Effect of Exhaust Gas Recirculation on Performance and Emission Characteristics of a Diesel Engine

M. Hawi, R. Kiplimo, H. Ndiritu and E. Munyao

Abstract — The exhaust system of a single cylinder, four stroke Direct Injection Compression Ignition (DICI) engine was modified to allow for exhaust gas recirculation (EGR) in order to investigate its effect on performance and emission characteristics of the engine. The EGR system was developed and tested with EGR rates of 0%, 10%, 20% and 30%. The effect on performance parameters of brake specific fuel consumption, brake power and brake thermal efficiency was studied. Emissions of carbon monoxide, unburned hydrocarbon and carbon dioxide were also recorded. The performance and emission characteristics of the engine under EGR were compared with those of the engine operation without EGR. The results showed that EGR leads to a decrease in specific fuel consumption and increase in brake thermal efficiency. With increase in percent (%) of EGR, the BSFC decreased by up to 10.71% at quarter load and decreased by up to 6.76% at full load. The percentage increase in brake thermal efficiency was up to 12.01% at quarter load and up to 14.52% at full load. On the other hand, the brake power decreased by up to 6.13%. Exhaust emissions of HC and CO₂ both increased with EGR by up to 26.57% and 30.48% respectively. Emission of CO₂ however, decreased with EGR.

Keywords — DICI engine, EGR, engine performance, exhaust emission.

I. INTRODUCTION

The use of compression ignition (CI) engines as power source for automobiles is common in many parts of the world due to their high thermal efficiency, excellent fuel economy and low regulated emissions of unburned hydrocarbon (HC), carbon monoxide (CO) and carbon dioxide (CO₂) compared to those of spark ignition (SI) engines [1]. However, diesel engines generally exhaust a larger amount of particulate matter (PM) and nitrogen oxide (NOₓ) pollutant emissions than those of gasoline engines [1, 2]. High NOₓ and PM emission from diesel engines remains a major problem in the pollution aspect and in order to reduce NOₓ emission levels, some external engine features can be applied, such as Exhaust Gas Recirculation (EGR) or after-treatment systems.

EGR is a technique used to reduce NOₓ emission in which part of exhaust gas is recirculated and taken back to the combustion chamber along with the intake air [3, 4]. Exhaust consists of CO₂, N₂ and water vapour, mainly and it acts as a diluent to the combustion mixture, reducing oxygen concentration while increasing specific heat of incoming charge. This ultimately reduces peak combustion temperature under which NOₓ is generated. The specific heat of the exhaust gas is much higher than fresh air; hence EGR increases the heat capacity (specific heat) of the intake charge, thus decreasing the temperature rise for the same heat release in the combustion chamber [5]. NOₓ formation is a highly temperature dependent phenomenon and takes place when the temperature in the combustion chamber exceeds 2000 K. Formation of NOₓ is almost absent at temperatures below 2000 K [5]. Therefore, in order to reduce NOₓ emissions in the exhaust, it is necessary to keep peak combustion temperatures under control. EGR has also the advantage of resupplying of unburned hydrocarbons, giving them an opportunity to re-burn [6]. [7]. Depending on the engine operating conditions, these systems divert 5-30% of an engine exhaust stream back to the combustion chamber [8].

Many researchers have investigated the effect of EGR on performance and emission characteristics of diesel engines, with most of the research work considering EGR rates of up to 15% [8, 9]. There has however been some variation in the results of various researchers on performance and emission characteristics of the diesel engine under EGR. There is need therefore, to investigate the effect of higher EGR rates on engine performance and emission characteristics. More research also needs to be done to clarify the differences in some of the research findings. A. Kumar et al. [5] studied the effect of EGR on exhaust gas temperature and exhaust opacity in CI engines. They found that the exhaust gas temperature reduces drastically by employing EGR. They also reported that thermal efficiency and brake specific fuel consumption were not affected significantly by EGR. Another research by K. Rajan et al. however showed that EGR causes a significant decrease in BSFC and increase in BTE [9]. The research by K. Rajan et al., also showed that unburnt hydrocarbon (HC) increases with increase in load and EGR rate because of lower oxygen content available for combustion, that is, lower excess oxygen concentration results in rich mixture which results in incomplete combustion and higher hydrocarbon emission.
while research by Jan-Ola Olsson et al shows decrease in HC emission with EGR [10]. Such differences need to be harmonized through further research.

When exhaust gas recirculation is applied, it is also important that its effect on the overall performance of the engine be investigated. In the current study, experiments were done on a single cylinder 4 stroke diesel engine by varying load on the engine and percentage of exhaust gas recirculated. The effect of EGR on Brake Power, Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC) and exhaust emissions of CO, HC and CO\textsubscript{2} was studied.

II. EXPERIMENTAL PROCEDURE AND EQUIPMENT

A. The Experimental Set up

The engine used for this study is a single cylinder four stroke Direct Injection (DI) diesel engine. It is water cooled, naturally aspirated constant speed compression ignition engine whose major specifications are shown in Table 1. The engine was coupled to a hydraulic dynamometer through which load was applied by increasing the water supply to rotor blades via a centrifugal pump. The engine was tested at 0, 25, 50, 75 and 100 percent brake load conditions. The experimental apparatus consisted of the test engine, the dynamometer, the fuel supply and control systems, the exhaust emission analyzer and temperature measurement system as shown in Fig. 1. The properties of the diesel fuel used are shown in Table 2.

<table>
<thead>
<tr>
<th>Specfication</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Number of cylinders</td>
<td>1</td>
</tr>
<tr>
<td>Number of strokes</td>
<td>4</td>
</tr>
<tr>
<td>Number of holes in injector</td>
<td>3</td>
</tr>
<tr>
<td>Rated power (kW)</td>
<td>7.5</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>1500</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16.5:1</td>
</tr>
<tr>
<td>Injection pressure (bar)</td>
<td>200</td>
</tr>
<tr>
<td>Injection timing (\textdegree\text{btdc})</td>
<td>23</td>
</tr>
<tr>
<td>Cylinder capacity (cc)</td>
<td>950</td>
</tr>
<tr>
<td>Fuel consumption (g/kWh)</td>
<td>251</td>
</tr>
<tr>
<td>Combustion system</td>
<td>Direct injection</td>
</tr>
</tbody>
</table>

B. Experimental Procedure

The engine load was controlled using the hydraulic dynamometer while the exhaust gas was analyzed by Horiba MEXA-544GF emission analyzer. The dynamometer reading (load), engine speed, fuel consumption and exhaust gas temperature were recorded during experiments. Exhaust gases were analyzed on line by the emission analyzer in which HC, CO and CO\textsubscript{2} were measured. A portable Laser type digital tachometer - RS 445-9557 was used to measure the engine speed at all operating conditions. Thermocouples were fixed at the exhaust manifold and at engine coolant inlet and outlet to the engine to measure the temperature of exhaust gas, temperature of cooling water at entry to the engine and temperature of cooling water at exit from the engine respectively. The diesel fuel was pressurized by the high pressure injector system and the flow rate measured by the fuel flow meter.
The EGR system used in this research is shown in Fig. 2. The investigation of the effect of EGR on engine performance was started by running the engine at a rated speed of 1500 rpm till the warm-up period was reached. The engine was then loaded in terms of 0%, 25%, 50%, 75% and 100% corresponding to the loading conditions of no load, quarter load, half load, three quarter load and full load respectively. At each load, the engine was run with different EGR conditions. The exhaust gases were tapped from exhaust pipe and directed to the air inlet through the EGR system, consisting of two control valves and a graduated flat metal plate to indicate the degree of valve opening. After attaining the steady state condition, observations were made for various parameters such as exhaust gas temperature, fuel consumption, torque and actual engine speed which were then recorded at various loads. Exhaust emissions of CO, CO₂ and HC were recorded simultaneously by the exhaust gas analyzer.

C. Performance Evaluation of the Engine
The engine was tested at the engine speed 1500 rpm and five loading conditions (0%, 25%, 50%, 75% and 100%). Each test was conducted with four replications. During each test, the engine load, engine speed and fuel consumption were measured. The observed data were utilized to calculate the engine brake power, specific fuel consumption and thermal efficiency.

III. RESULTS
The data collected from experiments were used to draw graphs showing variation of various performance parameters with engine load. The experimental results were as shown in the graphs (Fig. 3 to Fig. 8).
Fig. 4 shows that the brake thermal efficiency increases with increase in engine load for all operating modes. The BTE increases also with the amount of exhaust gas that is recirculated. The reason for increase in BTE with EGR is due to re-burning of HC that enters combustion chamber with the recirculation of exhaust gases and also EGR increases intake charge temperature which increases the rate of combustion of the fuel. The maximum increase in BTE at quarter load due to EGR was 12.01% with the maximum increase at full load being 7.28%.

C. Brake Power

![Graph showing brake power variation with load](image)

Fig. 5 Variation of brake power with load

Fig. 5 shows a linear increase in power output of the engine with increase in load, from no load to full load for all conditions of EGR. The figure shows that there was no significant change in engine power output with EGR. The decrease in brake power at quarter load was up to 6.13% while at full load the decrease recorded was up to 1.89%.

D. Carbon monoxide emission

![Graph showing CO emission variation with load](image)

Fig. 6 Variation of carbon monoxide emission with load

The increase in emission of CO at no load was up to 16.67% while at full load an increase of up to 13.01% was recorded. The deficiency of oxygen with the increase in EGR percentage can be attributed to the increase in CO emission for EGR. This clearly shows that though EGR has the potential of reducing emission of NO\textsubscript{X}, it increases CO emission. It therefore implies that a trade-off has to be reached between emission of CO and NO\textsubscript{X} if EGR is to be applied.

E. Unburned Hydrocarbon (HC) Emission

Fig. 7 shows the effect of EGR on HC emissions at various engine loads. It can be seen from the figure that HC emission increases with engine load for all operating modes of EGR. HC emissions increase also with increase in percent EGR. At no load, there was an increase in HC emission of up to 20% while at full load the increase was up to 28.6%. The increase in HC emission with EGR is as a result of increase in the CO\textsubscript{2} content of the inducted mixture instead of fresh-air, leading to incomplete combustion of the fuel in the combustion chamber. EGR leads to increase in HC emission implying that if EGR is applied as a means of reducing NO\textsubscript{X} emission, the effect on other emissions must be considered.
IV. CONCLUSION

The study was conducted to investigate various effects of EGR on the performance and exhaust emission characteristics of a single cylinder four stroke DI diesel engine under various experimental conditions. The following conclusions were drawn from the analysis:

1) The effect of EGR on engine brake power is not very significant, though brake power reduces slightly with EGR (by up to 6.13%).
2) The BSFC decreases (improves) with EGR (up to about 20% EGR) while BTE increases with the same for all loading conditions.
3) Both CO and HC emissions increase with EGR due to substitution of fresh air needed for combustion with exhaust gases hence leading to incomplete combustion of fuel.
4) Emission of CO₂ decreases with EGR due to incomplete combustion of fuel.

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NOMENCLATURE

DICI-Direct Injection Compression Ignition
DI-Direct Injection
CI-Compression Ignition
SI-Spark Ignition
BTE-Brake Thermal Efficiency
BSFC-Brake Specific Fuel Consumption
EGT-Exhaust Gas Temperature
PM-Particulate Matter
CO-Carbon monoxide
CO₂ –Carbon dioxide
HC-Hydrocarbons
NOX –Oxides of Nitrogen

REFERENCES


