Study of Combustion Characteristics of an SI Engine Fuelled with Ethanol and Oxygenated Fuel Additives

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Abstract: This study investigates the effects of ethanol-blended gasoline with oxygenated additives on a multi – cylinder Spark Ignition (SI) Engine. The experiments were conducted in two stages. In stage I, the test fuels were prepared using 99.9% pure ethanol and gasoline with a cycloheptanol blend, in the ratio of E69.5 + 0.5 cycloheptanol, E64.6 + 0.4 cycloheptanol, E59.7 + 0.3 cycloheptanol, E49.8 + 0.2 cycloheptanol. The remainder was gasoline. In stage II, the test fuels were prepared using 99.9% pure ethanol and gasoline with cyclooctanol blend, in the ratio of E69.5 + 0.5 cyclooctanol, E64.6 + 0.4 cyclooctanol l, E59.7 + 0.3 cyclooctanol, E49.8 + 0.2 cyclooctanol. The remainder was gasoline. Performance and emission tests were conducted on a multi – cylinder SI Engine coupled with an eddy current dynamometer. The emission tests were measured using an exhaust gas analyzer. The experimental results proved that the blend increased brake thermal efficiency more than a sole fuel, such as gasoline. The emission tests found that the CO slightly decreased, while HC and O_2 increased moderately and CO_2 and NO_x appreciably decreased. In addition, combustion analyses were made with the help of combustion analyzer, in which cylinder pressure and heat release rate were analysed.

Keywords: CO – Carbon monoxide, HC – Unburnt Hydrocarbon, CO_2 – Carbon dioxide, O_2 – Oxygen, NO_x – Oxides of Nitrogen, Ethanol, Cyclooctanol, Cycloheptanol.

1. Intorduction

Ethanol (C_2H_5OH) is a renewable fuel. It can be produced from agricultural feedstocks, such as sugarcane and also from forestry wood wastes and agricultural residues. It can also be derived chemically from ethylene or ethane. Ethanol has a simple molecular structure with well-defined physical and chemical properties. Ethanol can be employed as a transportation fuel even in its original form and can also be easily blended with other fuels, such as gasoline and diesel.

Currently, there is a lot of interest in ethanol production from renewable feedstocks, to minimize the emissions of carbon dioxide, which is a greenhouse gas that contributes to global warming. The addition of ethanol to gasoline results in the enhancement of the octane number in blended fuels and changes the distillation temperature, as well as reducing CO_2 emissions [11].

Today, the reserves of petroleum based fuels are being rapidly depleted. It is well known that the future availability of energy resources, as well as the need for reducing CO_2 emissions from the fuels used has increased the need for the utilization of regenerative fuels [8].

Alcohols, such as ethanol, are colorless liquids with mild characteristic odors that can be produced by fermentation of biomass crops, such as sugarcane, wheat and wood. Using alcohols as fuel for Spark Ignition (SI) engine have some advantages over gasoline. Ethanol has better anti-knock characteristics and the engine's thermal efficiency improves with the increase in compression ratio [9].

Alcohol burns with lower flame temperature and luminosity owing to the decrease of the peak temperature inside the cylinder so that the heat loss and NO_x emissions are lowered. Ethanol has high latent heat of vaporization. The latent heat cools the intake air and hence increases the density and volumetric efficiency. However, the oxygen content in ethanol reduces the heating value more than gasoline does. It is evident that ethanol can be used as a fuel in SI engines [10].

Hsieh et al. [1] experimentally investigated the engine performance and the emission of an SI engine using an ethanol–gasoline blend fuel in the ratios of 5%, 10%, 20% and 30%. The results showed that when the ethanol rate increased, the heating value of the blended fuel was found to have decreased but at the same time, it increased the engine torque. Ethanol has high affinity for water as it contains a certain amount of water in it. This is not a problem for pure ethanol because it fully mixes with water, but some serious problems may arise when gasoline-ethanol blends are used. Phase separation can occur in these blends since gasoline and ethanol are immiscible. This problem can be prevented by using semi-polar co-solvents (solubility improvers) such as isopropanol [4].

Guerrieri et al. [2] tested gasoline and gasoline–ethanol blends on six in-use vehicle to determine the effect of ethanol content on emissions and fuel economy. HC and CO emissions as well as fuel consumption decreased in most vehicles when the ethanol content was increased in the fuel. At the highest ethanol concentration of 40%, HC emissions, CO emissions and fuel consumption decreased by about 30%, 50% and 15%, respectively.

Wu et al. [3] investigated the effects of air–fuel ratios on SI engine performance and pollutant emissions using ethanol–gasoline blends. The result of engine performance tests showed that torque output was improved on using gasoline-ethanol blends. However, there is no appreciable change on the brake-specific fuel consumption. CO and HC emissions reduced with the increase in ethanol content in the blended fuel. This study found that by using 10% ethanol fuel, pollutant emissions can be efficiently reduced.

He et al. [5] investigated the effect of ethanol–gasoline blends on emissions and catalyst conversion efficiencies. The blended fuels reduced CO, HC and NO_x emissions.

Fikret et al. [12] investigated a new dual fuel system that could be serviceable by making simple modifications to the carburetor without causing any complications in the carburetor system. The carburetor was redesigned to use a gasoline–alcohol mixture as fuel. The ethanol–gasoline blend, with 60% of ethanol and 40% of gasoline, was exploited to test the engine's performance, fuel consumption and exhaust emissions.

Bang-Quan He et al. [13] had studied the effect of ethanol blended gasoline fuels on emissions and catalyst conversion efficiencies investigated in SI engines with an EFI system. The Tailpipe emissions of THC, CO and NO_x have close relations to engine-out emissions, catalyst conversion efficiency, the engine's speed and load, and air/fuel equivalence ratio. Moreover, the blended fuels can also decrease the brake-specific fuel consumption. General conclusions arrived from the above literature review reveals that ethanol can be produced abundantly and economically. It will prove to be an attractive alternative fuel for SI engines. It can be used either as a pure fuel or as a gasoline additive. Gasoline–ethanol blends including ethanol at low proportions can be used without any modifications to the engine, but high percentages of ethanol require e major modifications to the engine design and fuel system. Fuel modification techniques are employed in the form of fuel additives blended with gasoline or ethanol–gasoline blends to enhance the fuel's properties. Fuel additives are combustion improvers, and so, many of these additives can be added to fuel in order to improve combustion efficiency and performance. Palmer [7] reported that all oxygenated blends gave a better anti-knock performance during low speed acceleration than hydrocarbon fuels of the same octane range. Consequently, the use of gasoline-ethanol blends with fuel additives in the SI engines is more practical than using ethanol alone. Based on this previous work, the present experimental studies have been focused on fuel modification techniques using gasoline-ethanol blends with fuel additives on SI engines to analyze the performance and exhaust emissions.

This study aims to run a SI engine with different percentages of blending of gasoline and ethanol with the oxygenated additives so as to reduce the exhaust emissions, and also to increase the brake thermal efficiency of the engine. The percentages of blending are given in Table 1.

Table 1(a). Stage I Sample volumetric composition**.**

Sample Name	Gasoline	Ethanol	Oxygenated Additive [Cycloheptanol]
Sample 1	50.00	49.80	0.20
Sample 2	40.00	59.70	0.30
Sample 3	35.00	64.60	0.40
Sample 4	30.00	69.50	0.50
Sole Fuel	100.00	-----	-----

Table 1(b). Stage II Sample volumetric composition.

Sample Name	Gasoline	Ethanol	Oxygenated Additive [Cyclooctanol]
Sample 1	50.00	49.80	0.20
Sample 2	40.00	59.70	0.30
Sample 3	35.00	64.60	0.40
Sample 4	30.00	69.50	0.50
Sole Fuel	100.00	-----	-----

2. Experimental

2.1 Experimental setup

A vertically inclined, water cooled, three cylinders, four stroke, 86.5 mm bore, 72 mm stroke, 796 cc displacement, 8.7:1 compression ratio, 12.56 kW power with rated speed of 3000 rpm and ignition timing of 10^0 bTDC engine with carburetor was used for the experimental work. The engine was coupled to an eddy current dynamometer for load measurement. The amount of hydrocarbon, carbon monoxide, carbon dioxide, NO_x, O_2 was measured by using exhaust gas analyzer. The exhaust gas analyzer was periodically calibrated through carrier gas.

Combustion parameters were analyzed using a combustion analyzer. The cylinder pressure and heat release rate were analyzed. The experiments were performed at variable speeds of 2000, 2200, 2400, 2600 and 2800 rpm with a constant output of 7.53 KW. The volumetric percentages of ethanol–gasoline blends with oxygenated additives are in the ratio of E69.5 + 0.5, E64.6 + 0.4, E59.7 + 0.3, E49.8 + 0.2. These represent the ratios of ethanol + oxygenated additives and rest gasoline in the total blend for stage I and stage II. Ethanol with a purity of 99.9% was used in the blends. The schematic views of the test equipments are shown in Fig.1.

The engine was allowed to run with gasoline (Sole Fuel) at speeds of 2000, 2200, 2400, 2600 and 2800 rpm with a constant output of 7.53 KW. After completing the experiment with gasoline, the experiment was conducted with 4 samples. After completing the experiments with the first sample blend, the engine was allowed to run for about half an hour with gasoline to eliminate the interference of the previous sample blend. All sample blends were tested with the same procedure. The samples were also tested without additives to identify the effect of the additives. Exhaust emissions, such as HC, were found to be higher when additives were not used. Samples with additives reduced all exhaust emissions when compared to sole fuel (gasoline).

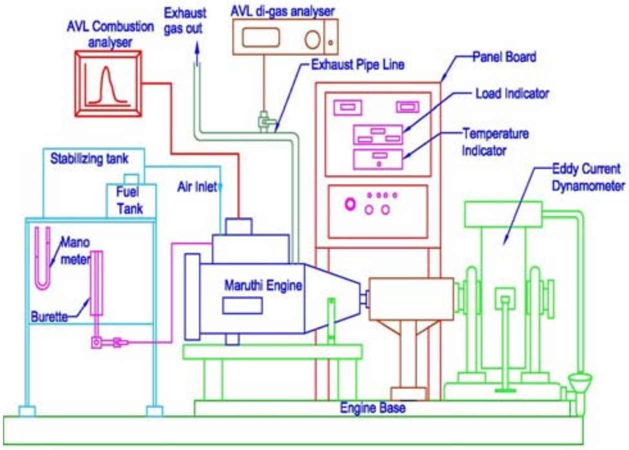

Figure1. Experimental setup.

3. Results and discussion

The effects of ethanol addition to gasoline with oxygenated additives on SI engine performance and exhaust emissions at variable engine speeds were investigated.

3.1 Brake Thermal Efficiency

The effect of the gasoline-ethanol with oxygenated additives blends, on the brake thermal efficiency is shown in Fig. 2 The brake thermal efficiency was higher for all the samples than these from using the sole fuel. In stage I, the brake thermal efficiency was 31.89% for sample 1 at 2600 rpm which was higher than for the sole fuel. In stage II, the brake thermal efficiency was 32.15% for sample 2 at 2600 rpm which was higher when compared to the sole fuel. A margi nal increase of brake thermal efficiency was observed for all four samples at all speeds as shown in Fig. 2. This was also due to the increase in the octane number of the samples. Hence, it is evident that the blended fuel has relatively higher calorific value. This is due to the addition of fuel additives that enhance the calorific value of the fuel.

3.2 CO Emission

The effect of the gasoline-ethanol with oxygenated additives blends on CO emissions is shown in Fig. 3. It can be seen that ethanol with oxygenated additive concentration increases and reduces the CO emission. In stage I, it was found that in samples 2, 3, and 4 at 2000 rpm, the concentration of CO emissions decreased by about 0.08% by volume. Samples 3 and 4 show the same trends, whereas in sample 4, it is slightly less than the other samples at a maximum speed of 2800 rpm. In stage II, it was observed that in sample 4 at 2200 rpm, the concentration of CO emission decreased by about 0.08% by volume. However, at 2400 rpm the reduction rate of CO emission is found slightly less at above speeds. The combined effect in two stages, the variation of CO emission for sample 4 is less when compared to other samples and sole fuel. This is due to the increase in the percentage of ethanol and additive concentrations that has resulted in leaner combustion and also due to the presence of oxygen in ethanol. Due to leaning, CO emissions decrease tremendously. In general, for all concentration blends, CO emissions are found to be reduced when concentration is increased. The pressure of the OH group in alcohol makes alcohol combustion an interesting variation of the analogous paraffin hydrocarbons. The mass air-fuel ratios for alcohol are relatively lower (stoichiometric value being about 6.44:1 for methanol; about 8.95:1 for ethanol and about 14.6:1 for gasoline), and therefore, the addition of alcohol to gasoline provides an effective leaning to the mixture. A similar leaning effect can be expected for other oxygenates additives.

3.3 CO_2 Emissions

The effect of the gasoline-ethanol with oxygenated additives blends on CO_2 is shown in Fig. 4. As the speed increases, the CO_2 emissions gradually decrease. It indicates the complete combustion of the fuel in the combustion chamber. In stage I, it was found that in sample 4, the CO_2 value was 8% by volume at 2800 rpm. This was minimal when compared to the sole fuel. In stage II, it was observed that in sample 4, the CO_2 value was 8.1% by volume at 2800 rpm. This was minimum when compared to the sole fuel. It is obvious that there is significant reduction in CO_2 emission when using ethanol blend samples. There was an appreciable reduction in sample 4 when compared to other samples. This is due to the maximum blend of oxygenated additive in the ethanol–gasoline blends.

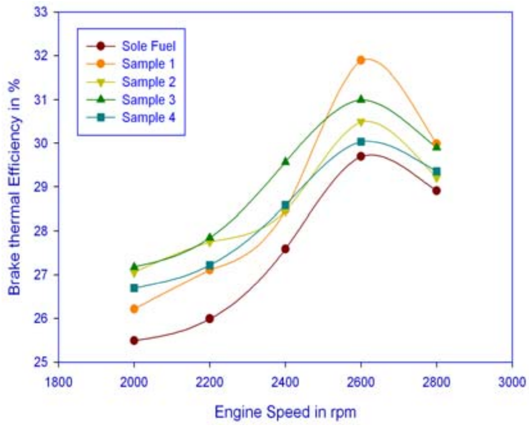

Figure 2(a) Stage I Brake Thermal Efficiency vs Engine Speed.

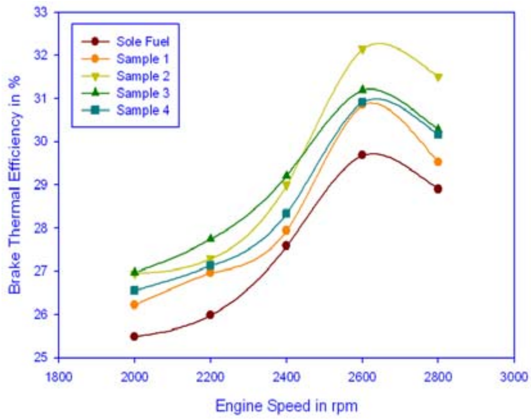

Figure 2(b) Stage II Brake Thermal Efficiency vs Engine Speed.

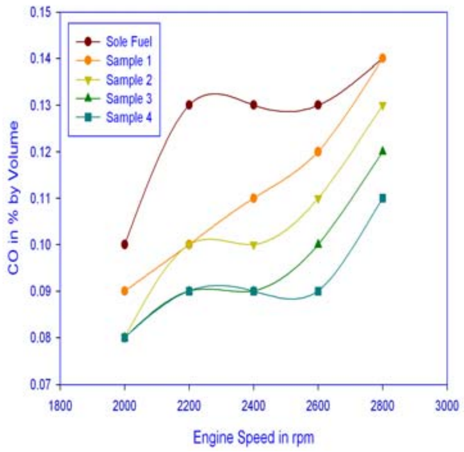

Figure 3(a) Stage I CO vs Engine Speed

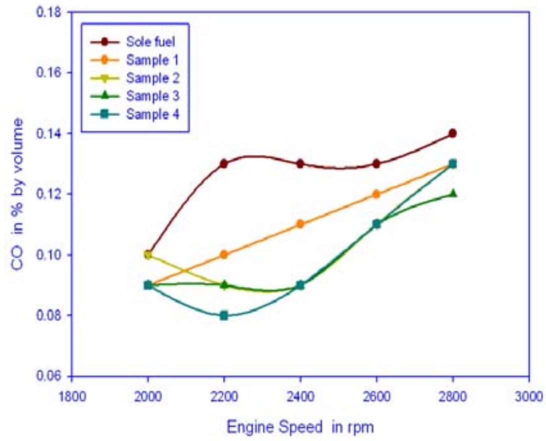

Figure 3(b) Stage II CO vs Engine Speed

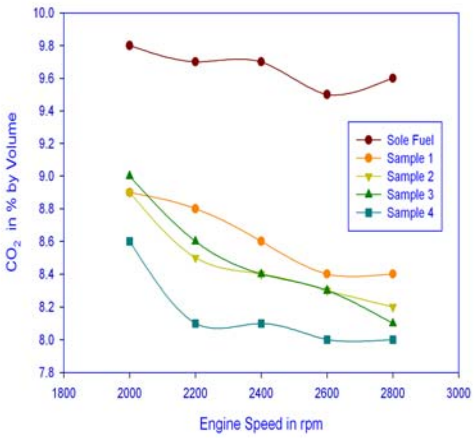

Figure 4(a) Stage I CO2 vs Engine Speed

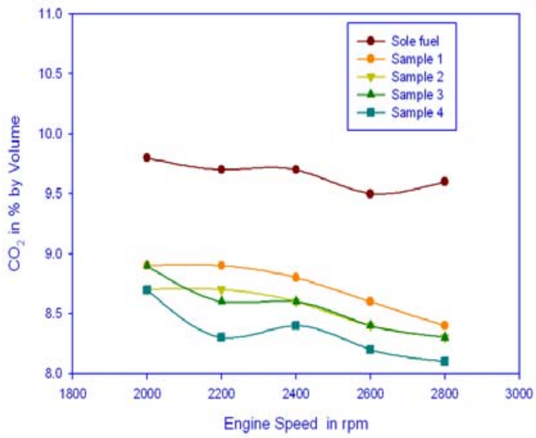

Figure 4(b) Stage II CO2 vs Engine Speed

3.4 HC Emissions

Fig. 5 shows the effect of the alcohol percentage in the blend oxygenated additives on the HC emissions. In all the four samples, HC emissions were found to have increased at all speeds. At this point, it has to be noted that ethanol has a lower flame speed as compared to sole fuel operation. As a result, less mass fraction of the fuel is burnt in the case of ethanol-blended gasoline. Hence, higher amounts of unburnt fuel are left in each cycle. On account of the cooling effect and increasing quench volume of ethanol in the combustion chamber, the HC emissions were enhanced. In addition to the cooling effect that increases engine volumetric efficiency, it may also have been the effect of using ethanol as arising fuel.

3.5 NO_X Emissions

The effect of the gasoline-ethanol with oxygenated additives blends on NO_x emissions is shown in Fig. 6. It can be seen that the blend decreases NO_x emissions. For sample 4, it was found that the NO_x emission level was significantly reduced for all speeds. The percentage of reduction in NO_x emission level ranges from 1000 to 800 ppm for sample 4. The other samples also followed the same trend but slightly more than sample 4. This indicates that they had a lower heating value for ethanol than for gasoline resulting in decrease in the combustion heat energy and reducing the combustion temperature in the cylinder. The major factors contributing to NO_x emissions include high flame temperature and presence of excessive oxygen during combustion. Due to the much lower flame temperatures for ethanol combustion, its NO_x emissions are usually lower than those of gasoline. It is apparent that in any HC oxidation process that takes place during the combustion of alcohol fuels provides leaning of mixtures that reduces the NO_x emissions. It is evident that the heat release rate decreases for blended fuels.

3.6 O_2 Emissions

The effect of the gasoline-ethanol with oxygenated additives blends on O_2 is shown in Fig. 7. All four samples were found to increase the O_2 emissions at all speeds. In sample 4, the maximum oxygen content in the exhaust gas was 9.26% by volume and 9.32% by volume at 2800 rpm respectively for stage I and II. The increase in the oxygen content of the exhaust gas was due to the increase in the ethanol and the oxygenated additive percentages.

3.7 Air Fuel Ratio

The effect of the gasoline–ethanol with oxygenated additives blends, on the air-fuel ratio with CO for optimum sample 4 for the two stages is shown in Fig. 8. When the lambda value increased the level of CO value is also increased. The reason for this is that a rich air fuel mixture is required to maintain the higher speed of 2800 rpm.

4. COMBUSTION ANALYSIS

SI engines do not maintain a perfectly stable operation under steady state conditions and the cyclic variations have inconsistencies of the combustion process and appear to cause higher engine emissions. Hami et al. [6] studied the incomplete mixing of fuel, Air and residuals contributed to cycle variations during combustion. After reviewing the literature on SI engine and its influence on cyclic variations, it was found that a good spark ignition system reduces cycle variations. In this study combustion analyses are made with a maximum load of 40 N at 3000 rpm. If the cylinder pressure increases, the heat release rate is also increased. For alcohol fuels, if the cylinder pressure decreases, the heat release rate is also decreased.

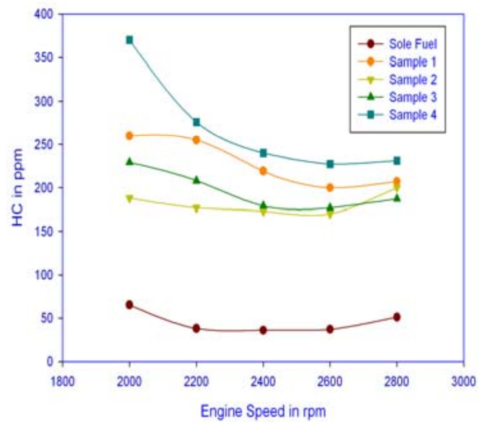

Figure 5(a) Stage I HC vs Engine Speed

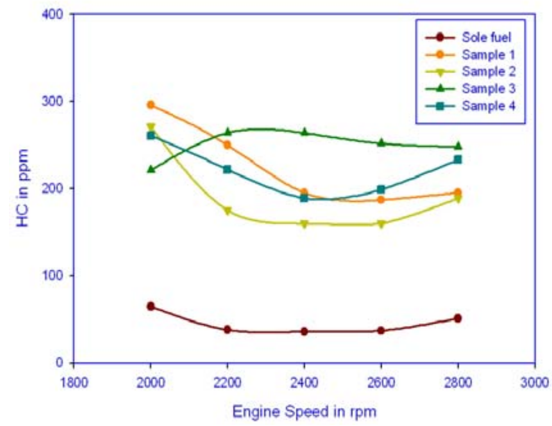

Figure 5(b) Stage II HC vs Engine Speed

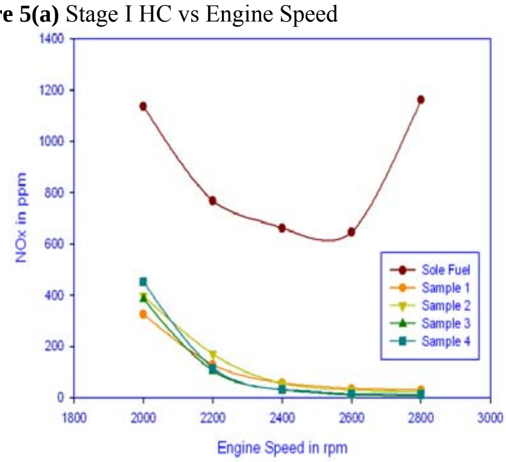

Figure 6(a) Stage I NOx vs Engine Speed

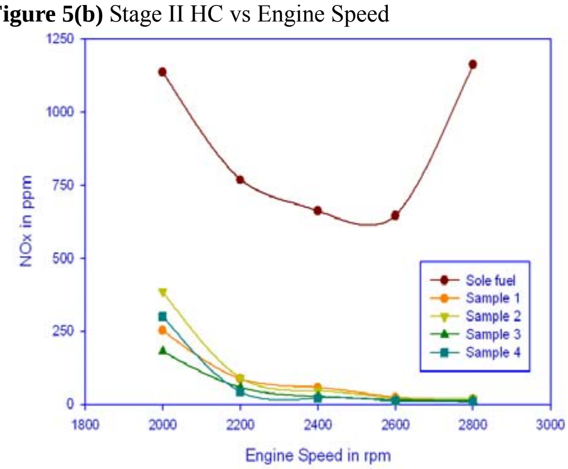

Figure 6(b) Stage II NOx vs Engine Speed

4.1 Pressure and Crank Angle

Fig. 9 presents the variation of cylinder pressure for gasoline and its blend with respect to the crank angle. In stage I, it can be seen that the cylinder pressure was higher for sample 1 than with the sole fuel. The maximum cylinder pressure for sample 1 was 40.5 bar pressure followed by the sole fuel. In stage II, it can be seen that the cylinder pressure was higher for sample 1 than with the sole fuel. The maximum cylinder pressure for the sample 1 is 42.5 bar pressure followed by the sole fuel. If the engine is fuelled with gasoline and blends, the peak pressure was obtained at 10^0 after TDC as shown in Fig. 8. This value is nearly equal to 26% of pressure obtained when the engine was operated with gasoline. The effect of the blending of the additives had a higher heating value than ethanol, and consequently, produces a higher peak pressure. This trend can be seen in the P – θ diagram.

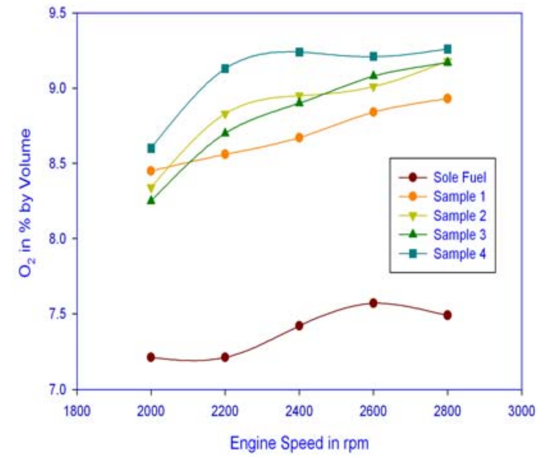

Figure 7(a) Stage I O2 vs Engine Speed

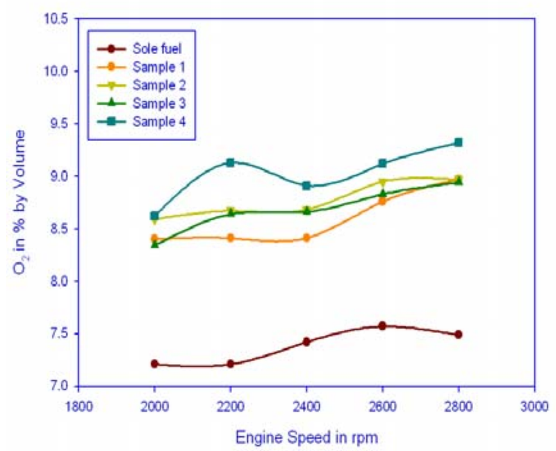

Figure 7(b) Stage II O2 vs Engine Speed

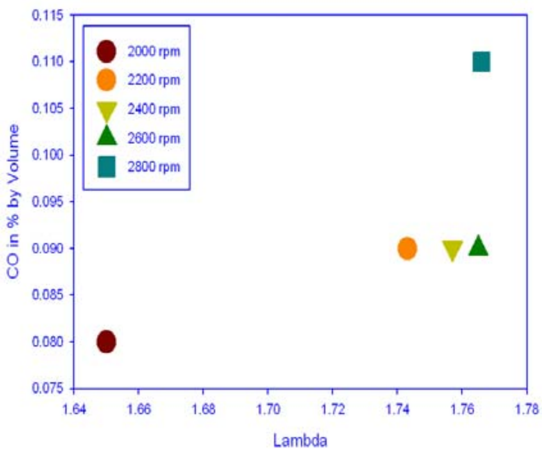

Figure 8(a) Stage I CO vs Lambda

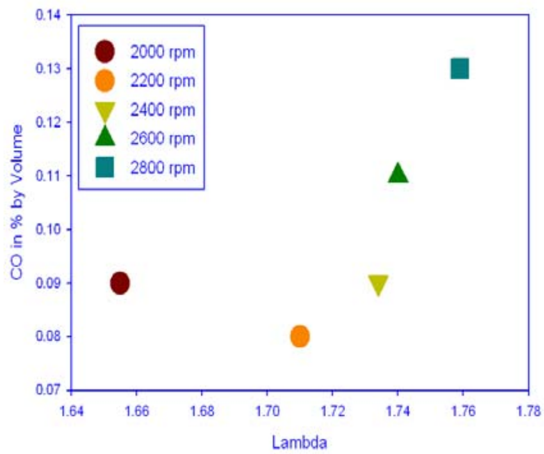

Figure 8(b) Stage II CO vs Lambda

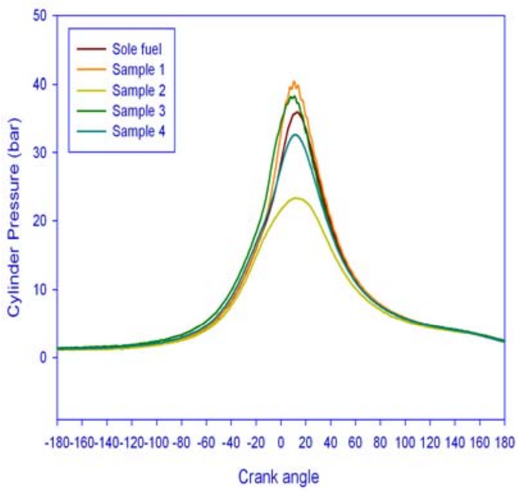

Figure 9(a) Stage I Cylinder Pressure vs Crank angle

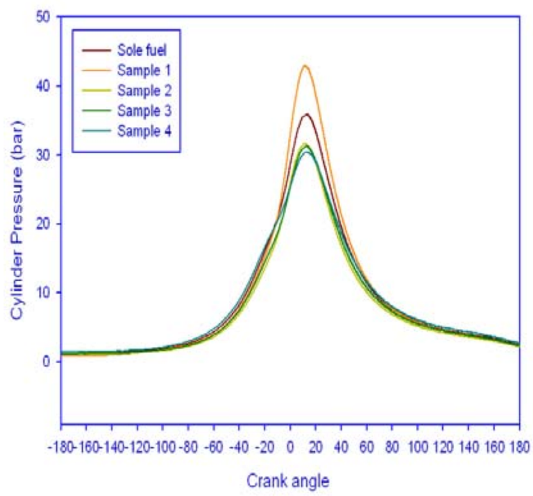

Figure 9(b) Stage II Cylinder Pressure vs Crank angle

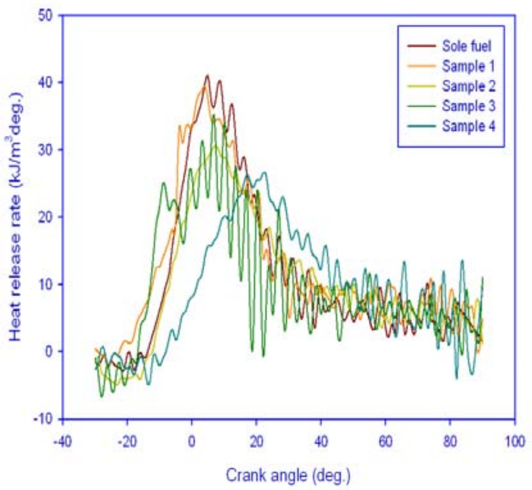

Figure10(a) Stage I Heat Release Rate vs Crank angle

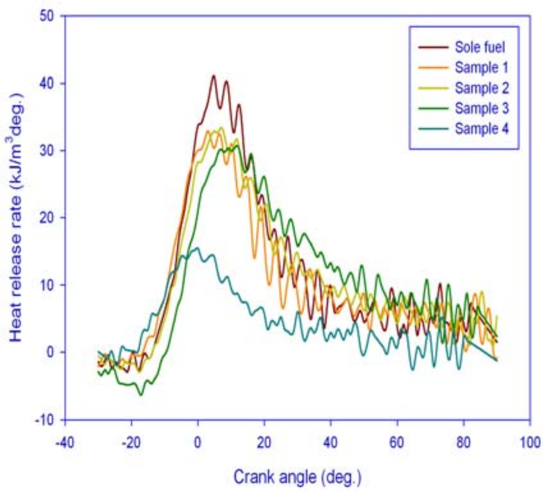

Figure10(b) Stage II Heat Release Rate vs Crank angle

4.2 Heat Release Rate

Fig. 10 shows the heat release rate varying with the crank angle. For the sole fuel, the rate of heat release was faster and reached a peak at 15^0 after TDC which was 10^0 earlier than that of the ethanol-blended gasoline fuel, Subsequently, the heat release rate came down sharply on account of the amount of unburnt fuel available due to the quenching effect. This is one of the main reasons for the reduction in the heat release rate in ethanol–gasoline blended fuels. In the two stages, the four samples had more or less the same variation in the heat release rate. This may be due to lower heating values and higher percentages of blends of ethanol in the gasoline.

5. Conclusion

From the study, the following conclusions can be deduced:-

1. Ethanol blends and oxygenated additives in gasoline cause improvements in engine performance and reduce exhaust emissions.

2. Ethanol-blended gasoline with oxygenated additives leads to a significant reduction in exhaust emissions. As all engine speeds, the values of CO, CO_2 and NOx were reduced. On the other hand, HC and O_2 emissions were significantly increased.

3. The addition of 69.5% of ethanol-blended gasoline with oxygenated additives was achieved in the experiments without any problems during engine operation. However, without additives the performance was better by to 40 % beyond what was absorbed resulting in abnormal combustion, vibration and starting problems.

For stage I

4. The sample 1 ethanol blend gave the best result in engine performance with a brake thermal efficiency of 31.89%

5. Sample 4 with the combined effect of the ethanol blend and oxygenated additives gave the best results in the exhaust emissions.

i. The CO emission was reduced to 0.08% by volume at 2000 rpm.

ii. The CO_2 emission was reduced to 8% by volume at 2800 rpm.

iii. The O_2 was increased to 9.26% by volume at 2800 rpm.

iv. The lambda was 1.766 at 2800 rpm.

6. For the NO_x emissions, sample 3 gave the best results with 7 ppm at 2800 rpm.

7. In the combustion analysis, the maximum cylinder pressure occurred for sample 1 with a cylinder pressure value of 40.5 bar with crank angle.

For stage II

8. The sample 2 ethanol blend gave the best results in engine performance with a brake thermal efficiency of 32.15%.

9. Sample 4 with the combined effect of the ethanol blend and oxygenated additives gave the best results in the exhaust emissions.

i. The CO emission was reduced to 0.08% by volume at 2200 rpm.

ii. The CO_2 emission was reduced to 8.1% by volume at 2800 rpm.

iii. The O_2 was increased to 9.32% by volume at 2800 rpm

iv. The NO_x emission was reduced to 9 ppm at 2800 rpm.

v. The lambda was 1.759 at 2800 rpm.

10. In the combustion analysis, the maximum cylinder pressure occurred for sample 2 with a cylinder pressure value of 42 bar with crank angle.

6. References

[1] Hsieh WD, Chen RH, Wu TL, Lin TH, Engine performance and pollutant emission of an SI engine using ethanol–gasoline blended fuels, *Journal of Atmospheric Environment* 36/3 (2002) 403–410.

[2] Guerrieri DA, Caffrey PJ, Rao V, Investigation into the vehicle exhaust emissions of high percentage ethanol blends, *Journal of SAE Paper No: 950777* (1995) 85–95.

[3] Wu CW, Chen RH, Pu JY, Lin TH, The influence of air–fuel ratio on engine performance and pollutant emission of an SI engine using ethanol–gasoline blended fuels, *Journal of Atmospheric Environment* 38/40 (2004) 7093–7100.

[4] Al-Hasan M, Effect of ethanol–unleaded gasoline blends on engine performance and exhaust emission, *Journal of Energy Conversion and Management* 44 (2003) 1547–1561.

[5] He BQ, Wang JX, Hao JM, Yan XG, Xiao JH, A study on emission characteristics of an EFI engine with ethanol blended gasoline fuels, *Journal of Atmospheric Environment* 37/7 (2003) 949–957.

[6] Hami K, Kawajiri H, Ishizuka T, Nakai M, Combustion Fluctuation Mechanism Involving cycle – to – cycle Spark Ignition Variation due to Gas Flow Motion in SI Engines, *Twenty First Symposium (International) on combustion* (1986).

[7] Palmer FH, Vehicle performance of gasoline containing oxygenates, paper C319/86. In: International Conference on Petroleum Based Fuels and Automotive Applications. London: I. Mech. E Conf. Publication 1986-11, MEP; 1986, pp. 36–46.

[8] Gao J, Jiang D, Huang Z, Spray properties of alternative fuels: A comparative analysis of ethanol–gasoline blends and gasoline, *Journal of Fuel* 86 (2007) 1645–1650.

[9] Keith O, Trevor C, *Automotive fuels reference book*, 2nd Edition, New York: SAE. (1995).

[10] Yu¨cesu HS, Sozen A, Topgu T, Arcakliog E, Comparative study of mathematical and experimental analysis of spark ignition engine performance used ethanol–gasoline blend fuel, *Journal of Applied Thermal Engineering* 27 (2007) 358–368.

[11] Parag S, Raghavan V, Experimental investigation of burning rates of pure ethanol and ethanol blended fuels, *Combustion and Flame* 156/5 (2009) 997–1005.

[12] Yuksel F, Yuksel B, The use of ethanol–gasoline blend as a fuel in an SI engine, *Renewable Energy* 29 (2004) 1181–1191.

[13] He BQ, Wang JX, Hao JM, Yan XG, Xiao JH, A study on emission characteristic of an EFI engine with ethanol blended gasoline fuels, *Atmospheric Environment* 37 (2003) 949–957.