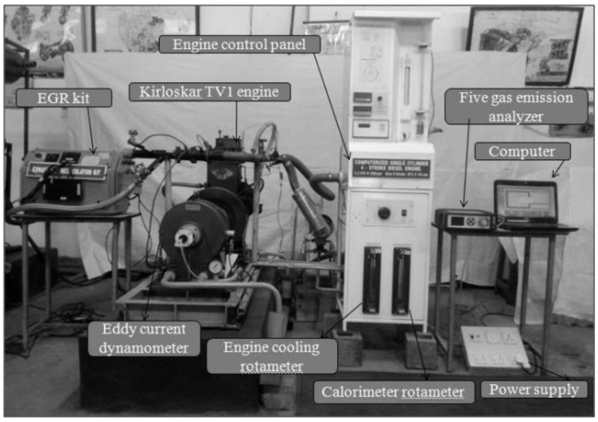

Figure 1. Experimental setup

TABLE 1. Specification of the engine

Engine parameter	Specification
Make of model	Kirloskar TV1 engine
Engine type	Four stroke, water cooled, single cylinder, DI diesel engine
Power	5.2 kW
Bore (mm)	87.5
No. Of cylinder	1
Connecting rod length (mm)	234
Compression ratio	17.5:1
Stroke (mm)	110
Rated power at 1500rpm (kw)	5.2
Nozzle opening pressure (bar)	200
Nozzle spray hole diameter (mm)	0.28

EGR kit connection system

EGR system used to control exhaust gas recirculation is fully automatic and computer controlled setup. The connections of EGR to the computer are shown in the Fig. 2. Although there was no restriction on percentage exhaust gas recirculation, we restricted our investigations up to 30% only with the denominations of 10% at each time. The cooling water is being used to cool the recirculated exhaust to the ambient conditions.

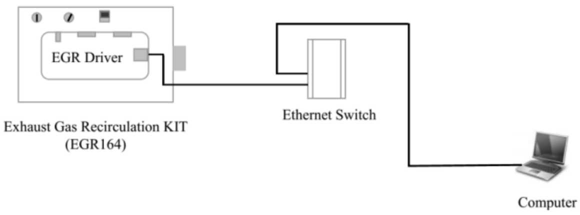

Figure 2. Schematic of EGR kit

RESULTS AND DISCUSSION

The Computerized single cylinder naturally aspirated diesel engine was run on different loads at constant speed of 1500 rpm with different EGR rates (10%, 20% and 30%) to investigate the effect on engine performance, combustion and emission characteristics. These characteristics were analyzed and presented for Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), exhaust gas temperature, cylinder pressure heat release rate, NO_X, CO, HC, O_2 and CO_2.

Engine performance and Combustion:

The Brake Thermal Efficiency (BTE) is almost increasing at all part – loads of an engine with EGR (Fig. 3). This could be attributed for re-burning of unburned hydrocarbons and possible running of engines with relatively lower equivalence ratios. Low concentrations of CO_2, and partially cooled EGR which could preheats the incoming air also helps in complete combustion and increase in efficiency at part loads.

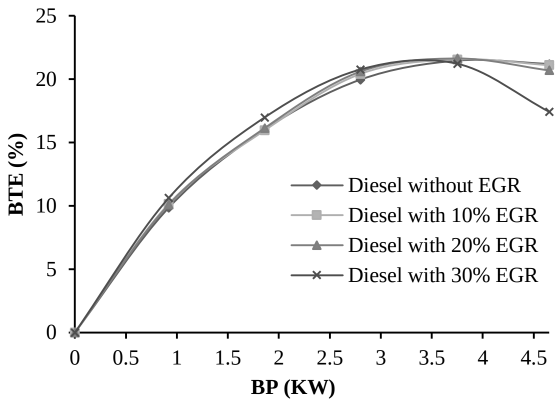

Figure 3. BTE vs BP (Brake horse power)

As the EGR concentration increases there is a reduction in BTE is found at near full load conditions. Higher concentrations of CO_2, reduction in combustion chamber temperature, oxygen and hence absence in the re-burning of HC are responsible in the deterioration of efficiency at higher loads.

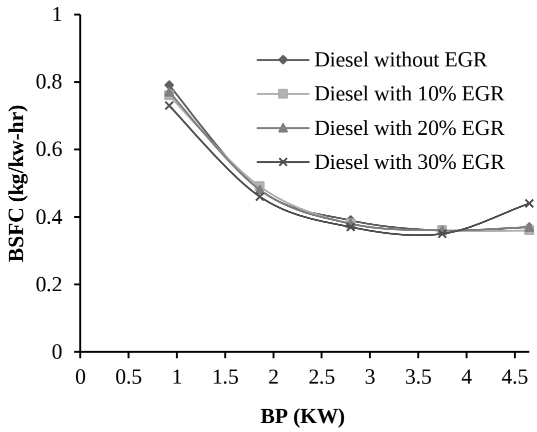

Figure 4. BSFC vs BP

The variations of Exhaust Gas Temperature (EGT) with respect to engine BP is shown in Fig. 5. In general the EGT increases with increase in engine loading. Exhaust temperature difference is observed as the engine was running with EGR and it decreases with increasing the EGR rate. This could be the effect of not sufficient O_2 for combustion and higher specific heats of combined O_2 and CO_2.

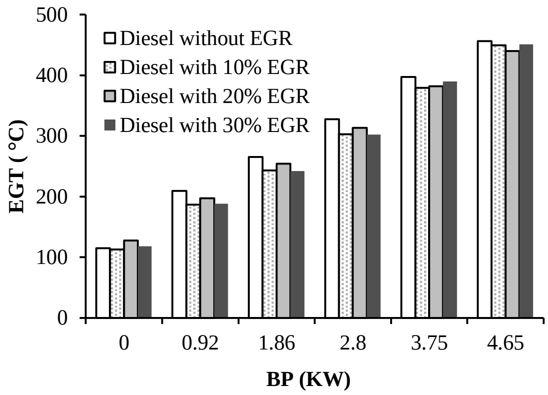

Figure 5. EGT vs BP

The variations of Exhaust Gas Temperature (EGT) with respect to engine BP is shown in Fig. 5. In general the EGT increases with increase in engine loading. When the engine is operated with EGR, the temperature of exhaust gas is usually lower than temperature of exhaust gas at normal operating condition. Exhaust gas temperature decrease with increase in EGR rate. The critical reasons for temperature reduction are relatively lower availability of O_2 for combustion and higher specific heats of combined O_2 and CO_2.

From Fig. 6, it is seen that the combustion chamber pressure is decreased with the increasing the EGR addition. EGR delays the start of combustion, increases the heat release suddenly and however, eventually lowers the combustion pressure with the absorption of released heat.

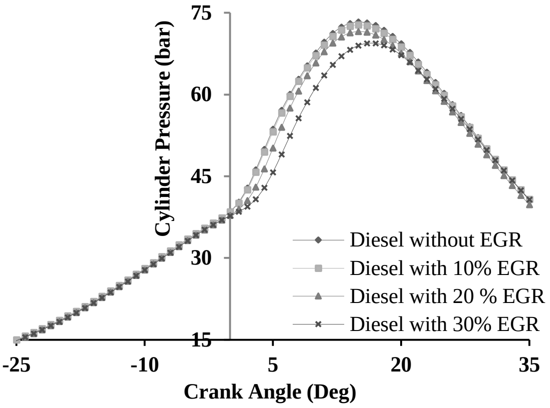

Figure 6. Cylinder pressure vs CA at Full BP

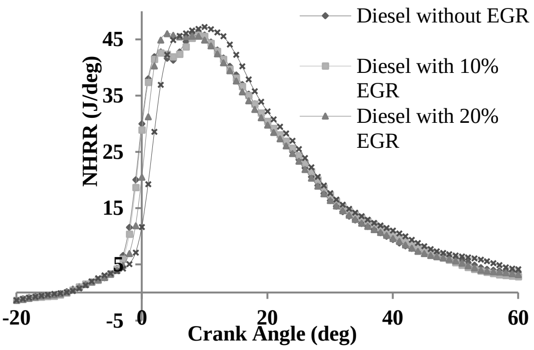

Figure 7. NHRR vs CA

Fig. 7 shows the variation of Net Heat Release Rate (NHRR) with crank angle for diesel at near full BP condition. The heat release rate is mainly used to identify the fraction of fuel burned in the premixed mode, the start of combustion and differences in combustion rates of fuels [10]. At near full engine load, the continuous reduction in oxygen availability in the combustion chamber with rising of the EGR rate deteriorates the main combustion process, which increases the ignition delay and the premixed portion of main combustion start to rises drastically. So the peak of heat release is increased with high exhaust gas recirculation rate.

Engine emission analysis:

A five gas exhaust analyser (AVL make of DIGI 444) has been used for the analysis. Percentage of improvement or reduction from the zero percentage EGR have been plotted on Y-axis with respect to BP. The negative Y-axis means the percentage reduction. The unburned hydrocarbon emission trends for different EGR rates for diesel shown in the Fig. 8. We knew that as the content of oxygen and cetane number is reduced the unburned hydro carbons are increased [11].

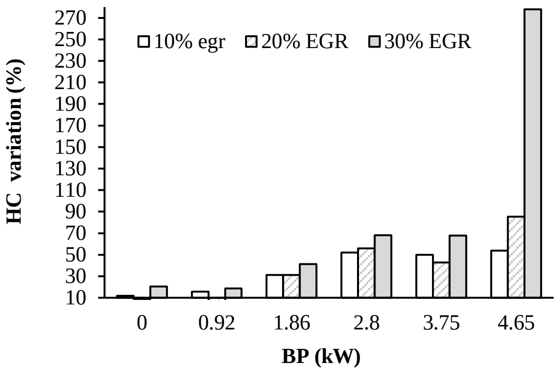

Figure 8. HC vs BP

Unburned hydrocarbon emissions are a very useful measure of combustion inefficiency. Unburned hydrocarbon emission consists of fuel that is incompletely burned. From the figure it is seen that as the EGR percentage is increased the unburned hydrocarbons are increased this is caused by reduction of oxygen in the inlet charge. The lack of O_2 is responsible for reduction oxidation rate, which leads to higher incomplete combustion.

The variations of carbon monoxide emissions with BP and also with various EGR percentages is depicted in Fig. 9. Generally, CI engine operates with lean mixture and hence the CO emission would be low. CO emission is toxic and must be controlled. At full load condition, emission of CO is therefore greatly reliant on the air fuel ratio relative to the stoichiometric proportions. Rich mixture invariably produce CO and emission raise linearly with the deviation from the stoichiometry.

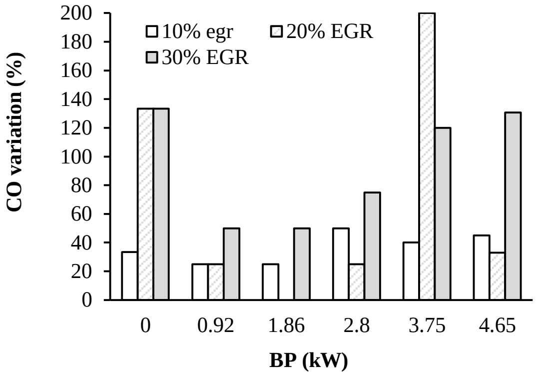

Figure 9. CO vs BP

Fig. 10 shows the variation of oxides of nitrogen emissions with BP and also with various EGR percentages is depicted. Generally, the oxides of nitrogen emission tend to reduce drastically with an increase in EGR quantity at all load conditions and this reduction as a result of the presence of inert gases (water and carbon dioxide) in the EGR and possess high specific heat. These high specific heat gases absorb heat and reduces the peak combustion process temperature inside the cylinder and it will also reduce O_2 inside combustion chamber. Finally, the lower temperature is the reason to decrease the oxides of nitrogen.

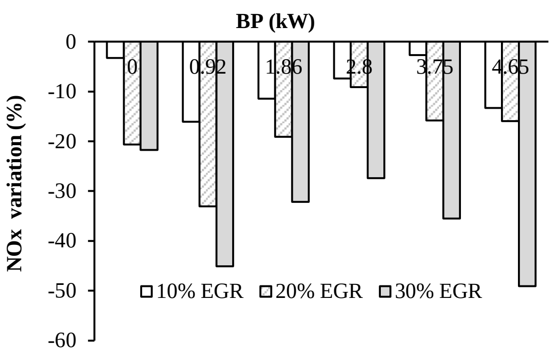

Figure 10. NO_X vs BP

Fig. 11 shows the variation of oxygen with BP and also with various EGR percentages is depicted. The oxygen decrease with increasing the EGR rate. Here the reduction in O_2 concentration in the cylinder curbs NO_X emission. The inert gas (CO_2, H_20 and N_2) in EGR, quenching action of these gases reduces the peak combustion temperature and also reduces the oxygen in the combustion chamber. It concludes that the reduction in temperature, oxygen and NO_X.

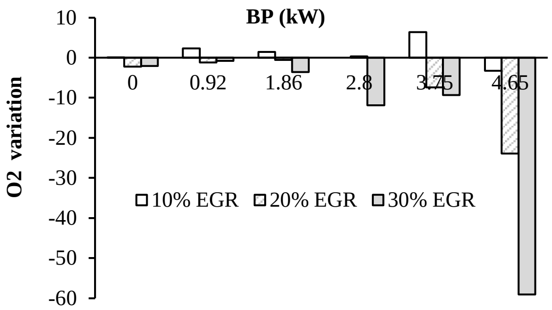

Figure 11. O_2 vs BP

The variation of carbon dioxide with BP and also with various EGR percentages is depicted in Fig.12. The CO_2 emission from a diesel engine shows how proficiently the fuel is burnt inside the cylinder. Here the CO_2 concentration decreases with increasing the EGR rates. At full load of 30% EGR rate CO_2 was reduced due to the late burning of fuel leading to incomplete oxidation of CO. At a few load conditions CO_2 was seen to be decrease due to the instability in combustion and lack of oxygen that makes the CO concentration to CO_2 concentration.

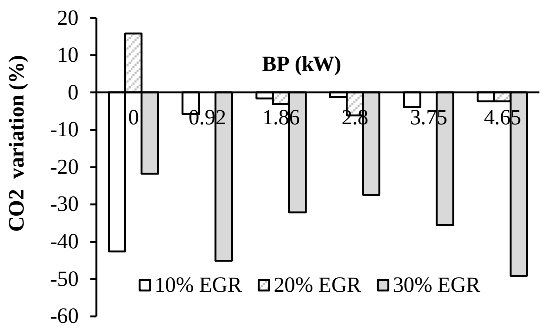

Figure 12. CO_2 vs BP

CONCLUSION

Following are the majors a conclusion drawn from the experimental work was conducted with diesel and with different EGR rates.

- The brake thermal efficiency is found to have slightly increased with increasing the EGR at lower loads. The reason may be the re-burning of unburned hydrocarbons that enter into the combustion chamber with EGR.
- At partial loads, run the engine with EGR , the BSFC is lower as compared to baseline data
- At higher loads condition, BSFC with EGR is almost similar to that of without EGR. At high load, amount of diesel supplied to the cylinder is increased at higher rate and O_2 available for combustion gets reduced. Thus, air fuel ratio is changed and increases the BSFC, mostly for EGR 30% at high load condition was increased due to the rich mixture.
- Exhaust gas temperature decrease with increase in EGR rate and this is due to lesser oxygen available for combustion in chamber.
- At full load condition, introducing the exhaust gases it will absorbs the heat energy released by the combustion which lower the combustion chamber pressure.
- At full engine load, the continuous reduction in oxygen availability in the combustion chamber with rising of the EGR rate deteriorates the main combustion chamber process, which raises the ignition delay and the premixed portion of main combustion start to rises drastically. So the peak of

heat release is increased with high exhaust gas recirculation rate.

- As the EGR percentage is increased the unburned hydrocarbons are increased this is mainly due to the reduction of oxygen in the inlet charge by the EGR into the cylinder. The lack of oxygen is responsible for reduction oxidation rate, which leads to higher hydrocarbon incomplete combustion.
- At full load condition, emission of carbon monoxide is therefore greatly dependent on the air fuel ratio relative to the stoichiometric proportions. Rich mixture invariably produce CO and emission increase linearly with the deviation from the stoichiometry.
- The reduction in NO_X emission with increase in EGR percentage may be due to the presence of inert gas (nitrogen, water and carbon dioxide) in the exhaust gas recirculation and possess high specific heat.
- The oxygen reduces with increasing the EGR rate. Here the reduction in oxygen concentration in the cylinder suppresses oxides of nitrogen emission. The inert gas (CO_2, H_20 and N_2) in EGR, the gases absorb energy released by combustion process which reduces the peak combustion temperature and also replaces the oxygen in the combustion chamber.
- Here the CO_2 concentration decreases with increasing the EGR rates. At full load of 30% EGR rate CO_2 was reduced due to the late burning of fuel leading to incomplete oxidation of CO.

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Persian Abstract

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چکیده

در کشورهای مختلف در سراسر جهان، انتشار NO_x از بنزین/گازوییل و موتور دیزل وسایل نقلیه با تصویب قانون محدود شده است. NO_x در محفظه احتراق موتور در دماهای بالا و فشار بالا تولید می‌شود. برای جلوگیری از NO_x، چرخش گاز اگزوز یک فناوری موثر کنترل انتشار است که باعث کاهش قابل توجه انتشار NO_x در بسیاری از موتورهای دیزل می‌شود. با این حال، موتورهای جدیدتر در حال حاضر برای رسیدن به استاندارد انتشار، نیاز به چرخش گاز اگزوز دارند. چرخش گاز اگزوز (EGR)، NOx را به دلیل کاهش غلظت اکسیژن و دمای سوختن در محفظه احتراق، کاهش می‌دهد. آزمایش بر روی سیلندر تنهای ۵/۲ کیلووات در موتورهای دیزل ۴ زمانه در حالت کامپیوتری شده به منظور بررسی عملکرد، انتشار و احتراق برای نرخ‌های مختلف EGR (۱۰، ۲۰ و ۳۰٪) انجام شد. از نتایج، کاهش در O_2، NO_x و دمای گاز اگزوز مشاهده شده اما با افزایش درصد EGR شاهد افزایش انتشار HC و CO بودیم.