Factors Affecting Performance of Diesel Engine Using DEE as an Ignition Enhancer by varying EGR and Intake Air Temperature

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https://doi.org/10.5109/7342479

出版情報：Evergreen. 12 (1), pp.608-615, 2025-03. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan
バージョン：

Factors Affecting Performance of Diesel Engine Using DEE as an Ignition Enhancer by varying EGR and Intake Air Temperature

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(Received September 23, 2023; Revised February 27, 2025; Accepted March 5, 2025).

Abstract: Rapid depletion of fossil fuel, all over the world attracts the energy researchers to develop an alternative source of fossil fuel with advanced technologies that efficiently utilizes all energies. The effective utilization of fossil fuel could be possible by transforming or extracting all the energy before complete extinct. In this context, researchers developed homogeneous charge compression ignition (HCCI) operation to extract maximum energy during combustion. With this concept, at attempt has been made to study the performance of diethyl ether (DEE) (act as ignition enhancer) with liquefied petroleum gas (LPG) as fuel in direct injection diesel engine. Furthermore, the experimental system was introduced with exhaust gas recirculation (EGR) technology and preheating of intake air to explore the effect on the performance of blended fuel. The investigation also covers the performance of the fuel at different load condition. An improvement of 1.5 % maintaining 15 % EGR and air preheats as 50° C was achieved in thermal efficiency by blending the DEE inside LPG. Tremendous improvement i.e. 85 % and 90 %, in smoke and particulate emissions respectively, was observed. The experimental analysis also explored that the techniques of intake air temperature and EGR showed superior performance.

Keywords: HCCI engine; Diesel; Liquefied Petroleum Gas; Diethyl Ether; Ignition Enhancer

1. Introduction

In today's circumstance, the automobile sectors are under tremendous pressure due to rise in awareness on emissions and increasing cost of petroleum fuels all over world. Furthermore, the strict rules imposed by world environmental protection agencies and governments impede the growth of this sector. These restrictions indeed require to develop zero emission vehicles (ZEV) instead of low emission vehicles (LEV) for sustainability of automobile sector. In this context, scientists developed HCCI (homogeneous charge compression ignition) operation to enhance the efficiency of system also to reduce the consumption of fuel. HCCI engines are developed by transforming the SI and CI combustion engine concepts into hybrid mode, which utilizes homogeneous mixture of air-fuel in appropriate proportion as in SI engine but combustion is initiated by fuel self-ignition as in CI engine. Unlike conventional SI and CI combustions, HCCI needs no centralized combustion initiation and gives near simultaneous oxidation and rapid energy release throughout cylinder charge[1-3]. The advantage associated with such auto-ignition and parallel combustion nature that persist to consume leaner air-fuel mixture during combustion and the tolerance to exhaust gas recycling (EGR) can be significantly extended[4].It is also found that any alternative fuel, either in liquid or gaseous fuel can be used in HCCI that make it as unique combustion mode. It is also observed that the gaseous state fuels supply inside the HCCI engine makes it easier to operate. The burning characteristics as well as storage benefits make LPG (liquefied petroleum gas) as an efficient gasoline fuel. The possession of higher octane number by LPG makes its suitable application in spark ignition engine fuel rather than for compression ignition. However, various techniques are being adopted to use LPG as a sole fuel in CI engine. One such technique, adopted in the present work is to introduce LPG with DEE (Diethyl Ether) along with intake air by carburetion into the cylinder[5-6].

The low cetane number (< 3) of LPG along with high self-ignition temperature (450°C) direly requires an additive that acts as an ignition enhancer and turns it as an efficient fuel. In this regard, DEE[7] showed as huge potential towards its application as an ignition enhancer. Since, ethanol produced from biomass which is a renewable source of energy hence consider as a future fuel. In general, dehydration process is conveniently used to produce the DEE from Ethanol. DEE has high cetane number (> 120) as well as low auto ignition temperature (160°C) makes it as excellent compression ignition fuel[8]. Furthermore, non-corrosive nature, highly volatile liquid having high heating value (33900 kJ/kg) compared to ethanol (27000 kJ / kg) makes its compatible application as additive in LPG. Therefore, the compatibility showed complete replacement for diesel fuel by using DEE with suitable modification of the engine. In this regard, Venkatachalam et al.[9] selected DEE as the fuel additive inside palm kernel methyl ester (PKME) and LPG to compare and evaluate the performance of fuels. A significant reduction in NO_x was observed around 30% at the cost of brake thermal efficiency by 26 % with LPG-DEE mode at 0.6 kg/h of LPG. Later, Makoś et al.[10] successfully demonstrated that the dimethyl ether (DME) had huge potential towards its application as clean high-efficiency compression ignition fuel blended with LPG, rather than conventional diesel fuel for reduction of environmental pollutants. Aguado-Deblas et al.[11] used triple blending i.e. diesel/ DEE/ vegetable oil to develop efficient fuel that had potential to used in compression ignition (C.I.) engines. The investigation showed that the straight vegetable oils (SVOs) and DEE were mixed in the proportion of 18% and 22% respectively, with fossil diesel to develop triple blends fuels. A remarkable reduction in the cold flow properties and emission levels of pollutants was achieved with the said composition of blending. Recently Putrasari and Lim[12] published a complied work on application of DEE as potential fuel to replace the conventional diesel in order to minimize the nitrogen oxides and particulate matter emissions. Researchers found limited publication and inconclusive finding on application of Dimethyl ether which is prominent substitute of fossil fuel. Researchers, also demonstrated that the high pressure storage system or in the liquid phase of dimethyl ether, alongside maintaining adequate amount flow rate lead to various problems that makes its application ineffective in pure phases. So, researchers suggested that the blending use of dimethyl ether always be preferred.

According to Sezer, İsmet[13] a direct injection (DI) diesel engine is an ideal choice for evaluating the performance of a new liquefied petroleum gas (LPG) blend with diethyl ether (DEE) as an ignition enhancer. The combination of LPG and DEE in a DI diesel engine offers a unique advantage by leveraging the benefits of both fuels while overcoming their respective limitations. The primary challenge with LPG in a diesel engine is its high auto-ignition temperature, making it difficult to ignite in compression ignition (CI) engines.

LPG has been primarily a spark ignition engine fuel rather than for compression ignition engine due to its higher octane number. LPG has a very low cetane number (< 3) with high self-ignition temperature (450°C)[14] and will not ignite within the time available in an engine cylinder, hence some means of ignition must therefore be provided. Therefore, for ignition purpose a sufficient quantity of DEE (instead of diesel fuel) is inducted into the cylinder through the intake manifold (a technique known as Fumigation) and is compressed like in a conventional diesel engine. During the compression stroke, due to low self-ignition temperature (160°C) the DEE fuel auto ignites first and acts as an ignition source for entire cylinder of the homogenous LPG-air mixture.

Another advantage of using LPG-DEE blends in a DI diesel engine is the potential improvement in thermal efficiency[15]. The direct injection system in diesel engines ensures precise fuel delivery, optimizing the air-fuel mixture and promoting complete combustion. This results in better engine performance, reduced specific fuel consumption, and extended engine life due to lower carbon deposits and reduced wear and tear.

Thus, in this study, direct injection diesel engine is selected to evaluate the performance of new liquefied petroleum gas (LPG) blended with diethyl ether (DEE) (acts as an ignition enhancer). Furthermore, this study also focused to analyze the effect as well as mechanism of air preheating and EGR on HCCI combustion with a suitable modification in the engine intake system. The blended fuel with modified engine work is rarely available and still in vague state that requires high end research to explore a conclusive remarks, which is encounter in this work (novel aspect). Furthermore, an ample number of investigations are also conducted to analyze the entire phenomenon that linked with the emission level and combustion parameters.

2. Experimental Setup and Methodology

Diethyl ether was used as additive fuel to study the potential of blended fuel in order to compare with conventional diesel engine. Four set of fuel composition i.e. LPG+ DEE @Ambient Temperature (F1), LPG+ DEE @50 ˚C (F2), LPG+ DEE @ 15 % EGR (F3) and Diesel(F4) were selected as input supply to test the performance at various load condition. The engine was started and brought to operating temperature using LPG-diesel in dual fuel mode. After the engine has reached the operating temperature, the diesel fuel supply was gradually reduced to zero. The tests were conducted from no load to full load of engine operation at rated speed of 1500 rpm with an uncertainty of ~ 1.50 %.

The experimental set-up has rated output as 3.73 kW at 1500 rpm for the diesel engine represented in Fig. 1 and 2 with all nomenclature. The set-up is naturally aspirated with single cylinder water cooled system. All the specification of experimental set-up is summarized in

Table 1. The appropriate amount of LPG with air was intact to engine cylinder through manifold connected with simple gas carburetor. A special arrangement of 2.5 mm. Factors Affecting Performance of Diesel Engine Using DEE as an Ignition Enhancer by varying EGR and Intake Air Temperature copper pipe was inserted in the intake manifold to interact the DEE present in vapor phase. The preheating of the air was carried out though electric heater having 2 kW capacity. Furthermore, the system was attached with Ktype (chromel-alumel) thermocouple to monitor the intake temperature just before the intake port. The key characteristics of LPG, DEE and diesel15) are summarized in Table2.

Table 1. Experimental Set-up specification.

Engine Type	DI Diesel Engine, Single Cylinder (4 Stroke)
Swept Volume	553 cm3
Rated capacity	3.7 kW @ 1500 rpm
Bore x Stroke	80 mm x 110 mm
Compression ratio	16.5 : 1
Cooling system	Water Cooled

The engine cylinder pressure was measured with KISTLER make water-cooled piezoelectric pressure transducer that has a sensitivity of 14.2 pC / bar. MATLAB software was used to obtain the heat release rate from pressure crank angle data. Standard BOSCH smoke measuring apparatus was used for smoke measurement. An infrared analyzer was used to measure HC and CO levels in the exhaust with an uncertainty of ~ 5 %. NO emission was measured with an uncertainty of ~ 6 %. Chromel-alumel (K-type) thermocouple was used to measure exhaust gas temperature with an uncertainty of ~ 0.25 o C. In addition, a controller was attached with the thermocouple to regulate the temperature of preheat air.

Table 2. Characteristics of LPG, DEE and diesel[12].

Properties	Propane (C_3H_5)	DEE ($C_2H_5OC_2H_5$)	Diesel (C_8toC_{22})
Density (kg/m^3)	505	713	833
Calorific value (kJ/kg)	46380	33900	42500
Auto Ignition Temp°C	465	160	257
Cetane Number	< 3	> 125	40-55
Boiling point temperature (°C)	N. A	34.4	163
Viscosity, Centipoise at 20°C	-	0.23	2.6
Stoichiometric air-fuel mass ratio	15.7	11.1	14.5

For EGR technique, a special metal pipe was introduced in between the exhaust and intake pipe. The metal pipe was made up of spring type flexible systems, beneficial in succeeding cycles that provide the route of exhaust gases back to the engine inlet system. The measured mass flow rates of air with and without EGR are considered to evaluate the EGR ratio. Furthermore, researcher Nicos Ladommatos et al 1996[13)] illustrated the formula to evaluate the EGR percentage shown by equation 1:

$$EGR\% = \frac{(\dot{m}_a)\text{withoutEGR} - (\dot{m}_a)\text{with EGR}}{(\dot{m}_a)\text{withoutEGR}} \quad (1)$$

For smoke measurements standard BOSCH smoke measuring apparatus was used. The exhaust emissions, including unburned hydrocarbons (UBHC), nitric oxide (NO), and carbon monoxide (CO) was analyzed through HORIBA gas analyzer. Particulate emission measurement was made by gravimetric method.

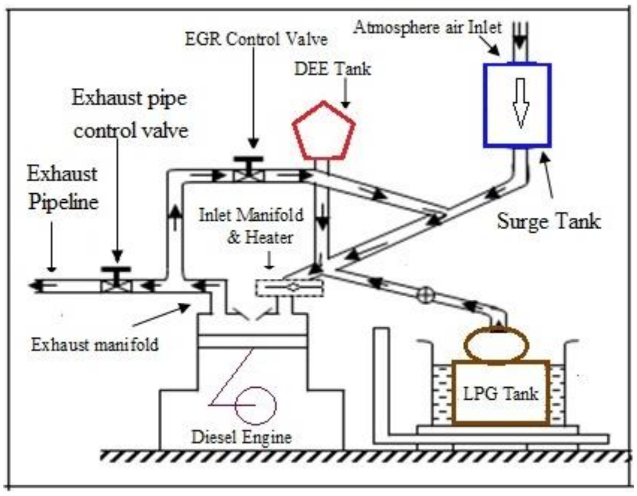

Fig. 1: Experimental set-up.

Fig. 2: Photographic view of the engine set-up.

3. Uncertainty analysis

The uncertainty analysis was carried out to address the errors and deviations that occurred during the experimental work in order to achieve precision. Moreover, before the trial, the test engine and any remaining instruments were adjusted. Three sample readings of the considered data were initially taken at regular intervals for the purpose of uncertainty analysis. The Uncertainty of different devices and instruments used in the experiment is shown in the Table 3.

Table 3. Uncertainty of different devices and instruments used in the experiment.

Device / instrument	Range	Accuracy	Uncertainty
AVL DiGas 480 Emission gas analyzer CO HC NO	0-10%Vol 0 -20000 ppm vol 0 – 5000 ppm vol	< 0.6% vol < 200 ppm vol < 500 ppm vol	± 0.3 ± 0.2 ± 0.5
Crank angle encoder	0 – 720 0CA	0.2CA bTDC	± 0.2
Fuel flow meter	0 - 500mm H2O	±0.1cc	±0.1
Air flow meter	25 – 60mbar	±0.25%	±0.25
Pressure sensor	-100 – 275 0F	±2%	±2
Precision weighing	0 – 220mg	±0.2mg	±0.1

4. Results and Discussion

4.1 Analysis on Brake Thermal Efficiency

The brake thermal efficiency against loads for inlet air temperature at 50 ^{0}C operated on neat LPG, F2, with EGR, F3 and compared with neat LPG operation at ambient condition, F1 and diesel, F4 is shown in Fig. 3. For neat LPG at an ambient temperature of 31° C, it varies from 7.8 % to 24.1 % where as in the case of inlet air temperature at 50 ^{0}C, it ranges from 8.6 % to 25.8 %. Furthermore, at 50° C the improvement in efficiency was found to be about 1 % to 1.5 % compared to that of neat LPG operation at ambient condition. The improvement in thermal efficiency may be due to the increase in inlet air temperature, which accelerates the vaporization of DEE and enhances the combustion of LPG.

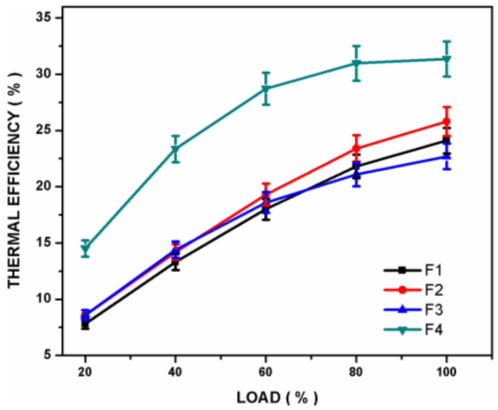

Fig. 3: Variation of brake thermal efficiency at different load condition.

It is also to be observed that at 15 % EGR i.e. F3, there is a reduction in the efficiency throughout the load spectrum, compared to all other operations. This result dedicated to higher specific heat capacities govern by CO_2 and H_2O resulting in more exhaust gases reduced the average combustion temperature in the engine cylinder; responsible for decrement of thermal efficiency earlier postulated by Ladommatos and his colleges[15,16].

4.2 Analysis on Hydrocarbon Emission

The relationships between hydrocarbon emission and various loads are depicted graphically in Fig. 4. From graph it can be observed that the LPG operation carried out at an ambient temperature of 31° C, the hydrocarbon concentration ranges from 2250 ppm at no load to 710 ppm at full load. Whereas, a significant decrement i.e. 2010 ppm at no load to 520 ppm at full load was observed for preheat air at 50 ^{0}C. The earlier study revealed that with increase in inlet air temperature consequences in the lower the HC levels inside the combustion chamber due to increase in in-cylinder temperature. For 15 % EGR operation, HC concentration ranges from 1950 ppm at no load to 1030 ppm at full load. The observations also reveal that the increase in HC emission is significant above 80 % load condition same is shown in Fig. 4. This was attributed to the incomplete combustion takes place, due to lack of O_2, admitted into the cylinder by EGR system, leads to higher HC emissions[17,18]. Earlier researchers showed that the problem could be mitigated by passing gaseous fuel that promptly responsible for a homogeneous, combustible mixture.

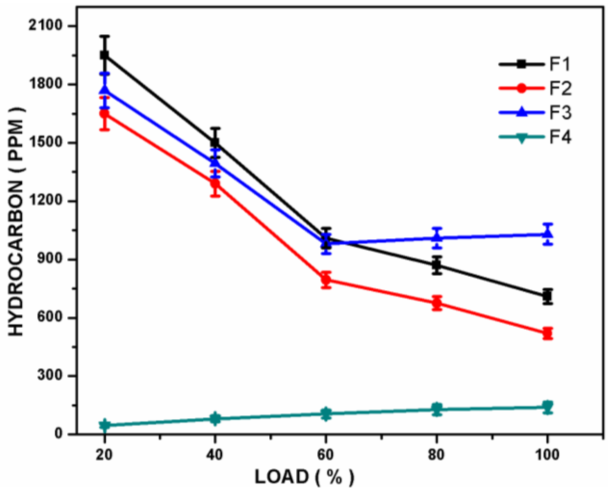

Fig. 4: Variation of hydrocarbon emission versus various loads.

4.3 Analysis on CO Emission

Figure 5 graphically represents the variation of CO level with various loads for intake air temperature at 50 ^{0}C (F2), 15 % EGR (F3), LPG at ambient temperature (F1) and diesel operation (F4). The observation revealed that the decrease in CO level was significant at 50°C. The reduction in the CO level may happen; because of the increase in intake air temperature that accelerates the reaction rates of the mixture. In the case of 15 % EGR (F3) operation, above 50 % load the CO level was increased. This may be attributed to the drop in volumetric efficiency with increase in intake temperature and thereby results lack of oxygen leads increases in the CO level.

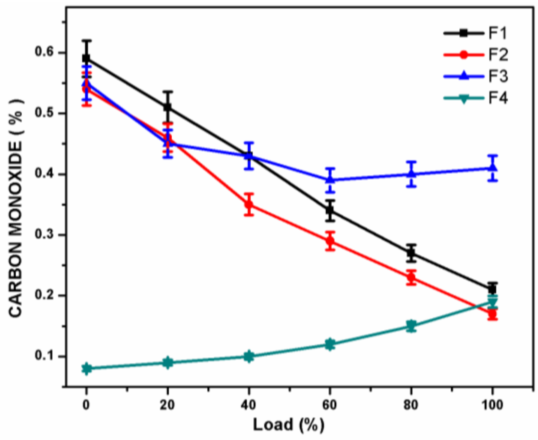

Fig. 5: Variation of carbon monoxide versus loads.

4.4 Analysis on Nitric Oxides Emission

Concentration of oxides of nitrogen at intake air temperature 50 ^{0}C (F2), 15 % EGR (F3), LPG at ambient temperature (F1) and diesel operation (F4) is shown in Fig. 6. It was noticed that the amount of NO increases with increase in intake air temperature throughout the load spectrum. This happened due to increase in intake air temperature consequences in the rise of the maximum cycle temperature inside the combustion chamber. In EGR operation the NO was observed to be lower at all loads when compared with other operation conditions. This may be due to the fact that the peak combustion temperature in the combustion chamber decreases due to release in EGR absorbed energy by CO_2 and H_2O. The results are in agreement with Tullis and Greeves[19].

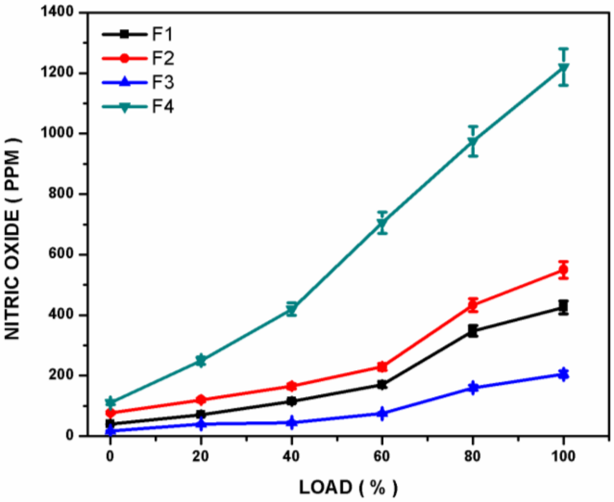

Fig. 6: Variation of of nitric oxide at various load condition.

4.5 Analysis on Smoke Emission

A graphical comparative study of smoke emission behavior at various load operated on neat LPG without (F1) and with EGR (F3) and intake air at 50 ^{0}C (F2) is shown in Fig. 7. The smoke level observed as 0.1 Bosch Smoke Unit (BSU) at 20 % load and 0.65 BSU at full load For F1, but with preheated air at 50^{0}C (F2) it was found as 0.03 BSU at 20 % load and 0.25 BSU at full load. At 50^{0}C, 85 % reduction in smoke was observed as compared to diesel operation[20]. The reduction in the smoke level attributed to the increase in intake air temperature further accelerates the combustion of LPG-air mixture, in addition to lower carbon to hydrogen ratio which results in better oxidation in the combustion chamber. From Fig. 7 it was also noticed that with EGR flow rate, the intensity of smoke level was gradually increased throughout the load spectrum may be due to improper combustion occurred. The reason for improper combustion attributed to the replacement of some oxygen in the inlet charge with EGR[21].

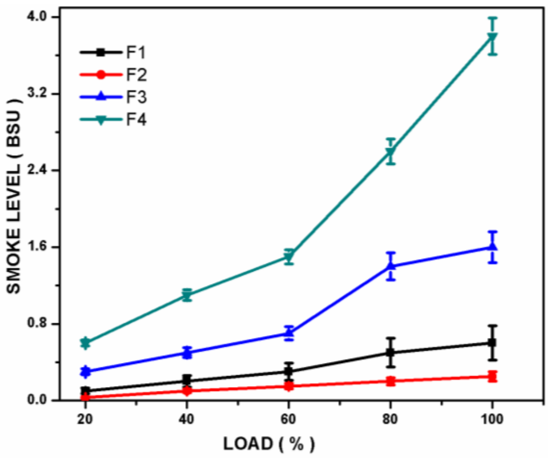

Fig.7: Relationships between smoke level and various loads.

4.6 Analysis on Exhaust Gas Temperature

Figure 8 showed the result for exhaust gas temperature under different load conditions for neat LPG (F1) with 15 % EGR (F2), inlet air temperatures at 50 ^{0}C (F3) compared with diesel mode (F4).

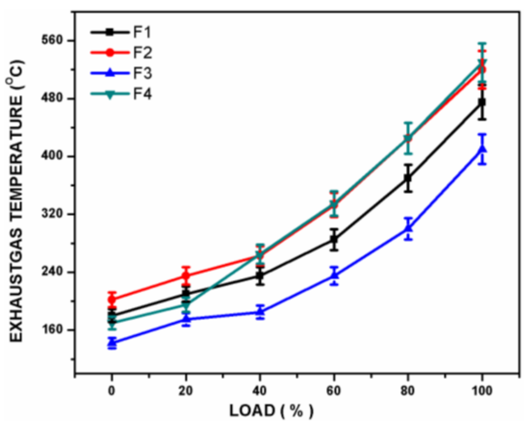

Fig. 8: Results of exhaust gas temperature for various loads.

The observation revealed that with increase in intake air temperature, the exhaust temperature also increases. The increment was also observed throughout the load spectrum, but substantial reduction in exhaust gas temperature at 15 % EGR was also noticed compared to all other operations. This may be happened due to introduction of EGR quantity into the cylinder. The presence of EGR quantity was responsible for reduction in peak combustion temperature that further diminishes the temperature of exhaust gas[22,23].

4.7 Analysis on Peak Pressure

The comparison of peak pressure for neat LPG (F1) with 15 % EGR (F2), inlet air temperatures at 50 ^{0}C (F3) compared with diesel mode (F4) at ambient temperature is shown in Fig. 9. From the figure it was observed that at inlet temperature of 50^{0}C, peak pressure was higher compared all other operating mode. This may be attributed to increase in maximum cycle temperature, which in turn increases in heat release as a result of higher cylinder charge temperature. Furthermore, at 15 % EGR (F2), the peak pressure observed as 34.24 bar and 50 bar at no load and full load respectively. The reduction in peak pressure is because the EGR serves as a heat-absorbing agent. The absorption of heat reduces the temperature of cylinder charge in the combustion chamber during the combustion process was also earlier showed by Yamin et al.[24].

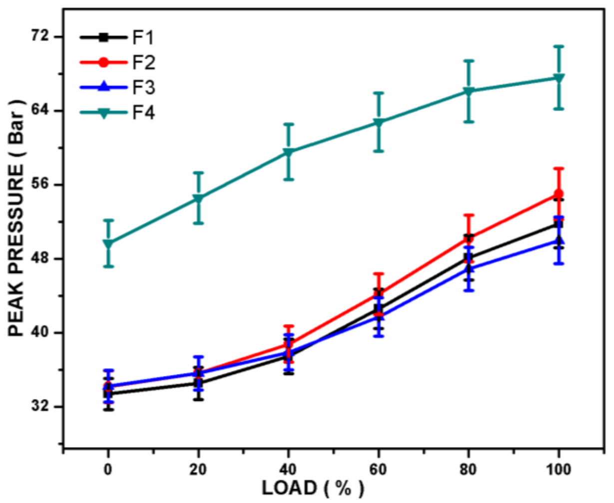

Fig. 8: Results of peak pressure for various loads.

4.8 Analysis on Pressure Crank-angle Diagram

The results obtained for pressure crank-angle diagram at full load condition is demonstrated graphically in Fig. 10. It was noticed that for neat LPG at ambient temperature of 31 ^{0}C (F1), the peak pressure was around 52 bar. Intake temperature at 50 ^{0}C, peak pressure was found to be 55 bar, whereas in the case of 15 % EGR it was 47.5 bar. Similar type of variation was earlier noticed by Oryshchyn et al.[25]. Researchers illustrated that a sharp increase in cylinder pressure just after Top Dead Centre (TDC) during the combustion stroke, reaching a peak pressure value before gradually declining as the combustion process attributed to leaner air-fuel mixture that could cause longer combustion times compared to a richer mixture. Alternatively, it could be influenced by the ignition timing, as variations in volumetric efficiency can impact the optimal ignition timing.

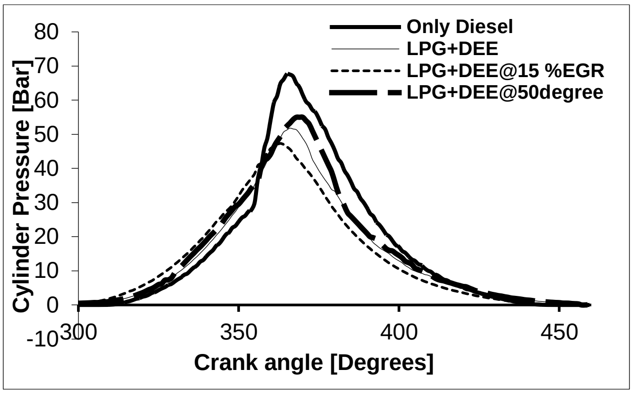

Fig. 9: Experimental result of pressure crank – angle diagram at full load.

4.9 Analysis on Heat Release Rate

Figure 10 shows the comparison of heat release rate for intake air temperature at 50 ^{0}C (F3), 15 % EGR (F2), LPG at ambient temperature (F1) and diesel operation (F4). The observation illustrated that; heat release rate was marginally higher in the case of LPG operation at inlet air temperature of 50 °C. As the intake air temperature increases, the larger peak as well as smaller peak advances by about 2 to 3 °CA before TDC. It was also noticed that, at 15 % EGR the peak pressure lowers by about 3 bar and delayed by about 3° crank angle, compared to LPG operation without EGR[25,26].

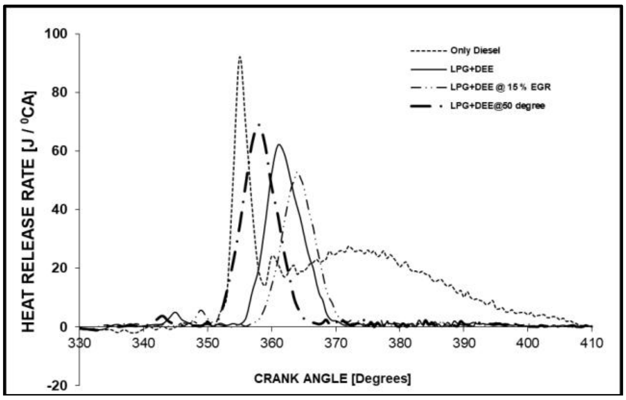

Fig. 10: Experimental result of heat release rate at full load.

5. Conclusion

The analysis demonstrated that the Diethyl ether (DEE) addition with LPG has been considered as alternative fuel to replace the fossil fuel like diesel. The findings and the results of the investigations are presented below.

- Intake air temperature at 50^{0}C the improvement in efficiency was found to be about 1 % to 1.5 %

compared to that of neat LPG operation at ambient condition. But at 15 % EGR (F2), the efficiency was observed lower throughout the load spectrum as compared to all other operations

- At 50 ^{0}C, there is a significant decrement in the HC level i.e. 2010 ppm at no load to 520 ppm at full load. The lower the HC levels is may be due to increase in in-cylinder temperature. For 15 % EGR operation, there is an increase in HC emission particularly above 80 % load condition.
- At 50 ^{0}C, the CO level was reduced significantly reduces due to raise in the intake air temperature that accelerates the reaction rates of the mixture, whereas of 15 % EGR (F3) operation, above 50 % load the CO level was increased.
- NO increases with increase in intake air temperature throughout the load spectrum. In EGR operation the NO is found to be lower at all loads when compared with other operation conditions.
- Increase in intake air temperature, the exhaust temperature was increased throughout the load spectrum, but substantial reduction in exhaust gas temperature at 15 % EGR was noticed compared to all other operations.
- The particulate matter is significantly reduced because, as the intake air temperature increases, which accelerates the oxidation rate and combustion reactions. Whereas at 15 % EGR, the particulate increases as compared other operating parameters.
- For LPG mode at ambient condition, the maximum reduction in smoke level is found to be about from 80 % to 85 throughout the load spectrum.
- At full load condition, peak pressure for LPG operation at ambient temperature of 31°C, intake air temperature at 50°C and at 15 % EGR were found to be 51.8 bar, 55 bar and 50 bar respectively

Acknowledgements

The authors are heartily paying their gratitude to the management of SECE for providing all necessary facilities and supports to carry the works.

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