International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 23 (2017) pp. 13677-13689

The Effects of Exhaust Gas Recirculation on the Performance and Emission Characteristics of a Diesel Engine – A Critical Review

Maroa Semakula[1] and Prof. Freddie Inambao[2]

[1,2] Discipline of Mechanical Engineering, University of Kwazulu-Natal, Howard College, Mazisi Kunene Road (King George V Avenue), Mechanical Engineering Building, Room 217, Durban 4041, South Africa.

[2]Orcid: 0000-0001-9922-5434

Abstract

Exhaust gas recirculation (EGR) is one of the most widely used methods of controlling emissions, particularly nitrogen oxide (NO_X), CO, CO_2, HC (hydrocarbons) and particulate matter (PM). EGR is a system where portions of the exhaust gases are re-introduced back into the combustion chamber via the intake manifold. The systems that are affected by the application of EGR are: brake specific fuel consumption (BSFC), lubricating system, diesel engine combustion characteristics, the brake thermal efficiency (BTE), the combustion characteristics of DI diesel engines, engine speed, CO_2 and HC emissions, the performance characteristics of turbocharged diesel engine, fuels, temperature, on EGR rates on the diesel engine performance and emission, the durability of engine components, and cooled EGR and the challenges of cooled EGR.

Keywords: EGR, BSFC, Carbon dioxide, PM, direct injection, brake thermal efficiency.

INTRODUCTION

The exhaust gas recirculation (EGR) technique is gaining widespread use as one of the most efficient methods or techniques for reducing emissions and particulate matter (PM) effluents from diesel automobiles, particularly nitrogen dioxide (NO_X), carbon monoxide (CO), and hydrocarbons (HC). This involves the circulation of part of the exhaust gas along with the intake fresh air charge, into the combustion chamber of the diesel engine for combustion together with the fuel injected in the normal power cycle of the diesel engine. EGR is an emission control system which allows significant reduction in NO_X gases in almost all types of diesel engines including Light Duty, Medium Duty and Heavy Duty engine use or applications, and primary engines as low as two stroke as used in marine operations and applications.

The use of EGR systems in diesel engines is not limited to increasing efficiency and reduction of emissions only [1], but also includes imparting knock resistance and reduction in the need for high load fuel enrichment in diesel engines. However, in spark ignition (SI) engines EGR systems also aide in or help in the vaporization of liquid fuels, though it is an enabler for closed cycle diesel engines in particularly improving ignition quality and reduction of high load fuel enrichment in diesel engines. Other benefits of EGR, particularly cooled EGR, is that it enables more EGR flow and cooler intake charge temperatures, thus reducing peak in-cylinder temperatures which improves ignition quality in diesel engines; reduction in lubricating oil consumption; increase in fuel injection pressures; increase in use of diesel oxidation catalysts; and increased intake manifold boost pressure. Currently, more efficiency is being demanded in the management systems of diesel engines as a way of reducing energy losses, particularly those being wasted through the exhaust system which typically wastes between 20% to 25% of all energy released. Thus, there has been tremendous development of ways or methods to continually reduce this energy wasted through re-tapping of the exhaust gases by utilizing EGR systems, for example, in scavenging for pre-heating purposes. This recycling of waste gate gases improves fuel efficiency economy, volumetric efficiency, brake thermal efficiency, brake specific fuel consumption, and reduces emissions and PM [2].

The phenomenal growth of the middle class of most emerging and developing countries, and the failure of most public transport systems and infrastructure in developing and emerging nations, has tended to increase the number of personalized transport vehicles on the road, with diesel propelled vehicles gaining popularity including in day to day commercial activities. This growth has produced many studies looking into ways of reducing energy spending through harnessing of systems gases and redirecting and harvesting the available energy within the gases which would have otherwise have been lost. This reduces demands on the primary sources of energy experienced in the world today. Although there have been tremendous achievements in technological advances in automobile manufacture and technology, there is a need for us to continue to reduce the amount of energy use and emissions, thereby reducing pollution in our primary and atmospheric environment. These studies and technological changes can initiate a reduction in global warming, which has seen a phenomenal growth in 21st century. It is imperative, therefore, for automobile and engine manufacturing industries to incorporate these new studies regarding reduction in emissions and energy wastage from engine exhaust systems and undertake deliberate measures to improve on and harness EGR system gases [1].

Agarwal, Singh and Agarwal [3] state that despite the high fuel efficiency provided by diesel engines, they have the disadvantage of emitting nitrogen NOx and PM which is considered as the main pollutants and main toxic gases emitted to the atmosphere and as significant contributors to air pollution in major urban centres and modern-day cities. Other challenges or disadvantages include: more HCs and soluble organic fractions (SOF), PM, more condensation HC and PM deportation in cooler fouling (i.e. degraded heat transfer and higher flow resistance). These emissions are currently legislated by stringent environmental protection agencies in most countries, making diesel propelled engines and machines more expensive and less appealing. However, with the introduction of the EGR system, NOx emissions of diesel engines are greatly reduced making it increasingly compelling to incorporate such a system in the design and manufacture of diesel engines.

THE REVIEW

A number of studies have been published regarding the effects of (EGR on the performance and emission characteristics of diesel engines. Several of these have been considered and are reviewed here to highlight the developments in this area of study.

Abaas [4] in his study "Effect of Exhaust Gas Recirculation (EGR) on the Performance Characteristics of a Direct Injection Multi Cylinders Diesel Engine," used a direct injection (DI), four-cylinder FIAT engine, coupled to a dynamometer and thermocouple with Ni-Cr and Ni-Al elements, air and fuel flow meters, together with engine speed tachometers. Fuel used during the test was Iraqi conventional diesel CN = 46.8 under varying EGR rates of 5%, 10%, 20%, and 30%. Engine speed was maintained at constant for all loads and variable speeds of 1250 rpm to 3000 rpm at constant engine load were used.

Abaas [4] noted that increasing the EGR percentage or mass flow rate increased the brake specific fuel consumption (BSFC). Other findings on the BSFC were that at low engine load ranges the BSFC was found to be high as compared to when medium engine load ranges were used. The researcher attributed this to the drop in combustion chamber temperature. However, with reducing temperature the researcher observed increased fuel delay period, thus reducing engine peak pressure resulting in lower engine output and a greater increase in the fuel consumed. Therefore, according to this study, the brake thermal efficiency reduces with an increase in EGR % mass flow rate application.

Other findings from Abaas [4] include the effect of reduction in oxygen availability during combustion, which is the factor explaining the relative incomplete combustion and the increase in particulate matter (PM), but credited with the reduction of NO_X emissions. On volumetric efficiency, Abaas [4] argues that at low engine loads, since diesels operate on lean mixture, the volumetric efficiency was observed to be very high, but increasing the engine load. He observed that the engine consumed more fuel in order to meet the load demands as the engine motor speed is increased. However, in increasing the load and engine speed he noted that the exhaust gas temperature increased, whereas increasing the EGR% mass flow rate reduced the temperatures (Figure 1).

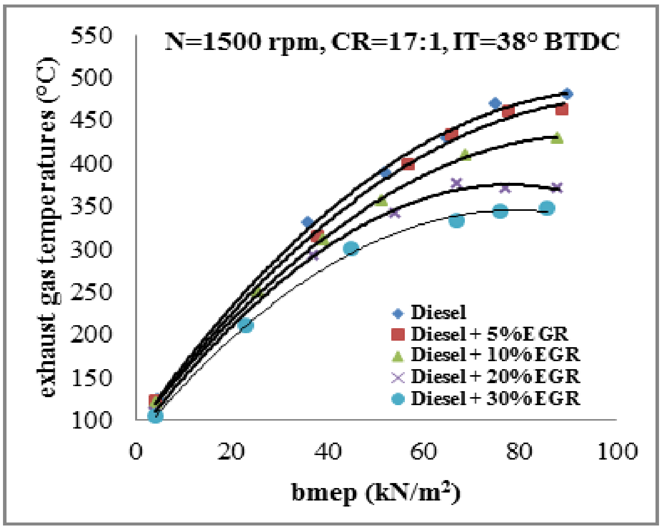

Figure 1: Abaas (2016)

Figure 1 Showing the relationship between the EGT and BSFC and application of EGR.

The increase in temperature is explained by the fact that more load and speed need more fuel to be burned; by increasing the load the work of dilution, as already explained, increases as more combustion reactants are exposed to the low temperature environment. Thus, increasing EGR% mass flow rate reduced exhaust gas temperature (EGT) by 1.41%, 15.64%, 16.08% and 26.38% for EGR% mass flow rate of 5%, 10%, 20% and30% respectively (Abaas, 2016). On the brake power (BP), Abaas [4] noted an increase as the engine speed increases. However, by increasing the percentage of the EGR mass flow rate, the brake power reduced 1.12%, 3.26%, 5.42%, and 16.79% when compared to EGR% mass flow rates of 5%, 10%, 20% and 30%, which indicate true effects of dilution in the combustion chamber and on the performance of a diesel engine.

Charola, Makwana and Makwana [5] in their study "Effects of EGR (Exhaust Gas Recirculation) on the Performance and Emission of a CI Compression Ignition Engine Fueled with a Blend" used a single cylinder, four stroke, water compression ignition engine, with the test fuel being methanol (industrial chemical) with purity or concentration level of 99%. The test set up consisted of a test engine, a hydraulic dynamometer, fuel and flow meters, and incorporated various measuring equipment and relevant modifications for test study.

In their findings, the BTE (brake thermal efficiency) increased as the load increased. Using 10% methanol diesel blend they found that it increased the BTE by up to 12.85% and a 20% blend of methanol and diesel improved the BTE by 26.23% on the level of 10% EGR, while in BSFC (brake specific fuel consumption) they observed a reduction of 3.57% in the BSFC in a 10%/90% methanol and diesel blend, and an increase of 4.28% when the 20%/80% was used [4]. On how the methanol diesel blend affects emissions of CO, they found that with the 10%/90% methanol diesel blend there was a 30% reduction in the emissions of CO, while with the 20%/80%, methanol diesel blend there was a reduction of 40% during the experiment study period. Regarding the HC in the exhaust system, it was observed that there was a reduction of 13.04% in the 10%/90% methanol diesel blend and a reduction of 17.39% with the 20%/80% methanol diesel blend. The NO_X emission showed a reduction of 5.55% with the 10%/90% methanol diesel blend, and 3.33% in the 20%/80% methanol diesel blend [4]. The exhaust temperature gas reduction was observed to reduce or drop by 4°C, when the 10% EGR mass flow rate was used, compared to 6°C when the EGR% mass flow rate was applied.

Rao, Mutyalu and Ramakrishna [6] in "Effects of Exhaust Gas Recirculation on The Performance and Emission Characteristics of a Diesel Engine Fueled with Waste Cooking Oil Methyl Ester", used a single cylinder, four stroke, water cooled direct injection, compression ignition engine, with a dynamometer coupled to an output shaft. Modifications were carried to allow the experiment to be carried out. In order to collect data a digital panel was installed, while an exhaust gas analyzer was used to investigate emission characteristics of the various gases in this study: CO, CO_2, HC, NO_X and O_2. Finally, the fuel they used was BO (Normal diesel), B10 (10%WCOME+90%) diesel by volume, B20 (20%WCOME+80%) diesel by volume, B30 (30%WCOME+70%) diesel by volume. The EGR % mass flow rate ranged from 0% to 20% graduated in intervals of 5%. During this experiment all the tests were conducted at constant 1500 rpm, in order to study the effects of EGR on the emission and engine performance characteristics when waste cooking oil is used together with diesel blends. The parameters investigated and their variations were: BSFC, BTE, EGT and emission characteristics of NO_X, HC and CO.

During their study they observed that the BTE remained unaffected by the application of an EGR% mass flow rate that is above 15%, but tended to decrease as the EGR% mass flow rate was increased beyond 15% EGR. This drop is explained by the fact that the availability of oxygen is reduced during combustion with the application of EGR of 15%. Regarding the BSFC it was observed to be independent of the rate of EGR% mass flow rate, particularly at lower rates of EGR% mass flow rate, but it increased as the rate of EGR% mass flow rate increased above 15%. This phenomenon is explained by the fact that there is formation of a rich mixture due to the dilution effect in the combustion chamber. This was identical to the findings of Charola et al. [5].

The effects of EGT that were observed if the engine was run on cooled EGR were that the in-cylinder temperatures were lowered, as compared to when the engine exhaust gases were run without being cooled. The cooling of the EGR gases affects the heat specific ratio of the intake air mixture by causing less oxygen in the combustion chamber. The NO_X emission findings indicate that for all the fuel blends used during the study, the NO_X emissions decreased with the increase in EGR% mass flow rate. This is explained by two factors: reduction in the availability of oxygen during combustion and the lower combustion temperatures. But since NO_X is temperature dependent for its formation to take place, this explains its decrease as flame temperatures drop. The HC and CO emission showed an increase with the increase of the EGR% mass flow rate above the 15% EGR rate level, as less oxygen becomes available for combustion, resulting in incomplete combustion and more HC and PM.

Kumar, Antony and Sahoo [7] In the "Effects of Varying EGR Rates in The Performance and NO_X Emission of an IDI Diesel Engine Fueled with JB100, JB80, JB60, JB40, JB20 and Diesel" used a single cylinder engine, water cooled IDI diesel engine, connected to an electrical loading system. The fuel line was connected to the fuel tank. NO_X, CO, CO_2 and HC were measured using an AVL gas analyzer, while the air intake mass flow rate was measured by a circle edge orifice plate. After conducting the study, they observed that at an EGR of 15% of the mass flow rate, using the blends of JB20% at 25% EGR mass flow rate, JB40% at 15% EGR mass flow rate, JB60% at 20% EGR mass flow rate, JB80% at 40% EGR mass flow rate and JB100 at 5%EGR mass flow rate [8], the NO_X emissions were seen to be reduced by 10.10%, 11.94%, 13.4%, 15.2%, 19.8% and 24.8% respectively. Soot emission, PM, CO, and CO_2 increased.

The NO_X emissions were observed in all the biodiesel blends at high levels, explained by the fact that biodiesel blends contain higher amounts of oxygen content; this trend is most visible at all full loads. Among the diesel blends the following values were found 882 ppm, 848 ppm, 806 ppm, 775 ppm, 737 ppm respectively, whereas for diesel only the value was 643 ppm [7]. The BTE was observed to be lower for all the JB blends compared to diesel due to the lower calorific value of the biodiesel but the viscosity index was seen to be very high. During the study, diesel and the JB20 blend of fuel showed a better maximum BTE value among all the blends used in the study with 5% EGR mass flow rate and the JB90 blend of fuel showing a maximum reduction of NO_X reduction percentage but with a decreased BTE of 1.25%. The decrease in BTE during this study was attributed to the reduced availability of oxygen in the fresh charge which is an effect from the EGR application, where the exhaust gases result in lower flame temperatures and velocity, leading to an increase in soot and PM. However, in the JB60 test fuel and 20% EGR mass flow rate, the NO_X emissions reduced to 19.81% with only a slight increase in the BTE of 0.77, attributed to the reburning of the unburned hydro-carbons together with the EGR% mass flow rate so helping to complete the combustion of the fuel. It is important to note that during the study the exhaust gas temperature for all the study fuels (biodiesel and the blends) was found to be lower than when conventional diesel alone was used.

Manieniyan and Sivaprakasam [1] in their study "Experimental Analysis of Exhaust Gas Recirculation on Diesel Engines Operating with Biodiesel" used a four stroke, water cooled, single cylinder direct injection DI engine, rated at 5.2 kW power with a 1500 rpm as the rated speed. The experiment was conducted in two phases. Phase 1 investigated the performance, combustion and emission of diesel fuel and biodiesel blends of B20 where the EGR application was 0 (zero) or not applied. Phase 2 of the experiment used the same equipment and test rig and fuel i.e. B20, but with the EGR application employed. The range of distribution for EGR% mass flow was 5%, 10%, and 20%, while the load distribution was 20%, 40%, 60%, 80% and 100%. The emission gases were measured using a gas analyzer and the density of the smoke was measured using a smoke meter. Finally, the exhaust gas temperatures were measured using a thermocouple. Other combustion parameters like cylinder pressure, heat release and cycle to cycle variations were measured using a combustion analyzer.

The tests and study found that the BSFC for the test fuel without EGR under engine full load was seen to be 0.2779 kg/KW-hr and 0.2794 kg/kW-hr for biodiesel. The value of the BSFC and the engine at full load and EGR% mass flow rate at 5%, 10%, 15% and 20%, were 0.2853 kg/kW-hr, 0.2796 kg/kW-hr, 0.2832 kg/kW-hr and 0.3050 kg/kW-hr respectively, whereas for the higher EGR% mass flow rate of 20% the BSFC increased for both diesel and biodiesel. This was attributed to the high calorific values, higher viscosity density and boiling point.

The BTE was found to be comparable for diesel and biodiesel with or without EGR. At full load the BTE returned a figure of 29.006% for a test with EGR and 29.4933% without EGR application in full load. At 20% EGR BTE was reduced by 1.5% in diesel and biodiesel and more exhaust gases were produced, predominantly due to the dilution effect of EGR resulting in a drop in efficiency.

The variations between the hydrocarbons and the brake power results and conclusions indicate that with an increase in EGR mass flow rate levels, the HC emissions also increased only for the biodiesel, attributed to the presence of high oxygen content in most biodiesels, thus compensating for the lack of oxygen to facilitate complete combustion thus the increase in BTE. The values for the NO_X during the study were found to be 736 ppm for diesel fuel running without EGR in full load environment and 796 ppm for the biodiesel at full load without EGR. However, with the application of EGR it was noticed that the levels of NO_X reduced to 157 ppm for diesel and 158 ppm for the biodiesel respectively, but a reduction in BTE was established with large increments in smoke density.

Carbon monoxide (CO) in relation to diesel and biodiesel with various levels of EGR% mass flow rate and load condition was noted to vary from 0.14% (by volume) for the diesel and 0.18% (by volume) for the biodiesel all under full engine load conditions. Thus, they concluded that as the EGR % mass flow rate increases so do the CO emissions, caused primarily by the lack of oxygen and poor mixing during the combustion process.

The smoke density was generally found to be lower or decreased for biodiesel as compared to diesel fuel and this was observed for all engine loads. As the EGR % mass flow rate is increased there is an observed increase in the smoke density. This is explained by the fact that EGR affects the oxygen availability leading to incomplete combustion and the formation of (PM.

The EGT was observed to increase with the increase in the load, especially noticeable for biodiesel compared to diesels at all engine applicable loads and conditions during the study. This increase in temperature was attributed to higher oxygen content in all biodiesel fuels particularly those used in the study. This study finding was identical to Hawi, Kiplimo and Ndiritu [9].

The cylinder pressure at full engine loads and EGR% at 0 (zero) was observed to be comparable to biodiesel, arising from the fact that there was a good mixing from the biodiesel mixture under high load, because EGR gases act like heat absorbing agents due to the presence of CO_2 and H_2O caused by disassociation in the chemical effects of EGR application. Thus the combustion analysis showing or revealing significant heat release rates, with or without the application of EGR% mass flow rate.

Abu-Jrai et al. [10] in their study "Performance, Combustion and Emissions a Diesel Engine Operated with Reformed EGR Comparison of Diesel and Gas to Liquid (GTL) Fueling," used a Lister-Pitter TR1 engine, single cylinder, direct injection, air cooled, and naturally aspirated. It was connected to an electric dynamometer with a motor and load cell. The crank shaft position timing was set at 22° CA (BTDC) in all the tests. The EGR% mass flow rate was set manually using a gate valve while EGR levels were determined by volume. The rig also included other instruments to do measurements for oil and air inlet/exhaust manifold temperature respectively.

Data was acquired using software for measurement of: peak cylinder pressure, IMEP (indicated mean effective pressure), COV (percentage coefficient variation) of IMEP, average values of COV of peak cylinder pressures, ROHR (rate of heat release). The AVL gas analyzer was used in the measurement of NO_X, CO and CO_2 gases. The test fuels used for the test were ULSD (ultra-low sulphur diesel) and the ultra-clean GTL (gas to liquid) which was obtained through a LTFT (low temperature Fischer-Trosph) process, which is a synthetic fuel.

The experiment was conducted at two engine speeds of 1200 rpm and 1500 rpm and two loads only tested at 25% load and 50% (medium load), while the EGR ratios chosen were classified into two; standard EGR and REGR (reformed exhaust recirculation) both using ratios of 0%, 10%, 20%, and 30%. The REGR was a simulation based on H_2 gas and CO gas in the ratios of 25% = H_2(gas) - 0% CO(gas)-75%EGR while in the second scenario 15% = H_2(gas)-10%CO(gas)-75% EGR.

The conclusions from this study were as follows: at low engine loads the GTL fuel was found to bring or return high BTE values as compared to the BTE efficiency values the ULSD returned, but when REGR was introduced it was observed that GTL had a higher fuel replacement than ULSD, thus showing an improvement in efficiency and reduced emissions. BTE was also found to be load dependent, i.e. at low engine loads efficiency decreased with increasing REGR [10]. However, when the loads were high it was observed that the high flame temperatures and velocity of hydrogen gas and the rapid expansion increased the BTE as the REGR was increased.

On rate of heat release, the high octane number of GTL resulted in less pronounced premixed combustion, leading to lower heat release rate and in-cylinder pressure, leading to reduction in NO_X emission where GTL fuels were employed, unlike when ULSD fuel was used in the experiment. Whereas the combustion pattern was affected by the REGR, the use of the 30% REGR brought efficient gas fuel combustibility and an increase in-cylinder pressure together with the ROHR [10]. At low engine loads the authors noted that an increase of REGR resulted in a decrease of both NO_X and smoke emissions. However, at higher engine loads higher REGR resulted in a decrease in smoke emission but compromised NO_X emission.

Lastly, when the combination was used of both REGR and GTL fuel, the results showed a marked improvement in the reduction of emissions The 30% REGR when combined with the GTL fuel produced a 60% decrease in smoke emission, while the NO_X emission showed a 75% decrease as compared to when ULSD fuel was used at 0% REGR and low engine loads [10].

Shahadat, Nabi, Akhter and Tushar [11] in their study on "Combined Effect of EGR and Inlet Air Pre-Heating on Engine Performance in Diesel Engines" used a four stroke diesel engine S195, single engine, with a maximum speed of 2000 rpm, direct injection, water cooled and naturally aspirated. The fuel used for this study was conventional diesel, with a density of 0.80g/cc@25°C. Other modifications to suit the experiment were made to provide measurement readings, particularly the preheating mechanism for inlet intake air. To maximize the heat loss, the inlet intake air passage was insulated by plaster.

The overall heat transfer between the two exchange mediums (the inlet intake air and the exhaust gas) was calculated using the equation from [12]. The experiment was conducted in two phases or two parts; Phase 1 was conducted without the inlet air preheating and without EGR% mass flow rate application, while Phase 2 involved preheating the inlet intake air charge and EGR% application. The gas emission measurements were made using a gas analyzer to obtain values for comparative analysis.

After running the experiment, the following results and conclusions were observed. The emission of NO_X from the test engine increased as the engine speed increased in both the phases of the experiment. i.e. when the inlet intake air preheating was applied without EGR application and vice versa, a factor they attributed to the decrease in the duration of ignition delay and combustion chamber premixing time of the inlet intake charge. In addition, they observed that the application of EGR reduced the in-cylinder combustion peak temperature due to the higher CO_2 heat specific ratio. This result is identical to results in other studies, particularly those where the EGR% rate application was limited to between 20% to 25%, this being identical to the study done by [13].

However, on the relation between the effects of EGR on inlet intake air preheating and NO_X emissions, they observed that with an increasing in the inlet intake air temperature, the emissions of NO_X and CO indicated a decrease. This factor was linked to the ignition delay and premixed combustion mixture, two factors whose time is shortened by the introduction of EGR. There are other identical studies whose findings are consistent with this study [14].

Lastly, the authors wanted to show the relationship between the effects of adiabatic flame temperature on the emission of NO_X particularly when conventional diesel fuel is applied or used. When conventional diesel was used the authors observed that as the equivalence ratio increased (hitting a maximum ratio of 0.9), the adiabatic flame temperature also increased. However, the equivalence ratio began to decrease as it hit the maximum value, though at this point the NO_X emission continued to increase and vice versa.

Regarding CO emissions, the application of inlet intake air charge preheating at a controlled temperature of 55°C and without application of EGR% brought about a lowering of CO emissions to almost a minimum as explained by the fact that inlet intake air preheating provides CO oxidation. However, when the EGR mass flow rate of 25% was applied it was observed that the CO emissions increased greatly. This concurs with the findings of a study conducted by Fathi, Saray and Checkel [15], where it was concluded that the application of EGR does not have similar effects on the different species of emission characteristics.

The BTE during this study was found to be affected by the inlet intake air preheating in combination with the application of 25% EGR mass flow rate but at varying engine speeds and constant load. The authors found that the BTE was higher for the preheated inlet intake air than when compared to when preheating is not applied. This was seen to be due to higher amounts of heat energy that were being transferred from the exhaust gas to the inlet intake air, thus providing better burning of the fuel in the combustion chamber, hence minimizing the overall heat loss by the system. In addition, they also observed that the BTE increased with the increase in engine speed both at low and intermediate speeds, but at higher speeds they noted a decrease in the BTE, a factor which they attributed to shorter mixing time of the air fuel that is normally associated with higher engine speeds leading to poor or low fuel efficiency.

Abdelaal and Hegab [16] in "Combustion and Emission Characteristics of a Natural Gas Fueled Diesel Engine with EGR," used a Ricardo E-6 engine modified to accommodate gaseous fuel and normal or conventional diesel use. The engine was single cylinder, indirect injection, four stroke, water cooled, with a maximum rated power of 9 kW, and a maximum rated speed of 3000 rpm. Modifications were made to testing and gathering of data. Following testing and experimentation it was observed that the introduction of CO_2, through the intake manifold resulted in a decrease in NO_X emissions, but showed a relative increase in unburned hydrocarbons.

The disassociation of CO_2 and its introduction into the intake charge is attributed to the reduction in NO_X. This is a chemical effect that is associated with the use of the EGR application. Another observation the authors' made was that by continuing to increase the inlet charge temperature there was an increase in the unburned hydrocarbons emissions mainly due to a decrease in ignition delay in relation to the rise in the intake charge temperature. Increasing the intake charge temperature resulted in improved combustion characteristics due mainly to the drop in the ignition delay, thus improving and increasing the BTE and BHP (brake horse power) power parameters and a decreasing the unburned HC emissions and carbon monoxide (CO). It is imperative to note at this point that the increase in intake charge temperature during this experiment resulted in an increase in the NO_X emission i.e. dual fuels reduce NO_X emissions during low engine loads only. The admission of diluents was shown to produce poor combustion characteristics if they were increased, thereby causing reduction in the NO_X due to the lowering of the cyclic cycle temperature and the oxygen concentration due to the dilution of the intake charge by introduction of the EGR gases.

Fathi et al. [15] in "The Influence of Exhaust Gas Recirculation on Combustion and Emissions of N-Heptane and Natural Gas Fuelled Homogeneous Charge Compression Ignition (HCCI)," conducted a study at the University of Alberta fuel and combustion emission research facility. They used a Waukesha CFR single cylinder research engine, water cooled, coupled to a dynamometer. The speed was maintained at 800 rpm at wide throttle. A temperature controlled air preheating system was installed using a 2.4 kW heater motor. Also included were two port fuel injectors controlled electronically via an AFS sparrow module. The EGR rate was manually controlled. The fuels used for this experiment were n-heptane and natural gas either as blends or used individually.

During their study the authors observed that the recycled gases from the exhaust contained tri-atomic molecules of H_2O and CO_2 species which increase the specific heat capacity of the combustion mixture and reduce the overall specific heat ratio. This makes the mixture act like a thermal heat absorbing sink, thereby decreasing the after-compression temperature. The other observation they made with EGR application is a reduction in peak in-cylinder charge temperature due to delayed auto ignition of the combustion charge.

Applying EGR they noticed affected the peak in-cylinder pressure by reducing it. This is explained by the fact that the recycled exhaust gases in the form of EGR act as a thermal sink as earlier mentioned above, thus reducing the charge temperature during combustion. The pressure rise during the combustion becomes reduced which is a means of avoiding engine knock.

Heat transfer was noticed to decrease with the application of EGR, since the heat transfer coefficient is proportional to pressure and inversely proportional to temperature [15]. Therefore, the heat transfer coefficient did not vary much with the application of EGR, since by increasing EGR% mass flow rate both the pressure and temperature decreased.

The gross heat release rate (HRR) was seen to be affected by the application of EGR flow rate because recycled exhaust gases replace or substitute part of the fresh air intake charge, thus affecting the in-cylinder equivalence ratio and the combustion process at large. EGR rate application can cause delay in SOC (start of combustion) hence prolonging the burning or exposing the elements of combustion to more time to combust, which in return leads to increase in the IMEP limit and the operating range of the EGR rate.

The effects of EGR on combustion timing demonstrated that since EGR increases specific heat ratio of the combustion elements, the in-cylinder inlet charge temperature decreases thus delaying ignition as mentioned in the discussion above, thereby introducing retardation of SOC and increasing the combustion duration. Defined as the indicated work output per unit of engine swept volume, the IMEP was seen to be less affected by the application of the EGR rate which is identical with other studies conducted in this area [17].

Regarding the indicated specific fuel consumption (ISFC) the authors found that the retardation of the start of combustion (SOC) reduced ISFC, whereas when the EGR rate was applied it produced the opposite effect i.e. increased the ISFC. This is explained by the fact that introduction of EGR rate removed the availability of oxygen thus causing incomplete combustion in the combustion process thereby decreasing efficiency.

The formation of NO_X emissions as observed during this study with EGR application, was due to the nature of the combustion in homogeneous charge compression ignition (HCCI) engines which show a fast combustion. The formation of NO_X is limited due to the low charge temperature of the air mass flow rate. This is explained by two factors: applying EGR rate flow depresses peak in-cylinder temperature thus reducing NO_X emissions formation, and secondly the application of EGR rate depresses the availability of O_2 concentration in the combustion chamber due to the EGR rate dilution effect. However, an increase of EGR rate was noticed to increase HC and CO emissions as the EGR rate continued to increase. The explanation provided by the authors was the unavailability of O_2 and reduced inlet intake charge temperature which resulted in incomplete combustion due to poor mixing.

Hawi et al. [9] in the "Effects of EGR on Performance and Emission Characteristics of a Diesel Piloted Biogas Engine" used a single cylinder, four stroke engine, water cooled, naturally aspirated constant speed CI engine, coupled to a hydraulic dynamometer for load application. Modifications were made to the engine to enable it to run on dual fuel with conventional diesel as a pilot fuel and biogas as the main fuel. A gas analyzer was used, with a digital portable laser tachometer for engine speed. Thermocouples were used to do temperature readings.

After conducting tests and the experiment they came out with the following findings on BSFC. Through the variation of EGR rates from 0% to 100% of engine load, the BSFC was found to decrease as the rate of EGR% rate was increased, obtaining a maximum value when the EGR rate was 20%. The decrease in the BSFC with the application of the EGR rate was due to an increase in the inlet intake charge temperature, thus increasing the rate of fuel consumption.

On the brake power (BP) they observed that the application of the EGR did not produce any significant effect on the total output power of the engine with the application rate of 30% EGR, while the BTE was observed to increase with the increase in the engine load for all operating conditions. However, it should be mentioned that the BTE showed some insignificant increase before the EGR rate passed the 20% mark, attributed to the returning of the hydrocarbons entering the combustion chamber for re-combustion together with EGR, and the increase of inlet intake charge temperature as a result of EGR rate application, which causes an increase in the rate of combustion. This is identical to the findings of Venkateswarlu, Murthy and Subbarao [18].

Regarding EGT, the authors concluded that it increases with engine load for all the operating conditions, which they attributed to the increase in input energy at high engine loads, as fuel consumption increases to accommodate high load and speed. Another observation they made during this study was that EGT temperature reduced with the increase of EGR% rate flow, which they attributed to the unavailability of O_2 when EGR is applied, leading to lowered combustion temperatures. This is identical to other studies conducted [19].

CO emissions variations in relation to the increase in EGR% rate was noted as increasing with the increase in the percentage of EGR, but was seen to significantly reduce as the EGR and engine load increased to 75% and 100%. This factor is explained by the lack of O_2 during combustion due to the dilution effect of EGR. On the other hand, HC emissions are noticed to increase in all the engine loads conditions as the EGR rate is increased, explained by the fact that the induced charge (intake air + EGR rate) has a higher CO_2 content when compared to fresh air only. However, the increased load across the entire engine load shows a decrease in HC emissions particularly when the dual fuel is employed for operation. This study finding was identical to those of Mahla, Das and Babu, [20].

Finally, on the CO emission and how they interacted with the EGR rate, the authors noted an increase of the CO emissions with an increase in the engine load. However, when a n EGR% rate of 10% to 30% was applied, there was a minimal decrease associated with the substitution of fresh charge with the elements of the exhaust gas which decreased the CO_2 emissions.

Hountalas, Mavropoulos and Binder [19] in the "Effect of Exhaust Gas Recirculation (EGR) Temperature for Various EGR Rates on Heavy Duty DI Diesel Engine Performance and Emissions." conducted their study using a heavy duty DI diesel, single cylinder engine, with high compression peak pressure. To improve the BSFC advanced timing was employed, while for NO_X emissions control the EGR was constantly cooled throughout the experiment. The test engine condition was maintained at full load with variations of engine speed employed, with the theoretical study on 3D multi zone model modified to suit the experimental set up under study to include the effects of EGR% and temperature and for calculation analysis. The boost pressure and injection pressure were kept constant at 280 BAR and 140°C for the EGR gas.

Figure 2 shows the comparison between the calculated and experimental cylinder pressure for EGR% rates at 1130 rpm, 100% load and -9 ATDC injection timing [19].

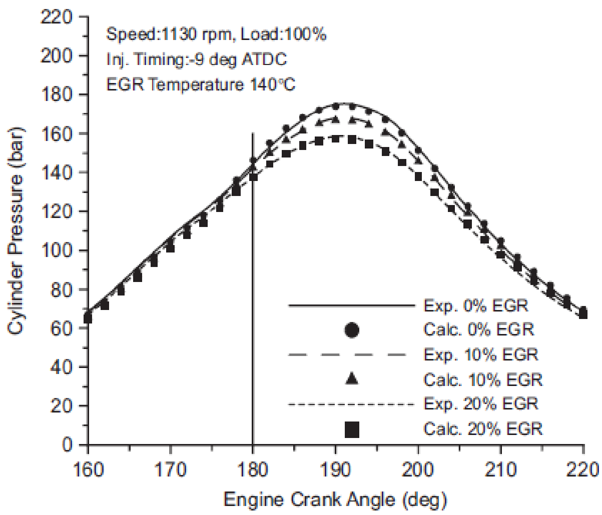

Figure 2: Showing the calculated and experimental cylinder pressure in relation to different EGR% rates.

Source: Hountalas, Mavropoulos and Binder [19]

As can be seen from Figure 2, simulated and theoretical measured values results show similarities and coincidences for the values of the EGR rate examined [19]. The study indicates a reduction in-cylinder pressure during combustion and expansion of the mixture in the combustion chamber. This increase in the SHC as occasioned by the presence of exhaust gas recirculation reduced the availability of O_2 thereby affecting the combustion process rate and the disassociation of

CO_2 and H_2O, further reducing the peak cylinder pressure values as EGR% rate mass flow increased. During part engine load different results were obtained, as the availability of O_2 was higher compared to when the engine was operated at full load. As the EGR inlet intake temperature increases with the EGR% rate mass flow this leads to delay in SOC leading to increased peak cylinder pressure as EGR % rate mass flow is increasing. These results are identical to those of [9], [19], [21].

The results indicated a negative effect of the EGR% rate mass flow on the BTE, especially at low engine speeds and full load, where an increase in EGR% rate mass flow showed a significant lineal decrease in BTE % of 5.5% @ 15% EGR. In relation to emissions of NO_X and soot emissions, the study found that the theoretical and measured values of NO_X and soot at full engine load and varying EGR% rates showed that as the rate of EGR mass flow increases it reduces the NO_X emissions linearly but increases the soot emissions significantly and exponentially [19], with the effects becoming more critical at low engine speeds.

The effects of EGR rate flow temperature on the engine performance and emission was investigated by Moiz [22]. The tests done for each case were 5% EGR, 10% EGR, and 15% EGR and the temperatures examined were from 90°C to 240°C calibrated in steps of 50°C. However, it is imperative to note here that this temperature range is a representative range value because the cooling media is the engine coolant. As the test results show it is evident that the increase in EGR% rate of mass flow at constant boost pressure led to a decrease in the intake air mass flow rate sucked or induced per cycle, leading to a drop in the AFR (volumetric efficiency). This type of result should be expected especially when the EGR gas temperatures are increased with the increase in EGR%, thus forming a lineal relationship between the AFR and EGR gas temperature. In all the examined test cases the authors observed that any increase on the EGR% rate mass flow temperature resulted in a decrease in AFR, but was more pronounced during low engine speeds i.e. at full loads thermal throttling becomes significant and increases with increase in EGR% rate mass flow gas temperature [19].

The effects of high EGR% gas temperature on the peak combustion pressure was noted by the authors as a reduction on the peak combustion pressure, which was noted to be significant at very high EGR% rates where one should note that the AFR was minimum. However, it should be emphasized that the use of the high EGR% rate gas temperature reduces O_2 availability thereby reducing the combustion rate or SOC. It is also important to remember or mention that the effect on ignition delay or retardation is negligible due to the high boost pressure and high charge temperature.

Yasin et al. [23] in their "Study of a Diesel Engine Performance with Exhaust Gas Recirculation (EGR) System Fuelled with Palm Biodiesel" intended to study the effects of EGR on the parameters of SFC, EGT, and the emissions of NO_X, CO, CO_2 and UHC both in experimental and simulated study situations. The study was conducted using a four-cylinder diesel engine with modified EGR application, naturally aspirated, air cooled, and with a maximum power of 64.9 kW @ 4500 rpm. The engine was coupled to an eddy current ECB dynamometer that was controlled by a Dynaelec load controller.

The result on the effect of EGR on the performance and combustion characteristics of the palm biodiesel and mineral diesel under normal modes, EGR application and at full load condition, was observed. The test fuel, which in this case was palm biodiesel, produced higher values of BSFC when the exhaust gas temperature was low compared to when the EGT gas temperature was high. This increase in BSFC was attributed to the power loss or drop in the efficiency of the engine and the lower heat release rate values that are associated with palm biodiesel, in addition to the unavailability of O_2 in the inlet intake air mass flow with the application of EGR [23], which mixes the inlet intake air with the EGR gases. The study further showed palm biodiesel increased the exhaust gas temperatures by 5.6% above the exhaust temperature values that were produced when mineral diesel was used [23]. This is attributed to the presence of greater O2 content in the palm biodiesel leading to a high combustion efficiency and high in-cylinder temperature, being identical to the findings of Badruddin et al. [24]. The experimental engine set up test rig is shown in Figure 3.

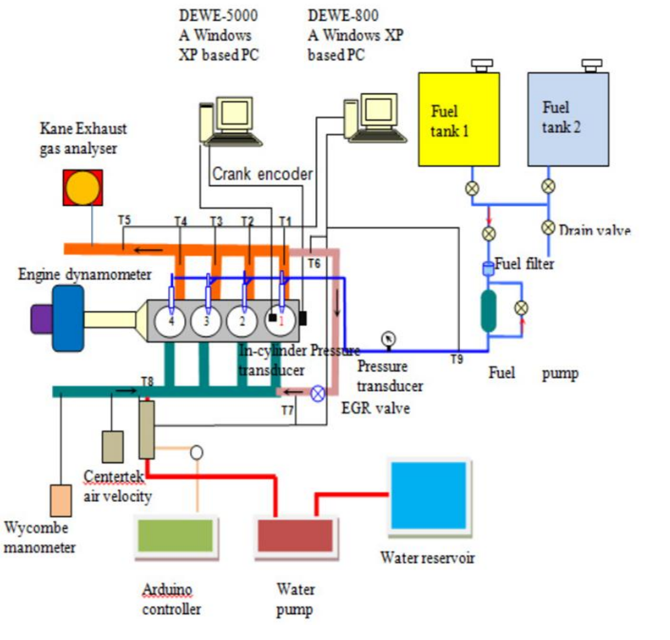

Figure 3: Showing the experimental set-up rig.

Source: Yasin et al. [23]

The application of EGR% mass flow rate mode on the palm biodiesel and mineral diesel fuels during the study lead to a noted decrease in the exhaust gas temperatures of 2.8% when palm biodiesel was used and a 1.6% decrease when mineral diesel was used [23]. This finding is similar to Saravanan [25] and therefore confirms that most biodiesel fuels produce lower

EGT temperature values at varied engine speeds and constant engine loads.This conclusion is attributed to the fact that the exhaust gases as mentioned earlier mix with the inlet intake fresh charge which dilutes the methyl ester rich oxygen content in the combustion, thereby improving combustion completion.

The palm biodiesel and mineral diesel emission characteristics compared to normal modes under EGR application and full engine load conditions at constant speed of 2500 rpm showed an increase in NO_X emissions, a factor that is linked to the increase in the in-cylinder temperature and the presence of more O_2 content within the natural chemical composition of the palm biodiesel fuel used during the study. The palm biodiesel thus seemed to contribute to an increase in the emissions of NO_X compared to the mineral diesel, because of the factor already mentioned regarding the oxygen content which causes high oxidation of the combustion mixture which leads to highly flammable rapid combustion thus increasing the exhaust gas temperatures.

Although the results obtained showed that palm biodiesel produced 4.7% higher NO_X emissions compared to the mineral diesel with EGR mass flow rate under normal engine conditions and loads, it should be noted that low NO_X emission of 5.4% was achieved when mineral diesel was used as compared to 22% when palm biodiesel was used. This is explained by the fact that an increase in total heat capacity (specific heat capacity) of the exhaust gases and reduction in in-cylinder peak temperature tends to reduce the NO_X emissions [23], these results being identical to the findings of Abdelaal and Hegab [16].

The carbon emissions for the test fuels used with application of EGR showed a decrease in carbon emissions for the palm biodiesel compared to mineral diesel. This is explained by the complete burning of the mixture as the palm biodiesel contains more O_2 content compared to mineral diesel, which provides the oxidation of CO to CO_2 which is an inert gas [23]. However, from the result obtained it is evident that there is an increase in CO emission of 9.7% when palm biodiesel was employed compared to a 2.45% increase using mineral diesel especially with the application of EGR, at full engine load i.e. both the fuels showed an affinity to produce CO emissions when EGR is applied under all engine operating conditions and load.

Rao [26] in the "Effect of EGR on Diesel Engine Performance and Exhaust Emission Running with Cotton Seed Biodiesel." used a single engine, four stroke, water cooled engine with cotton seed biodiesel (CSBD) and PBD (petroleum based diesel) blends as test fuels, where 0% PBD = CSBD10, 20%PBD = CSBD20 and 30%PBD = CSBD30. The EGR% rate of mass flow was limited to 0% to 20% in steps of 5%. The engine speed was kept constant at 1500 rpm. The set up was to examine the following parameters in relation to the effects of EGR: BSFC, BTE, EGT and the emission characteristics of NO_X, HC and CO. The engine was modified to allow experimental work to be done and for data to be obtained from the digital control panel. The gases were measured using an Indus gas analyzer. All tests were conducted under full engine load conditions and speed. The result from this study indicate that the BSFC is shown to be slightly independent at lower EGR rates, but increases as the EGR% rates increase to 15%. This can be explained from the fact that less oxygen means a rich mixture formation in the combustion chamber.

The results showed that BTE remains equally unaffected when low EGR rates and full engine loads were applied. However, BTE decreased with an increase in EGR above 15% in the combustion chamber, due to the displacement and replacement of the fresh air charge by the EGT gases. The EGT partly operated with cooled EGR% mass flow rate was observed to lower the exhaust gas temperatures compared to EGT at normal engine operating conditions without EGR. i.e. EGT decreased with an increase in EGR rate. This is informed by two factors, namely, unavailability of oxygen and the high specific heat ratio of the intake air mixture [26]. It is imperative to note here that a decrease in exhaust gas temperature is noticed irrespective of the continuous increase in EGR% rate even above the value of 15% EGR.

Regarding emission characteristics, the authors noticed a significant decrease in NO_X for all the test fuels used due to a reduction in O_2 and a decrease in flame temperature within the combustion chamber [26]. The hydrocarbon emissions showed an increase with the application of EGR% rate for all the test fuels used, especially when the EGR% was above 15%. This is explained by the incomplete combustion occasioned by the unavailability of O_2 resulting in poor oxidation of the combustion mixture causing incomplete combustion. The CO emissions were noted to increase with increase in EGR% rate for all the fuels used during the experimental study, mainly due to the aforementioned O_2 phenomenon.

Asad and Zheng [27] in their study of "Exhaust Gas Recirculation for Advanced Diesel Combustion Cycles" Used a four-cylinder Ford common rail diesel engine coupled to an eddy current dynamometer. The engine was operated in two modes. The first mode was a single cylinder mode (3 cyl to 1 cyl) where the 3 cylinders are operated in a conventional mode, with the #1 cylinder designated for research with independent controls of the parameters of intake pressure, exhaust back pressure and fuel injection. The second mode involved all the four cylinders with the engine running using a turbo charger, air fuel and EGR with no major system alterations. The exhaust gas analyzer was used to measure NO_X, THC, CO, CO_2 and O_2 concentration, while the intake CO_2 and O_2 were measured in the intake manifold using a different intake analyzer. The soot concentration was measured using an AVL smoke meter, while all the cylinder pressure data was processed with a 0.1° angle resolution using a pressure transducer mounted on cylinder #1 and connected to a data acquisition system.

After testing the models and how they interacted with the EGR% application, the following results and conclusions were reached. The impact of intake and in-cylinder charge composition was characterized with in-cylinder excess air ratio for the recycled O_2 with the EGR as a function of the EGR displacement [27]. The effects of EGR on intake pressure and engine load showed that the dilution of the intake charge with application of EGR could correctly be predicted through the intake oxygen concentration as compared to EGR fraction, as it was shown to lack additional information to show the effectiveness of the EGR ratio in relation to displacement [28]. It is imperative to note at this point about the EGR% ratio: there are two methods which Asad and Zheng, [27] propose in this study which are presently widely used to measure and quantify the value of EGR rate, the gas concentration based method and the mass based method. So far there has not been a standard method of defining EGR rate. The two equations for defining the EGR% rate flow as proposed by [27] are:

$$r_{EGR} \approx \frac{[CO_2]int - [CO_2]amb}{[CO_2]exh - [CO_2]amb} \approx \frac{[CO_2]int}{[CO_2]exh} \qquad \text{equation 1}$$

$$r_{EGR} = \frac{\dot{m}_{EGR}}{\dot{m}_{air} + \dot{m}_f + \dot{m}_{EGR}} \qquad \text{equation 2}$$

But since the fuel flow measurement is less than the mass air flow [27], equation 2 is modified to define the EGR ratio rate as shown in equation 3:

$$r_{EGR} = \frac{\dot{m}_{EGR}}{\dot{m}_{int}} = 1 - \frac{\dot{m}_{air}}{\dot{m}_{int}} \qquad \text{equation 3}$$

where $rEGR$ is the EGR fraction mass rate of the recirculated gases, $\dot{m}_{EGR}$ is the flow rate of the mass of EGR gas, $\dot{m}_{air}$ is the gas flow rate of intake air mass, $\dot{m}_f$ is the flow rate of the injected fuel mass, $[CO_2]amb$ is the carbon dioxide gas in the ambient air, $[CO_2]int$ is the carbon dioxide gas in the inlet intake air, $CO_2]exh$ is the carbon dioxide gas in the exhaust system.

During low engine loads and low EGR it was noticed that the effectiveness of EGR decreased as EGR gases displaced small amounts of fresh air in the intake system due to the fact that EGR gases contain O_2 and N_2 elements and vice versa i.e. increasing the intake reduced the intake charge dilution for the same EGR ratio [27], while increase in EGR (intake dilution) produced a leaner air fuel ratio with increased premixed combustion, which caused reduced soot emission, which is identical to the findings of Aoyagi, Osada, Misawa, Goto, & Ishii [29] and improved on combustion efficiency [28]. It should be emphasized here that O_2 in the EGR is both a function of the engine load and EGR ratio.

In mentioning and discussing the combustion models, it should suffice to say that the development of alternative fuels becomes of paramount importance. There are several methods that have been proposed for processing the alternative fuels otherwise called biodiesels, the commonly used ones being transesterification, hydrogenation, pyrolysis (used in plastics) and dilution. The use of alternative fuel for emission control has been increasing, particularly with the use of the EGR control technique to control and reduce NO_X, HC, CO and soot emissions. A number of authors have carried out research in this area and this review will present some of these studies and their current position in so far as this area is concerned.

Mani, Nagarajan and Sampath [30] in "An Experimental Investigation on a DI Diesel Engine Using Waste Plastic Oil with Exhaust Gas Recirculation" showed that plastic oil produced the most NO_X emissions but showed reduced NO_X emissions with increasing EGR of 20% onwards. There was no noticeable change in the smoke, CO and HC levels of emissions, thus reaching a conclusion that with the application of EGR% rate levels plastic oil can be used as an alternative to biodiesel fuel.

Xu, Gui and Deng [31] in "Fuel injection and EGR control strategy on smooth switching of CI/HCCI mode in a diesel engine" conducted an experiment by variation of the cam phase and tapped EGR gases as a heating or vaporizing mechanism of the fuel and to harmonize the mixture charge, while using the fuel injection to administer HCCI in an electronically controlled fuel injector. They used HCCI combustion modelling to study the effects of a premixed ratio in relation to performance and emission characteristics, when different EGR % rates are applied. They observed a 78% drop in NO_X and lowered smoke and soot emissions of 40%, when premixed ratio of 80% and 30% EGR respectively were applied. Increased PR lead to increase in IMEP and BSFC, but fared poorly on the HC and CO emissions.

Haber and Wang [32] in "A Robust Control Approach on Diesel Engines with Dual-Loop Exhaust Gas Recirculation Systems," discuss a number of control strategies to be employed in mitigating the effects of EGR and emission. One of the methods suggested is EGR. The authors point out that the application of EGR alters or affects the normal combustion process in several ways. Firstly, it alters the physical properties of the charge mixture; secondly it alters the air fuel ratio (A/F); and thirdly it alters the start of ignition and finally alters the heat release pattern [32]. Other effects they noted as responsible for NO_X reduction were the dilution effect, the chemical effect, and the thermal effect. They also noted that the application of EGR resulted in modification of both the composition and physical conditions of the inlet charge (by modification of composition they mean addition of CO_2 and H_2O, and by modification of physical conditions they mean temperature density) [32]. By replacing the intake air charge using EGR they observed that it decreases the air fuel ratio leading to a shortened delay in ignition. Other effects they noted in their study is that reduced oxygen availability due to the admission of EGR also explains the phenomenon of delayed ignition, which they observed to be due to increased mixing time between the amount of injected fuel and fresh oxygen [32]. In conclusion they argue that as a control strategy EGR cannot be used alone because of the increased soot emissions, fuel penalties, degradation of the combustion quality, increased piston cylinder wearing, deteriorating efficiency, operational instability, and higher EGR temperature accounting for low fuel efficiency [32].

Lehto, Elonheimo, Hakkinen, Sarjovaara and Larmi [33] in their study "Emission Reduction using Hydro Treated Vegetable Oil (HVO) with Miller Timing and EGR in Diesel Combustion." noted a marked reduction in the emissions of NO_X and smoke compared to conventional diesel. EN590, a HVO fuel blend, can allow the use of higher EGR% rates without compromising the PM, HC and smoke emissions but with exponential reduction in the NO_X emissions.

Chen, Liu, Wu and Lee [34] in "Effects of Port Fuel Injection (PFI) Of N-Butanol and EGR On Combustion and Emissions of a Direct Injection Diesel Engine," studied the effects of PFI on n-butanol and application of EGR and how they influence emission and combustion characteristics in a diesel engine. In their study the engine was equipped with independent inlet and outlet systems. The researchers varied the EGR% rate which they divided into three sections 0%, 15% and 45%, and the premixed fuel of the n-butanol was divided into four premixed ratios of 0%, 20%, 38% and 47% by volume.

They observed and noted that as the rate of EGR% increased to 45% there was a significant decrease of 97% of the NO_X emissions though there was an exponential increase in the soot emissions and the SOFs. However, when they combined the use of the PFI and the n-butanol of 47% while maintaining the EGR% rate at 45%, the emissions of NO_x and those of soot were drastically reduced by 88% and 17% respectively, thereby addressing the traditional basic fundamental problem of the NO_X – soot trade-off.

Zhao, Wang, Li, Lei and Liu [35] in their study on "Combustion and Emission Characteristics of a DME (Dimethyl Ether)-Diesel Dual Fuel Premixed Charge Compression Ignition Engine with EGR (Exhaust Gas Recirculation)" studied the effects of external EGR and di-methyl ether (DME) on the premixed ratio on the performance and emission characteristics of a two cylinder naturally aspirated diesel engine. They varied EGR% from 0% to 27% while they kept the premixed ratio at between 0% and 30%.

Their results indicated that an increase in EGR% mass flow reduced NO_X emissions, but increased CO_2 and HC emissions considerably. However, a very good result was obtained with higher PR% and higher EGR% rate especially in NO_X and smoke emissions.

Singh and Agarwal [8] in "Combustion Characteristics of Diesel HCCI Engine: An Experimental Investigation Using External Mixture Formation Technique," used a twin piston DI diesel engine to conduct a study by the modification of one cylinder to use HCCI premixed fuel and the other one using conventional diesel. During the study they varied their mixture concentration from $\lambda = 4.96$ (as the lean mixture level) or the misfiring limit and $\lambda = 2.56$ (considered as the rich mixture level) or the knock limit. The EGR applied was at the rate 20%. The results observed indicated an increased combustion efficiency, when the value of $\lambda \leq 3.70$ which is medium range engine loads, but when the engine load was increased to high levels it was observed that the values of λ was recorded was $\lambda \leq 3.0$ thereby producing knock and a very rough combustion experience.

CONCLUSION

It can be safely concluded that the use of the EGR as a technique for controlling emissions of NO_X, CO, CO_2, HC and SOF in conjunction with other techniques discussed in this review when implemented will adequately address the underlying issues of the effects of EGR on diesel engine performance parameters and reduction in emissions as was seen during the studies that were reviewed here.

However, more needs to be done to bridge the gap and disconnect between research and industry. For example, EGR cooling is not widely used in stationery engine systems and in marine applications and in industrial production where carbon emissions are more pronounced, but is relegated and left to industry handlers and policy makers to decide, something they might not be able to do.

EGR cooling will allow us to retain the benefits of low NO_X emissions but without compromising engine efficiency. EGR cooling is necessary as it reduces soot and soluble organic fraction (SOF) emissions, for example when used with other techniques like VGT technology, which proposes to recirculate all exhaust gases together with the intake mixture thus increasing the mixture heat capacity but leading to lowered combustion temperature and consequently lower NO_X emissions; due to O_2 concentration levels being maintained, oxidation of the soot emissions becomes insignificant.

During the review it was observed and noted, based on the studies that have been done, that the preheating of the inlet air reduced CO emissions by the introduction of EGR into the system, though it is observed that CO emissions increased linearly as the rate of EGR% was being increased; which raises the question of how the two systems can be harmonized to achieve low carbon emissions without compromising engine performance and emission control systems. From the combustion control strategies discussed, the question arises regarding what implementation strategies can be employed to improve combustion characteristics of the various fuels available, particularly the biodiesel fuels that have been developed, especially their chemical and physical properties, which sometimes lack proper testing and analysis facilities. Biodiesel is still a grey area in terms of industrial commercial development and industry regulators who impose stringent control on its use

ACKNOWLEDGEMENTS

First and foremost, to the good Lord for His enabling mercies, to my supervisor Prof. F. N. Inambao for his tireless effort to mold me, to my brother D.K. Marwa for his support and visionary leadership and lastly to the UKZN fraternity for the suitable environment, especially my fellow post-graduate students, which enabled me to complete this work.

REFERENCES

[1] Manieniyan V, and Sivaprakasam, S., 2013, "Experimental Analysis of Exhaust gas Recirculation on Diesel Engines Operating with Biodiesel," International Journal of Engineering and Technology (IJET), 3(2), pp. 129-134.

[2] Hussain, J., Palaniradja, K., Alagumurthi, N., and Manimaran, R., 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(4), pp. 241-247.

[3] Agarwal, D., Singh, S. K., and Agarwal, A. K., 2011, "Effect of Exhaust Gas Recirculation (EGR) on Performance, Emissions, Deposits and Durability of a Constant Speed Compression Ignition Engine," Applied Energy, 88(8), pp. 2900-2907.

[4] Abaas, K. I., 2016, "Effect of Exhaust Gas Recirculation (EGR) on the Performance Characteristics of a Direct Injection Multi Cylinders Diesel Engine," Tikrit Journal of Engineering Science (TJES), 23(1), pp. 32-39.

[5] Charola, H. B., Makwana, P. B., and Makwana, R. D., 2016, "Effect of EGR (Exhaust Gas Recirculation) on Performance and Emission Of CI (Compression Ignition) Engine Fuelled with Blend," International Journal on Advances in Engineering Technology and Science, 3(2), pp. 1-5.

[6] Rao K. S., Mutyalu, K. B., and Ramakrishna, A., 2015, Effects of Exhaust Gas Recirculation on the Performance and Emission Characteristics of a Diesel Engine Fueled with Waste Cooking Oil Methyl Ester," ARPN Journal oF Engineering and Applied Sciences, 10(11), pp. 4799-4804.

[7] Kumar, P. S., Antony, F., and Sahoo, P., 2013, "The Performance and NOx Emissions of a IDI Diesel Engine at Distinct EGR Rates Fuelled with JB100, JB80, JB60, JB40, JB20 & Diesel," International Journal of Engineering Science and Technology, 5(3), p. 519.

[8] Singh, A. P., & Agarwal, A. K., 2012, "Combustion Characteristics of Diesel HCCI Engine: An Experimental Investigation Using External Mixture Formation Technique," Applied Energy, 99, pp. 116-125.

[9] Hawi, M., Kiplimo, R., and Ndiritu, H., 2015. "Effect of Exhaust Gas Recirculation on Performance and Emission Characteristics of a Diesel-Piloted Biogas Engine," Smart Grid and Renewable Energy, 6(04), p. 49.

[10] Abu-Jrai, A., Rodríguez-Fernández, J., Tsolakis, A., Megaritis, A., Theinnoi, K., Cracknell, R., and Clark, R., 2009, "Performance, Combustion and Emissions of a Diesel Engine Operated with Reformed EGR. Comparison of Diesel and GTL Fuelling," Fuel, 88(6), pp. 1031-1041.

[11] Shahadat, M., Nabi, M., Akhter, M., and Tushar, M., 2008, "Combined Effect of EGR and Inlet Air Preheating on Engine Performance in Diesel Engine," International Energy Journal, 9(2).

[12] Holman, J., 2002, Heat Transfer, 9th edition, McGraw-Hill, New York.

[13] Jacobs, T., Assanis, D. N., and Filipi, Z. 2003, "The Impact of Exhaust Gas Recirculation on Performance and Emissions of a Heavy-Duty Diesel Engine," SAE Technical Paper 2003-01-1068, https://doi.org/10.4271/2003-01-1068.

[14] Ishiki, K., Oshida, S., Takiguchi, M., and Urabe, M. 2000, "A Study of Abnormal Wear in Power Cylinder of Diesel Engine with EGR-Wear Mechanism of Soot Contaminated in Lubricating Oil," SAE Technical Paper 2000-01-0925, https://doi.org/10.4271/2000-01-0925.

[15] Fathi, M., Saray, R. K., and Checkel, M. D., 2011, "The Influence of Exhaust Gas Recirculation (EGR) on Combustion and Emissions of n-Heptane/Natural Gas Fueled Homogeneous Charge Compression Ignition (HCCI) engines," Applied Energy, 88(12), pp. 4719-4724.

[16] Abdelaal, M., and Hegab, A., 2012, "Combustion and Emission Characteristics of a Natural Gas-Fueled Diesel Engine with EGR," Energy Conversion and Management, 64, pp. 301-312.

[17] Au, M. Y., Girard, J. W., Dibble, R., Flowers, D., Aceves, S. M., Martinez-Frias, J., . . . Maas, U., 2001, "1.9-liter four-cylinder HCCI engine operation with exhaust gas recirculation," SAE Technical Paper 2001-01-1894, https://doi.org/10.4271/2001-01-1894.

[18] Venkateswarlu, K., Murthy, B. S. R., and Subbarao, V. V., 2013, "The Effect of Exhaust Gas Recirculation and Di-Tertiary Butyl Peroxide on Diesel-Biodiesel Blends for Performance and Emission Studies," International Journal of Advanced Science and Technology, 54, pp. 49-60.

[19] Hountalas, D., Mavropoulos, G., and Binder, K., 2008, "Effect of Exhaust Gas Recirculation (EGR) Temperature for Various EGR Rates on Heavy Duty DI Diesel Engine Performance and Emissions," Energy, 33(2), pp. 272-283.

[20] Mahla, S. K., L. M. Das, and Babu, M. K. G., 2010, "Effect of EGR on performance and emission characteristics of natural gas fueled diesel engine," Jordan Journal of Mechanical and Industrial Engineering 4.4 (2010). Paper presented at the Jordan Journal of Mechanical and Industrial Engineering.

[21] Ladommatos, N., Abdelhalim, S. M., Zhao, H., and Hu, Z., 1998, "The effects on diesel combustion and emissions of reducing inlet charge mass due to thermal throttling with hot EGR," SAE Technical Paper 980185, https://doi.org/10.4271/980185.

[22] Moiz, A. A., 2016, "Low Temperature Split Injection Spray Combustion: Ignition, Flame Stabilization and Soot Formation Characteristics in Diesel Engine Conditions," PhD thesis, Michigan Technological University, Houghton, Michigan.

[23] Yasin, M. H. M., Mamat, R., Yusop, A. F., Idris, D. M. N. D., Yusaf, T., Rasul, M., and Najafi, G., 2017, "Study of a diesel engine performance with exhaust gas recirculation (EGR) system fuelled with palm biodiesel," Energy Procedia, 110, pp. 26-31.

[24] Badruddin, I. A., Badarudin, A., Banapurmath, N., Ahmed, N. S., Quadir, G., Al-Rashed, A. A., . . . Kamangar, S., 2015, "Effects of Engine Variables And Heat Transfer on the Performance of Biodiesel Fueled IC Engines," Renewable and Sustainable Energy Reviews, 44, pp. 682-691.

[25] Saravanan, S., 2015, "Effect of Exhaust Gas Recirculation (EGR) on Performance and Emissions of a Constant Speed DI Diesel Engine Fueled with Pentanol/Diesel Blends," Fuel, 160, pp. 217-226.

[26] Rao, K. S., 2016, "Effect of EGR on Diesel Engine Performance and Exhaust Emission Running with Cotton Seed Biodiesel," International Journal of Mechanical and Mechatronic Engineering, 16(02), pp. 64-69.

[27] Asad, U., and Zheng, M., 2014, "Exhaust Gas Recirculation for Advanced Diesel Combustion Cycles," Applied Energy, 123, pp. 242-252.

[28] Asad, U., Divekar, P., Zheng, M., and Tjong, J., 2013, "Low Temperature Combustion Strategies for Compression Ignition Engines: Operability Limits and Challenges," SAE Technical Paper 2013-01-0283, https://doi.org/10.4271/2013-01-0283.

[29] Aoyagi, Y., Osada, H., Misawa, M., Goto, Y., and Ishii, H., 2006, "Advanced diesel combustion using of wide range, high boosted and cooled EGR system by single cylinder engine," SAE Technical Paper 2006-01-0077, https://doi.org/10.4271/*2006*-01-0077.

[30] Mani, M., Nagarajan, G., and Sampath, S, 2010, "An Experimental Investigation on a DI Diesel Engine Using Waste Plastic Oil with Exhaust Gas Recirculation," Fuel, 89(8), pp. 1826-1832.

[31] Xu, M., Gui, Y., and Deng, K.-Y., 2015, Fuel Injection And EGR Control Strategy on Smooth Switching Of CI/HCCI Mode in a Diesel Engine," Journal of the Energy Institute, 88(2), pp. 157-168.

[32] Haber, B., and Wang, J., 2010, "A Robust Control Approach on Diesel Engines with Dual-Loop Exhaust Gas Recirculation Systems," MSc dissertation,Ohio State University, Columbus, Ohio.

[33] Lehto, K., Elonheimo, A., Hakkinen, K., Sarjovaara, T., and Larmi, M., 2011, "Emission Reduction Using Hydrotreated Vegetable Oil (HVO) with Miller Timing and EGR in Diesel Combustion," SAE International Journal of Fuels and Lubricants, 5(2011-01-1955), pp. 218-224.

[34] Chen, Z., Liu, J., Wu, Z., and Lee, C., 2013, Energy Conversion and Management, 7, pp. 725-731.

[35] Zhao, Y., Wang, Y., Li, D., Lei, X., and Liu, S., 2014, "Combustion and Emission Characteristics of a DME (Dimethyl Ether)-Diesel Dual Fuel 5remixed Charge Compression Ignition Engine with EGR (Exhaust Gas Recirculation)," Energy, 72, pp. 608-617.