Effect of EGR on Compression Ignition Engine parameters - a Review

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Abstract - This paper is a literature review on effect of exhaust gas recirculation (EGR) on CI engine parameters (i.e. performance and emission parameter). The emissions from CI Engines have adverse effects on human health, living organisms, and environment. The major emission form diesel engine are: unburned hydrocarbon, oxides of carbon (COX), oxides of nitrogen (NOX), oxides of sulphur (SOX), and solid carbon particulate matter (PM). Similarly, for biodiesel it was observed that HC, CO, CO2 were lowered, while NOX remains still higher.

For in-cylinder reduction of emission exhaust gas recirculation (EGR) and some fuel additives are effective for CI Engines. It was found that using EGR system reduces the NOx emission effectively.

Keywords— EGR, emission, CI engine etc.

I. INTRODUCTION

The survey of literature for diesel, biodiesel, CI Engines applications and there challenges to face emission control problems for respective fuel motivated to work for emission control technique. As we know that CI Engines are better power source due to higher compression ratio, higher efficiency, performance, and reliability than SI Engines. Hence, in most of on-road transportation, and off- road stationary applications, CI Engines are widely used [1]. However, all these versatile applications face a common and major challenge which is to meet present and future emission norms. The emissions from CI Engines have adverse effects on human health, living organisms, and environment. The major emission concerns for diesel engine are: unburned hydrocarbon (UHC), oxides of carbon (COX), oxides of nitrogen (NOX), oxides of sulphur (SOX), and solid carbon particulate matter (PM). Similarly, for biodiesel it was observed that HC, CO, CO2 were lowered, while NOX remains still higher.

II Exhaust Gas Recirculation (EGR)

Exhaust gas recirculation is a technique that works with a principle of reducing the oxygen content from fresh air (charge) and combustion flame temperature. An oxide of nitrogen (NOX) formation takes place at higher temperature about 2000 K [8] and more molecules of oxygen. When a part of exhaust gas is re-circulated to engine, it mixes with fresh air and increasing specific heat of mixture leads to lower combustion temperature and hence reduced air/fuel ratio causing decreased oxygen content. During EGR it serves for decreasing oxygen content, hence combustion flame temperature, and thus reduces oxides of nitrogen (NOx)[1,3]. Exhaust gas recirculation (EGR) is effective technique to reduce nitrogen oxides (NOx) from diesel engines because it lowers the flame temperature and the oxygen concentration of the working fluid in the combustion chamber. However, as NOx reduces, particulate matter (PM) increases, resulting from the lowered oxygen concentration. When EGR further increases, the engine operation reaches zones with higher instabilities, increased carbonaceous emissions and even power losses [8].

III Engine Characteristics Fitted with EGR System

A) Using Diesel (experimentation results)

a) Performance - Combustion characteristics

N.V. Deshpande, P.V. Walke et al., [4] had given emphasis to control oxides of nitrogen (NOx). Experiments were conducted on computerized
single cylinder four-stroke diesel engine fitted with EGR cooler and control valve to regulate rate of EGR. The author reported the effect of EGR rate on NOx, smoke, and on performance parameter like BSFC, and brake thermal efficiency etc. It was found that with increasing rate of EGR for different torque there was marginal decrease in brake thermal efficiency. This was due oxygen deficiency at higher load, which lead to incomplete combustion. In addition, BSFC was also marginally increased at high load.

A.K. Agrawal, S.K. Singh et al., [8] worked out an experimental investigation to observe effect of EGR on exhaust gas temperature and exhaust opacity in CI Engines. Matrix of experiments were conducted on two cylinders, DI, air cooled CI Engines. It was observed that, as EGR rate increases exhaust gas temperature decreases significantly. However, this result surely concludes that NOx can be decreased by increasing EGR rate. The reason for decreasing exhaust gas temperature was stated as considerable decrease in oxygen content in recirculation of exhaust gas to fresh air/charge. On other hand, BSFC and brake thermal efficiency were unaffected at part load and EGR rate of 15%. Moreover, marginal reduction was observed at full load and EGR rate above 15%. This may be due to fact that amount of fresh oxygen was decreased by replacement of exhaust gas.

D.T. Hountalas, G.C. Mavropoulos et al., [13] had established effect of EGR temperature for various EGR rate on HDDI engine, performance and emission. They have examined the effect of cooled EGR and hot EGR on EGR rate for turbo-charged HDDI diesel engine using multi-zone combustion model, computational investigation. Author stated, in general, introduction of EGR influences diesel engine combustion in three different ways, thermal chemical and dilution. The thermal effect is related to the increase of inlet charge temperature that affects volumetric efficiency (thermal throttling) and the increase of charge specific heat capacity due to the presence of CO2 and H2O. On the other hand the chemical effect is related to the dissociation of species during combustion, while dilution is related to the reduction of O2 availability. In addition, advanced injection timing was used to improve its brake specific fuel consumption (BSFC) that had negative impact on NOx. The negative effect of EGR on AFR increased with the increase of EGR temperature. At full load effect of thermal throttling (reduced amount of charge to cylinder) was significant and increases as EGR temperature was increased to higher values.

The BSFC was decreased linearly with increase in EGR temperature. This decrease in BSFC was mainly due to decrease in AFR, which affects combustion rate of fuel and to increase of in-cylinder mean gas temperature. The maximum reduction in brake thermal efficiency was in order of 5.5% relative to value without EGR, observed at 15% EGR for an engine speed 1130 rpm.

Timothy Jacobo, Dennis Assanis, et al., [9] had studied the work on complex interactions resulting from application and control of EGR also, heat rejection on a production HD diesel engine system and its effectiveness in NOx reduction. They investigated that, the coupling between EGR, the variable geometry turbo-charging (VGT), and EGR cooler critically affects boost pressure, air/fuel ratio (A/F), combustion efficiency and pumping work. Quantification of the sources of system inefficiencies shed an improved understanding of the fuel economy penalty associated with EGR, thus providing direction for future work on optimizing the engine charging system design and its control. In particular, the study examined in detail operation with various levels of EGR under three characteristic operating conditions: low speed/low load, low speed/mid-load and mid speed/mid-load. Engine thermal efficiency tends to decrease with EGR as a result of decreasing indicated work and increasing pumping work. However, re-optimized injection timing could offset part of the negative impact of changing EGR rates. For conditions allowing the VGT to maintain high enough boost and hence A/F ratio, combustion deterioration with increased EGR is minimal and efficiency losses are largely attributed to increased pumping work. Increased pumping work is the result of VGT’s actions necessary to maintain the pressure drop across the engine required for driving the EGR flow. Hence, there are significant opportunities for reducing the fuel economy penalty through...
optimization of design and control of the turbo charging and EGR system. The somewhat increased temperature and reduced A/F ratio seem to offset the dilution effect on ignition delay, hence the ignition delay remains generally unchanged with increasing EGR for given test conditions. The total system heat rejection increases significantly due to EGR cooling. However, the heat rejection from the combustion chamber may increase or decrease. The former is attributed to increased bulk gas temperatures. The latter is observed in cases with deteriorated combustion, leading to reduced peak combustion temperatures.

M. Ghazikhani, M.E. Feyz et al., [14] carried out an experimental study to investigate effect of EGR on various exergy terms of IDI diesel engine cylinder. In this study, also the effectiveness of total in-cylinder irreversibility on brake specific fuel consumption (BSFC) was investigated. An availability study was performed in order to investigate the effects of EGR on various exergy terms in an IDI, four cylinders, four strokes naturally aspirated diesel engine of diesel engine cylinder. Also the influence of total in-cylinder irreversibility on engine BSFC was discussed. The test was conducted in three engine speeds of 1500, 2000 and 3000 rpm and in four loads of 25, 50, 75 and 100 percent of maximum achievable load. In the tests, four EGR mass ratios percentage of 0, 10, 20, 30 were employed. Results showed that at lower engine load and speed there was considerable decrease in total in cylinder reversibility. This was proved from the act that EGR at low load conditions acts as intake pre-heater which increases the cycle temperature. At higher speeds and low load conditions, the positive effect of EGR as intake pre-heater was vanished by the negative effects of EGR which decline the cycle temperature, and total in-cylinder irreversibility almost remains unchanged. But when the EGR was implemented in high load conditions, a significant increase in total irreversibility is observed in all speeds. This was mainly caused by the work deterioration which implied the dominant effects of EGR in decreasing cycle temperature and more ignition delay. The comparison of the irreversibility and engine BSFC variations shows that, at all operating conditions, when the EGR was employed there were similarities between the trends of the cylinder total irreversibility and BSFC.

b) Emission characteristics
Dr. N.V. Deshpande. P.V. Walke et al., [3] reported the effect of EGR on NOx and smoke opacity opeared with diesel. It was studied that, smoke emission increases with increase in EGR rate for different torque. This significant increase in smoke was due to EGR reduces over-all air/fuel ratio, this enhances increase in PM. Variation of NOx with EGR rate reveled that, with increase in EGR rate the concentration of NOx decrease, as the exhaust gas absorbs some energy, oxygen content and hence lowers the peak combustion temperature. Thus, it was concluded that, in diesel engines NOx formation as temperature phenomenon and does takes place when temperature in combustion chamber is at or above 2000\textup{\textdegree}k.

A.K. Agrawal, S.K. singh et al., [8] reported the effect of EGR on opacity and NOx. Experimental study revealed that, opacity of exhaust gas increase as rate of EGR increased. However, at higher EGR rate and higher load it was found to be more PM emission. It was proved by experimental set-up that EGR can be effective technique to control NOx.

D.T. Hountalas, G.C. Mavropoulos, et al., [13] revealed the variation of NO as function of EGR temperature for various EGR rates. As, NO emissions at full load remain almost constant when altering EGR temperature (in the range examined). A small increase was observed only at high EGR rates. Considering that the formation of nitrogen oxide is temperature and O$_2$ sensitive, it was concluded that the temperature increase inside the combustion chamber, as shown later on in due to the increase of EGR temperature is compensated by the reduction of AFR ratio. On the other hand the effect of EGR rate is slightly higher at low engine speed. This, results from the lower AFR observed at low engine speed. In the case of hot EGR (no cooling) the increase of charge temperature would be significant and is expected to lead to an increase of NO compared to the cooled EGR case examined. As far as soot emissions are concerned an increase of their value is observed when increasing EGR.
temperature. This results mainly from the reduction of AFR. Oxygen concentration is reduced affecting both soot formation and oxidation. The effect of EGR temperature is almost linear and more pronounced at high EGR rates and low engine speeds. The effect of EGR rate on soot is stronger at high EGR temperatures. Furthermore, the effect of EGR temperature is higher at low speed where the maximum values of soot variation. In the case of soot emissions it could be expected that using a higher EGR temperature would enhance soot oxidation leading to a reduction of emitted soot. The present study had demonstrated that EGR cooling is favorable if we wish to retain the benefits of low NOx emissions, without sacrificing significantly the engine efficiency. EGR cooling was necessary to prevent soot emissions from rising to unacceptable levels. The need for EGR cooling was more evident at high EGR rates and low engine speeds. From the theoretical investigation it has been revealed that a different effect of EGR temperature is to be expected at part load operation. Timothy Jacobo, and Dennis Assanis, et al., [9] study addressed EGR effects on in-cylinder processes, such as combustion efficiency, flame temperatures and NOx formation, as well as system level effects, such as the variations of pumping work due to changing VGT flow characteristics or the impact of EGR cooling on heat rejection. The rate of NOx reduction with increased EGR was much steeper under low A/F ratio conditions. Increased boost provided by VGT at higher engine speed does not appear to have a negative effect on NOx emissions. In-cylinder flame temperature contours, obtained through application of video-scope technology and two-color pyrometers, reveal a distinct decrease in flame temperature as EGR increases. This happened despite the fact that bulk gas temperature may actually increase with increasing EGR, due to increasing intake charge temperature and decreasing trapped mass. Hence, significant reductions of nitric oxides with increasing EGR can be correlated with flame temperatures effects. Combustion deterioration is predominant at higher load/low speed and low boost conditions, due to a significant decrease of A/F ratio with increase of EGR. This is accompanied by increased CO and unburned HC emissions.

### III Engine characteristics fitted with EGR system using Biodiesel

#### a) Performance-Combustion characteristics

D. Agrawal, A. K. Agrawal et al., (2006) [10] research has showed that engine operated with rice bran oil (RBO) biodiesel while employing EGR results in NOx reduction without compromising engine performance and emissions. It was found that with increase in load exhaust gas temperature also increases, however, temperature of exhaust gas was found to be lower in case of EGR-operated engine. The reason stated was lower availability of oxygen molecules higher specific heat of intake air mixture and reduction in air fuel mixture.

In associated, the trend of thermal efficiency for diesel operated engine was found to be slightly increased with EGR at lower load due to re-burning of HCs that were re-circulated through EGR. The thermal efficiency for higher load found to be unaffected with EGR. An important observation was that, all biodiesel blends had thermal efficiency higher than baseline data. This was so because biodiesel are oxygenated fuel. Also, researcher investigated that for diesel BSFC was lower at lower engine loads operation with EGR compared to without EGR. However, at higher engine loads BSFC with EGR is almost similar to that of without EGR. Furthermore, for biodiesel operated engines BSFC increases with increase in blends in biodiesel. Generally, this increase in BSFC for biodiesel blends was due to lower calorific value of biodiesel than diesel. Moreover, BSFC was found minimum at 20% blend when only biodiesel blends were compared. Reason stated was higher thermal efficiency for RBO 20% biodiesel blend. BSEC was lower for diesel with EGR compared to baseline data at lower loads. But at higher load with and with EGR follows the same trend. When engine was operated on biodiesel blends BSEC reduces with increase in blends of biodiesel. Reason for lower BSEC may be better thermal efficiency. Moreover, RBO 20% blends gave lower BSEC with EGR.

K. Rajan and K.R. Senthilkumar et al., [12] investigated that EGR along with sunflower oil...
methyl ester (SFME) biodiesel was a most effective technique for reduction of NOx emission. Result showed that for twin cylinder, 7.5kW rated power output at 1500 rpm with 20% blends of SFME and 15% EGR rate, produces 25% less NOx. The brake thermal efficiency were improved with increasing concentration of bio-diesel. The SFME blend with 15% EGR, which improves 4% of thermal efficiency at lower load (0-75%) compared to diesel without EGR. Moreover, BSFC were lower for diesel at lower loads operated with EGR as compared to without EGR. BSFC at higher load were almost same with and without EGR. BSFC for biodiesel blends was found to be marginal increased as compared to diesel with and without EGR. This was so because lower calorific value and higher viscosity. The BSFC increased 10% for BD20 while 15% BSFC was increased for BD40 sunflower oil methyl esters blends at full load operation with EGR.

H.E. Saleh et al., [11] study showed that JME is an alternative fatty acid methyl ester (FAME) fuel. The author stated that JME along with effective EGR technique would quantify the thermal efficiency and reduction in exhaust emission especially NOx emission. The study showed that JME has higher calorific value 47,380 kJ/kg when compared with 44,300 kJ/kg of diesel. Furthermore, the engine output efficiency with JME was higher than that with diesel without EGR. Also, BSFC with JME was lower than that with diesel fuel. The BSFC were lower than that with diesel by 8.2% and 9.8% at N=1200 rpm and 1600 rpm respectively. The main reason for this was higher CV and JME as oxygenated fuel which has beneficial effect on combustion. On other side, BSFC was decreased or fuel economy was with increasing EGR rate up-to 5% at 25% load. This increase in efficiency and fuel economy along with reduction in NOx was achieved due to re-burning of un-burnt HC in re-circulation of exhaust. At, 25% load maximum reduction in NOx can be achieved with minimum in fuel economy was obtained by increasing EGR rate to 15-20%. Thus, a large EGR rate (25-40%) could be used for high reduction efficiency of NOx (50-55%) as expected increase in BSFC less than 5%. So, researcher showed that it was difficult to employ an EGR rate larger than 12% at higher load, since excessive increase in BSFC up-to 11% and reduction in NOx was 33%. One interesting side effect of using various high level of EGR rate was coefficient of variation (COV) of indicated mean effective pressure. The COV of indicated mean effective pressure quantifies degree of change in combustion completeness with increasing the levels of EGR rate. COV of imep should no longer be more than 5%. As expected, COV of imep was increased with increasing value of EGR rate at all operating condition. COV of imep was ranged from 1.0%-1.4% for all data studied for EGR rate of 5-40% at 25% load. However, at full load COV imep was found to be 1.0% to 2% for EGR rate of 12%. Beyond, 40% and 12% EGR rate for part load and full load respectively COV of imep will exceeds 2%. This supports fluctuating combustion and increased cyclic desperation. On the other hand, CI Engines with diesel and JME biodiesel blend will remain stable with very little fluctuation in output work for EGR rate less than 40% and 12% at part load and full load respectively. Investigation also proved that to increase engine efficiency or in other words to decrease BSFC at full load with EGR rate above 12% an EGR cooler was added. This was so for cooling hot exhaust gases in EGR system to reduce peak EGR temperature in an EGR system to regain volumetric efficiency and maintain A/F ratio lost by EGR operation. However, use of EGR cooler has positive effect on improving engine economy and decreasing exhaust emission.

b) Emission characteristics

D. Agrawal, A. K. Agrawal et al., [10] investigated that rice bran oil (RBO) biodiesel blended with diesel produces less HC, CO, UHC, and PM. However, it was found that higher NOx emission. EGR as effective technique to reduce NOx was used with diesel-RBO blends. Because, it reduces oxygen content of fresh air charge and lowers flame temperature during combustion. The experiments showed that, when EGR was applied to diesel NOx were reduced but PM was considerably increased. As, biodiesel was used in CI Engines smoke opacity was decreased but NOx was significantly increased. Thus, biodiesel with EGR can be effectively used to
reduce NOx and smoke opacity simultaneously. RBO 20% blends. It was concluded by researcher that, biodiesel and EGR can be employed together to reduce NOx and smoke simultaneously. In addition, for higher EGR rate recirculation at higher load causes increase in PM, CO, HC due to decrease in Air fuel ratio, reduced oxygen content, incomplete combustion etc. However, 20% RBO biodiesel with 15% EGR was found to be optimum operating condition which improves thermal efficiency and reduces exhaust emission and BSEC. Other emission such as HC, CO, also found to be decreased at this optimum operating condition.

K. Rajan and K.R. Senthilkumar et al., [12] compared there research with conventional diesel fuel, it was found that NOx was reduced about 25% at 20% BD of SFME and 15% EGR. The reason stated was due to less oxygen available in exhaust gas which reduces flame temperature in a combustion chamber. Total UBHC and CO emissions were decreased by 5% and 10% for BD20 of SFME biodiesel blends respectively compared to diesel fuel. Also, smoke emission was observed as increases due to incomplete combustion. However, engine operated with high rate of EGR at high load found to reduce 25% NOx with penalty of reduction in thermal efficiency, and increase in smoke, CO, and UBHC were observed as compared to diesel. Researcher showed that CO, UBHC, smoke emission for SFME was comparatively lower than diesel fuel. Also, stated that emissions were increased with increase in load and EGR rate. CO emissions were 10% and 20% lower respectively for 20% and 40% BD SFME as compared to diesel at full load operated with EGR. In continuation, results for UHCE stated that for 20% and 40% biodiesel blends with 15% EGR gave 5% and 15% lower UBHC emissions respectively at full load operation compared to diesel with EGR.

H.E. Saleh et al., [11] proved that for all operating condition, a better trade-off among HC, CO, and NOx emission can be archived by limited EGR rate of 5-15% with very little or no economy penalty. At, 25% load maximum NOx emission can be achieved by increasing EGR rate to 15-20% without any dues to economy. Notably, author said that, EGR can bring satisfactory results for NOx reduction, but same time the higher increase in rate of EGR may lead to increase in emissions of CO, HC smoke. However, better trade off among HC, CO, and NOx emissions was limited to EGR rate of 5-15%. Using cooled EGR has a positive effect on NOx reduction by 15%, HC emission by 24%, and also reduces CO emission by 15%.

Jinlin Xue et al., [5] presented that biodiesel, produced from renewable and often domestic sources, represents a more sustainable source of energy and will therefore play an increasingly significant role in providing the energy requirements for transportation. The use of biodiesel will lead to loss in engine power mainly due to the reduction in heating value of biodiesel compared to diesel, but there exists power recovery for biodiesel engine as the result of an increase in biodiesel fuel consumption. The majority of studies have shown that PM emissions for biodiesel are significantly reduced, compared with diesel. The higher oxygen content and lower aromatic compounds has been regarded as the main reasons. It was seen that the vast majority of literatures agree that NOx emissions will increase when using biodiesel. This increase is mainly due to higher oxygen content for biodiesel. Moreover, the cetane number and different injection characteristics also have an impact on NOx emissions for biodiesel. It was concluded that the blends of biodiesel with small content by volume could replace diesel in order to help in controlling air pollution and easing the pressure on scarce resources to a great extent without significantly sacrificing engine power and economy.

IV Conclusion

The exhaustive review of literature on CI Engines fitted with EGR using diesel and biodiesel was carried out. It was noticed that, numerous work has been done on single cylinder, twin cylinder and multi cylinder CI Engines. It was noticed that little work has been done so far on biodiesel with altering engine parameters. The literature pertaining to exhaust gas recirculation (EGR) for diesel and biodiesel fuel show that, cooled EGR, short loop EGR, EGR with high pressure loop, EGR for HSDI, high rate EGR, have significant effect on NOx
reduction. It was also suggested that, better trade-off among EGR rate, PM, HC, CO emissions, BTHE and BSFC should be determined. EGR for biodiesel was reported more efficient.

References


