International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Experimental Analysis of Dual Fuel Compression Ignition Engine with Exhaust Gas Recirculation

Machindra Gaikwad*, **Keshav Jadhav and Avinash Kolekar**

Department of Mechanical Engineering, VPKBIET Baramati, Pune, India

Accepted 15 June 2016, Available online 20 June 2016, **Special Issue-5 (June 2016)**

Abstract

EGR (Exhaust gas recirculation) is one of effective method which has been used to reduce nitrogen oxides (NOx) emissions from diesel engine. Diesel-LPG (liquefied petroleum gas) dual fuel CI (compression ignition) engine with 60% energy share of LPG were used for this investigation. In present study, EGR method is used for LPG-Diesel dual fuel engine with four flow rates (5% to 20% with step 5) at ambient temperature. Experimental tests were performed on a Kirloskar CI engine (single cylinder, four stroke, water cooled) to examine engine performance and emission characteristics. Experimental results showed that the dual fuel engine without EGR gives better performance from quarter load to full load as compared to the straight diesel engine and the EGR improves the performance at part load (50% & 75%) in dual fuel engine. The emission of NO_X significantly reduces with EGR and most reduction seen at 20% EGR. It is also observed that there was reduction in CO emission at part load while at no load and full load it slightly increase in case of EGR.

Keywords: *LPG, Dual Fuel, CI Engine, EGR, Performance, Emission.*

1. Introduction

The use of different alternative gaseous fuels like CNG (compressed natural gas), hydrogen, LPG, ethanol with fumigation etc. is a promising method for dropping the dependency on petroleum based liquid fuels and to reduce the emissions of pollutants from diesel engine. Mostly gaseous fuels have high octane number and hence, suitable for relatively high compression ratio engines. These fuels also resist knock at higher compression ratio, as well as reduce the polluting exhaust gases if suitable conditions are satisfied for its operating condition. So, it is more efficient and of environmental benefit to use gaseous fuel in diesel engines (Ashok, *et al,* 2015), (Sahoo, *et al,* 2009). CI engines (mostly referred as diesel engines) are most attractive for researchers due to its higher compression ratio, high thermal efficiency and engine power, fuel economy, durability and lower emissions of CO. They are widely used in stationary applications, transportation sectors and constructional areas.

LPG is a possible alternative gaseous fuel for diesel engines which is commonly referred as auto-gas or auto-fuel. It is a gas product of petroleum purifying principally consisting of propane, butane, propylene, and additional light hydrocarbons. LPG is a suitable fuel for spark ignition engine due to its high octane number. However, it cannot use in diesel engine as sole fuel due to its high auto-ignition temperature. So the ignition source needed to ignite LPG fuel (Ashok, *et al,* 2015).

Therefore it is need to some modifications in existing diesel engines. There are mainly two approaches have been employed to use LPG in diesel engine (a) Dual fuel operation and (b) spark ignition. When diesel fuel and LPG fuel in the diesel engine used simultaneously called as LPG-diesel dual fuel engine. In this dual fuel engine, the LPG fuel is supplied into the combustion cylinder either direct injection or fumigated with intake air stream and small amount of diesel fuel is injected to provide ignition source. In case of spark ignition CI engine instead of diesel, spark plug is used to provide ignition source. In the LPG-diesel dual fuel engine, LPG fuel is a main source of energy so it is referred as primary fuel and the diesel fuel is referred as pilot fuel (Ashok, *et al,* 2015). Currently research in dual fuel engines are attracted tremendous interest to the many scientists due to several reasons including (1) limited resources of conventional liquid fuels (2) the environment concerns and (3) the necessity to use a durable, reliable, and proficient engine (Elnajjar, *et al,* 2013a).

The diesel engines have a serious problem regarding its emissions especially NO_X. An international concern is strict about its control and restriction. Therefore, it is very important to reduce the NO_X emissions from the engine exhaust gas in order

Corresponding author: **Machindra Gaikwad

to meet the environmental regulations (Saleh, 2008). Nitric oxide (NO) and nitrogen dioxide (NO_2) usually called oxides of nitrogen and both are considered to be harmful to human being as well as environment. NO_2 is more poisonous than NO. It directly disturbs human health, precursor to ozone formation and responsible for formation of smog. In the diesel engine exhaust the ratio of NO_2 and NO is relatively small, but NO_2 generate from NO because NO becomes rapidly oxidized in the environment. Since diesel engine mostly emits NO therefore it is necessary to reduce the NO formation (Hussain, *et al*, 2012).

The exhaust gas recirculation (EGR) is a promising technique to reduce the emission of nitrogen oxides investigated by many researchers. In which some amount of exhaust gases is returning into the combustion cylinder with intake air stream so an air entering the combustion chamber displaces by the re-circulated exhaust gases. Exhaust gases mainly consists of carbon dioxide (CO_2) and water vapour. Due to the air displacement, the availability of oxygen in the intake mixture reduces for combustion. The effective air–fuel ratio lowers because of reduced oxygen available for combustion. Therefore it affects exhaust emissions considerably. In addition to that exhaust gases in the intake air raises specific heat of intake mixture which outcomes in the reduction of flame temperature. Thus the combination of lower amount of oxygen in the intake air and reduced flame temperature reduces rate of NO_X formation reactions (Agarwal, *et al*, 2011). Principally there are two types of EGR; cooled EGR and hot EGR. In the hot EGR system exhaust gases is returned without cooling. Hot EGR improves thermal efficiency in dual fuel engine due to increased intake temperature and re-burning of the unburned fuel in the re-circulated gas. In case of cooled EGR, it gives lower thermal efficiency and lower NO_X emission as compared to hot EGR (Abd-Alla, 2002).

Several researchers have investigated the nature of LPG-diesel dual fuel engine as well as EGR coupled LPG-diesel dual fuel engine in terms of performance and emission characteristics with different operating condition. Ashok *et al* (Ashok, *et al*, 2015) have critically reviewed the LPG-diesel dual fuel engine. From the several studies they put the conclusion is the part load characteristic can be enhanced by optimizing the engine operating parameters and design factors such as engine load, speed, pilot fuel quantity, injection timing, intake gaseous fuel compositions and intake manifold condition. Wang *et al* (Wang, *et al*, 2016) have used LPG fuel as ignition inhibitor in DME (dimethyl ether)-diesel dual fuel engine for studying combustion and emission characteristics. They fumigated mixture of DME-LPG fuel into intake port with different composition ratio. They concluded that decreases the cylinder pressure, brake thermal efficiency (BTE) and NO_X emission with increasing concentration of LPG fuel. Surawski *et al* (Surawski, *et al*, 2014) have investigated LPG fumigated turbocharger coupled Euro III CI engine to discover its impact on engine performance, and gaseous and particulate emissions. They carried out experimentation with changing load zero to full with 14-29% energy substitution by LPG. Their results show that peak combustion pressure and the rate of pressure rise increases. They observed that decreases in NO and particulate matter (PM) emissions; but carbon monoxide (CO) and hydrocarbon (HC) increased

Elnajjar *et al* (Elnajjar, *et al*, 2013a) have experimentally analysed the effect of LPG fuel with different propane-butane composition (100, 70, 55, 25 and 0) on dual fuel engine. From their results 25 is appropriate for grate performance among the other fuel compositions with the highest level of efficiency with small noise. A mixture of both gaseous fuels performs relatively higher than the pure Propane or Butane. Same experimentation was carried out by Elnajjar *et al* (Elnajjar, *et al*, 2013b) and they concluded that different LPG composition not affected majorly on the engine efficiency but directly impacts on the levels of generate combustion noise.

The maximum increment in the BTE (of 6%) is achieved with 40% of secondary fuel when LPG is used as secondary fuel presented by Lata *et al* (Lata, *et al*, 2012). They resulted that proportion of un-burnt HC and CO increases, while emission of NO_X and smoke reduces in dual fuel operation compared to the pure diesel operation. They also used 40% of mixture of LPG and hydrogen (in the ratio 70:30) in dual fuel mode and obtained enhancement in BTE by 27% and reduction in HC emission by 68%.

Le and Nguyen (Le and Nguyen, 2011) have analysed dual fuel LPG/diesel engine. Their study shows that lower CO emissions and lower smoke number because of better combustion process but higher NO_X due to higher combustion temperature and higher total hydrocarbon (THC) due to unburned hydrocarbon.

Qi *et al* (Qi, *et al*, 2007) establishes a different technique of utilizing LPG for diesel engine by using blended LPG/diesel fuel, and states that it is a promising method for controlling both smoke emissions and NO_X. For this technique requires only a slight modification of the engine structure even on existing diesel engines.

Yasin *et al* (Yasin, *et al*, 2015) have studied EGR coupled dual fuel engine. They reported that EGR gives higher emissions of CO, CO_2 and HC while lower emission of NO_X. Brijesh *et al* (Brijesh, *et al*, 2014) have carried out the comparative study between oxygenated EGR (OEGR) and LPG on diesel engine in terms of emission characteristics at 75% load. Their study shows that NO_X and particulate matter (PM) decreases with increasing OEGR while increase ignition delay. In case of LPG dual fuel operation they observed reduction in NO_X, PM and CO with increased percentage of LPG but have an adverse effect on BTE and HC. Finally they put predictive statement is that, to achieve ultra-low emissions level in CI engines, combination of LPG and OEGR will be considered as a scope of future work.

Poonia and Mathur (Poonia and Mathur, 2012a) have found the effect of EGR and load on cyclic variations of LPG-diesel dual fuel engine. They observed the cyclic variation in peak cycle pressure and indicated mean effective pressure are lower with EGR up to 60% load compared to without EGR. The effect of hot EGR and cold EGR on the combustion characteristics of LPG-diesel dual fuel engine is investigated by Poonia and Mathur (Poonia and Mathur, 2012b). The effect of hot EGR on delay period is insignificant while cold EGR increases the delay period. Both EGR rate gives higher rate of pressure rise and longer total duration of combustion.

Kumaraswami and Durga Prasad (Kumaraswami and Durga Prasad, 2012) have used LPG as secondary fuel with EGR. Their results show that the dual fuel engine emits less NO_X over wide range of engine operating conditions (Speed, load). At low loads results indicated that higher CO and HC emissions and BSFC (brake specific fuel consumption). Saleh (Saleh, 2008) found that 5% rate of EGR improves performance at part load in LPG-diesel engine with 70% propane in LPG.

In the literature there is little information about the lower EGR temperature with different flow rates. The objective of this study is to examine the LPG-diesel dual fuel engine with EGR at ambient temperature. The parameters like heat release rate, peak cylinder pressure, BTE, BSFC, and emissions of CO, CO_2 and NO_X are checked in this investigation.

2. Experimentation

The line diagram of experimental set-up is shown in Fig. 1. Experiments were carried out on a single cylinder, four stroke and water cooled CI engine. The details specifications of research engine are given in Table 1.

Table 1 Engine specifications

Parameters	Specifications
Constructor	Kirloskar
Engine type	1 Cylinder, 4 Strokes, Water Cooled, Modified VCR Diesel Engine
Bore (mm)*Stroke(mm)	87.5*110
Compression ratio	12:1 to 18:1
Speed (RPM)	1500
Power output(kW)	3.5
Cylinder capacity (cc)	661

Whole experiments are performed at constant speed 1500 rpm with varying load 0 to 100% of full load with step of 25% by using eddy current dynamometer which is coupled to engine shaft. An 18 compression ratio and the injection timing of this engine 23^0CA (crank angle) before TDC (top dead center) are used during experimentation. Indian commercial diesel and LPG fuel are used for experiments. LPG is fumigated with intake air stream at ambient pressure and the diesel is injected by traditional way with injection pressure of 190bar of this engine. A calibrated LPG flow meter is used to measure LPG flow rate and diesel flow rate is measured on volumetric basis by using burette and time taken to consume the diesel. Air flow rate to the engine is measured using orifice meter. For avoiding gas pulsations a gas stabilizer/box is attached in the LPG flow line. In dual fuel engine lower LPG energy share will not have any effect on engine performance and emission characteristics. On other hand much larger LPG energy share will be responsible to rapidly increment in-cylinder pressure and harms the engine (Ashok, *et al*, 2015). So as per total energy requirement the 60% energy share of LPG was used for the experimentation and which is calculated by following equation.

$$LPG(\%) = \frac{\dot{m}_{LPG} \times LCV_{LPG}}{(\dot{m}_{LPG} \times LCV_{LPG}) + (\dot{m}_{diesel} \times LCV_{diesel})} \times 100 \quad (1)$$

Where, $\dot{m}_{LPG}$ and $\dot{m}_{diesel}$ are the mass flow rate of LPG and diesel respectively. LCV_{LPG} and LCV_{diesel} are the lower calorific values of LPG and diesel respectively.

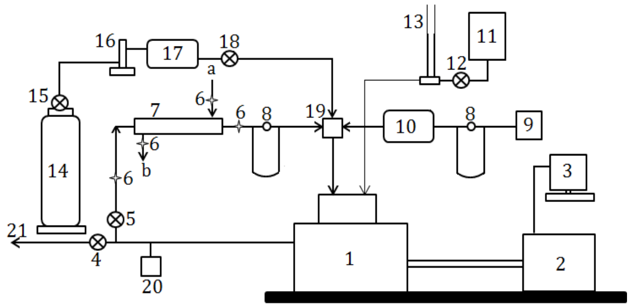

Fig. 1 Experimental set-up diagram

1-Test engine, 2-Dynamometer, 3-Computer interface of the control panel, 4-Exhaust gas backpressure valve, 5-EGR control valve, 6-Temperature sensor, 7-EGR cooler, 8-Orifice with manometer, 9-Air filter, 10-Air surge tank, 11-Diesel fuel tank, 12-Diesel measurement valve, 13-Burette, 14-LPG cylinder, 15-LPG regulator, 16-LPG flow meter, 17-Gas box, 18-Flow control valve, 19-Mixing of Air, LPG and EGR, 20-Exhaust gas analyser, 21-Exhaust gas to atmosphere, a-Cooling water in to the EGR cooler, b-Cooling water out from EGR cooler.

An EGR system consisting of back pressure valve, EGR control valve and EGR cooler are used to supply part of engine exhaust gas into the intake port. A simple four pass EGR cooler is used to achieve the ambient temperature of re-circulated gas. Temperature sensors are provided to record the temperature of cooling water and gas at inlet and outlet on the EGR cooler. An ambient EGR temperature was achieved by adjusting the flow rate of water. To removing condensate a drain plug is provided in the EGR cooler. An orifice is fitted in the recirculation line to measure the EGR flow rate. Four flow rates of EGR (5%, 10%, 15% and 20%) are used for the experimentation and which are calculated by following relation.

$$EGR\ (\%) = \frac{\dot{m}_{EGR}}{\dot{m}_i} \times 100 \quad (2)$$

Where, $\dot{m}_{EGR}$ is the mass of re-circulated gas and $\dot{m}_i$ is the mass of total intake mixture.

A six exhaust gas analyser is used to measure exhaust emissions. Experiments were performed for plain diesel, LPG-diesel and LPG-Diesel-EGR operation.

3. Results and Discussion

The net heat release rate (NHRR) and peak cylinder pressure from combustion characteristics, BTE and BSFC from performance characteristics and emission of NO_X, CO and CO_2 from emission characteristics are determined for straight diesel (SD) mode, dual fuel (DF) mode without EGR and EGR equipped dual fuel mode. The NHRR is calculated using equation (3) which is based on the application of first law of thermodynamics.

$$\frac{dQ_{net}}{d\theta} = \frac{\gamma}{\gamma-1} P \frac{dv}{d\theta} + \frac{\gamma}{\gamma-1} V \frac{dp}{d\theta} \quad (3)$$

Where, θ is the crank angle (CA), γ is the ratio of specific heat of the fuel and air, P is the in-cylinder pressure at a given crank angle, V is the cylinder volume at that point.

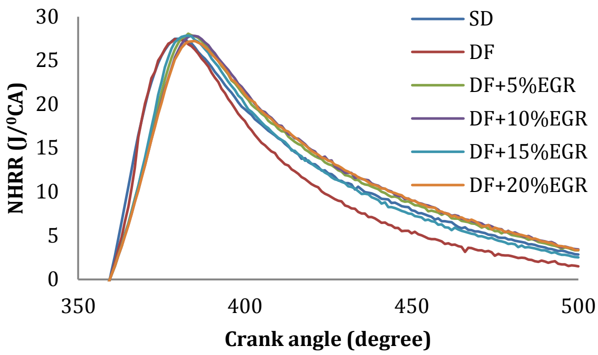

Fig. 2 NHRR vs crank angle for full load

3.1 NHRR and peak cylinder pressure

Fig. 2 and Fig. 3 shows NHRR vs crank angle for full load and 50% load respectively. From these diagrams it is seen that the peak HRR (heat release rate) is slightly higher in dual fuel mode without EGR than straight diesel mode this is because at these load sufficient amount of diesel fuel present in combustion chamber leads to better combustion for LPG, as a result more heat released. But at higher load it is observed that HRR curve of dual fuel mode without EGR falls down with a slower rate than that of its rise after reaching the peak value of HRR, because of the diesel fuel residue of the mixing-controlled combustion that releases some heat and hence causes the HRR curve to diverse somehow.

In the presence of EGR delay period increases in dual fuel operation. At 50% to full load, the unburned fuel molecules and sufficient amount of active radicals contains in the EGR.

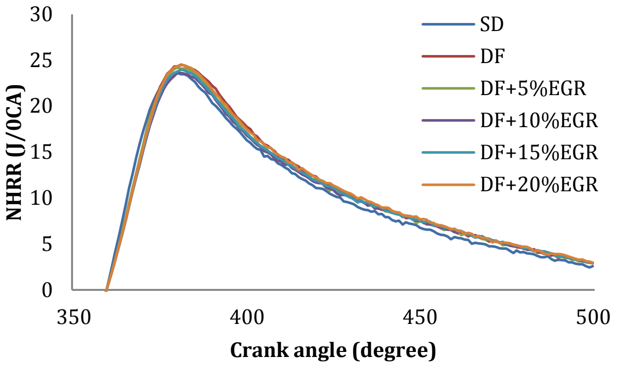

Fig. 3 NHRR vs crank angle for 50% load

The unburned fuel molecules are expected to re-burn in the mixture while the active radicals are expected to improve the combustion process. Due to this, higher HRR in case of EGR compared with the dual fuel mode without EGR particularly 20% EGR at 50% load. HRR less for 5 to 15% EGR at 50% load this may be because of the lower contents of unburned fuel and active radicals. At full load, 20% EGR shows lower HRR reason may be that lower oxygen due to higher fuel supply to the cylinder with addition EGR.

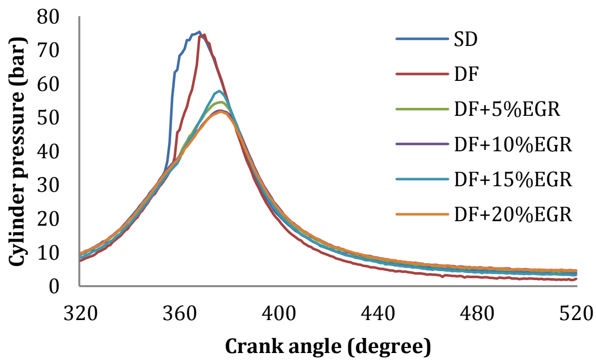

Fig. 4 Cylinder pressure vs crank angle for full load

Fig. 4 and Fig. 5 respectively show that cylinder pressure vs crank angle of full load and 50% load. The peak cylinder pressure of dual fuel mode without EGR is lower than straight diesel mode because dual fuel mode without EGR has higher ignition delay than straight diesel mode. Also the LPG fuel has lower cetane number than diesel fuel results greater ignition delay. The higher delay period, causes the whole combustion process to be shifted further into the expansion stroke in dual-fuel mode. Therefore, the rise of pressure is moderated as the piston moves in the expansion stroke towards the bottom dead center (BDC) so increasing the volume and reducing the peak pressure. At full load, dual fuel mode without EGR gives higher peak cylinder pressure but it is slightly lower than straight diesel mode. This is may be due to the higher HRR of dual fuel mode compered to straight diesel mode at that period. In the presence of EGR, dual-fuel mode decreases the cylinder pressure. The effect is more noticeable with high EGR percentages of 20% at full load, where more amount of O_2 is replaced by EGR and fuel. This defeats the combustion process and damps the pressure rise. As a result, the peak pressure becomes lower. But at 50% load, 20% EGR gives some higher peak cylinder pressure than 10 & 15% EGR but it is lower than plain dual fuel this may be due to the unburned fuel improves the combustion process which presents in EGR.

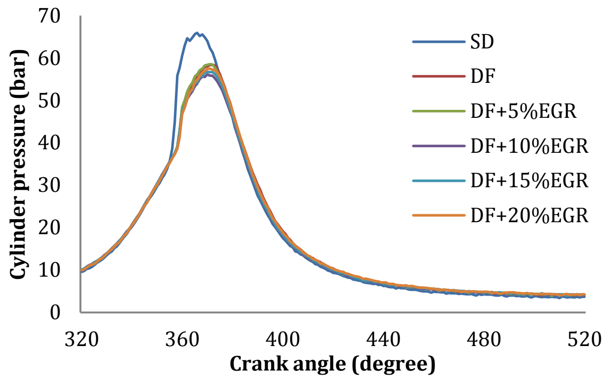

Fig. 5 Cylinder pressure vs crank angle at 50% load

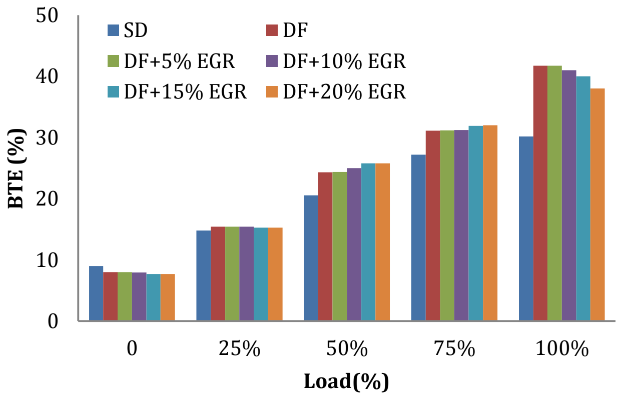

Fig. 6 BTE vs load

3.2 BTE and BSFC

Fig. 6 shows BTE vs load for all operation mode. BTE is higher in case of dual fuel mode without EGR as compared to straight diesel. This is because for higher loading condition pilot fuel quantity increases and it lead to better combustion of LPG fuel. When EGR is applied on dual fuel mode there is no significant change in BTE at low load (especially at 25% load). At 50% and 75% load, a slight increment in the BTE is obtained with EGR and it increased with EGR rate. This may be due to the re-combustion of some of the unburned hydrocarbons that is contained in the circulated gas. Slight reduction in BTE is observed with EGR at full load and it decrease with EGR rate but higher than straight diesel operation. This is due to the total amount of fuel supplied to the cylinder is increased at higher rate, and also the addition of EGR. Therefore oxygen presented for the combustion reduced considerably.

BSFC of all operating mode is illustrate in Fig. 7. At 25% to full load, the results shows that the total BSFC is lower in dual fuel mode without EGR than diesel alone mode.

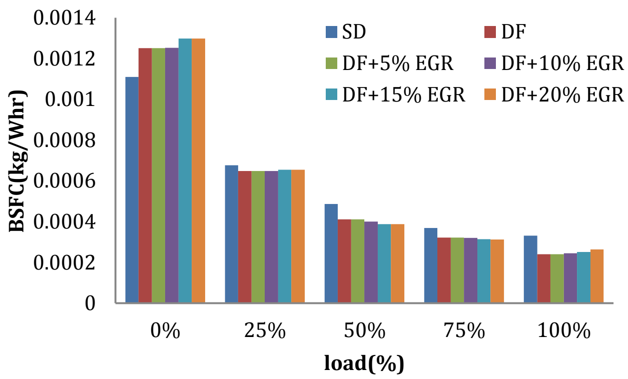

Fig. 7 BSFC vs load

This is because the improvement of gaseous fuels utilization due to higher temperatures and richer mixture, leads to improvement of the total BSFC with dual fuel mode. Also the lower heating value of LPG is higher than the neat diesel; so the total BSFC is lower for all dual fuel modes without EGR at high load condition. In case of EGR, BSFC increases with increasing EGR percentage particularly at, 25% load and full load. This is due to the adverse effect of EGR on combustion which leads to imperfect combustion and fall of speed and to keep the engine run on constant speed needs more of BSFC compared to without EGR. At 50% and 75% load, there is slightly reduction in BSFC for 15% and 20% EGR this may be due to the unburned fuel takes participate in combustion process.

3.3 Emission of NO_X, CO and CO_2

Fig. 8 Shows the NO_X emission for different operating modes. It can be evidently noted that dual fuel engine without EGR emits less NO_X emission as compared to straight diesel mode. This is due to very lean mixture that results in low-temperature combustion. At zero load condition, there is no significant change in NO_X emission in case of dual fuel mode and EGR mode. But all other load NO_X emission reduces significantly with EGR, especially at full load. The application of EGR dilutes the mixture and increases its heat capacity; as a part of O_2 is replaced by CO_2 and some H_2O. Therefore, the combustion temperature is lowered because of the oxygen concentration is reduced.

CO formation is a function of the unburned gaseous fuel and lower mixture temperature, both of which control the rate of fuel oxidation and decomposition. It can be clearly seen that CO emission with dual-fuel mode with or without EGR is always higher than straight diesel mode at lower load illustrate in Fig 9. This is because in dual fuel mode incomplete combustion occurs due to poor utilization of fuel. From 25% load to full load CO emission reduces continuously for all operating condition. This is due to the load is increased; the enhancement in the combustion process reduces CO emission; as additional fuel experiences a complete combustion. In case of EGR in dual fuel mode, the CO emission increases with EGR rate at no load condition because of lower combustion temperature and lack of oxygen due to EGR. Further loading condition EGR contributes a reduction in CO emission, because it provides the opportunity to re-combustion a part of the unburned hydrocarbons, increasing the possibility of complete combustion and also the active radicals improve the combustion conditions which are present in EGR. At full load, CO emission increases for 15% and 20% EGR. This is may be due to the reduction in oxygen concentration of the charge due to increasing fuel quantity and also the presence of EGR.

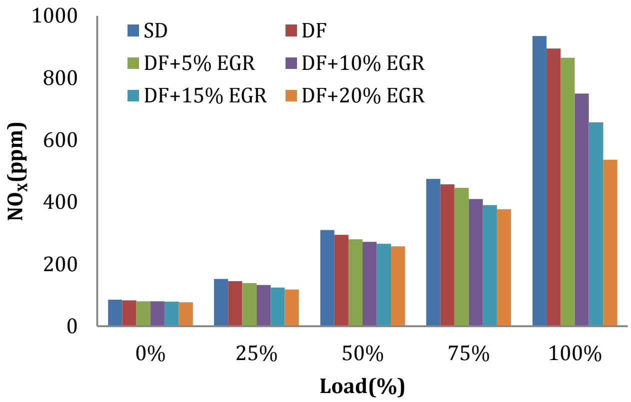

Fig. 8 NO_X emission vs load

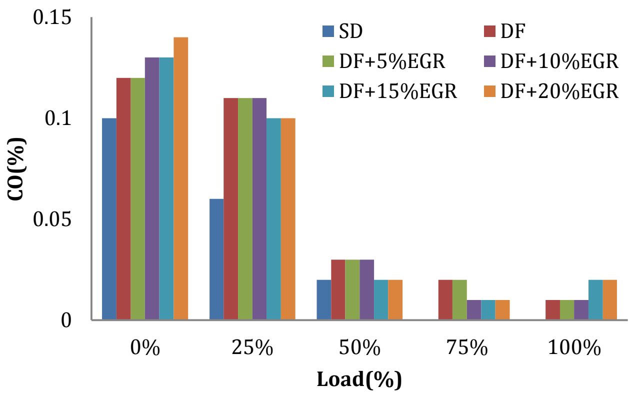

Fig. 9 CO emission vs load

It can be seen that dual-fuel mode with and without EGR emits noticeably lower CO_2 emission, compared with straight diesel mode (Fig. 10). This is because of the clean nature of combustion of the LPG fuel due to lower carbon to hydrogen ratio of LPG. The second reason may be the high emission of hydrocarbon of dual-fuel mode and the incomplete combustion, as revealed by the high CO emission. In all operating mode CO_2 increases with load due to improvement in combustion process. The application of EGR to dual-fuel mode increases CO_2 emission up to medium loads. This is happened due to the increased CO_2 concentration in the intake charge as a result of the application of EGR. It is seen that, CO_2 emission decreases with EGR at 75% and 100% load this may be because of the reduced oxygen concentration as the EGR is employed adversely affects the combustion process.

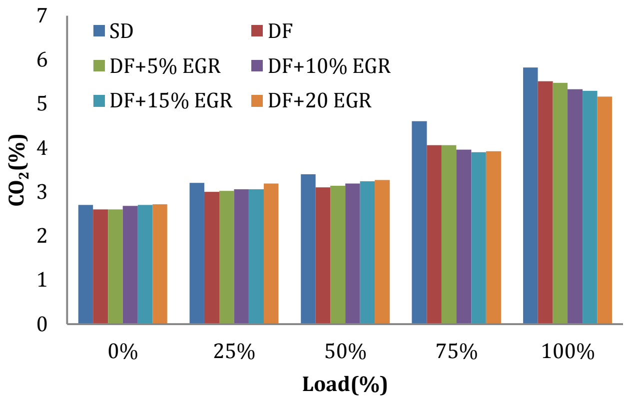

Fig. 10 CO_2 emission vs load

Conclusions

The engine parameters, NHRR, peak cylinder pressure, BTE, BSFC and emissions of NO_X, CO, CO_2 are examined for straight diesel engine, plain dual fuel engine and EGR equipped dual fuel engine. The four flow rates of EGR 5% to 20% with step 5% are tested at ambient temperature in dual fuel mode. The main conclusive points are as follows:

1) EGR increases delay period in dual fuel engine especially at full load. Net HRR is higher in case of EGR compared to the without EGR in dual fuel mode particularly for 20% EGR at 50% load.
2) The peak cylinder pressure of dual fuel mode with and without EGR is lower than that of straight diesel. In the presence of EGR in dual-fuel mode the cylinder pressure decreases with increasing EGR rate at full load. The 20% EGR gives some higher peak cylinder pressure at 50% load than 10% and 15% EGR but it is lower than plain dual fuel.
3) At 50% and 75% load, a slight increment in the BTE is obtained with EGR and it increased with EGR rate in dual fuel mode.
4) Dual fuel mode without EGR gives lower emissions of NO_X than straight diesel engine. When the EGR is used in dual fuel mode NO_X emission decreases significantly and it decreases with increasing EGR rate.
5) Dual fuel engine with and without EGR emits higher CO than straight diesel engine. EGR (15% and 20%) reduces CO emission in dual fuel engine particularly at 25%, 50% and 75% load but it is higher than straight diesel. At full load 15% and 20% EGR gives higher CO emission.

References

B. Ashok, S. Denis Ashok, C. Ramesh Kumar,(2015), LPG diesel dual fuel engine—A critical review, *Alexandria Engineering Journal*, 54, pp. 105-126.

B.B. Sahoo, N. Sahoo, U.K. Saha, (2009), Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines—A critical review, *Renewable and Sustainable Energy Reviews*, 13, pp. 1151-1184.

Emad Elnajjar, Mohammad O. Hamdan, Mohamed Y.E. Selim, (2013a), Experimental investigation of dual engine performance using variable LPG composition fuel, *Renewable Energy*, 56, pp. 110-116.

H.E. Saleh, (2008), Effect of variation in LPG composition on emissions and performance in a dual fuel diesel engine, *Fuel*, 87, pp. 3031-3039.

Jaffar Hussain, K. Palaniradja, N. Alagumurthi, R. Manimaran, (2012), Effect of exhaust gas recirculation (EGR) on performance and emission characteristics of a three cylinder direct injection compression ignition engine, *Alexandria Engineering Journal*, 51, pp. 241-247.

Deepak Agarwal, Shrawan Kumar Singh, Avinash Kumar Agarwal, (2011), Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine, *Applied Energy*, 88, pp. 2900-2907.

G.H. Abd-Alla, Using exhaust gas recirculation in internal combustion engines: a review, (2002), *Energy Conversion and Management*, 43, pp.1027-1042.

Ying Wang, Hong Liu, Zhiyong Huang, Zhensheng Liu, (2016), Study on combustion and emission of a dimethyl ether-diesel dual-fuel premixed charge compression ignition combustion engine with LPG (liquefied petroleum gas) as ignition inhibitor, *Energy*, 96, pp. 278-285.

N.C. Surawski, B. Miljevic, T.A. Bodisco, R. Situ, R.J. Brown, Z.D. Ristovski,(2014), Performance and gaseous and particle emissions from a liquefied petroleum gas (LPG) fumigated compression ignition engine, *Fuel*, 133, pp. 17-25.

Emad Elnajjar, Mohamed Y.E. Selim, Mohammad O. Hamdan, (2013b), Experimental study of dual fuel engine performance using variable LPG composition and engine parameters, *Energy Conversion and Management*, 76, pp. 32–42.

D.B. Lata, Ashok Misra, S. Medhekar, (2012), Effect of hydrogen and LPG addition on the efficiency and emissions of a dual fuel diesel engine, *International Journal of Hydrogen Energy*, 37, pp. 6084-6096.

Tuan Anh Le, Truc The Nguyen, (2011), Experimental Study on Performance, Emissions and Combustion Characteristics of a Single Cylinder Dual Fuel LPG/Diesel Engine, JSAE20119562/SAE2011-32-0562.

D.H. Qi, Y.ZH. Bian, ZH.Y. Ma, CH.H. Zhang, SH.Q. Liu, (2007), Combustion and exhaust emission characteristics of a compression ignition engine using liquefied petroleum gas–Diesel blended fuel, *Energy Conversion and Management*, 48, pp. 500–509.

Mohd Hafizil Mat Yasin, Perowansa Paruka, Rizalman Mamat, Mohd Hafiz Al, (2015), Fundamental Study of Dual Fuel on Exhaust Gas Recirculation (EGR) operating with a Diesel Engine, *Applied Mechanics and Materials,* 773-774, pp. 415-419.

P. Brijesh, A. Chowdhury, S. Sreedhara, (2014), Advanced combustion methods for simultaneous reduction of emissions and fuel consumption of compression ignition engines, *Clean. Techn. Environ. Policy*, DOI 10.1007/s10098-014-0811-y.

Poonia M. P., and Mathur Y. B, (2012a), Effect of EGR injection rate and engine load on cyclic variations of an LPG diesel dual fuel engine, *Journal of Environmental Research and Development*, 7, pp. 746-755.

Poonia M. P., and Mathur Y. B, (2012b), Effect of Exhaust Gas Recirculation on the Combustion of an LPG Diesel Dual Fuel Engine, *Engineering Science and Technology: An International Journal*, 2, pp. 2250-3498.

A. Kumaraswami and B. Durga Prasad, (2012), Performance analysis of dual fuel engine using LPG and diesel with EGR system, *Procedia Engineering*, 38, pp. 2784-2792.

H.E. Saleh, (2008), Effect of variation in LPG composition on emissions and performance in a dual fuel diesel engine, *Fuel*, 87, pp. 3031–3039.