Engine performance and emissions of a diesel engine operating on jojoba methyl ester with exhaust gas recirculation at 1600 rpm

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Abstract
The aim of this study mainly was to quantify the efficiency of exhaust gas recirculation (EGR) when using Jojoba Methyl Ester (JME) fuel in a fully instrumented, two-cylinder, naturally aspirated, four-stroke direct injection diesel engine. The tests were made in two sections. Firstly, the measured performance and exhaust emissions of the diesel engine operating with diesel fuel and JME are determined and compared. Secondly, tests were performed at 1600 rpm and loads to investigate the EGR effect on engine performance and exhaust emissions including nitrogenous oxides (NO\textsubscript{x}), carbon monoxide (CO), unburned hydrocarbons (HC) and exhaust gas temperatures. Also, effect of cooled EGR with high ratio at full load on engine performance and emissions was examined. The results showed that EGR is an effective technique for reducing NO\textsubscript{x} emissions with JME fuel especially in light duty diesel engines. With the application of EGR method, the CO and HC concentration in the engine-out emissions increased. Large EGR rate (25%-40%) can be used at 25% load for high NO\textsubscript{x} reduction was 50% are being researched. Technologies like exhaust gas recirculation (EGR), soot traps and exhaust gas aftertreatment are essential to cater to the

Keywords: Diesel engine, Jojoba methyl ester, Nitrogenous oxides, Exhaust gas recirculation

1. Introduction
Concerns about energy conservation and environmental protection are placing increasingly rigorous demands on internal combustion engines for improved fuel efficiency and used renewable fuels. There is also a need to reduce carbon dioxide (CO\textsubscript{2}) emissions to prevent global warming. Diesel engine had found wider and wider application as it has good fuel economy and lower emissions of carbon dioxides. However, the harmful effects on human health and environment brought by its pollutant emissions are causing great concern. As a result, various methods for reducing the tailpipe emissions from diesel engine vehicles

challenges posed by increasingly stringent legislations from the Environmental Protection Agency (EPA) [1]. jojoba ranks high as the vast area of the Egyptian deserts can be used for production the seeds are used to produce the jojoba fuel [9-12]. Several problems, however, have impaired the widespread use of biodiesel. They are related to the economics and properties of biodiesel. Some researchers reported that the most detrimental parameter in the use of vegetable oil as fuel is its higher viscosity [13-14]. The high viscosity will lead to blockage of fuel lines, filters, high nozzle valve opening pressures and poor atomization. The problems of high fuel viscosity can be overcome by using esters, blending and heating. The methyl esters of vegetable oils, which are produced by combining methanol with the vegetable oil [15], these fuels tend to burn cleaner, perform comparably to conventional diesel fuel, and combust similarly to diesel fuel. It is generally recognized that biodiesel has lower emissions, with
in 2 hours. In addition, these studies concentrated on measuring the ignition delay period of JME and JME-gas oil blends at different conditions in shock tube. It was found that JME liquid and its blend with light diesel fuel exhibit shorter ignition delay than light diesel fuel.

An experimental investigation has been carried out to examine for the first time the performance and combustion noise of an indirect injection diesel engine running with new fuel derived from pure jojoba oil, JME, and its blends with gas oil [10]. A Ricardo E6 compression swirl diesel engine was fully instrumented for the measurement of combustion pressure and its rise rate and other operating parameters. Test parameters included the percentage of JME in the blend, engine speed, load, injection timing and engine compression ratio. Results showed that the new fuel derived from jojoba is generally comparable and good replacement to gas oil in diesel engine at most engine operating conditions, in terms of performance parameters and combustion noise produced. Also, with the same test rig, JME was investigated as a pilot fuel as a way to improve the performance of dual fuel engine running on natural gas or liquefied petroleum gas at part load [11-12]. Results showed that using the JME fuel with its improved properties has improved the dual fuel engine performance, reduced the combustion noise and extended knocking limits.

An experimental evaluation of using jojoba oil as an alternate diesel engine fuel has been conducted by Bawady et. al [19]. Measurements of jojoba oil chemical and physical properties have indicated a good potential of using jojoba oil as an alternative diesel engine fuel. Experimental measurements of different performance parameters of a single cylinder, naturally aspirated, direct injection diesel engine have been performed using gas oil and blends of gas oil with jojoba oil. Measurements of engine performance parameters at different load conditions over the engine speed range have generally indicated a negligible loss of engine power, a slight increase in brake specific fuel consumption and a reduction in soot emission using blends of jojoba oil with gas oil as compared to gas oil. The reduction in engine soot emission has been observed to increase with the increase of jojoba oil percentage in the fuel blend. Heat flux mapping and metal temperature distribution was carried out using a single cylinder, naturally aspirated, indirect injection four-stroke diesel engine. Since heat fluxes and metal temperatures in the combustion chamber component parts play a paramount role in engine reliability and life time [16]. Results at variable loads and speeds were taken with JME and were compared with those obtained with gas oil. It was found that the heat flux level and gas face metal the exception of nitrogen oxides (NO\textsubscript{x}), than conventional petroleum fuel.

Many studies have been working on Jojoba as a promising vegetable oil fuel for diesel engines for many years [9-12]. During this time, many tests have been performed on neat jojoba and Jojoba Methyl Ester (JME). These studies showed that this fuel is a very good gas oil substitute and offered the same product guarantees for JME as for gas oil due to the fact that the physiochemical properties of JME are close to those of gas oil. An increase in the emissions of nitrogenous oxides (NO\textsubscript{x}) at all operating conditions have been observed by [16]. The objective of this work was to quantify the efficiency of exhaust gas recirculation (EGR) when using JME as a renewable fuel. In this paper, all experiments described here were performed on a direct injection diesel engine in first to compare diesel fuel and JME fuel in terms of engine performance and exhaust emissions at various speeds under full load and the second to investigate the effect of various EGR rates with JME fuel for NO\textsubscript{x} reduction. Also, effect of cooled EGR with high ratio at full load on engine performance and emissions was examined. EGR effects on engine performance, engine emissions, exhaust gas temperature, combustion quality and fuel economy for both high and low load engine operating conditions at 1600 rpm were investigated.

2. Jojoba seed oil extraction and biodiesel production

The jojoba shrub was grown in Africa and also grown in the Sonora Desert at the south of the USA. El-Moogy [17] has collected a considerable amount of data about jojoba and its cultivation for investment in Egypt and he termed the oil as "green gold". The term "green gold" stems from the fact that the seeds are used to produce oil while the residue can be used as fodder or solid fuel implying that there is no waste. Each acre which accommodates 900-1000 shrubs can produce about 540-600 kg of seeds when the plant is four years old; but the production increases gradually till it reaches 1350-1500 kg when the plant is ten years old. Jojoba seeds contain 50% of its weight as oil, so the Egyptian acre can produce 270-300 kg of oil after four years but will increase to 675-750 kg of oil after ten years of cultivation. The viscosity of jojoba raw oil is high and thus warrants treatment of oil before it becomes a viable engine fuel.

Abdel Kader [18] synthesized the jojoba oil in the laboratory and showed that methyl ester formation was 60% to 65% complete at respective molar ratios of methanol/jojoba oil 4.6:1. The alkaline catalyst used was (NaOH) and was added with a percentage of 1% which proved to produce maximum yield. At 60°C, 65% JME was produced.
particulate reduction to supply nearly particle-free exhaust gas.

4. Experimental equipment
The experiments were carried out on a two-cylinder, water cooled, four-stroke, direct injection diesel engine. It was necessary to make some modifications in the engine since the original engine had no EGR. It was necessary to connect the exhaust manifold with the air intake manifold, with an EGR valve at this connection. The experimental set up is shown schematically in Fig.1 and comprises a hydraulic dynamometer, a pressure tank, a diesel particulate bag filter, a heat exchanger, an EGR valve, a liquid and gas fuel metering systems, and an exhaust gases analysis system. The engine specifications are given in Table 1. It was necessary to connect the exhaust manifold with the air intake manifold, with a pressure tank, bag filter, a heat exchanger and an EGR valve at this connection. The bag filter is used for particulate reduction and supply of clean gas for EGR. The pressure tank is used for reduction of exhaust pressure pulse and the heat exchanger is used as an exhaust cooler for cooling exhaust gas by water flow. An EGR valve was installed in this connection that enabled manual to control the flow rate of EGR to the intake manifold to attain various EGR ratios. The EGR mass rate is the ratio between recirculated exhaust mass flow and the total mass flow allowed to pass into the engine.

\[
\text{EGR rate (\%)} = \left( \frac{m_{\text{EGR}}}{m_{\text{Air}} + m_{\text{Fuel}}} \right) \times 100
\]

The flow rate of air into the engine was measured using a laminar flow element. The laminar flow element was a honeycomb-like structure, which provides for a certain pressure drop across itself for a certain volumetric flow rate of air. This pressure drop was measured using an inclined manometer. The flow rate of EGR into the engine was measured with a sharp edge orifice mounted on a pipe connected to the pressure tank. An inclined manometer was used to measure the pressure drop across the orifice. The fuel consumption is measured by a fuel meter. The air temperature, exhaust gas temperature were measured using type K thermocouples and the CO, HC and NO\(_x\) levels were obtained with a testo 350 gas analyzer was used to measure engine exhaust pollutant emissions. Pressure gauges were fitted to measure the pressure of EGR, inlet mixer and fresh intake air. A full set of readings was taken for each data point recorded thus the EGR rate can be calculated based on the above data.

3. Mechanism of NO\(_x\) formation and EGR technique
Oxides of nitrogen are formed during combustion when localized temperatures in the combustion chamber exceed the critical temperature that molecules of oxygen and nitrogen combine. Oxygen interacts at the boundary surface between the air and fuel. This boundary surface is where combustion takes place. Due to burning of the fuel droplets, the localized temperature in the vicinity of the fuel droplets exceeds the limit at which NO\(_x\) are formed. In general, high amounts of oxygen and high temperatures will result in high levels of NO\(_x\) formation and these conditions are always present in the combustion chamber of diesel engines. Since diesel engines always run at a lean air-fuel mixture and at high compression ratios [20].

Recently, exhaust gas recirculation, has received attention as a potential solution. Research work results showed that EGR is one of the most effective methods used in modern engines for reducing NO\(_x\) emissions [21,22]. There are two types of EGR; internal and external. Internal EGR uses variable valve timings or other devices to retain a certain fraction of exhaust from a preceding cycle. External EGR uses piping to route the exhaust gas to the intake system, where it is inducted into the succeeding cycles and it is used in this study. External EGR has emerged as the preferred type of EGR for heavy-duty diesel engines and that due to external EGR can be cooled and that improves fuel economy and engine performance. EGR reduces NO\(_x\) because EGR gases contain much lower concentrations of oxygen as compared to ambient air. As a result, EGR gas slows down the rate of combustion as there is less oxygen in the cylinder to combust with the fuel. In addition to having low levels of oxygen, EGR gas also has a higher heat capacity than ambient air. This aids in slowing down combustion because more heat can be absorbed in an air-fuel mixture that contains EGR gases.

While EGR is effective in reducing NO\(_x\), it also has adverse effects on the engine efficiency and may cause pollution of lubricating oil and corrosion of inlet manifold and moving parts as exhaust gas contains a lot of particulate matter. Some simple algorithms for adjusting EGR with engine power have been explored in the past to minimize its impact on the engine thermal efficiency [23]. In this paper diesel particular filter adopted for diesel...
The experimental results are given in two sections. The first section compares diesel fuel and JME fuel in terms of engine performance and exhaust emissions at various speeds under full load. The second section investigates the effect of various EGR rate with JME fuel on the engine emissions, exhaust gas temperatures and engine fuel economy and combustion quality under various conditions. The tests and data collection were performed at two different engine loads at 1600 rpm. The engine evaluation at 1600 rpm-25% load, this is a low-load condition for highway operation. 1600 rpm-full load to represent heavy load operation. Table 2 shows the JME fuel with its improved properties versus diesel fuel [12]. Three runs of tests were performed under identical conditions to check for the repeatability of all results and the experimental error is evaluated according to Ref. [25]. The maximum uncertainty in any quantity is in the range 1.5-5.5%.

5. Experimental results and discussion
The experimental results are given in two sections. The first section compares diesel fuel and JME fuel in terms of engine performance and exhaust emissions at various speeds under full load. The second section investigates the effect of various EGR rate with JME fuel on the engine emissions, exhaust gas temperatures and engine fuel economy and combustion quality under various conditions. The tests and data collection were performed at two different engine loads at

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**Table 1** Specification of the engine used.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>112M- Helwan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>4-stroke direct injection</td>
</tr>
<tr>
<td>Cooling</td>
<td>Water cooling</td>
</tr>
<tr>
<td>Number of cylinder</td>
<td>2</td>
</tr>
<tr>
<td>Diameters of cylinder (mm)</td>
<td>112</td>
</tr>
<tr>
<td>Stroke length (mm)</td>
<td>115</td>
</tr>
<tr>
<td>Capacity (cm$^3$)</td>
<td>2266</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16.4</td>
</tr>
<tr>
<td>Rated speed (rpm)</td>
<td>1500</td>
</tr>
<tr>
<td>Max. power at 1500 rpm (HP)</td>
<td>26</td>
</tr>
</tbody>
</table>
JME fuel was higher combustion chamber temperature as indicated from measured exhaust gas temperature, as shown in Fig. 3. The NOx concentration with JME fuel is higher than that with diesel fuel and that is may be due to the higher calorific value of JME. As shown in Fig. 3, at N= 1200 rpm, the increase of approximately 16% in the NOx emissions with JME than that with diesel fuel and about 14% at N= 1600 rpm.

The variation of carbon monoxide (CO) emissions versus engine speed at full load is shown in Fig. 4. The reduction in engine speed produced higher CO in the exhaust and that due to the increasing of the amount of fuel per stroke and decreasing in swirl intensity within the cylinder which causes poorer mixing since there is insufficient oxygen to convert all carbon in the fuel to carbon dioxide [28]. As shown in Fig 4, at low speed, CO concentration with JME is slightly higher than the diesel fuel and that due to the higher viscosity of JME which causes poorer atomization and distribution of the JME fuel air. Also it has been shown by [29] that CO emissions increased when the coconut oil amount increased in the diesel fuel blends and that due to the poor spray characteristics of coconut oil, poor mixing, and consequently poor combustion because of coconut oil has a viscosity of about 8 times as much as that of diesel fuel. The author [29] has been investigated the effect of coconut oil-diesel blends using a single cylinder, direct-injection diesel engine. At high speed, CO concentration with JME is lower than that with diesel fuel that may be due to the beneficial effect of JME as an oxygenated fuel as mentioned before.

The variation of unburned hydrocarbons (HC) emissions versus engine speed at full load is shown in Fig 5. The reduction in engine speed produced higher HC concentration due to poorer mixing, since the fuel-air pocket can be mixed to stoichiometric proportions and then diluted by more air before autoignition occurs in that element [28]. As a result there are contours for lean equivalence ratios and when autoignition occurs there is fuel and air mixed locally to proportions less than the lean flammability limit. Thus this

<table>
<thead>
<tr>
<th>Properties</th>
<th>JME</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density @ 15 °C</td>
<td>0.866</td>
<td>0.820</td>
</tr>
<tr>
<td>Kinematic viscosity @ 40 °C(cSt)</td>
<td>19.2</td>
<td>1.6–7.0</td>
</tr>
<tr>
<td>Flash point</td>
<td>61</td>
<td>Min. 55</td>
</tr>
<tr>
<td>Calorific value (kJ/kg)</td>
<td>47380</td>
<td>44300</td>
</tr>
<tr>
<td>Cetane number</td>
<td>63.5</td>
<td>46</td>
</tr>
<tr>
<td>Water content % by mass</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Carbon residue % by mass</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Ash content % by mass</td>
<td>0.002</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 2 shows the properties of the JME fuel versus diesel fuel [12].

5.1 Comparison of performance and emissions with JME and diesel fuel

5.1.1 Engine performance

The variation of engine speed on the brake thermal efficiency (ηb) and the brake specific fuel consumption (bsfc) with JME and diesel fuel at full load is shown in Fig. 2. The experimental results of both JME and diesel fuel indicate that the brake thermal efficiency variations were in harmony with the speed variations as the engine speed increases the thermal efficiency increases for both JME and diesel fuel. At low speeds, the engine power and brake thermal efficiency with JME are slightly higher than the diesel fuel. At high speed, the engine output and efficiency with JME were higher than that with diesel fuel. The bsfc with JME is lower than that with diesel fuel by 8.2%, 9.8% at N = 1200 rpm and N = 1600 rpm respectively. The main reason for the higher power and efficiency or on the other hand, lower brake specific fuel consumption may be explained by the higher calorific value of JME [12,16]. Furthermore, JME as an oxygenated fuel has a beneficial effect on combustion, especially in fuel rich zones as indicated by [26,27]. The author [26] found that the power and the engine efficiency increased slightly with indirect diesel engine running on the tobacco methyl ester-diesel blends.

5.1.2 Engine Emissions

The nitrogenous oxides (NOx) concentration versus engine speed is shown in Fig. 3. The results show that as the speed decreases, NOx increases for both diesel fuel and JME and that due to the reduction in engine speed at full load increases the engine volumetric efficiency, the maximum rate at which fuel is discharged from the injector nozzle and the quantity of fuel injected per stroke [28]. Increasing in the amount of fuel injected leads to higher cylinder temperatures which result in higher NOx concentration. It would be expected that the fuels with the highest in-cylinder temperature levels would have the highest NOx [20]. Since
Also, CO and HC emissions, exhaust gas temperatures, combustion quality and fuel economy are obtained for wide range of various EGR rates.

5.2.1 Effect of EGR on NOx emissions and fuel consumption with JME

Figure 6 shows influence of the various EGR rate on NOx emissions and fuel consumption when the diesel engine was operated with JME at 1600 rpm-25% load and 1600 rpm-100% load. It is shown that, EGR rates produced a corresponding decrease in NOx emissions. As stated before; this is caused mainly by exhaust gas dilution of fresh local fuel mixture does not burn and will increase the HC concentration. Also, the percentage of heat loss to the coolant is increasing with decreasing the engine speed and that leads to higher HC concentration in the exhaust gases. As shown in Fig. 5, at low speeds, HC concentration with JME is higher than the diesel fuel and there is no appreciable difference between HC concentration with JME and diesel fuel at high speed.

5.2 Experimental study on diesel engine with JME using EGR technique

In the above section have been observed a decrease in the emissions of CO and HC in the almost of the operating conditions but an increase in the NOx emissions in all operating conditions and the overall engine performance with JME was equivalent to that of the conventional diesel fuel. Thus, the aim in this section is to reduce NOx emissions using JME as fuel. The measurements of an experimental investigation of the effect of various EGR rates on NOx reduction with JME at different engine parameters are presented and discussed in the present section.
rate larger than 12% as shown in Fig. 6 (b) and this may result in an excessive increase in bsfc up to 11%. At that level of EGR rate, the reduction in NO\textsubscript{x} was 33%.

As shown in Fig. 6, the bsfc is decreased or the fuel economy is raised with increasing EGR rate up to 5% at 25% load. Very important to note this increase in fuel economy and reduction in NO\textsubscript{x} emissions with EGR is obtained. This is due to increase of engine thermal efficiency because of unburnt hydrocarbons contained in the EGR which would possibly re-burn in the mixture, leading to lower unburnt fuel in the exhaust [30]. Furthermore, lower combustion temperatures with EGR reduced heat loss to the walls. At 25% load, the maximum reduction in NO\textsubscript{x} emissions with minimum in fuel economy is obtained by increasing EGR rate to 15-20%. It has also been shown by [21] that at low loads, the CO\textsubscript{2} and H\textsubscript{2}O concentrations in the exhaust gas are low, since EGR routes exhaust gas from preceding engine combustion cycles into the combustion chamber for succeeding combustion cycles. Because of this, the heat capacity of the cylinder charge decreased. So, large EGR rate (25% ~ 40%) can be used for high reduction efficiency of NO\textsubscript{x} (50% ~ 55%) without obvious increase of bsfc (less than 5%). Increasing of EGR rate above 40%, the combustion of mixture deteriorates. Since EGR in a diesel engine displaces a unit of fresh air with an equal unit of burned exhaust products, it not only alters A/F ratio, but causes a dilution effect. By reducing the oxygen concentration, the mixing time between the direct-injected fuel and the fresh oxygen increases and reduce the burn rate once diffusion combustion starts, therefore, makes stable combustion more difficult [21,28] to achieve and which indicates a speed and power output decrease and bsfc increases up to 17%.

At high load, the heat capacity increases as the concentrations of CO\textsubscript{2} and H\textsubscript{2}O are substantially higher. Both these molecules have higher than air heat capacities and with H\textsubscript{2}O being much higher than CO\textsubscript{2} at typical combustion temperatures [28]. With the higher heat capacity of the mixture, more energy is required to pre-heat the incoming mixture, thus lowering the flame temperature and deterioration in diffusion combustion. Furthermore, at high load, the temperature of the mixture of EGR and fresh air increase, the cylinder trapped mass decrease and that has a detrimental effect on the volumetric efficiency [21]. So, it is difficult to employ EGR

![Fig. 6 Variation of NO\textsubscript{x} and bsfc with EGR rate at N= 1600 rpm](http://www.ijettjournal.org)
5.2.3 Effect of EGR on exhaust gas temperature with JME

The effect of EGR rate on the exhaust gas temperatures under the different operating conditions is presented in Fig. 8. As expected, the exhaust gas temperatures were reduced continuously with increasing EGR rate. As stated before, Increasing EGR rate augments the amount of inert gas in the combustion chamber, lowering the burned gas temperature and therefore lowering the NO \_x emissions. Since the composition of the EGR of diesel engine varies with load. At 25% load and N= 1600 rpm, there is a little of CO \_2 and H\_2O concentrations in exhaust gas, so large EGR 35%~40% can be used for significant reduction in exhaust gas temperature about 42%~48% compared with the baseline case (without EGR) as shown in Fig. 8. At high load the heat capacity increases as the concentrations of CO \_2 and H\_2O are substantially higher so low EGR rate 14%~17% can be used for the same reduction in exhaust gas temperature.

![Graph showing variation of exhaust gas temperature with EGR rate at N= 1600 rpm](image)

Fig. 8 Variation of exhaust gas temperature with EGR rate at N = 1600 rpm

6. Conclusions

In this paper, an experimental investigation of the effect of exhaust gas recirculation on exhaust emissions and performance in diesel engine operating with JME. Tests were made at two loads and 1600 rpm. Engine performance, exhaust emissions, exhaust gas temperatures and combustion quality were investigated. From the study carried out the following conclusions may be drawn:

1. The brake power output with JME was higher than that with diesel engine but NO \_x emissions was higher with JME than those with diesel engine at different conditions.

increase rapidly with greater levels of EGR rate and this mean that the combustion quality worsens with the increase of EGR rate. Also, it can be observed that HC emissions at 25% load are higher than that at full load since the lighter load reduce turbulence and fuel mixing to too lean an equivalence ratio. This has a negative impact on the combustion efficiency and therefore leads to higher HC emissions.

Also, Fig. 7 shows engine-out CO emissions versus EGR rate for speed/load cases as before. As previously, data points have been shown that the trend of CO emissions is similar to HC emissions change under the different working conditions. Increasing EGR rate above 15%, the CO emissions increased rapidly. The CO production is most likely due to an incomplete combustion caused by the diluted mixture. Trade-off between HC, CO and NO \_x concentrations with increasing EGR rate because of reduction of HC and CO needs high temperature and complete combustion, which requires good fuel/air mixing and enough oxygen. Therefore, EGR can bring satisfactory results for NO \_x reduction, but at the same time HC and CO increase. From the emissions data presented above, a better trade-off between HC, CO and NO \_x emissions can be attained within a limited EGR rate of 5% ~ 15%.

![Graph showing variation of CO and HC emissions with EGR rate at N=1600 rpm](image)

Fig. 7 Variation of CO and HC emissions with EGR rate at N=1600 rpm
2. Increase in fuel economy with the reduction in NO\textsubscript{x} emissions is obtained at EGR rate of 5%.
3. Large EGR rate (25%–40%) can be used at 25% load for high NO\textsubscript{x} reduction was 50% ~55% with increase of bsfc less than 5%.
4. The optimal level of EGR rate should be used is less than 12% at full load as engine economy worsens as more than 11% increase in bsfc and the reduction in NO\textsubscript{x} was 33%.
5. With the application of EGR method, the CO and HC concentration in the engine-out emissions increased.
6. The exhaust gas temperatures were reduced continuously with increasing EGR rate. At 25% load, large EGR 35%~40% can be used for reduction in exhaust gas temperature about 42%~48% compared with the baseline case (without EGR).
7. At high load, low EGR rate 14%~17% can be used for reduction in exhaust gas temperature about 42%~48% compared with the baseline case (without EGR).
8. For all operating conditions, a better trade-off between HC, CO and NO\textsubscript{x} emissions can be attained within a limited EGR rate of 5%~15% with little economy penalty.

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