Effects of Exhaust Gas Recirculation (EGR) on Performance and Emissions of a Compression Ignition (CI) Engine Fuelled with Diesel

Sudhir Kumar Pathak, Ashish Nayyar, Chandan Kumar
Department of Mechanical Engineering,
Swami Keshvanand Institute of Technology, Management & Gramothan, Jaipur, India
Email: sudhirpathak95@gmail.com

Received 17 July 2017, received in revised form 14 August 2017, accepted 23 August 2017

Abstract: **In compression ignition (CI) engines, nitrogen oxides (NOx) formation is a temperature dependent function and occurs when the temperature in the combustion chamber exceeds 2000 K. Therefore in order to reduce the NOx emissions from exhaust of the engine, it is compulsory to keep peak cylinder temperature under control. NOx can be reduce by late injection of fuel in the combustion chamber. This is an effective technique but increase the fuel consumption rate. So the most promising way to reduce the NOx emission by using EGR technique. In this research work, the effects of different EGR ratios on the performance and emission characteristics of a diesel engine are investigated. The tests were carried out on a four cylinder variable speed CI engine at different load conditions like: partial load, half load and full load. The three EGR rates (5%, 10% and 15%) were utilized with an intention to reduce the high NOx emissions that were occur at high engine loads. The use of EGR in diesel engine resulted in maximum reduction in NOx emissions up to 10% at partial load, up to 5% at half load and up to 8% at full load without any significant penalty in particulate matter emissions. Smoke opacity increased up to 15 % EGR rate. There was also an increase in hydrocarbon (HC) and carbon monoxide (CO) emissions when compared to pure diesel.**

Keywords: EGR; NOx; Pollution; CI Engine.
Nomenclature: m_(EGR=)Mass flow rate of EGR, m_(i=) Mass flow rate of intake air

Abbreviation:

BSFC	**Brake Specific Fuel Consumption**
BTE	**Brake Thermal Efficiency**
CI	**Compression Ignition**
CO	**Carbon Monoxide**
EGR	**Exhaust Gas Recirculation**
HC	**Hydrocarbons**
NOx	**Nitrogen Oxides**
RPM	**Revolution per Minute**

1. INTRODUCTION

From a protection and ecological point of view, the compression ignition direct injection (CIDI) diesel engine, is an attractive aspirant as a prime mover for automobiles with respect to spark ignition engines [1]. Diesel engines are fundamental power source for the heavy duty vehicles because of their durability and better fuel economy. They have higher thermal efficiency because of high compression ratio and lean fuel combustion. Diesel engine operates at excess air ratio, which is mainly responsible for the generation of large amount of NO_x because of high flame temperature in the presence of excess oxygen and nitrogen in combustion chamber [2]. However diesel engine emits large quantities of particulates and nitrogen oxides. Both of which administered for closer regulation in near future. A problem exists in modifying the CIDI (compression ignition direct injection) engine processes to decrease both of these pollutants: strategies to reduce either NO_x or particulate emissions induced an increased emission of other. For instance advancing timing of start of injection decreases particulate emissions but simultaneously increases NO_x emissions [3]. Various works have been carried out on the engine development including the engine exhaust, inlet system, combustion chamber geometry and fuel injection system for the reduction of NO_x and particulate emissions. In this work the homogeneous diesel combustion with EGR has been investigated. The technique is very useful to reduce the NO_x and soot emissions simultaneously [4].

1.1 MECHANISM OF NOX FORMATION

No_x are the most significant emissions among the gaseous pollutants emitted by the diesel engines. In many engines, NO_x varies from a few hundreds to 1000 ppm. The mechanism of NO_x formation occurs at the highest temperature up to 2000 K and the sufficient quantity of O_2. The pre-combustion chamber engines produce less NO_x compare to direct injection diesel engines because of low peak temperature [5]. Emissions of NO_x from combustion are in form of NO. According to Zeldovich, the NO is generated to the limit of available oxygen in the air at a temperature above 1500K. The Zeldovich equations are:

$$N_2 + O \rightarrow NO + N$$
$$N + O_2 \rightarrow NO + O \quad (1)$$
$$N + OH \rightarrow NO + H$$

1.2 SOOT AND PARTICULATE MATTER

The engine out emissions poses negative effects on the environment and composition of earth's atmosphere. However, diesel engines are one of the major contributors to environmental pollutions. The main hazards emissions of diesel engines are NOx and particulate matters (PM). NO_x emissions are one of the major causes of photochemical smog and it is also responsible for acid rain. Particulate matters have extremely harmful effects on human health and on environment. Numerous studies have proved that these particles cause respiratory and cardio vascular health problems [6].

2. LITERATURE SURVEY

Many studies about the performance and emission characteristics of a CI engine using EGR have been carried out in this literature survey.

A.Tsolakis et al. [7] investigated the effects of exhaust gas fuel reforming CI engine fueled with mixture of diesel and biodiesel. The results showed that partial replacement of diesel with hydrogen with EGR resulted in reduction in NOx and soot emissions without affecting efficiency too much. Vinod Singh Yadav et al. [8] were explored the performance and emission characteristics of a dual fuel diesel engine. The results were showed that brake thermal efficiency of the engine increased up to 1.83% and HC emissions decreased up to 5.13% without EGR under dual fuel mode. It was found that with the use of 20% EGR, NOx emissions slightly decreased from 470 ppm to 440 ppm. Wang Ying and Zhou Longbao [9] conducted an experiment on a four cylinder water cooled, compression ignition engine. Experimental results showed that NOx emission can be reduced about 40% at large EGR ratio without affecting the efficiency of DME engine. However CO emission increased at high EGR. A. k. Agrawal et al. [10] investigate the effects of fuel injection timing with EGR on combustion and emissions of diesel engine. At advanced injection timing, higher NOx was observed. While the particulate matter size increased with the increase of load. M. M. Abdelaal et al. [11] conducted an experiment on a single cylinder, four strokes, water cooled, and high-speed direct injection diesel engine. The experiment test was conducted at a speed of 1600 rpm with a wide range of loads. It was found that under dual fuel operation the NOx emissions were decreased at part load. But the engine was suffering from the lower thermal efficiency and higher CO emissions.

3. EXHAUST GAS RECIRCULATION (EGR)

EGR is a process in which a segment of exhaust gas recirculated into the intake air for decreasing the nitrogen oxides emission from the exhaust of engine. The H_2O and CO_2 in the exhaust gas can affect the combustion phenomenon in the CIDI engine in

Exhaust gas recirculation is a promising technique for decreasing the NOx formation due to lowering the temperature of the gas inside the combustion chamber. [12] EGR technique can only be used in light duty engines. By the use of EGR in diesel engines, the specific fuel consumption and particulate matters are increased. [13] The percent of exhaust gas recirculation EGR (%) is defined as the percent of the total intake mixture which is recycled through the intake manifold

$$EGR_{-}(\%) = \frac{m_{EGR}}{m_i} \times 100 \quad \text{(ii)}$$

Where, mi= $[m_a + m_f + m_{EGR}]$ m_{EGR} is the mass of the EGR. Up to 30% of the exhaust can be recirculated.

4. EXPERIMENTAL SETUP WITH EGR

The experiments were carried out on a 7.5 kW water cooled, variable speed, and compression ignition diesel engine. A hydraulic dynamometer was coupled with engine to varying the load condition. The nominal injection timing was 22º CA after bottom dead center. The EGR flow was controlled by automatic control unit and EGR level in percentage of total intake volume was set by keyboard of digital computer. The complete setup of test engine connected with commercial EGR set up as shown in fig.1

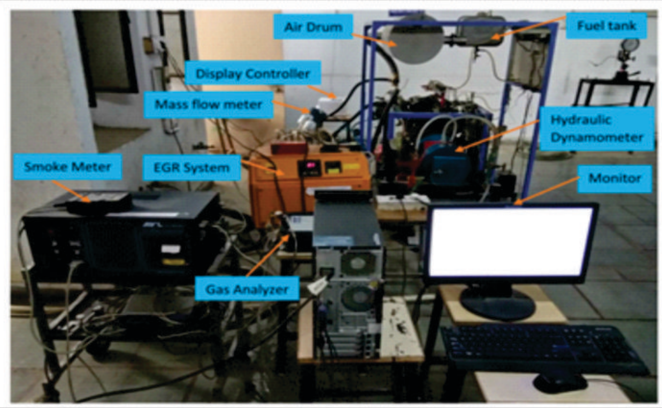

Fig.1 Complete setup of experimental test engine with EGR

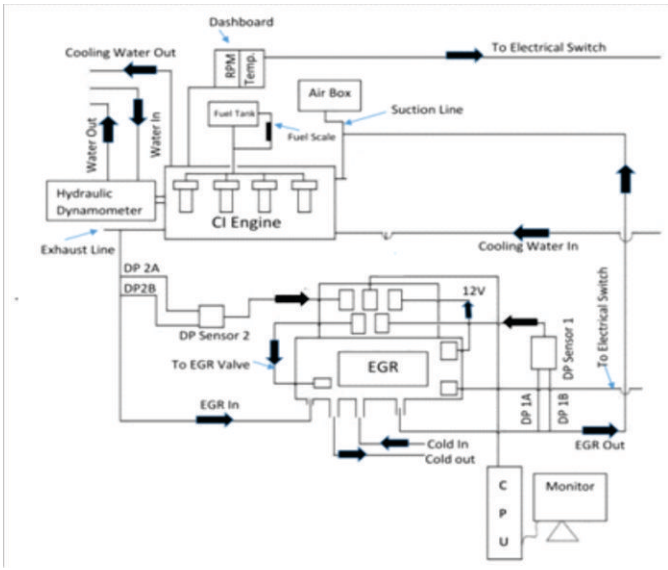

Fig.2 Schematic diagram of experimental test engine with EGR

Fig.2 shows the schematic line diagram of experimental setup. The technical specification of test engine was shown in Table 1.

Table 1 Thermo physical properties of fluid and nanoparticles given by Oztop and Abu-Nada

Make	Hm Stride
BHP	10 HP
Speed	1500 Rpm
Compression Ratio	23:1
Bore	73 mm
Stroke	88.9 mm
Orifice Diameter	17 mm
Type Of Ignition	Compression Ignition
Method Of Loading	Hydraulic Dynamometer

5. TEST CONDITION AND PROCEDURE

The experimental tests presented in this paper were carried out at a constant engine speed 1500 RPM with different load conditions: 2 kg, 6 kg and 12 kg respectively. The fuel flow rate was measured on the volumetric basis using a burette and stop watch. Calculation of actual load is done by hydraulic dynamometer which is directly connected to the engine. In this experimental work, first of all, the electrical and ignition connections were checked and battery was connected with the ignition points. All the water inlet/outlet points which are required for the cooling start. Now gradually increase the engine RPM up to 1500 RPM by changing the nobe direction. After reaching the engine speed at 1500 RPM, water inlet valve was opened to the hydraulic dynamometer for adjusting the load by spring balance as per requirement (say partial load, half load, and full load). At each load condition, the engine speed was set to 1500 RPM. After 15-20 minutes of engine running, observations for performance and exhaust gas emissions were taken and recorded. In this experimental work exhaust gas emissions have been measured using AVL exhaust gas analyzer and AVL smoke meter.

6. UNCERTAINTY OR ERROR ANALYSIS

Error analysis of physical parameters involved in experimental work is performed in the present section. It is known as uncertainty analysis. The uncertainty calculations for different measuring data's like fuel consumption, efficiency, power etc. are presented here. Error estimation for diesel engine experiments are categories in two errors, one is biased error and second is the precision error. In present study, bias errors are treated as constant errors. These errors are set down by calibration measurements, which were already discussed in the previous section for the present study.

Outcome parameters that have been dependent on two or more independent parameters, the formation of uncertainty is carried out as per formula:

$$\frac{\nabla y}{y} = \sqrt{\left(\frac{\nabla x_1}{x_1}\right)^2 + \left(\frac{\nabla x_2}{x_2}\right)^2 + \cdots \ldots \ldots + \left(\frac{\nabla x_n}{x_n}\right)^2}$$

Here y is dependent output parameter, and x1, x2 are independent parameters. This uncertainty analysis is based on suggestions by Kline and McClintok.

Uncertainty analysis of brake specific fuel consumption

$$BSFC = \frac{WF}{BHP}$$

Uncertainty calculation:

$$\frac{\nabla \mathrm{BSFC}}{\mathrm{BSFC}} = \sqrt{\left(\frac{\nabla \mathrm{X_{cc}}}{\mathrm{X_{cc}}}\right)^2 + \left(\frac{\nabla \mathrm{T}}{\mathrm{T}}\right)^2} + \sqrt{\left(\frac{\nabla \mathrm{W}}{\mathrm{W}}\right)^2 + \left(\frac{\nabla \mathrm{N}}{\mathrm{N}}\right)^2}$$

Here Xcc is volume of fuel consumption in T sec and WF is the weight of fuel in Kg/hr.

7. RESULT AND DISCUSSION

In this section the performance and emission characteristics of CI engine fueled with diesel is discussed and then followed by the discussion of the increasing EGR rates.

7.1 ENGINE PERFORMANCE

7.1.1 BRAKE THERMAL EFFICIENCY

Fig.3 shows the effects of EGR on brake thermal efficiency as a function of load. The BTE for different EGR rates slightly fluctuates due to change in thermochemistry of combustion process. The BTE for 10 % EGR increases due to reduce of burning rate in the combustion chamber. The maximum efficiency was recorded for 10% EGR at full load condition. So it was concluded that at optimum EGR rate the efficiency was slightly increased.

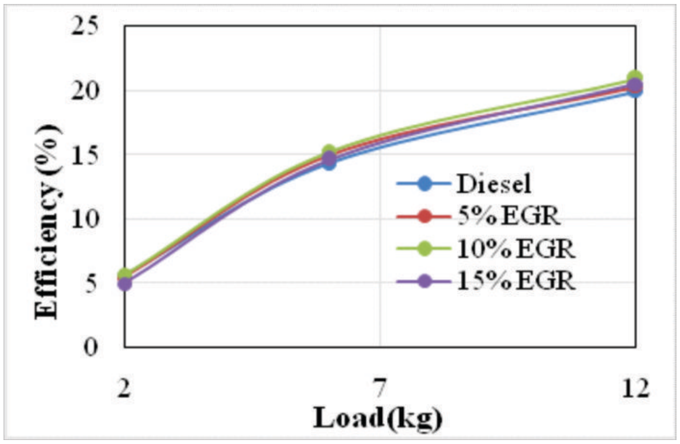

Fig.3 BTE at different EGR rates

7.1.2 BRAKE SPECIFIC FUEL CONSUMPTION

Fig.4 shows the effects of EGR on BSFC as a function of engine load. It can be seen from the figure that BSFC decreases with the increase of load at different EGR rates. Generally BSFC decreases for all EGR rates due to improper combustion. The maximum 12% BSFC decreases for 10% EGR at full load condition compare to pure diesel. This is because of reduction of peak cylinder temperature. It was observed that BSFC in (kg/kW.h) without EGR was 0.601 with neat diesel and with 10 % EGR the BSFC is 0.547 at half load condition. The BSFC decreases with the increase of brake power. This trend maintained in all four cases.

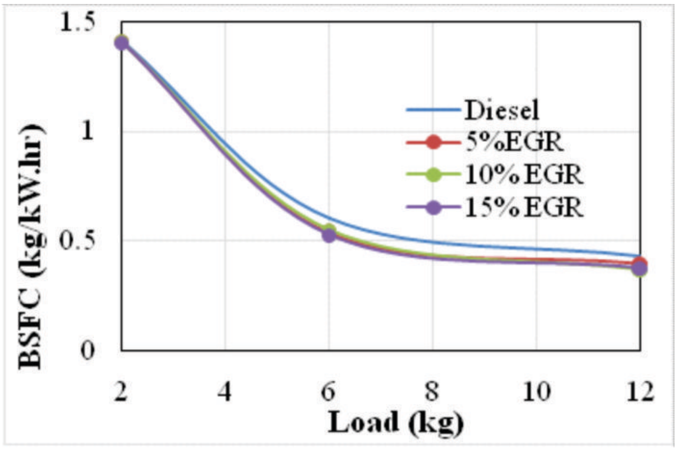

Fig.4 BSFC at different EGR rates

7.2 ENGINE EMISSIONS

7.2.1 EFFECTS ON HYDROCARBONS (HC)

Fig.5 shows the variation of HC emissions (ppm volume) of diesel engine at different EGR rates with reference to pure diesel. HC emission decreases with use of EGR compare to diesel. In this experimental work low cetane number of charge due to EGR causes longer ignition delay. It could be observed that HC emissions for neat diesel at full load are 13 ppm with 10 % EGR the HC emission was 7 ppm and for 5 % EGR it was 6 ppm and for 15 % EGR it was 7ppm. Due to excess oxygen in the combustion chamber incomplete combustion will occurred which leads to increase of HC emission.

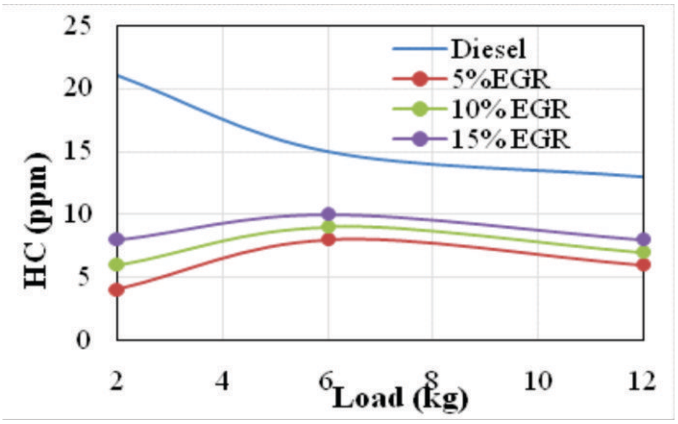

Fig.5 HC emission at different EGR

7.2.2 EFFECTS ON CARBON MONOXIDE (CO)

Fig.6 shows the variation of CO emissions with different loads for pure diesel. At half load the maximum CO emission was recorded for all cases. The CO emission was decreased with the use of EGR as compared to pure diesel.

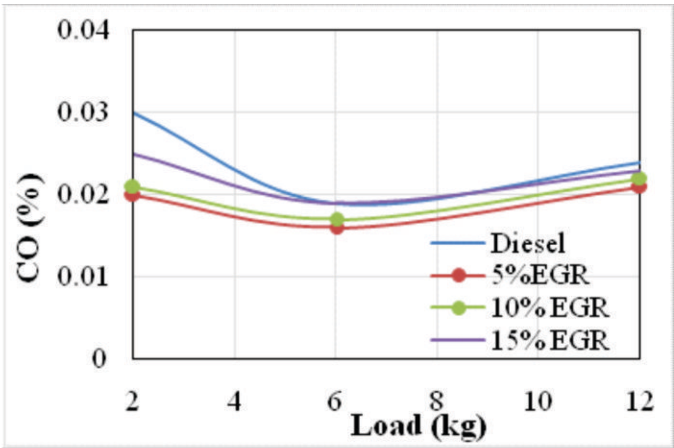

Fig.6 CO emission at different EGR

7.2.3 EFFECTS ON CARBON DIOXIDE (CO_2)

The variation of CO_2 emissions with different load conditions for pure diesel and EGR rates as shown in fig.7. At half load condition the maximum CO_2 occurred for 15 % EGR. The CO_2 emissions were lowered for 5 % and 10 % EGR as compared to diesel. It was observed from the figure that at full load condition the CO_2 emission are lowered at 15 % EGR was 6.5 % by volume.

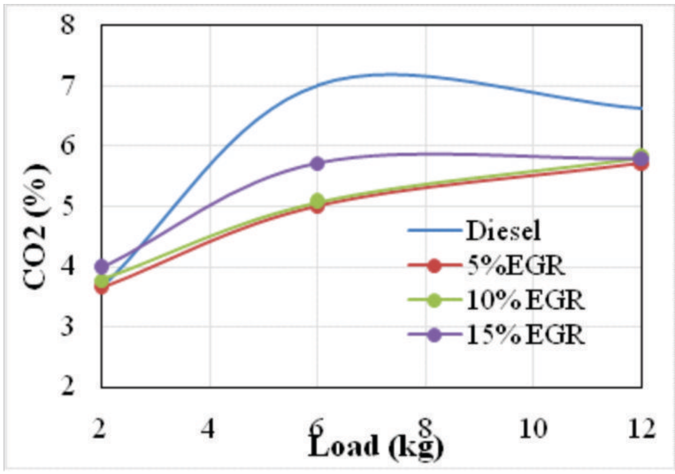

Fig.7 CO_2 emission at different EGR

7.2.4 EFFECTS ON NITROGEN OXIDES (NO_X)

Fig.8 shows the variation of NO_x in (ppm) with three loading conditions at different EGR rates. The EGR is mainly used to reduce the NO_x emissions. The NO_x emission for diesel fuel without EGR was 280 at partial load condition and with use of EGR, it was 253. From the figure it was observed that at full load condition the maximum NO_x emission was 381 for pure diesel and with the use of 10% EGR the maximum NO_x emission was 352. So it was concluded that by using EGR NO_x formation was decreased. The exhaust gases generally consists the inert carbon dioxide, nitrogen and high specific heat. When it was recirculated to engine inlet it can reduce the oxygen concentration and acts as sink. Due to this phenomenon the whole combustion is shifted to expansion stroke, lower combustion temperature is mainly reduce the NO_x.

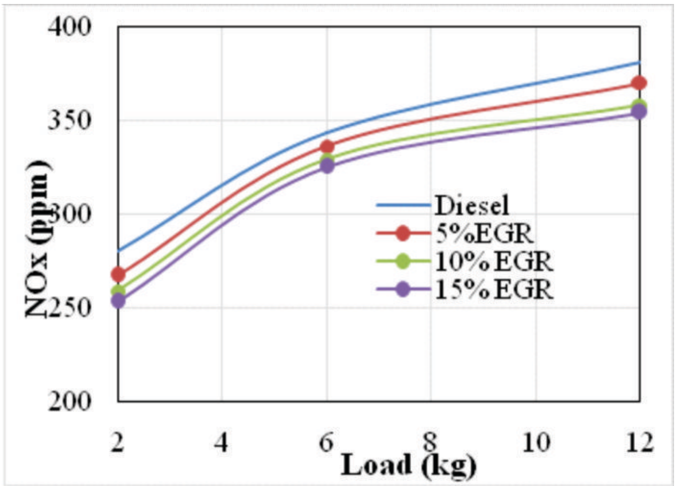

Fig.8 NO_x emissions at different EGR

7.2.5 EFFECTS ON SMOKE

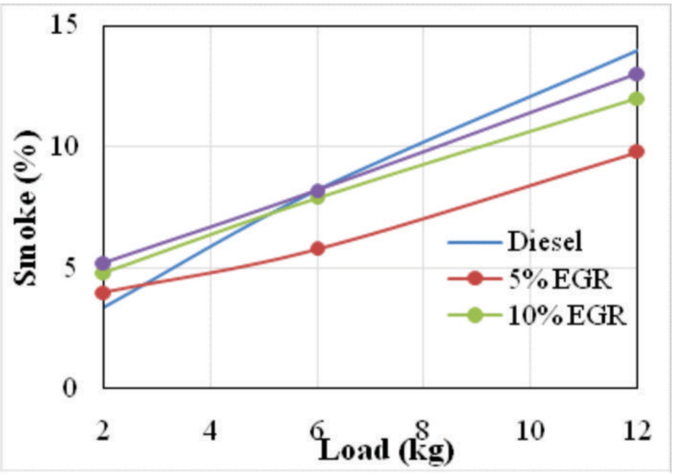

Fig.9 Smoke emission at different EGR

Fig.9 shows the variation in smoke emission with the use of EGR at different loading conditions. It was observed from the figure that the smoke at partial load slightly increased at 10% and 15% EGR as comparison of pure diesel. The maximum smoke emission was recorded for 10% EGR at full load condition but slightly low as compare to pure diesel.

8. CONCLUSIONS

In this paper CI diesel engine is used to investigate the performance and emission parameters for pure diesel (D100) with different EGR rates for three load conditions as 2 kg, 6 kg and 12 kg respectively. In this experimental work exhaust gas recirculation with 5%, 10% and 15% was used to reduce the NOx emissions of engine up to a certain level. Based on the results of this study following conclusions have been made:

- The brake thermal efficiency was fluctuates from 1-2% with the use of EGR. However at 15 % EGR the efficiency was increased by 2.01 % due to dilution effect of EGR on combustion behavior.
- The BSFC in case of EGR decreased 2-3 % as compared to neat diesel operation. This was due to mixing of EGR with fresh charge resulting in incomplete combustion of fuel. With the increase of EGR percentage the BSFC decreased.
- The HC and CO emissions were decreased by 4-5% and 6.15 % with respect to pure diesel at full load condition. Due to excess oxygen availability for the incomplete combustion, still emission was at low level.
- CO_2 emission was increased by 8.12 % with 15 % EGR at 80 % load condition as compared to diesel. The reason in reduction of CO_2 emission due to absence of high carbon content at cold EGR.
- The smoke emission was decreased by 7.2 % for 5 % EGR at full load condition.
- EGR technique is used to reduce the NOx emission. At full load condition the NO_x value for 10 % and 15 % EGR was 352 ppm and 354 ppm as compared to pure diesel value 381ppm.
- The optimum results are observed for 10 % EGR at full load condition.

REFERENCES

[1] B. R. Kumar and S. Saravanan, "Effect of exhaust gas recirculation (EGR) on performance and emissions of a constant speed DI diesel engine fueled with pentanol/diesel blends," Fuel, 2015.

[2] K. Rajan and . K. R. Senthilkumar , "Effect of Exhaust Gas Recirculation (EGR) on the Performance and Emission Characteristics of Diesel Engine with Sunflower Oil Methyl Ester," Jordan Journal of Mechanical and Industrial Engineering , vol. 3, pp. 306-3011, 2009.

[3] A. K. AGRAWAL, S. S. KUMAR , S. SINHA and M. K. SHUKLA, "Effect of EGR on the exhaust gas temperature and exhaust opacity in compression ignition engines," Sadhana, vol. 29, no. 3, pp. 275-284, 2004.

[4] E. Rajasekar, A. Murugesan, R. Subramanian and N. Nedunchezhian, "Review of NO x reduction technologies in CI engines fuelled with oxygenated biomass fuels," Renewable and Sustainable Energy Reviews, vol. 14, p. 2113–2121, 2010.

[5] A. V. Domkundwar and V. M. Domkundwar, Internal Combustion Engines, New Delhi: Dhanpat Rai & Co., 2005.

[6] A. Abu-Jrai, J. . R. Fernández, A. Tsolakis, A. Megaritis, . K. Theinnoi and R. H. Clark, "Performance, combustion and emissions of a diesel engine operated with reformed EGR. Comparison of diesel and GTL fuelling," Fuel, vol. 88, p. 1031–10, 2009.

[7] A. Tsolakis, A. Megaritis and M. . L. Wyszynski, "Application of Exhaust Gas Fuel Reforming in Compression Ignition Engines Fueled by Diesel and Biodiesel Fuel Mixtures," Energy & Fuels, vol. 17, pp. 1464 - 1473, 2003.

[8] V. S. Yadav, . S. L. Soni and D. Sharma, "Performance and emission studies of direct injection C.I. engine in duel fuel mode (hydrogen-diesel) with EGR," International journal of hydrogen energy, vol. 37, pp. 3807-3817, 2012.

[9] W. Ying and Z. Longbao, "Experimental study on exhaust emissions from a multi-cylinder DME engine operating with EGR and oxidation catalyst," Applied Thermal Engineering , vol. 28, p. 1589–1595, 2008.

[10] A. K. Agarwal, D. K. Srivastava , A. Dhar, R. . K. Maurya , P. C. Shukla and A. P. Singh , "Effect of fuel injection timing and pressure on combustion, emissions and performance characteristics of a single cylinder diesel engine," Fuel, 2013.

[11] M. M. Abdelaal and A. H. Hegab, "Combustion and emission characteristics of a natural gas-fueled diesel engine with EGR," Energy Conversion and Management, vol. 64, p. 301–312, 2012.

[12] Z. Gao and W. Schreiber, "The Effects of Egr and Split Fuel Injection on Diesel Engine Emission," International Journal of Automotive Technology, Vol. 2, No. 4, P. 123 − 133, 2001.

[13] D. Agarwal, S. Sinha and A. K. Agarwal, "Experimental investigation of control of NO x emissions in biodiesel-fueled compression ignition engine," Renewable Energy, vol. 31, p. 2356–2369, 2006.

[14] M. Mani, G. Nagarajan and S. Sampath, "An experimental investigation on a DI diesel engine using waste plastic oil with exhaust gas recirculation," Fuel, vol. 89, p. 1826–1832, 2010.

[15] M. Gomaa, A. J. Alimin and K. A. Kamarudin , "The Effect Of Egr Rates On No X and Smoke Emissions Of An Idi Diesel Engine Fuelled With Jatropha Biodiesel Blends," International Journal of Energy and Environment , Vol. 2, No. 3, Pp. 477-490 , 2011.

◆ ◆ ◆