Experimental Analysis of Combine Effect of Exhaust Gas Recirculation (EGR) and Inlet Air Pressure on Performance and Emission of Constant Speed Compression Ignition Engine

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***Abstract*— Concern of environmental pollution and energy crisis all over the world have caused the research attention on reduction of diesel engine exhaust emissions and saving of energy simultaneously. Better fuel economy and higher power with lower maintenance cost has increased the popularity of diesel engine vehicles. Diesel engines are used for bulk movement of goods, powering stationary/mobile equipment, and to generate electricity more economically than any other device in this size range. As we know that the diesel engine are known for their high NOx formation and Exhaust Gas Recirculation (EGR) is being used widely to reduce and control the oxides of nitrogen (NOx) emission from diesel engines. EGR controls the NOx because it lowers oxygen concentration and flame temperature of the working fluid in the combustion chamber. However, the use of EGR leads to a trade-off in terms of soot emissions moreover it exhausted more unburned hydrocarbons (20–30%) compared to conventional engines and it also affect the volumetric efficiency and BSFC of engine performance. The increased in inlet air pressure results in better scavenging and reduced exhaust temperature in the engine, better mechanical efficiency and improved volumetric efficiency. Therefore, by using EGR with pressurized inlet air have different effect on both engine emission such as CO, UHC and NOx and on the engine performance such as BSFC, torque, thermal and volumetric efficiency.**

***Keywords- Exhaust* gas recirculation, Diesel engine, Inlet air pressure, Emission.**

I. INTRODUCTION

Diesel engines are among the most effective engines in the world. Known as strong, economical and robust, they are also recognized for their traditional smoke and high level of nitrous oxides, NOx emissions. The diesel cycle was developed by the German engineer, Rudolf Christian Karl Diesel, considered the first engineer who applied the thermodynamic theory to develop combustion engines. Continuous research and development turned the diesel engine highly efficient. Its application includes propulsion units for ships, train and load vehicles such as buses and trucks besides; it is used as power source in auxiliary machinery, such as emergency diesel generators, pumps and compressors. At the same time, a drawback of diesel engines is that they are harmful to human health and the environment due to pollutant emissions. A Comparison between Otto engines, largely applied to passenger cars and diesel engines, in general terms, shows a diesel engine characterized by low specific fuel consumption and low CO and UHCs (unburned hydrocarbons) emissions. On the other hand, NOx emissions are huge in the diesel cycle [3].Hence, in order to meet the environmental legislations, it is highly desirable to reduce the amount of NOx in the exhaust gas. In most of the global car markets, record diesel car sales have been observed in recent years [1]. The exhorting anticipation of additional improvements in diesel fuel and diesel vehicle sales in future have forced diesel engine manufacturers to upgrade the technology in terms of power, fuel economy and emissions. Diesel emissions are categorized as carcinogenic [2]. Therefore Diesel manufacturers and researchers have been investigating a variety of techniques in the hope of reducing diesel emissions and comply with exhaust emission legislation as far as reasonably practicable. For reducing vehicular emissions, several baseline technologies are being used. These technologies can be classified into two different categories, according to their emission-control techniques. The first prevents emission formation in the engine cylinder through the use of improved combustion technologies, such as high-pressure injection, low compression ratio bowls, and exhaust gas recirculation (EGR). The second uses purifying devices, such as diesel particulate filters (DPFs), selective catalytic reduction (SCR), and lean NOx traps (LNTs).

Instead of using after-treatment systems to comply with exhaust emission legislation, it is also possible to avoid the formation of emissions during the combustion. The raw emissions are reduced and thus no after-treatment is needed. It is common practice nowadays, to use EGR to reduce the formation of NOx emissions. Exhaust Gas Recirculation (EGR) System Exhaust Gas Recirculation (EGR) is an effective pre-treatment technique, which is being used widely to reduce and control the oxides of nitrogen (NOx) emission from diesel engines. The exhaust mixture has higher specific heat compared to atmospheric air. EGR controls the NOx because it lowers oxygen concentration and flame temperature of the working fluid in the combustion chamber. Re-circulated exhaust gas displaces fresh air entering the combustion chamber with carbon dioxide and water vapor present in engine exhaust. As a consequence of this air displacement, lower amount of oxygen in the intake mixture is available for combustion.

Reduced oxygen available for combustion lowers the effective air–fuel ratio. This effective reduction in air–fuel ratio affects exhaust emissions substantially. In addition, mixing of exhaust gases with intake air increases specific heat of intake mixture, which results in the reduction of flame although the various table text styles are provided. The formatter will need to create these components, incorporating the applicable criteria that follow temperature.

Thus combination of lower oxygen quantity in the intake air and reduced flame temperature reduces rate of NOx formation reactions [4, 5].The EGR (%) is defined as the mass percent of the recirculated exhaust (MEGR) in the total intake mixture (Mi).

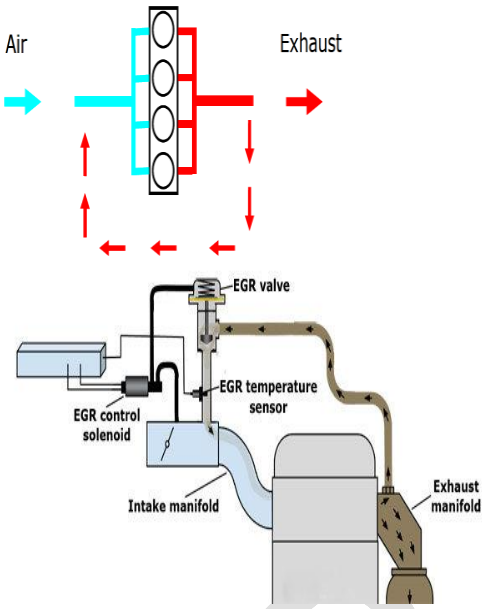


Figure- 1.1: Exhaust Gas Recirculation

II. NOx FORMATION MECHANISM

A major hurdle in understanding the mechanism of formation and controlling NOx emission is that combustion is highly heterogeneous and transient in diesel engines. While NO and NO2 are lumped together as NOx, there are some distinctive differences between these two pollutants. NO is a colorless and odourless gas, while NO2 is a reddish brown gas with pungent odour.

Both gases are considered as toxic; butNO2 has a level of toxicity 5 times greater than that of NO. Although NO2 is largely formed from oxidation of NO, attention has been given on how NO can be controlled before and after combustion [3].

NO is formed during the post flame combustion process in a high temperature region. The most widely accepted mechanism was suggested by Zeldovich [19]. The principal source of NO formation is the oxidation of the nitrogen present in atmospheric air. The nitric oxide formation chain reactions are initiated by atomic oxygen, which forms from the dissociation of oxygen molecules at the high temperatures reached during the combustion process. The principal reactions governing the formation of NO from molecular nitrogen are,

$N2 + O \rightarrow NO + N$,

$N + O2 \rightarrow NO + O$,

$N + OH \rightarrow NO + H$.

In diesel engine NO2 can be 10 to 30% of total exhaust emissions of oxides of nitrogen. A plausible mechanism for the persistence of NO2 is as follows. NO formed in the flame zone can be rapidly converted to NO2 via reactions such as

$NO + HO2 \rightarrow NO2 + OH$.

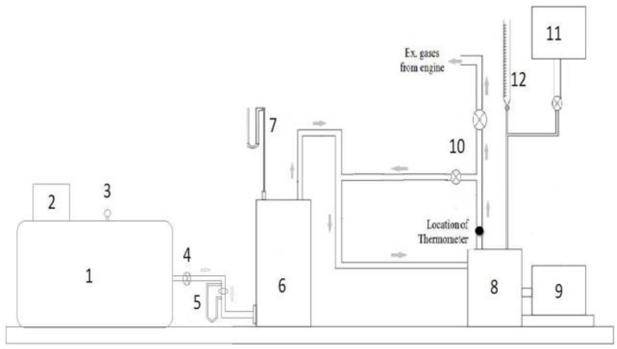
Subsequently, conversion of this NO2 to NO occurs via

$NO2 + O \rightarrow NO + O2$

Unless the NO2 formed in the flame is quenched by mixing with cooler fluid. This explanation is consistent with the highest NO2=NO ratio occurring at high load in diesels, when cooler regions which could quench the conversion back to NO are widespread [12].

III. EXPERIMENTAL SETUP DESCRIPTION

A single-cylinder, 4-stroke, direct injection water-cooled diesel engine of 5 hp rated power is considered to study the combine effect of EGR and varying inlet air pressure on the performance and emissions of engine. The engine is coupled with a rope brake dynamometer through a load cell. It is integrated with a data acquisition system to store the data for the offline analysis. A pipe arrangement was established for recirculation of exhaust gas from engine. Two manually operated valves are provided in the exhaust gas circuit to get the desired mass flow rate of exhaust gas. Asbestos insulation was provided on the exhaust pipe line therefore not allowing the recirculated exhaust gases to cool down. The schematic layout of the experimental set up is shown in below Fig. 3.1.



1. Two stage reciprocating air compressor, 2. Compressor motor, 3. Pressure gauge, 4. Compressor discharge valve, 5. Orifice plate connected with U-tube manometer, 6. Surge tank, 7. U-tube manometer, 8. Diesel engine,9. Rope brake dynamometer, 10. EGR regulating valve, 11. Fuel tank, 12. Burette for the fuel flow measurement

Figure 3.1 Schematic diagram of Engine setup.

Table 3.1: Engine Specification

Parameter	Detail
Engine	Single cylinder high speed DI diesel engine
Cooling	Water cooled
Bore	80 mm
Stroke	110 mm
Compression ratio	16 : 1
Maximum power	5 hp or 3.7 kw
Rated speed	1500 rpm
Capacity	553 CC

The percent of exhaust gas recirculation (EGR (%)) is defined as the percent of the total intake mixture which is recycled exhaust,

$$EGR\ (\%) = (mEGR/mi) \times 100$$

Where, $mi = ma + mf + mEGR$

An alternative defination of percent EGR is also used based on the ratio of EGR to fresh mixture (fuel and air):

$$EGR\ (\%) = [mEGR/\ (ma + mf)] \times 100$$

In this experiment second definition for the calculation of exhaust gas percentage is used.

IV. RESULTS AND DISCUSSION

The engine was run on different loads condition at 1500 rpm with different EGR rates (0%, 5%,10%and 15%) and different inlet air pressure (100 kPa, 120 kPa and 140 kPa) to investigate the effect of EGR on engine performance and emissions. The performance and emission data was analyzed and presented graphically for thermal efficiency, BSFC, exhaust gas temperature, NOx, HC, CO and CO2 emission.

A. Engine Performance Analysis

The trends of Brake thermal efficiency for different load condition are shown in Fig. 4.1 (a) and (b). The brake thermal efficiency is calculated by dividing the actual brake work to the amount of fuel energy input. Brake thermal efficiency is found to have decreased with increasing rates of EGR but with increasing inlet air pressure the brake thermal efficiency is increased. The possible reason may be with increasing in EGR rates, exhaust gas has higher amount of CO_2, which reduces maximum temperature in combustion chamber along with oxygen availability therefore burning of fuel is not significant but with increasing inlet air pressure along with EGR it increase oxygen availability and significantly burning of fuel is occurred.

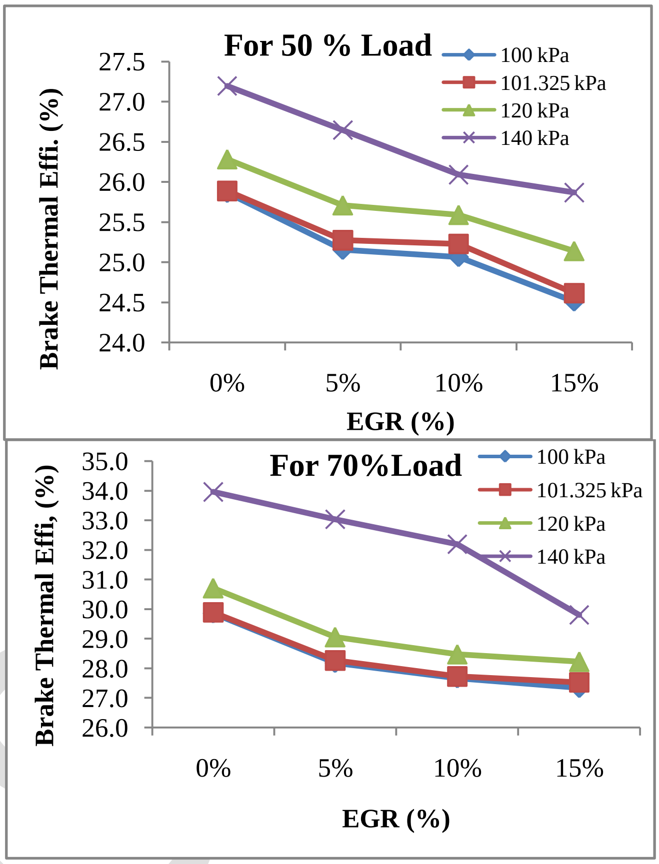
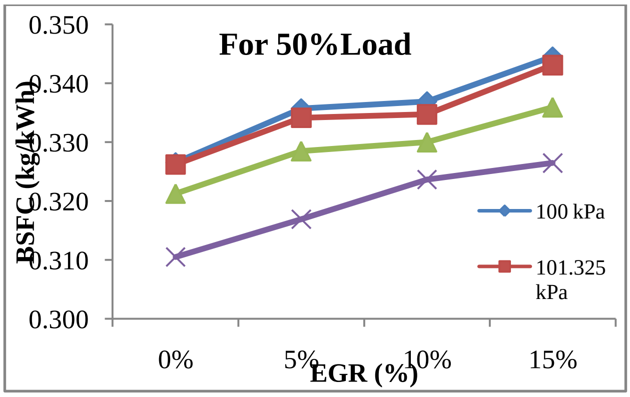


Figure 4.1 Brake thermal efficiency for different inlet air pressure and EGR rate: (a) at 50% load, (b) at 70% load.

Fig. 4.2 (a) and (b) represents comparison of BSFC for all datasets using EGR with inlet air pressure for 50% and 70% load condition. The BSFC is clearly a function of AFR as discussed in details by Heywood [19]. The discharge air decreases when the EGR rate increases and increases when inlet air pressure increasing. It was found from the experiment that BSFC is increased with increasing in EGR rate because oxygen available for combustion gets reduced for the amount of fuel supplied. Thus, air fuel ratio is changed and this increases the BSFC. But by increasing inlet air pressure with EGR system, BSFC is decreased because by supplying pressurized inlet air, density of air increased and thus more oxygen available for combustion.



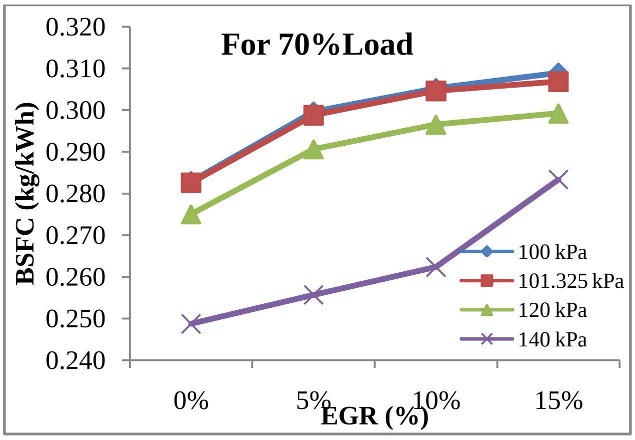


Figure 4.2 BSFC for different inlet air pressure and EGR rate: (a) at 50% load, (b) at 70% load.

V. EQUATIONS USED FOR CALCULATION:

1) Torque (T) = W x Re

Where, W = Weight acting on engine in Newton,

= Load (kg) x Gravity (9.81 m/s2)

Re = Effective radius of drum.

= Radius of drum (m) + Thickness of Belt (m)

= 0.135 + 0.006 = 0.141 m

2) Brake Power (kW) = 2πNT/(60 ×1000)

Where, N = Speed of engine in RPM,

T = Torque in Nm.

3) Friction Power (kW) is calculated with the help of William line's method by plotting graph fuel consumption (g/s) vs. brake power (kW).

Indicated power (kW) =Brake power (kW)+ Friction power (kW).

4) Mechanical Efficiency:

ηm (%)=(Brake Power (kW))/(Indicated Power (kW))x 100

5) Fuel consumption (FC):

$$\frac{10 \times 3600 \times \text{DensityofDiesel } (0.8226 \text{ gm/cc})}{tf \times 1000}$$

Where, tf = time required for 10 cc fuel in second.

6) Brake Specific Fuel Consumption (BSFC):

= (Fuel Consumption)/(Brake Power)kg/kWh

7) Brake Specific Energy Conservation (BSEC):

= Brake Specific Fuel Consumption x Calorific Value of Fuel

8) Brake thermal efficiency (%):

$$\eta_{bth(\%)} = \frac{\text{Brake Power (kW)} \times 3600}{\text{mass of fuel (kg/hr)} \times \text{Calorific Value (kJ/kg)}} \text{ x 100}$$

9) Indicated thermal Efficiency (%):

$$\eta_{ind}(\%) = \frac{\text{IndicatedPower (kW)}}{\text{Massoffuel (kg/hr)} \times \text{CalorificValue (kJ/kg)}} \text{ x 100}$$

10) Air head across orifice (H):

$$= \frac{hw}{100}\left(\frac{\rho water}{\rho air} - 1\right) \text{ meter}$$

Where, hw= head of water in cm,

ρwater= density of water (1000 kg/m3),

ρair = density of air in kg/m3 (ρair= P/RT),

Where, P = Pressure in Pascal,

R = Characteristic gas constant (287 J/kgK)

T = Ambient temperature in K.

11) Mass of air flow (ma):

=Cd×(Ao×Ap)/(√(Ap2-Ao2))√(2×g×H)x3600xρair kg/hr

Where, Cd=Coefficient of Discharge of Orifice, (0.62)

Ao= Area of orifice, (0.0002 m2)

Ap= Area of Pipe, (0.0008 m2)

g = gravity, 9.81 m/s2,

H= Head of air in meter.

VI. ADVANTAGES OF EGR:

- EGR can be used for both S.I. and C.I. engines.
- Decrease in NOx, and also other harmful gases like HC and CO2.
- Noise reduction.
- Engine performance and fuel economy can be actually enhanced by when EGR is operating as per design.

- EGR is found mandatory Euro-3 and Bharat stage-4 norms,so every vehicle following these norms, will be having EGR
- Potential reduction of throttling losses on spark ignition engines at part load.
- Improved engine life through reduced cylinder temperatures (particularly exhaust valve life).

Disadvantages and Difficulties of EGR

- Since EGR reduces the available oxygen in the cylinder, the production of particulates (fuel which has only partially combusted) is increased when EGR is applied. This has traditionally been a problem with diesel engines, where the trade-off between NOx and particulates is a familiar one to calibrators.
- The deliberate reduction of the oxygen available in the cylinder will reduce the peak power available from the engine. For this reason the EGR is usually shut off when full power is demanded, so the EGR approach to controlling NOx fails in this situation.
- The EGR valve cannot respond instantly to changes in demand, and the exhaust gas takes time to flow around the EGR circuit. This makes the calibration of transient EGR behaviour particularly complex- traditionally the EGR valve has been closed during transients and then re-opened once steady.

CONCLUSIONS

An experimental setup was developed to measure the combine effect of increasing inlet air pressure and EGR

system on engine performance and emission like brake thermal efficiency, brake specific fuel consumption, NOx, CO, CO2 and HC. From the result following conclusion has been derived.

- It was found from the experiment that combined effect of increasing inlet air pressure attachment and EGR system provided better result on engine performance. BSFC decreases and brake thermal efficiency increases by increasing inlet air pressure with EGR system than individual EGR system.
- Combined effect of increasing inlet air pressure attachment and EGR system is also more beneficial way to reduce significantly NOx emission than individual EGR system because NOx is reduced as the combustion temperature decreases.
- The increase in CO, HC, and CO2 emissions can be reduced by using exhaust after-treatment, techniques, such as diesel oxidation catalysts (DOCs) and soot traps.

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