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Influence of cooled exhaust gas recirculation on performance, emissions and combustion characteristics of LPG fuelled lean burn SI engine

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Abstract: On fuel perspective, Liquefied Petroleum Gas (LPG) provides cleaner emissions and also facilitates lean burn signifying less fuel consumption and emissions. Lean burn technology can attain better efficiencies and lesser combustion temperatures but this temperature is quite sufficient to facilitate formation of nitrogen oxide (NOx). Exhaust Gas Recirculation (EGR) for NOx reduction has been considered allover but extremely little literatures exist on the consequence of EGR on lean burn LPG fuelled spark ignition (SI) engine. The following research is carried out to find the optimal rate of EGR addition to reduce NOx emissions without settling on performance and combustion characteristics. A single cylinder diesel engine is altered to operate as LPG fuelled SI engine at a compression ratio of 10.5:1 and arrangements to provide different ratios of cooled EGR in the intake manifold. Investigations are done to arrive at optimum ratio of the EGR to reduce emissions without compromising on performance. Significant reductions in NOx emissions alongside HC and CO emissions were seen. Higher percentages of EGR further diluted the charge and lead to improper combustion and thus increased hydrocarbon emissions. Cooled EGR reduced the peak in-cylinder temperature which reduced NOx emissions but lead to misfire at lower lean limits.

1. Introduction

Customer demand for greater fuel economy and cleaner emissions has placed immense pressure on the automotive industry. Automobile industry is facing a challenge of meeting stringent emission norms. The growing concern regarding the environmental pollution has increased attention towards the alternative engine fuels. So, it is essential that economical and feasible techniques for emission reduction are found. Gaseous fuels show potential as alternative fuel source due to their higher octane content, lucrative costs, higher calorific content and lesser polluting emissions. However, emission control strategies attain maximum conversion efficiency only when the spark ignition engines are run at stoichiometric air-fuel ratio. On account of depletion of fuel resources, this theme has to focus on lesser fuel consumption and hence lean operation proves to be a solution. LPG fuel being a better option has higher octane rating and produces less CO_2 emissions in comparison with gasoline. Also higher compression ratio can be achieved without knocking due to higher octane rating of the fuel. Combustion instability totally depends on the mixture preparation effects which had been proven effective in gaseous fuels like LPG than gasoline counterpart. Also regarding the power output, which is a major concern in SI engines LPG seems to produce lower power output as the volumetric efficiency is decreased. Sulaiman et al.[1] examined the characteristics of LPG fuelled single cylinder spark ignition engine in context with unleaded petrol. It was found out that there is slight reduction in power when LPG is used in petrol engine due to decrease in volumetric efficiency as the LPG displaces more air than petrol and unaltered ignition timing. The fuel consumed by LPG is less compared to the unleaded petrol for the same amount of power generation. Regarding the combustion instability using gaseous fuels, Campbell et al. [2] correlated the COV of IMEP for LPG and gasoline found that COV of IMEP at a particular lambda was lesser for LPG than for gasoline.

This result was attributed to greater combustion stability of LPG when compared to gasoline which was proved by greater cyclic variation of IMEP for gasoline than that for LPG [3, 4, 5]. When compared to stoichiometric operation, the peak in-cylinder temperature is lower for lean burn combustion of LPG but it is well suited and adequate for NOx formation. However lean combustion engines engage in formation of NOx emissions pertaining to unstable combustion variations [6, 7]. NOx emissions are evidently seen in lean burn conditions of LPG and gasoline engines due to the presence of excess air in the air-fuel mixture [8, 9]. Exhaust Gas Recirculation (EGR) for NOx reduction has been always considered as an effective solution in automotive engines for a longer period. Hence, the following research work considers cooled EGR technique for NOx reduction rather than hot trapped EGR [10]. In this case, EGR displaces the oxygen present in the intake when it is re-circulated to it. These exhaust gases reduce the concentration of oxygen in the combustion chamber and thereby increase the specific heat of intake air mixture, resulting in decreased flame temperatures. Cooled EGR reduces peak temperatures and thus retard the NOx formation [11]. This is responsible for absorbing the heat of combustion (high heat capacity CO absorbs) that results in reduction of peak in-cylinder temperature and thereby reducing knock.

Keeping these factors into account, the following work aims at studying the effect of EGR on performance and emission aspect of lean burn SI LPG engine.

2. Background

Efficient methods for reducing fuel consumption, emissions, and increasing the efficiency have been the priority of automotive industries. Helpful techniques to sort these issues have been considered. The following research works carried out by several researchers earlier has motivated the authors to sort out the issues faced by EGR in SI engines running on LPG fuel. Caton [13] and Tang et al [14] carried out a parallel study on lean burn operation alongside EGR. The former reported that the two dilution techniques reduce the pumping losses at low loads by increasing the inlet manifold pressure and hence reduces the fuel consumption. The work explains that the decrease in indicated specific fuel consumption is due to reduced peak cylinder temperature and reduced heat loss between the charge and the cylinder walls. Also he explained that the NOx reduction associated with the dilution techniques was due to decrease in peak temperature inside the cylinder and predominantly due to increased ratio of specific heat. But, it was observed that initial decrease of equivalence ratio from stoichiometric to lean, the NOx formation increased due to the presence of excess oxygen. EGR has an advantage of diluting the charge without adding additional oxygen and hence prevents NOx formation. So, it supported the combined use of EGR and lean operation to exploit the benefits of both the techniques. In addition, the study provided evidence of increased brake thermal efficiency with decrease in equivalence ratio and increased rate of EGR. This is attributed to reduced heat loss due to lesser peak temperature and also due to reduced pumping losses. Bhargava et al.[15] demonstrated that EGR is an effective method to reduce the NOx emissions. It was noticed that the addition of EGR reduced the NOx emissions but the diluted mixture increased the hydrocarbon emissions. Also it was concluded that a finest blending of EGR and lean fuel mixture can definitely reduce NOx emissions without having an adverse effect on HC emissions.

Engines that are equipped with EGR have lesser quantity of exhaust at the tail pipe [16]. For a given volumetric concentration, the quantity of harmful elements emitted is lowered; however the quality may remain the same. Hu et al. [12] showed the reduction in NOx emission with increase in EGR rate and attributed this effect to the presence of high heat capacity gases such as N_2 and CO_2 which changed the heat capacity of the combustible mixture reduced the combustion temperature and thus NOx emission. Ladommatos et al. [16] explains that the NOx emissions can be reduced by cooling the exhaust gas before it enters the inlet manifold. In case of hot EGR, the temperature is already higher than the intake air; hence heat absorption is not possible to prevent NOx formation. However, using cooled EGR take in the heat forcing out more oxygen thereby reducing the in-cylinder temperature preventing the NOx formation. Kaiser et al. [17] explained that cooled EGR assists in reducing engine knock and reducing combustion end gas temperature. The use cooled EGR increase level of engine efficiency as cooled EGR act as diluent for combustion process resulting in reduced combustion temperature. Thus the addition of cooled EGR in SI engines result in higher compression ratios and production of more torque at low engine speed [18]. These advantages of cooled EGR enable to downsize the engine and improve fuel economy along with increased levels of thermal efficiency. However, Takasu et al. [19] proclaimed NOx reduction and reduced fuel consumption with EGR reducing the temperature whereas HC emissions reported high due to slow combustion process. Pan et al. [20] noticed that EGR ratio above 20% increased COV of IMEP by 10% posing a problem in drivability by instable combustion. Hence, this limits the EGR percentage on account of NOx emission formation.

Keeping into account of the previous literatures, an SI engine fueled with LPG which is suitable for lean operation was chosen and the effect of EGR on its operation was experimentally tested at wide open throttle conditions [21, 23, 24].

The EGR flow rate was interpreted as the percentage of EGR in the total charge (air + fuel+ exhaust) on the volume basis.

$$\%EGR = \left(\frac{V_{EGR}}{V_{EGR} + V_{Air} + V_{Fuel}}\right) * 100$$

where,

V_{EGR} = Volume flow rate of exhaust gas (m^3/h)

V_{Air} = Volume flow rate of fresh air (m^3/h)

V_{Fuel} = Volume flow rate of fuel (m^3/h)

3. Experimental Procedure

3.1 Experimental set up

A single cylinder, four stroke, air cooled direct injection diesel engine is modified to operate as SI engine at a compression ratio 10.5:1 developing 4.4 kW at 1500 rpm with LPG as fuel. Generally, LPG fuelled SI engines would operate at higher compression ratio than gasoline engine. The engine specification is as given in Table.1. The compression ratio is customized by varying the clearance volume on the piston without changing the squish velocity [22]. The engine is coupled to a water cooled eddy current dynamometer (Make: Dynalec, India) which is set to operate at constant speed mode to carry out the experiments at 1500 rpm. LPG at a pressure of 1.03 bar (abs) is made available by heating its storage cylinder in a constant temperature hot water bath to avoid condensation in the flow line. The schematic diagram of the experimental setup is shown in Figure 1. The intake manifold was especially designed to conduct experiments on carburetion with a provision made to accommodate EGR accordingly. The manifold was provided with throttle valve and a gas mixer unit for carburetion, while an EGR cooler fixed in line with exhaust pipe was provided for cooled EGR set up. A gate valve was provided in the EGR set up in order to let desired amounts in the intake manifold.

Table 1. Engine specifications

Type	Kirloskar TAF1, air cooled, single cylinder CI engine
Displacement	661 cc
Stroke	110 mm
Bore	87.5 mm
Connecting Rod	234 mm
Compression ratio	17.5:1 (CI version), 10.5:1 (SI version)
Rated Power	4.4 kW @ 1500 rpm
Inlet Valve Open	4.5° bTDC
Inlet Valve Close	35.5° aBDC
Exhaust Valve Open	35.5° bBDC
Exhaust Valve Close	4.5° aTDC

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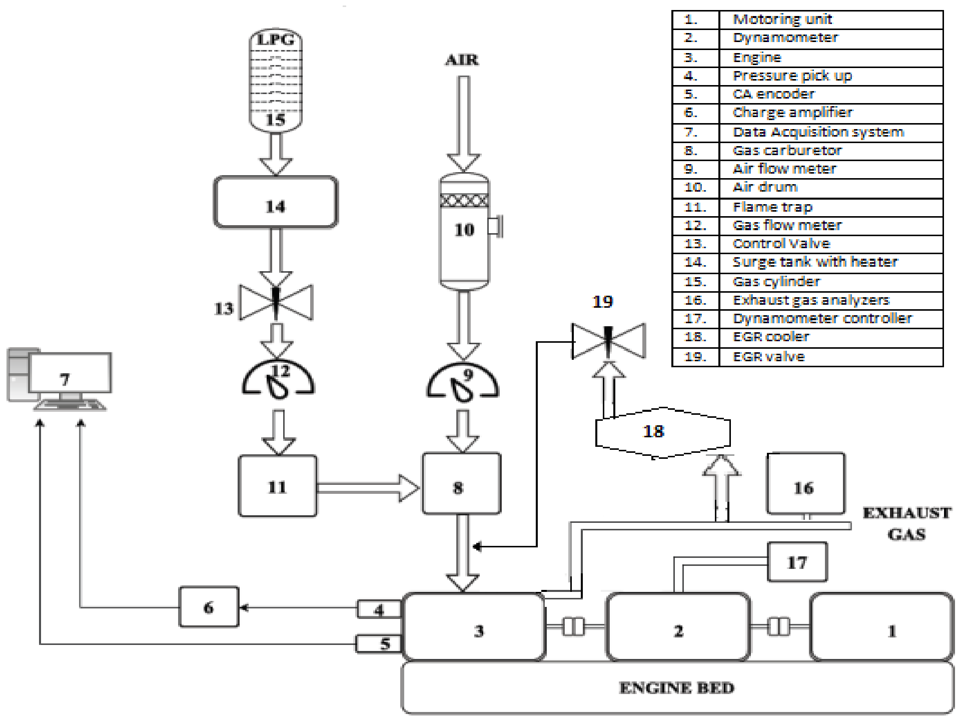

Figure 1. Schematic layout of Experimental Setup

Airflow is measured with a positive-displacement type air flow meter (Make: Dresser, USA), with a surge tank connected on the suction side to smoothen the air flow. The LPG flow is throttled by a control valve and the gas flow is measured using a positive displacement type gas flow meter (Make: Toshniwal, India). The equivalence ratio is determined from the measured air and fuel flow rate. A micro controller based spark timing system is developed in the laboratory. The reference signals to the device are taken from the optical crank angle encoder (Make: AVL, Austria) to fire the spark at the specified crank angle. A flush mounted piezoelectric pressure transducer (Make: Kistler, Switzerland) is mounted on the cylinder head to measure the cylinder pressure. The fluctuating intake manifold pressure is measured using piezoresistive transducer (Make: Kistler, Switzerland) at each crank angle.

An optical angle encoder (Make: AVL, Austria) is mounted on the cam shaft to record the corresponding pressures and crank angle values and also to vary the spark timing in accordance with the crank angle rather than on the time basis. A PC based data acquisition system (Gantner Instruments, Germany) is used to record the cylinder pressure and the manifold pressure. At each operating condition 100 cycles are acquired. The pressure signals from the piezoelectric transducer are referenced based on the cylinder pressure at suction BDC, which is assumed to be equal to the mean manifold pressure obtained from the intake pressure piezoresistive transducer. A MATLAB code is developed to analyze the combustion parameters and its cyclic variations at each operating condition. Cylinder pressure against crank angle data is analyzed based on the first law of thermodynamics to get the heat release and the mass burn rate. The exhaust gas is analysed with a Non Dispersive Infra-Red (NDIR) analyzer for HC, CO, CO_2 and electrochemical sensors for the O_2 and NOx measurements (Make: Horiba, MEXA 554JA, Japan).

3.2 Experimental conditions

Tests are carried out on different EGR percentages at different fuel flow rates (FFR) over fixed load conditions. The mixture strength was varied from richest to the leanest possible by controlling the amount of fuel using a fine tune adjuster. At each of the equivalence ratio, MBT (Minimum spark advance for best torque) was set. However, under knocking conditions the spark timing was adjusted for knock free operation rather than MBT adjustment. Such an adjustment was required only during rich operating conditions which are of no significance in this research work. Readings were always taken on after the engine attains stability of operation. Torque, MBT timing, intake pressure, cylinder pressure, air flow rate, LPG fuel flow rate, EGR rates, inlet and exhaust temperatures, exhaust emission levels of HC,CO,NO and NOx were recorded for different EGR rates. Dedicated software was developed using LABVIEW to calculate the pressure average against crank angle for the obtained number of cycles. Combustion duration, heat release rate, IMEP, COV of IMEP, cyclic variations, average cylinder pressure, flame development period are calculated from the measured cylinder pressure.

4. Results and Discussions

4.1. Performance and emission parameters at different EGR rates

A decrease in brake thermal efficiency is observed with increase in EGR rates. This can be attributed to higher specific heat of the inert EGR mixture that hamper the normal combustion process which deteriorates the burning rate, but leads to reduction in average combustion temperature in the cylinder. Thermal efficiencies remain fairly constant with lower amounts of EGR and then rapidly decrease as mass % EGR increases, due to deteriorating combustion characteristics. The effect of dilution by EGR on the indicated thermal efficiency is shown in Figure.2. The percentage of EGR that can be tolerated reduces with raise in fuel flow rate. Higher flow rates of EGR lead to a scarcity of oxygen, which causes partial combustion that result in reduction of thermal efficiency. It can be observed that at a fuel flow rate of 1.21 kg/h, the fall in brake thermal efficiency is not much affected up to an EGR flow rate of 9% EGR. Further raise in the EGR flow rate influence combustion and affects the brake thermal efficiency. 9% EGR is the optimum value for reducing NO emission without much drop in brake thermal efficiency. Similarly, for different fuel flow rates, different EGR levels were found to be optimal. Thus control of the rate of EGR is critical as too much of it will influence output and efficiency appreciably. When the inlet fuel air mixture was diluted with EGR at stable inlet pressure, the EGR substitutes some of the inlet air resulting in decrease of air flow rate. Hence there is a reduction in engine power with the increase of percentage of EGR dilution due to insufficient oxygen. It can be inferred that with increase of EGR (Figure 3), the same power can be obtained at higher equivalence ratio without compromising on efficiency towards higher limit. This is also indicative of possibility of spoiling the extension of lower lean limit with EGR because of onset of misfire.

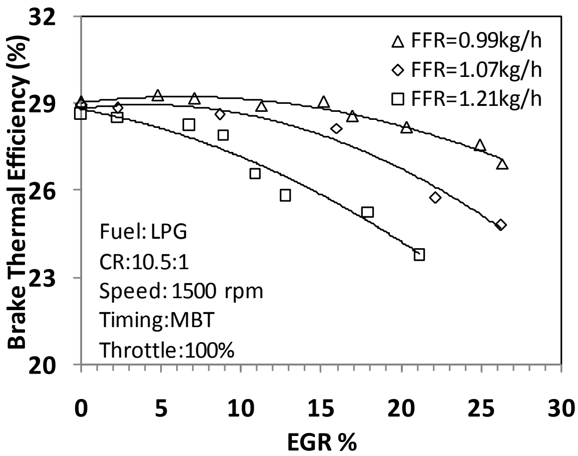

Figure 2. Variation of Brake Thermal Efficiency

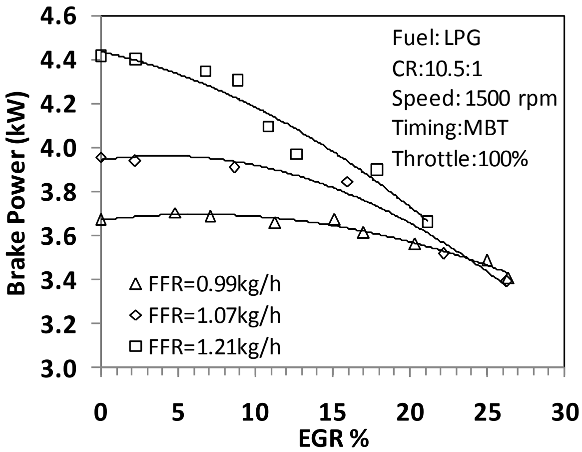

Figure 3. Variation of Brake Power with EGR

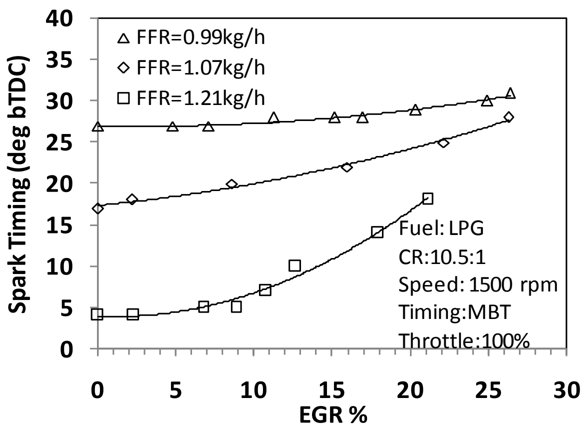

Figure 4. Variation of MBT Spark Timing

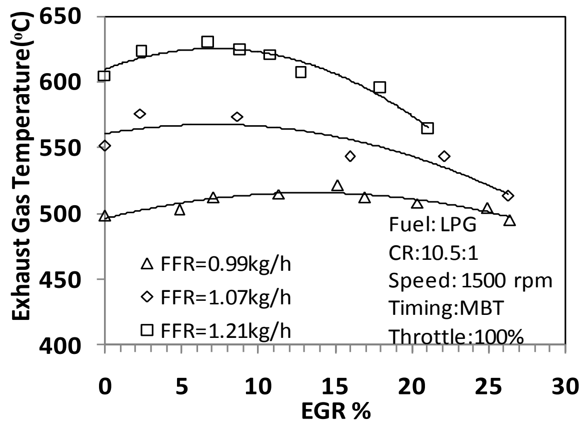

Figure 5. Variation of Exhaust Gas Temperature

The spark timing needs to be advanced with EGR. The advance needed with raise in EGR flow rate is more for high fuel flow rates than that of low flow rates as seen in Figure 4. This is mainly because of the higher thermal effect of EGR at high fuel flow rate as the proportion of water vapor in exhaust gas is high. The exhaust gas temperature has shown a tendency to decrease with greater in-cylinder dilution, which is also an indication of lower in-cylinder gas temperature, resulting in less in-cylinder heat loss (Figure 5). Thus there is a raise in the exhaust gas temperature even though the combustion is unaffected, which is attributed to the increase in the charge temperature. However, beyond the optimal EGR flow rate, the exhaust gas temperatures decrease due to incomplete combustion with too much dilution as also reflected through the drop in thermal efficiency.

Figures 6 and 7 show the variation of NO and NO_x emission with raise in EGR. For the fuel flow rates of 0.99, 1.07 and 1.21 kg/h, small levels of EGR increase the NOx level. Even though, EGR decreases the oxygen concentration and improves the specific heat capacity of charge, it also boosts the intake charge temperature and thereby the peak temperature also rises. It was concluded that the increase in the temperature of the charge dominate at small EGR level result in slight increase of the NOx emission level. However, beyond a certain percentage of EGR dilution, the NO emission reduces when the thermal effects are predominant. Also, at low fuel flow rates, the water vapour content in the exhaust gas is low which does not result in a strong thermal effect. When the EGR flow rate is improved, the concentration of water vapour in exhaust gas also increases. It can be observed that the percentage of EGR needed is quite high for low fuel flow rates to achieve a significant reduction in NO. At a fuel flow rate of 0.99 kg/h, the NO and NOx emission was reduced from 1710 and 1960 to 350 and 520 ppm with the about 25% of EGR. But, at a fuel flow rate of 1.21 kg/h, 13% of EGR brought down the NO emission from 2730 and 2930 to 440 and 460 ppm.

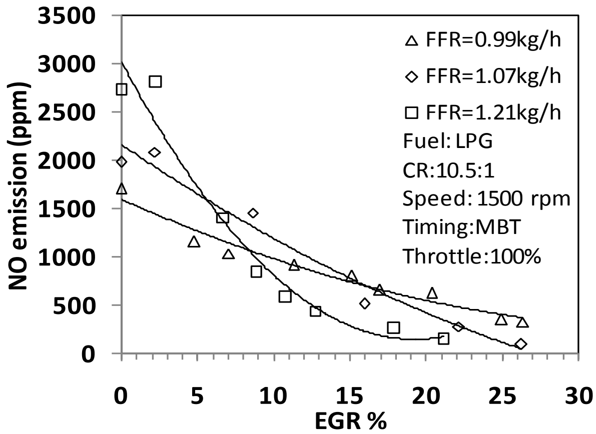

Figure 6. Variation of Nitric oxide emission

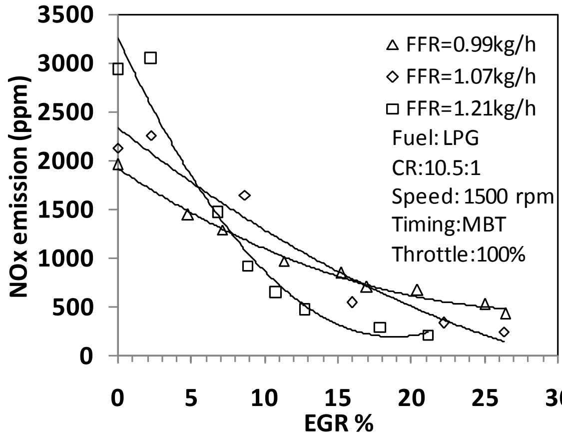

Figure 7. Variation of NOx emission

Figure 8 shows the variation of HC emission with EGR flow rate. The HC emission follows the trend of exhaust gas temperature due to fact that HC emission depends on cycle temperature. Increased levels of EGR lead to a rapid increase in HC emissions, indicating misfires and deteriorating combustion quality. This rapid increase in HC emissions occurs increasingly at lower levels of EGR, as the engine goes leaner, signifying a weakening tendency of the engine to sustain increased dilution in the intake.

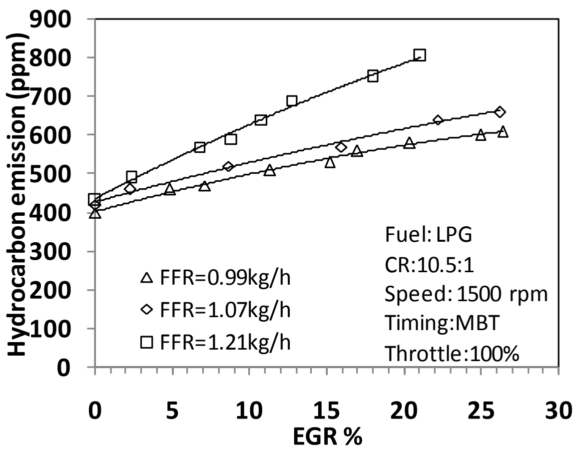

Figure 8. Variation of Hydrocarbon emission

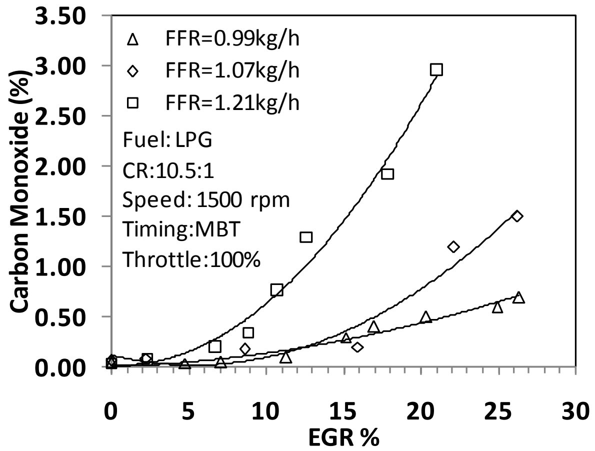

Figure 9. Variation of Carbon monoxide emission

CO emissions remain fairly insensitive to EGR addition till a limit is reached as seen from fig 9, after which they increase due to excessive dilution of charge. The rapid increase in CO and HC emissions signifies the deteriorating burn quality and onset of misfire due to excessive dilution of charge. Also noteworthy was the relative insensitivity of CO and HC emissions with respect to timing with the exception of highly retarded timing. For retarded timing, the start of combustion was delayed into the

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expansion stroke and as a result of the rapid drop in in-cylinder temperature and pressure, quenching of the flame and the oxidation reactions occurred, resulting in increased HC and CO emissions.

4.2. Combustion parameters at different EGR rates

The peak cylinder pressure decreases with EGR addition in the case of low fuel flow rates as shown in Figure 10. This is because at these setting the EGR has a low temperature and hence the thermal effect is noteworthy. On the other hand, at high fuel flow rates, the EGR has a high temperature and this leads to an increase in the combustion rate and rise in the peak pressure when inducted in smaller amount. In all cases, for high EGR rates, the effect of EGR on slowing down the combustion results in low cylinder pressures. This ultimately reduces the stresses in the engine components. Figures 11, 12 and 13 depict the variation of in-cylinder pressures with crank angle for fuel flow rates 0.99, 1.07 and 1.21 kg/h. The maximum cylinder pressure reduces while the crank angle at which the maximum cylinder pressure occurs is further moved away from TDC with the raise of EGR level.

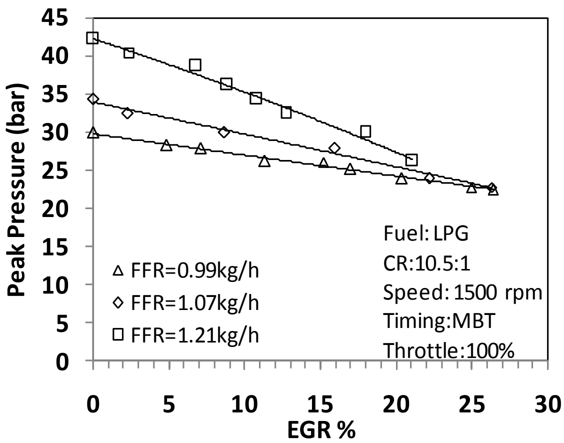


Figure 10. Variation of Peak Pressure

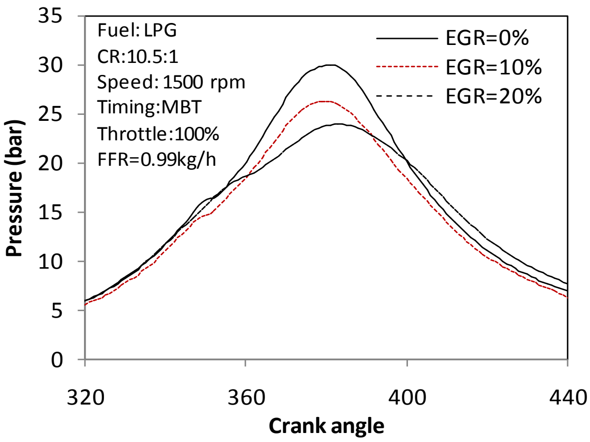


Figure 11. Variation of Pressure at FFR=0.99 kg/h

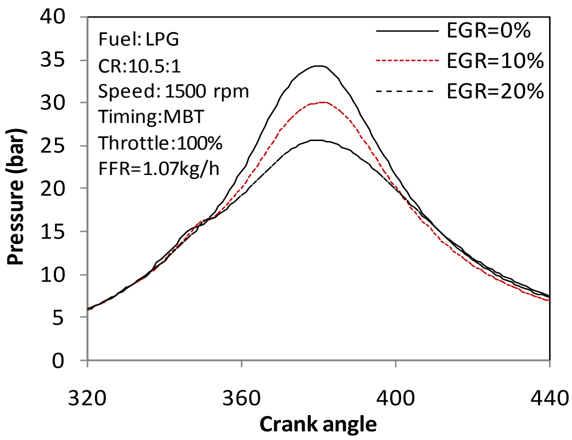


Figure 12. Variation of Pressure at FFR=1.07 kg/h

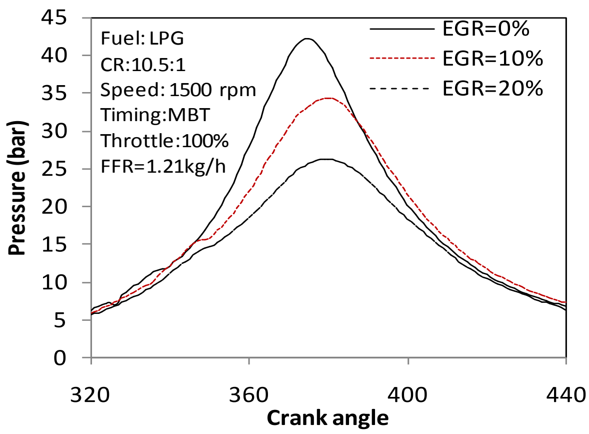
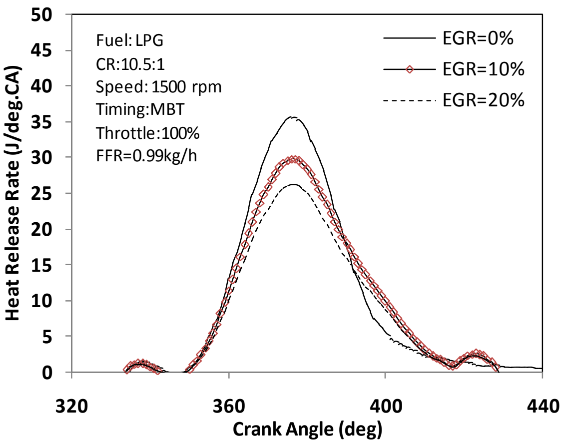


Figure 13. Variation of Pressure at FFR=1.21 kg/h

This can substantiate that EGR dilution is capable of reducing in-cylinder stresses, and consequently, it can be used to suppress abnormal combustion occurrence such as surface ignition and knock. The COV defines the cycle to cycle variations in indicated pressure per cycle and it can be considered as a good pointer for engine stability. The combustion process can be improved to make the engine combustion sufficient by investigation of combustion cycling variations, thus effectively controlled emissions and improving fuel economy. EGR does not encompass any adverse effect on combustion stability. The COV of IMEP was not found to change significantly with EGR flow rate, which is shown in Figure 14. This may be due to the only slight reduction in the rate of combustion while introducing the EGR. Studies showed the variation is well within the limits as the engine stability starts to deteriorate when COV increases above 5%



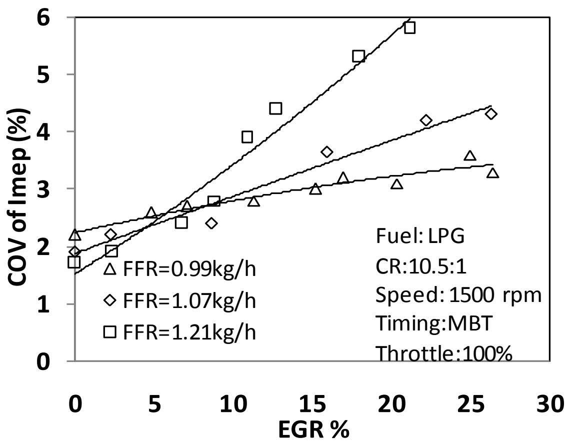
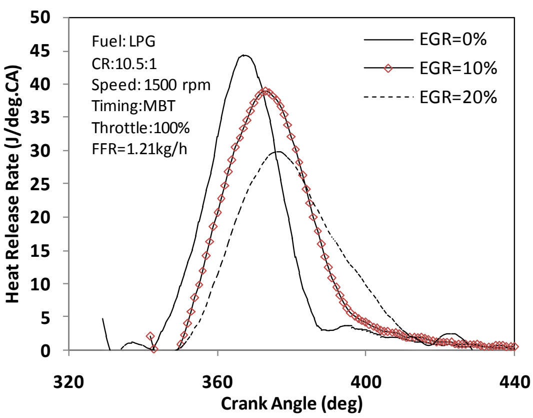


Figure 14. Variation of COV of IMEP **Figure 15.** Comparison of HRR at FFR=0.99kg/h

The heat release rate for the fuel flow rates of 0.99, 1.07 and 1.21 kg/h with various degrees of exhaust gas dilution is shown in Figs.15, 16 and 17 respectively. At low EGR flow rate, the heat release pattern does not show any significant difference. However, significant decrease in heat release rate is observed with high flow rates of EGR. For example, at a fuel flow rate of 0.99 kg/h, all the EGR flow rates shows almost similar heat release pattern. Similarly, at a fuel flow rate of 0.78 kg/h, the heat release rate trend starts decreasing only after an EGR flow rate of 8.5%.



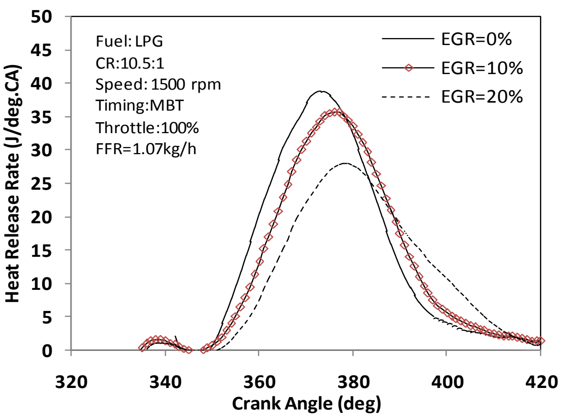


Figure 16. Comparison of HRR at FFR=1.07kg/h **Figure 17.** Comparison of HRR at FFR=1.21kg/h

On the whole, EGR emerge to be reasonably attractive tool to control NO emission at high loads but it is not so effective at low loads. This technique has the benefit of not requiring any supplementary equipment or additional gases. On the contrary EGR may also endorse the engine wear and thus lower the life of engine.

5. Conclusion

Amount of EGR needed for bringing the NOx emission to the level of less than 500 ppm with less than 2% associated drop in indicated thermal efficiency is the optimum level of EGR ratio for that particular operating conditions. To summarize,

- At a fuel flow rate of 0.99 kg/h, about 25% of EGR is required.
- At a fuel flow rate of 1.07 kg/h, about 16% of EGR is required.
- At a fuel flow rate of 1.21 kg/h, about 9% of EGR is required.

EGR is quite attractive to manage NO emission at higher loads, but it is not so efficient at lower loads. Moreover, based on the performance parameters 5-10% EGR could be seen as a viable option under lean operation limit. In order to reach the best operating condition as well as extend the lean limit, further investigations involving hydrogen supplementation could be carried out. This could be the aim of further researches compiling to efficient energy usage and reducing emissions.

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