Available online at www.sciencedirect.com

ScienceDirect

International Journal of Thermal Sciences 47 (2008) 450–457

International Journal of Thermal Sciences

www.elsevier.com/locate/ijts

LPG fueled diesel engine using diethyl ether with exhaust gas recirculation

N.K. Miller Jothi, G. Nagarajan *, S. Renganarayanan

Department of Mechanical Engineering, Anna University, Chennai – 600 025, India

Received 22 February 2006; received in revised form 19 June 2006; accepted 21 June 2006

Available online 11 December 2007

Abstract

The present investigation was to study the effect of Exhaust Gas Recirculation (EGR) on homogeneous charge ignition engine. A stationary four stroke, single cylinder, direct injection (DI) diesel engine capable of developing 3.7 kW at 1500 rpm was modified to operate in HCCI mode. In the present work the diesel engine was operated on 100% Liquified Petroleum Gas (LPG). The LPG has a low cetane number (<3), therefore Diethyl ether (DEE) was added to the LPG for ignition purpose. DEE is an excellent ignition enhancer (cetane number >125) and has a low auto ignition temperature (160 °C). Experimental results showed that by EGR technique, at part loads the brake thermal efficiency increases by about 2.5% and at full load, NO concentration could be considerably reduced to about 68% as compared to LPG operation without EGR. However, higher EGR percentage affects the combustion rate and significant reduction in peak pressure at maximum load.

Keywords: Liquified Petroleum Gas; Diethyl ether; Emissions; Ignition enhancer; Homogeneous charge ignition engine; Exhaust gas recirculation

1. Introduction

Diesel engines are widely used in commercial vehicles because of their high thermal efficiency and durability, hence play an important social and economic role. At the same time emissions emanating from internal combustion engines, in particular diesel engines have been a great source of concern from an environmental standpoint, especially oxides of nitrogen, smoke and particulates. Several techniques are being adopted to effectively reduce them, and one such technique is Homogeneous Charge Compression Ignition (HCCI) operation. However there are certain number of obstacles and problems in its application that have not been resolved. These problems are the control of ignition and combustion, difficulty in operation at higher loads, higher rate of heat release, higher CO and HC emissions particularly at light loads, difficulty with cold start, increased NO_x emissions at high loads etc., [1,2]. Some investigations recently reported by Bruno Walter et al. [3] developed an engine to reach near zero particulate and NO_x emissions particularly at full load in HCCI operation. They remarked that at higher engine speed it is possible to achieve good HCCI combustion at higher load.

Different methods that are widely used to reduce NO_x from diesel engines are exhaust gas recirculation, retarded injection timing, fuel denitrogenation, staged injection of fuel, water injection, exhaust catalysts, reduction of premixed burn fraction by reducing ignition delay, and application of optimized usage of HCCI engines.

Among the above methods, Exhaust Gas Recirculation (EGR) is one of the most effective techniques currently available for reducing NO_x emissions from I.C. engines [4,5]. 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 the preceding cycle. Internal EGR provides very short response time, its practical application is not possible until camless technology becomes widely available [6]. Furthermore, in internal EGR the gases cannot be cooled, whereas in external EGR it can be cooled. Therefore external EGR has emerged as the preferred current approach. External EGR involves diverting a fraction of the exhaust gas into the intake manifold where the recirculated exhaust gas mixes with the incoming air before being inducted into the combustion

Abbreviations: LPG, Liquified Petroleum Gas; DEE, Diethyl Ether; HC, Hydrocarbon; NO, Nitric Oxides; CO, Carbon Monoxide; PM, Particulate Matter; EGR, Exhaust Gas Recirculation; CA, Crank Angle; CO_2, Carbon dioxide; HCCI, Homogeneous Charge Compression Ignition.

* Corresponding author. Tel.: +91 44 22203265; fax: +91 44 22203255.
E-mail address: nagarajan@annauniv.edu (G. Nagarajan).

1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2006.06.012

Table 1
Specifications of the engine

Engine type	Single cylinder, 4 stroke, naturally aspirated DI diesel engine
Bore × stroke	80 mm × 110 mm
Displacement volume	553 cm^3
Compression ratio	16.5:1
Type of cooling	Water cooled
Rated power	3.7 kW @ 1500 rpm

chamber [7]. The recirculation of exhaust gases raises the total heat capacity of the working gases in the engine cylinder and thus lowers the peak gas temperature [8–10]. In HCCI engine, the most practical means of controlling charge temperature is through the addition of high levels of EGR into the intake. It has been well confirmed that hot EGR enhances combustion in four-stroke HCCI engines mainly due to the high temperature of the resulting intake mixture, rather than the existence of active radicals. In addition to the thermal effect, the inert gases contained in the EGR can be used to control the heat release rate due to its impact on chemical reaction rate, which can delay the auto-ignition time, reduce the heat release rate, and thus lower peak cylinder pressure.

In the present work, an attempt has been made to experimentally investigate the effect of EGR on a 100% LPG fueled HCCI engine throughout the load spectrum.

2. Experimental setup and experiments

The engine employed for the experimental work was a four-stroke, single cylinder, water-cooled, naturally aspirated DI diesel engine developing 3.73 kW at 1500 rpm. The technical specifications of the engine are given in Table 1. The engine was modified to operate in HCCI mode by mounting gas-air mixture arrangement in the intake manifold. LPG was used as a primary fuel that was carburetted with intake air and admitted into engine cylinder. LPG has a very low cetane number, hence DEE (self ignition temperature of DEE is around 160 °C) was added in liquid state as drops and just before the intake manifold it mixes in the form of vapour with LPG–air mixture. The diffusion of DEE fuel was enhanced by centering the nozzle outlet and directing it against the flow direction. During the compression stroke, due to low self-ignition temperature the DEE fuel auto ignites first and acts as an ignition source for entire cylinder of the homogeneous LPG–air mixture.

The ambitious goal of this present work is to achieve the engine could be operated smoothly throughout the load spectrum by properly adjusting the DEE quantity. At each load, the quantity of DEE was progressively adjusted in such a way that the lower level of DEE was determined by the onset of unstable operation or misfiring and knocking observed from the pressure-crank angle diagram. The LPG and DEE flow rate were varied manually according to the load with an uncertainty of ±2.40% and ±1.50% respectively. Typical physical and combustion properties of important fuels are given in Table 2 [11–14].

A spring type flexible metal pipe was installed between the exhaust pipe and the intake pipe, to route the exhaust gases back to the engine inlet system, where the hot gases were inducted into the succeeding cycles. The EGR ratio was obtained from the measured mass flow rate of air with and without EGR with an uncertainty of ±1.80% and the EGR percentage was calculated using the following formula [15].

$$\text{EGR\%} = \frac{[M_a]\ \text{without EGR} - [M_a]\ \text{with EGR}}{[M_a]\ \text{without EGR}}$$

Where = $[M_a]$ Mass flow rate of air, kg/s

EGR flow rates were varied in steps of 5% i.e., 10%, 15% and 20%. 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 engine cylinder pressure was measured with KISTLER make water-cooled piezoelectric pressure transducer that has a sensitivity of 14.2 pC/bar. The cylinder pressure signals were recorded on a personal computer using an analogue to digital converter and average pressure was obtained from 100 consecutive cycles. Special software was used to obtain the heat release rate from pressure crank angle data. A schematic arrangement of the experimental setup is shown in Fig. 1.

Standard BOSCH smoke measuring apparatus was used for smoke measurement. The particulate matter was filtered by the filter paper and it was weighed by a micro-weighing machine. 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 °C. The instruments used for various measurements are listed in Table 3.

Table 2
Physical and combustion properties of selective fuels and ethers

Properties	Propane	Diethyl ether	Diesel	Dimethyl ether
Formula	C_3H_5	$C_2H_5\,O\,C_2H_5$	C_8 to C_{20}	CH_3OCH_3
Density, kg/m^3	505	713	833	667
Viscosity, centipoise at 20 °C	–	0.23	2.6	–
Boiling point °C	N.A.	34.4	163	−25
Cetane number	<3	>125	40–55	>55
Auto ignition temperature, °C	465	160	257	235
Stoichiometric air fuel ratio, mass	15.7	11.1	14.5	9
Flammability limits, vol% (rich)	9.5	9.5–36	5	27
Flammability limits, vol (lean)	2.4	1.9	1	3.4
Calorific value, kJ/kg	46 380	33 900	42 500	28 800

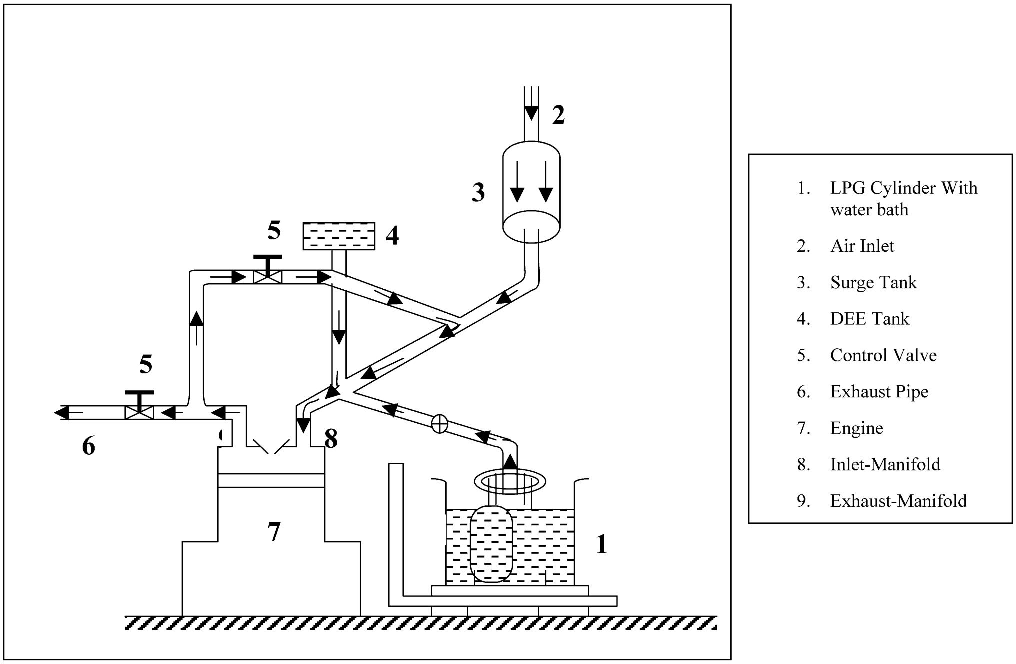

Fig. 1. Schematic view of the EGR set-up.

Table 3
Specifications of the measuring instruments

Measuring instruments	Measured
Horiba (NDIR) gas analyser	Carbon monoxide and unburned hydrocarbons
Technovation gas analyzer	Nitric oxide
BOSCH type smoke meter	Smoke intensity
Smoke pump (330 cc) and weighing balance	Particulate matter
K-type (chromel-alumel) thermocouples	Exhaust gas temperature

Table 4 shows without EGR, the concentration of DEE required for stable combustion of LPG at various loads. The quantities of DEE required for starting the engine and for idling were 58 percent by mass. The concentration of DEE required under normal operation from low load to full load varied between 49.7% to 28.8% percent (on mass basis). The increase in quantity of DEE at no load may be due to lower charge temperatures and also due to the dilution of LPG, which was introduced in small quantities (lean mixture). At full load condition, decreasing percentage of DEE concentration may be due to the hotter environment created in the combustion chamber from the previous cycle. The engine could be operated smoothly throughout the load spectrum by properly adjusting the DEE quantity.

The concentration of DEE required for various EGR percentage at various loads is also shown in Table 4. It can be observed that from no load to 40% load for all EGR percentages, there is a reduction in DEE concentration when compared with LPG operation without EGR. This is because as the EGR percentage is increased, it leads to richening of the inducted gas-air mixture and thereby results in better combustion of LPG and hence lesser quantity of DEE is required. Beyond 50% load the concentration of DEE progressively increased as the EGR percentage increases from 10% to 20% when compared to LPG operation without EGR. This may be due to the fact that at higher loads as well as with higher EGR percentages, the concentration of both CO_2 and H_2O present in the EGR is more, which reduces the peak combustion temperature in the combustion chamber. Hence for stable combustion of LPG the concentration of DEE increases gradually.

3. Results and discussion

In Exhaust Gas Recirculation (EGR) technique, the engine was operated throughout the load spectrum to study the effect on emissions and combustion parameters. Combustion parameters like peak pressure, maximum rate of pressure rise and heat

Table 4
DEE requirements at various EGR percentage

Load at 1500 rpm	Percentage of DEE on mass basis				
	Without EGR	5% EGR	10% EGR	15% EGR	20% EGR
No load	58	57.6	56.9	55.7	54.3
20%	49.7	48.8	48.3	47.1	46.3
40%	43.4	42.2	41.3	40.6	40.4
60%	37.4	35.8	36.7	37.9	39.4
80%	31.5	28.4	29.9	32.1	34.3
Full load	28.8	26.3	29.2	30.1	32.3

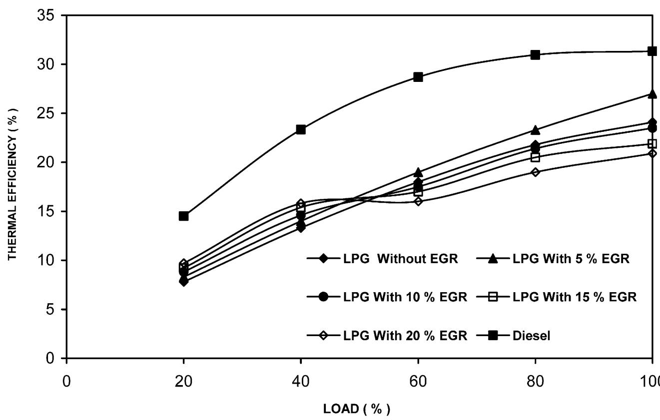

Fig. 2. Variation of brake thermal efficiency for various EGR percentages.

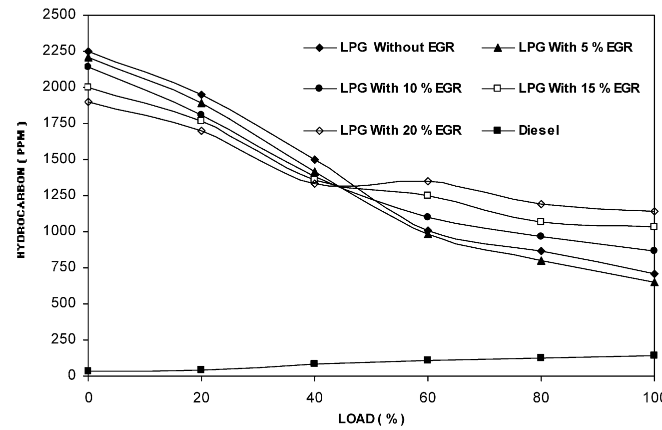

Fig. 3. Variation of hydrocarbon for various EGR percentages.

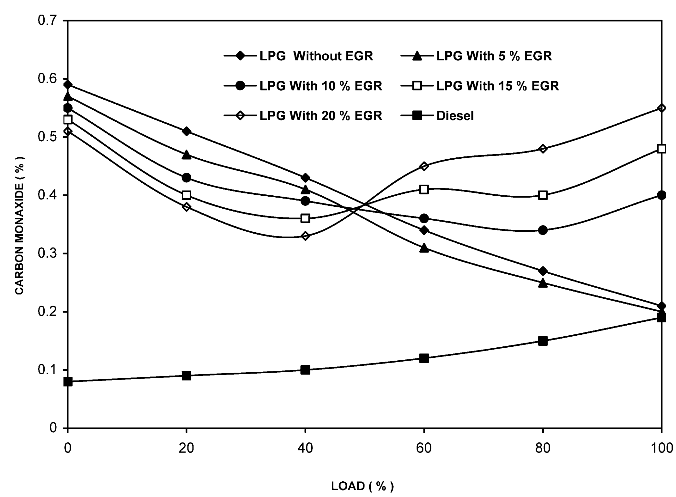

Fig. 4. Variation of carbon monoxide for various EGR percentages.

release rate were evaluated from pressure-crank angle data. The results are compared with standard diesel operation.

3.1. Brake thermal efficiency

The effect of exhaust gas recirculation on brake thermal efficiency is shown in Fig. 2 for different load conditions. For diesel operation the efficiency varies from 14.5% at no load to 31.4% at full load where as in the case of neat LPG operation without EGR it ranges from 7.8% at no load to 24.1% at full load. From the figure it can be observed that at part loads (20% and 40% load), the brake thermal efficiency increases with increase in EGR percentage as compared to LPG operation without EGR. From 5% to 20% EGR at part loads, the improvement in efficiency is about 0.5% to 2.5%.

This is because at low loads lean mixture is admitted into the engine cylinder during suction stroke and increasing the quantity of EGR results in reduction in air–fuel ratio towards stoichiometric ratio and thus results in better combustion of LPG. Moreover at part loads, EGR improves the combustion by recirculating active radicals, which will enhance combustion in the combustion chamber [16,17].

It can also be seen that at 5% EGR, the efficiency was found to be higher throughout the load spectrum as compared to LPG operation without EGR and improvement is about 0.5% at 20% load to 2.2% at full load. This is because as the load increases, the recycled exhaust gas temperature also increases which leads to accelerated combustion reaction in the combustion chamber and thereby increases thermal efficiency [18].

Beyond 50% load the efficiency progressively decreases as the EGR percentage increases from 10% to 20% when compared to LPG operation without EGR. This may be due to higher specific heat capacities of both CO_2 and H_2O which are more in exhaust gases at higher loads as well as higher quantity of EGR flow rates, which reduces the average combustion temperature in the engine cylinder, hence decrease thermal efficiency [9,19].

3.2. Hydrocarbon emission

The variation of hydrocarbon emissions for LPG operation with various EGR percentage is shown in Fig. 3. For diesel operation it ranges from 30 ppm at no load to 139 ppm at full load, whereas in the case of neat LPG operation without EGR, its concentration varies from 2250 ppm at no load to 710 ppm at full load. It can be observed that from no load to 40% load for all EGR percentages, there is a reduction in HC emissions when compared with LPG operation without EGR. This may be due to the reason that at part loads the mixture available inside the cylinder is lean. When the EGR percentage is increased, it leads to richening of the inducted gas–air mixture and thereby results in better combustion of LPG.

It can also be seen that at 5% EGR there is a reduction in HC emissions at all power outputs, it reduces from 2205 ppm at no load to 650 ppm at full load. At 80% and full load condition, the increase in HC emission is significant, particularly at 15% and 20% EGR. This may be due to the reduction of O_2 in the inlet charge by the EGR admitted into the cylinder. The lack of O_2 was responsible for reduced oxidation rate, which leads to incomplete combustion hence higher HC emissions.

3.3. Carbon monoxide emission

Fig. 4 depicts the variation in CO levels for LPG operation with various EGR percentage for different load conditions. CO

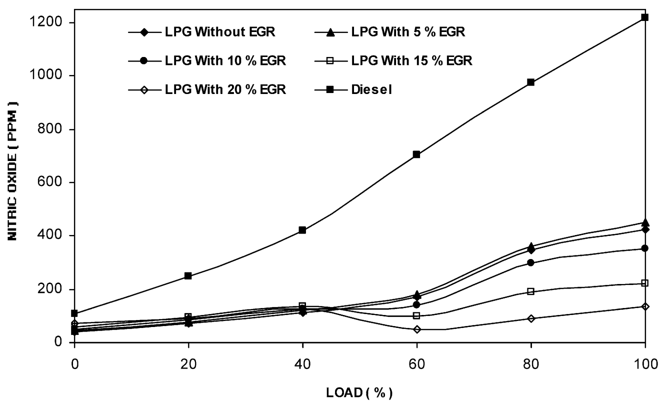

Fig. 5. Variation of nitric oxide for various EGR percentages.

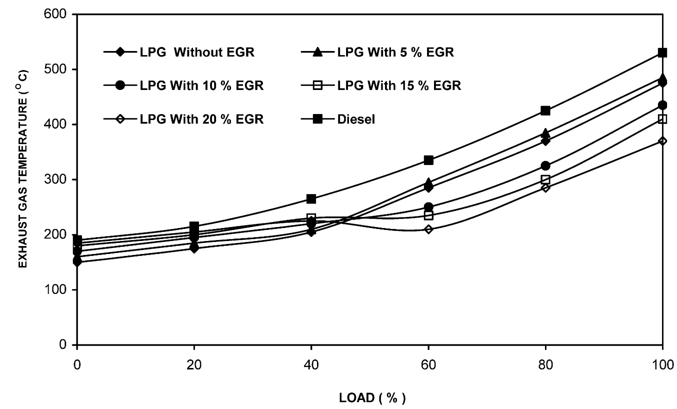

Fig. 6. Variation of exhaust gas temperature for various EGR percentages.

level for diesel varies from 0.08% at no load to 0.19% at full load, whereas in the case of LPG operation without EGR, it ranges from 0.59% at no load to 0.21% at full load. A similar trend like HC emission can be observed in CO level for LPG operation with EGR. From no load to 40% load for all EGR percentages, there is a reduction in CO level when compared with LPG operation without EGR.

At 5% EGR a favorable reduction in CO emission can be seen at all loads. Because the EGR raises the intake air temperature it could lead to a reduction in CO level. Above 50% load, increase in CO level is significant particularly as the EGR percentage increases from 10% to 20%. This may be due to some of the oxygen in the inlet charge is replaced with hot EGR. This causes incomplete combustion due to lack of oxygen in the combustion chamber leading to formation of CO.

3.4. Nitric oxides emission

The effect of various EGR percentages on nitric oxide emission for neat LPG operation is shown in Fig. 5. Generally EGR raises the total heat capacity of the working gases in engine cylinder and lowers the elevated peak temperature. The concentration of NO in the case of diesel operation ranges from 110 ppm at no load to 1220 ppm at full load and for LPG operation without EGR it ranges from 40 ppm at no load to 425 ppm at full load.

From the figure it can be observed that at no load to 40% load, for all EGR percentages, the NO is found to be slightly higher when compared with LPG operation without EGR. This is because the exhaust gas mixes with intake air and raises the inlet air temperature slightly which will also enhance the combustion rate, thereby leading to an increase in the cylinder temperature and hence higher NO emissions in the engine exhaust [20].

At higher power outputs, significant reduction in NO concentration particularly with high EGR percentages is observed. From 10% to 20% EGR, at 80% load, the NO reduces from 300 ppm to 90 ppm whereas in the case of full load it reduces from 350 ppm to 135 ppm, respectively. This may be due to the fact that at higher loads as well as with higher EGR percentages, the concentration of both CO_2 and H_2O present in the EGR is more. These gases absorb energy released by combustion, which reduces the peak combustion temperature in the combustion chamber resulting in the reduction of NO emissions in the engine exhaust [10]. This is reflected in low exhaust gas temperature as shown in Fig. 6.

3.5. Exhaust gas temperature

The variation of exhaust gas temperature for LPG mode of operation with various EGR percentages is shown in Fig. 6. It can be observed that the exhaust gas temperature is lower by about 50 °C in the case of LPG operation without EGR throughout the load spectrum as compared to diesel operation. From no load to 40% load, there is a slight increase in exhaust gas temperature for all EGR percentages.

Above 40% load, it can be seen that there is a substantial reduction in exhaust gas temperature particularly with high EGR percentage at higher loads. From 10% to 20% EGR, at 80% and at full load condition the exhaust gas temperature decreases from 325 °C to 285 °C and from 435 °C to 370 °C respectively. In general increase in EGR quantity into the engine cylinder, results in reduction in peak combustion temperature and hence reduction in exhaust gas temperature.

3.6. Particulate matter

Fig. 7 depicts the variation of particulates for LPG operation with different EGR percentages. The particulate matter emitted from the diesel operation varies from 1.13 g/h at 20% load to 4.12 g/h at full load, whereas for LPG operation without EGR it varies from 0.098 g/h at 20% load to 0.418 g/h at full load. It can be seen that at 20% and at 40% load there is a slight reduction in smoke level for all EGR percentages.

Above 40% load, there is a significant increase in particulates and much higher particularly with high EGR percentages at higher power outputs. From 10% to 20% EGR, at 80% and at full load condition the particulate increases from 0.484 g/h to 0.85 g/h and from 0.521 g/h to 0.924 g/h respectively. This is because, particulates present in the EGR is reintroduced into the combustion chamber, which act as nuclei for new particles and agglomerate to form larger particles due to lack of oxygen [21].

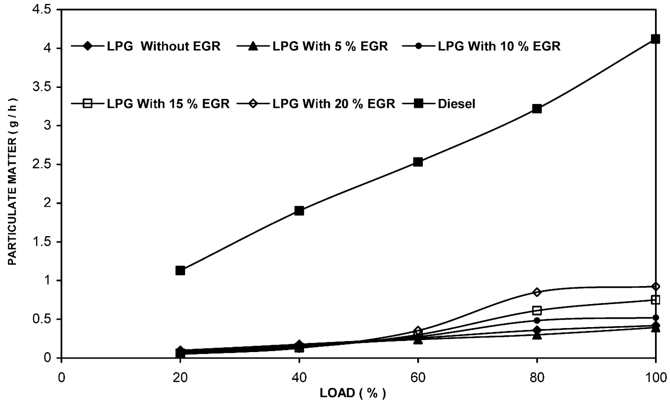

Fig. 7. Variation of particulate matter for various EGR percentages.

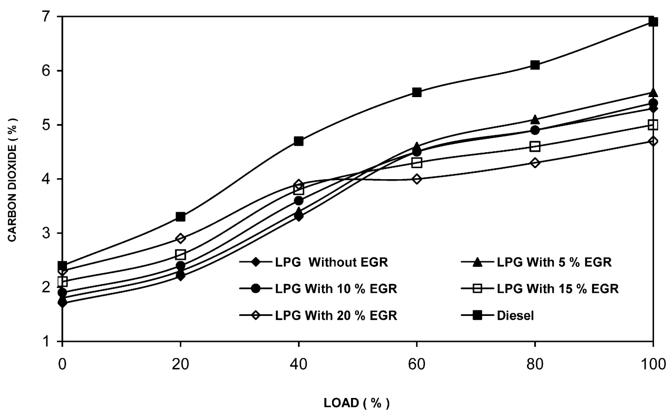

Fig. 8. Variation of carbon dioxide for various EGR percentages.

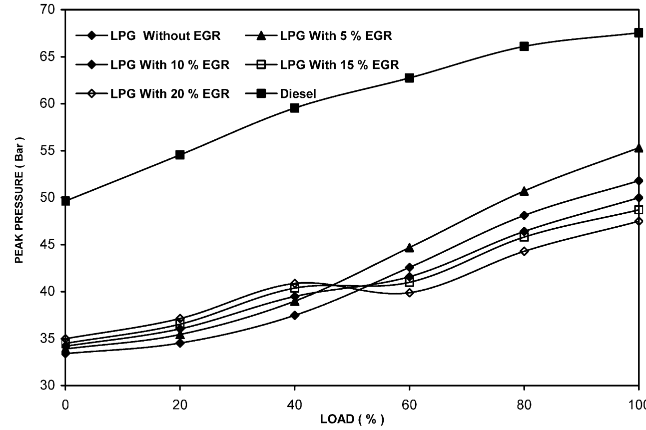

Fig. 9. Variation of peak pressure for various EGR percentages.

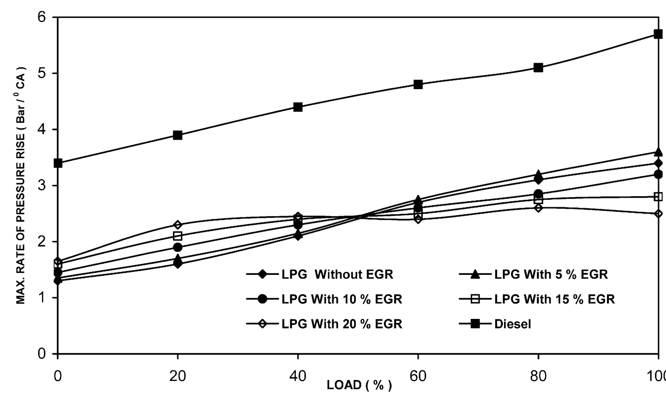

Fig. 10. Variation of rate of pressure rise for various EGR percentages.

3.7. Carbon dioxide emission

Fig. 8 depicts the variation in CO_2 levels for LPG mode operation with different quantities of EGR percentage. Carbon dioxide is a principal constituent of exhaust gas. The nature of CO_2 is higher heat capacity and it serves as a heat-absorbing agent during the combustion, which reduces the peak temperature in the engine cylinder. It can be observed that the CO_2 emissions from diesel operation ranges from 2.4% at no load to 6.9% at full load whereas in the case of neat LPG without EGR operation it ranges from 1.7% at no load to 5.3% at full load. It can also be noticed that from no load to 40% load for all EGR percentages, there is an increase in CO_2 level when compared with LPG operation without EGR.

At 80% and full load the CO_2 emissions decreases progressively as the EGR increases from 10% to 20%. This is because circulation of higher EGR percentage reduces the peak combustion temperature and lack of oxygen present in combustion chamber leads to poor combustion and results in lesser CO_2 emissions during the combustion process.

3.8. Peak pressure

Fig. 9 portrays the comparison of maximum cycle pressures for diesel and neat LPG with various EGR percentages at different loads. For diesel operation it ranges from 50 bar at no load to 68 bar at full load and in the case of neat LPG operation it varies from 33 bar to 52 bar. It can be seen that from no load to 40% load, there is an increase in peak pressure for all EGR percentages. It can also be observed that at 5% EGR there is an increase in peak pressure throughout the load spectrum. This is because as the load increases the exhaust gas temperature also increases that leads to better combustion of LPG–air mixture, which in turn results in an increase in peak pressure.

Above 50% load, there is a significant decrease in peak pressure with higher EGR percentages. At 80% load, from zero to 20% EGR, the peak pressure decreases from 48 bar to 44 bar whereas in the case of full load condition it decreases from 52 bar to 47 bar. This is because the EGR serves as a heat-absorbing agent, which reduces the cylinder charge temperature in the combustion chamber during the combustion process.

3.9. Rate of pressure rise

Fig. 10 depicts the rate of pressure rise for LPG operation with various EGR percentages. In the case of diesel and neat LPG operation it varies from 3.4 bar/°CA at no load to 5.7 bar/°CA at full load and 1.3 bar/°CA at no load to 3.4 bar/°CA at full load respectively. It can be observed that from no load to 40% load, for all EGR percentages, the rate of pressure rise is found to be slightly higher when compared with LPG operation without EGR. This is because EGR improves the combustion by recirculating radicals, which will enhance

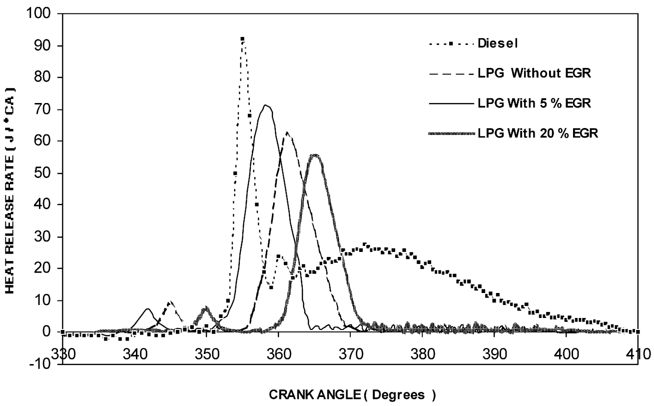

Fig. 11. Variation of heat release rate at full load.

the combustion reactions that takes place during the compression stroke [22].

It can also be seen that above 50% load, the reduction in rate of pressure rise is significant with high EGR percentages at higher loads. From 10% to 20% EGR, at full load condition the rate of pressure rise decreases from 3.2 bar/°CA to 2.5 bar/°CA. The decrease in rate of pressure rise may be due to the reduction in peak temperature in the combustion chamber.

3.10. Heat release rate

A comparison of heat release rate for various EGR percentages adopted in the utilization of neat LPG with diesel operation is shown in Fig. 11. In the case of LPG operation, two peaks can be seen. The appearance of large peak corresponds to the main combustion. The smaller peak that appears like a small 'bump' (small protuberance) corresponds to a preflame reaction before the start of main combustion. The two peaks in the heat release rate are also called the cool flame (low temperature reaction) and hot flame (high temperature reaction) respectively. The cool flame and hot flame are commonly observed in homogeneous low temperature auto ignition [23] (DEE is known for its low temperature auto-ignition characteristics).

From the figure it can be seen that, heat release rate is slightly high in the case of LPG operation at 5% EGR. The smaller peak (cool flame) is decreased and advanced by about 2 to 3° crank angle before TDC as compared to LPG without EGR. The reason for peak advancement and increase in heat release may be attributed to the increase in inlet air temperature that leads to enhanced combustion rate.

It can also be observed that at 20% EGR, the heat release rate is found to be lesser. In addition the larger peak (high temperature reaction) as well as smaller peak (low temperature reaction) shifts by about 4° crank angle further away from TDC. The reason for the shift in peak and delayed start of heat release may be due to lower cylinder charge temperature as a result of EGR and thereby reduces maximum cycle temperature.

4. Conclusions

The following conclusions are drawn based on the experimental investigations:

- It is possible to operate the DI compression ignition engine with stable combustion on neat LPG over the entire range of loads by the introduction of 58% to 28.8% of DEE on mass basis.
- At higher power outputs admitting too rich mixture causes a very rapid combustion and cause severe knock, which would affect the engine performance and the engine itself.
- The brake thermal efficiency increases by about 2.5% at part loads for all EGR percentages as compared to LPG operation without EGR. However at full load higher EGR percentage affects the performance of the engine.
- 5% EGR gives improved performance throughout the load spectrum and improvement in efficiency is about 2.2% at full load.
- HC emissions are lower for all EGR percentages at part loads. Maximum reduction at 20% EGR ranges from 1900 ppm at no load to 1330 ppm at 40% load.
- NO concentrations are lowest at full load for 20% EGR (135 ppm) when compared to LPG operation without EGR (425 ppm).
- LPG with EGR operation exhibits lower exhaust gas temperature particularly with high EGR percentage at higher loads. From 10% to 20% EGR, at 80% and at full load condition the exhaust gas temperature decreases from 325 °C to 285 °C and from 435 °C to 370 °C respectively.
- Particulates are lesser especially at part loads for LPG with EGR operation (0.049 g/h–0.128 g/h) compared to LPG operation without EGR (0.098 g/h–0.176 g/h). For 20% EGR, at full load condition, particulate emissions increase by about 55% when compared to LPG operation without EGR.
- Peak pressures are higher at 20% EGR particularly at part loads (35 bar–41 bar) when compared to LPG operation without EGR (33 bar–37.48 bar) whereas for 20% EGR at full load condition the peak pressure is lower when compared to LPG without EGR (48 bar)
- The rate of pressure rise is marginal for all EGR percentages at part loads however the rate of pressure rise reduces significantly at higher loads.

References

[1] F.F. Zhao, Homogeneous Charge Compression Ignition (HCCI) Engine: Key Research and Development Issues, Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096-0001, USA, 2003.
[2] Z. Chen, M. Konno, S. Goto, Study on homogeneous premixed charge CI engine fueled with LPG, JSAE Paper 20014339, 2001.
[3] B. Walter, B. Gatellier, Development of the high power NADI concept using dual mode diesel combustion to achieve zero NO_x and particulate emissions, SAE Transaction 2002-01-1744, 2002.
[4] C. Robert, S.M. Shahed, Effects of injection timing and exhaust gas recirculation on emissions from a DI diesel engine, SAE Transaction 811234, 1981.
[5] S. Kohketsu, Kazutoshimori, K. Sakal, T. Hakozaki, EGR technologies for a turbocharged and intercooled heavy-duty diesel engine, SAE Transaction 970340, 1997.
[6] T. Jacobs, D. Assanis, Z. Fillipi, The impact of exhaust gas recirculation on performance and emissions of a heavy-duty diesel engine, SAE Transaction 2003-01-1068, 2003.

[7] J.W. Girard, L.D. Gratz, J.H. Johnson, S.T. Bagley, D.G. Leddy, Study of the character and deposition rates of sulfur species in the EGR cooling system of a heavy-duty diesel engine, SAE Transaction 1999-01-3566, 1999.

[8] S. Ohigashi, H. Kuroda, Y. Nakasma, Y. Hayashi, K. Sugihara, Heat capacity charges predict nitrogen oxides reduction by exhaust gas recirculation, SAE Transaction 710010, 1971.

[9] H. Zhao, J. Hu, N. Nadommatos, Cylinder studies of the effects of CO_2 in exhaust gas recirculation on diesel combustion and emissions, Proc. Inst. Mech. Engineers Part D 214 (2000).

[10] S. Tullis, G. Greeves, Improving NO_x versus BSFC with EVI 200 using EGR and pilot injection for heavy-duty diesel engines, SAE Transaction 960843, 1996.

[11] S. Kajitani, C.L. Chen, M. Oguma, M. Alam, K.T. Rhee, Direct injection diesel engine operated with propane-DME blended fuel, SAE Transaction 982536, 1998.

[12] B. Bailey, J. Eberhardt, S. Goguen, J. Erwin, Diethyl ether (DEE) as a renewable diesel fuel, SAE Transaction 972978, 1997.

[13] M. Konno, S. Kajitani, M. Oguma, T.I.K.-I. Shima, NO emission characteristics of a CI engine fueled with neat dimethyl ether, SAE Transaction 1999-01-111, 1999.

[14] Z. Chen, M. Konno, M. Oguma, T. Yanai, Experimental study of CI natural-gas/DME homogeneous charge engine, SAE Transaction 2000-01-0329, 2000.

[15] N. Ladommatos, R. Balian, R. Horrocks, L. Cooper, The effect of exhaust gas recirculation on combustion and NO_x emissions in a high-speed direct-injection diesel engine, SAE Transaction 960840, 1996.

[16] M.P. Poonia, A. Ramesh, R.R. Gaur, Experimental investigation of the factors affecting the performance of a LPG-diesel dual fuel engine, SAE Transaction 1999-01-1123, 1999.

[17] V. Pirouzpanah, K. Sari, Reduction of emissions in an automotive direct injection diesel engine dual-fuelled with natural gas by using variable exhaust gas recirculation, Proc. Inst. Mech. Engineers Part D 217 (2003).

[18] Y.E. Mohamed, Selim, A study of some combustion characteristics of dual fuel engine using EGR, SAE Transaction 2003-01-0766, 2003.

[19] N. Ladommatos, S.M. Abdelhalim, H. Zhao, Z. Hu, The effects of carbon dioxide in exhaust gas recirculation on diesel engine emissions, Proc. Inst. Mech. Engineers Part D 212 (1998).

[20] S.L. Plee, T. Ahmad, J.P. Myers, Flame temperature correlation for the effects of exhaust gas recirculation on diesel particulate and NO_x emissions, SAE Transaction 811195, 1981.

[21] R.M. Wagner, J.B. Green, Jr., J.M. Storey, C. Stuart Daw, Extending exhaust gas recirculation limits in diesel engines, in: A & WMA 93rd Annual Conference and Exposition Salt Lake City, June 18–22, 2000.

[22] S. Onishi, S. Hong Jo, K. Shoda, P.D. Jo, S. Kato, Active thermo-atmosphere combustion (ATAC) – a new combustion process for internal combustion engines, SAE Transaction 790501, 1979.

[23] N. Lida, T. Igarashi, Auto-ignition and combustion of n-butane and DME/air mixtures in a homogeneous charge compression ignition engine, SAE Transaction 2000-01-1832, 2000.