An Experimental Investigation and Comparative analysis on a Four Stroke CI Engine with two Straight Bio-Diesel Blends: Hazelnut and Palm

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Abstract— *An experimental analysis was made to investigate two non edible oils (hazelnut and palm), blending with neat diesel fuel with the proportions of 5%, 10%, 15%, 20% and 25% by volume and used as fuel in a single cylinder, four stroke, water cooled, Compression Ignition engine. Experimental tests were conducted by using the above bio-diesel blends as fuel operated with the above mentioned engine working at various loads. Performance parameters and exhaust emissions of hazelnut and crambe bio-diesel blends are compared with the same results of diesel fuel. Performance parameters selected to analyze are Brake Thermal Efficiency(BTHE), Brake Specific Fuel Consumption(BSFC) and Exhaust Gas Temperature(EGT) and exhaust emissions selected to investigate are Carbon Monoxide emissions(CO), Oxides Of Nitrogen(NOx) and smoke density(SD). From the results of all blends used as fuel in the engine, it is clarified that CI engine showing better performance by using a hazelnut bio-diesel blend with proportions of 20% hazelnut bio-diesel and 80% normal diesel fuel. Traditional Engine with bio-diesels as fuel are showing acceptable reduction in emissions like hydro carbons and oxides of carbon but with marginal increase in oxides of nitrogen compared with diesel fuel. But BTHE of Bio-diesel blend is less than the BTHE of diesel fuel operating in the same engine. From all the blends Hazelnut bio-diesel blends are giving better performance parameters and decreased emission characteristics hazelnut oil having better properties immediately after diesel fuel when compared with remaining bio-diesel blends.*

Keywords*— *Biodiesel, Emissions, Non-edible oils, Performance.

I. INTRODUCTION

Along with techniques related to the engine to meet emission regulations imposed [1–4], researchers of engine are also focusing their interest on the domain of fuel-related techniques, such as for example oxygenated fuels which are able to decrease particulate emissions [5–10]and alternative gaseous fuels that are renewable in nature.

To develop the sources of alternate fuel, many countries of the world are stepping forward by paying considerable attention. Alternative fuels which are produced from the products of agriculture are reducing the oil imports in the world. They are also supporting agricultural industries, which increases the farming incomes despite of all these advantages they are also reducing the exhaust emissions. The bio fuels which are considered as most promising fuels are the fuels derived from vegetable oils, bio alcohols, and vegetable oils. Among all the industries in the world bio fuel production is one of the rapidly growing industries. In spark ignition engines bio-ethanol is the primary alternative to gasoline. Vegetable oil and their derived bio fuel as well as diesel fuel mixing with small proportions of ethanol are alternative fuel for compression ignition engines. Whereas other alternative fuels like bio-mass derived hydro-carbon fuel, bio-butanol and hydrogen are being research at present which are considered as alternative fuel for next generation.

Apart from renewability, bio-fuels are more advantageous than normal diesel in some aspects like they are having very less sulphur content and aromatic contents, higher lubricity, higher flash point, non-toxicity and higher bio-degradability. On the other side the disadvantages of bio-fuels includes very high pour point, very high viscosity, the lower cetane number, lower volatility and lower calorific value. One of the great disadvantages of bio-fuel is its highly increased viscosity, which is approximately

10-20 times greater than normal diesel fuel. More over short term tests by using bio-fuels are giving promising results but when engine has been operated for longer periods then problems are appearing, which includes more carbon deposits, injector coking with trumpet formation, piston oil ring sticking, as well as the thickness of engine lubricating oil also increases. The following methods are adopted to avoid the problems associated with their high viscosity. Micro emulsification with methanol or ethanol blending in small blend ratios with diesel fuel, cracking, preheating and conversion in to bio-fuel mainly through the transisterification process. [22–25].

The advantages of bio-diesels as diesel fuel, apart from renewability, are the minimal sulfur and aromatic content, the higher flash point, the higher lubricity, the higher cetane number, and the higher biodegradability and non-toxicity. On the other hand, their disadvantages include the higher viscosity (though much lower than the vegetable oils one), the higher pour point, the lower calorific value and the lower volatility. Furthermore, their oxidation stability is lower, they are hygroscopic, and as solvents they may cause corrosion of components, attacking some plastic materials used for seals, hoses, paints and coatings. They show increased dilution and polymerization of engine sump oil, thus requiring more frequent oil changes.

Because of all the above reasons, maximum up to 25% of bio-fuels and vegetables are generally accepted as blends with diesel fuel and can be used in existing diesel engines without modifications. Experimental studies on the CI engines with the use of bio-fuels blending with neat diesel have been reported.

The present experimental work studies and compares the above bio-fuels of various origins, in blending with ordinary diesel fuel, by fuelling a single cylinder, direct injection, naturally aspirated CI engines. A companion paper extended the present investigation for hazelnut oil and its methyl esters for different blend ratios, followed by another paper dealing with their heat release and stastical analysis using insulated combustion chamber of the same engine.

As mentioned above, the results of performance and emissions have been evaluated by this research work by using blends of neat diesel fuel with two bio-fuels (hazelnut and palm) [28], in the single-cylinder, water-cooled, direct injection, 'kirlosker' diesel engine concerning the present work. The interpretation of the experimental measurements was based on the differences of properties between the fuels tested.

Most of the experimental works reported on the use of bio-fuels in the compression ignition engines are referred to mainly single-cylinder naturally aspirated engines have been used only one or two bio-fuel oils. But the present research work steps forward in reporting on the use of two bio-fuel oils on a single-cylinder, four stroke and water-cooled diesel engine.

Widely differing chemical and physical properties of bio-fuels against those of diesel fuels, are combining with the theoretical aspects of diesel engine combustion, and are used to aid the correct interpretation of the observed engine emissions and performance wise behavior.

II. DESCRIPTION OF THE ENGINE TEST FACILITY

Facilities to monitor and control engine variables were installed on a test-bed, Kirloskar single cylinder, four stroke, vertical, water cooled, compression ignition engine (Fig. 1) was used and mounted on the ground. The test engine was directly coupled to an eddy current dynamometer with suitable switching and control facility for loading the engine. Engine specifications were as follows: bore & stroke, 87.5 mm x 110 mm; compression ratio, 17.5: 1; speed, 1500 rpm; fuel timing, 27° by spill (btdc); clearance volume, 37.8 cc; and rated power, 5 hp.

For fuel consumption measurement a tank and flow metering system is used for various blend samples as follows. A piezometer of known volume was used with the measurement of time for the complete evacuation of the sample fuel which is feeding to the engine. In order to have a quick drain of a fuel sample, including the return fuel from injector and pump and refilling of fuel metering system with new fuel sample a system is provided with valves and pipes.

A system which is used for the measurement of exhaust gases consists of group of analyzers for measuring carbon monoxide (CO), oxides of nitrogen (NO_x), hydrocarbons (HC), smoke density (SD), particulate and soot. The concentration of CO (in ppm) present in the exhaust gases was measured by using 'Signal' Series-7200 non-dispersive infrared analyzer (NDIR) equipped with a 'Signal' Series-2505M Cooler. 'Bosch' RTT-100 opacimeter, is used to measure the smoke level in the exhaust gas the readings of which are provided as equivalent smoke density in (mg of soot/ m^3 of exhaust gases). The concentration of nitrogen oxides in ppm (parts per million, by vol.) present in the exhaust gases was measured by using 'Signal' Series-4000 chemiluminescent analyzer (CLA) that was fitted with a thermostatically controlled heated line. The total unburned hydrocarbons concentration (in ppm) present in the exhaust gases was measured with a 'Ratfisch-Instruments' Series RS55 flame-ionization detector (FID) that was also fitted with a thermostatically controlled heated line.

Fig.1: Experimental Setup

Table.1: Engine Specifications And Injection System Basic Data.

Engine model and type :	Kirlosker single-cylinder, four, stroke, compression ignition, direct injection, water-cooled.
Speed	1500 rpm
Engine total displacement	661 cm3
Bore/stroke	87.5 mm/110 mm
Compression ratio	17.5:1
Maximum power	5.2 HP @ 1500 rpm
Maximum torque	29.0376 Nm @1500rpm
opening pressure	250 bar

III. PROPERTIES OF FUELS TESTED

Two typical types of straight Bio-diesel oils, viz. safflower, crambe, corn, hazelnut, and palm oil are tested as supplements of the normal diesel fuel, at blend ratios of 05/95% ,10/90%, 15/85% and 20/80% 25/75% (by vol.) with the conventional diesel fuel.

Diesel fuels which contains very less amount of sulphur content approximately (0.035 wt %) forms the base line for present study. To reduce the viscosity of bio-fuels they are to be de-gummed and refined, nearly the edible type without any pre-heating and adding any additives. All important properties of two bio-fuels and diesel are provided in table-2. All the values mentioned in the table are the mean values taken from various sites and references mentioned with this paper. In this study it required to note that the cetane number and kinematic viscosity values mentioned are not used computationally. In order to explain qualitatively the relative performance and emissions behavior of different fuel blends they are only referred to for indicative purposes.

Table.2: Fuel Properties.

Fuel	Density at 15^0c. Kg/mm^3	Kinematic viscosity at 40^0c. cST	Calorific value. MJ/kg	Flash point
Diesel	837	1.3	42.70	369
Hazelnut	875	3.59	42.12	425
Palm	867	3.94	41.24	434

Table.3: Accuracy of Measurements and Uncertainty Of Computed Results.

Measurements	Accuracy
NOx	±5 ppm
HC	±0.5 ppm
CO	±0.2%
Smoke opacity	±0.1%
Speed	±5rpm
Specific fuel consumption	±1.5
Time	±5%
Torque	±0.5 Nm
Fuel volumetric rat	±1
Power	±1

IV. EXPERIMENTAL SECTION, TRANSESTERIFICATION PROCESS

To reduce viscosity of vegetable oils, transesterification method is adopted for preparation of biodiesel[11]. In this process, non-edible oil (1000 ml) was taken in a three way flask. In a beaker, sodium hydroxide (NaOH, 12 g) and methanol (CH_3OH, 200 ml) were thoroughly mixed until it is properly dissolved. The solution obtained was mixed with non-edible oil in three way flask and stirred properly. Methoxide solution with non-edible oil was heated to 60°C and continuously stirred at constant rate for 1 h. The solution is poured down in a separate beaker and is allowed to settle for 4 h. Glycerin settles at the bottom and methyl ester floats at the top (coarse biodiesel). Methyl ester is separated, heated above 100°C and maintained for 10-15 min to remove untreated methanol. Certain impurities like NaOH etc. are still dissolved in the obtained coarse biodiesel. These impurities are cleaned up by washing with 350 ml of water for 1000 ml of coarse biodiesel. Cleaned biodiesel is methyl ester of non-edible oil[12].

V. PARAMETERS TESTED AND EXPERIMENTAL PROCEDURE

Engine testing was done in a laboratory at a constant temperature. Engine was started and warmed-up at low idle, long enough to establish the recommended oil pressure, and was checked for any fuel, oil leaks. After completing warm-up procedure, engine was run on no-load condition and speed was adjusted to 1800 rpm by adjusting fuel injection pump. Engine was run to gain uniform speed, after which it was gradually loaded. Experiments were conducted at different levels of load. For each load condition, engine was run at a minimum of 10 min and data were collected during the last 4-min of operation. Simultaneously, engine exhaust emissions were also determined.

The series of tests are conducted using each of the above mentioned blends, with the engine working at speed of 1500 and at different torque mentioned above. Because of the differences in oxygen content and calorific values of different fuels tested, the analysis is effected at the same engine brake power and not the air fuel ratio or same injected fuel mass.

In each test exhaust smokiness, volumetric fuel consumption rate, and exhaust gas emissions such as carbon monoxide, nitrogen oxides, and total unburned hydrocarbons are measured. From the first measurement brake thermal efficiency (BTHE.) and brake specific fuel consumption (b.s.f.c.) are computed using the fuel sample density and lower calorific value. Table 3 shows the uncertainty of the computed results of various parameters and the accuracy of the measurements.

The analysis of experimental work was started with a preliminary investigation of the compression ignition engine fueled with neat diesel fuel, to find out the exhaust emission levels and engine operating characteristics which constitute a base line can be used to compare with the corresponding cases when using each of the blends forming with the combination of neat diesel and bio-fuel with appropriate proportions. By keeping the same operating conditions the same procedure was repeated for each fuel blend. For every time when the fuel is changed, the lines through which fuel flows were cleaned and then the engine is allowed to run for about 30 minutes to reach and stabilize its new desired conditions.

VI. RESULTS AND DISCUSSION

Investigation on the engine was made with different bio-diesel blends as fuels and time for 10 cc fuel consumption was calculated. Among two biodiesels, along with its blends Hazelnut biodiesel is showing lesser viscosity than other oils at various temperatures (Fig. 2), may be due lower density of hazelnut biodiesel than others.

A. Brake Thermal Efficiency (BTHE)

Fig. 2 shows, the brake thermal efficiency (BTHE.) for the conventional diesel fuel, and 20% blends of the hazelnut and palm bio-diesel blends with diesel fuel, at various loads. BTHE of diesel is maximum compared with all biodiesels blends at all loads (Fig. 3). Among biodiesels, hazelnut showed better BTHE than other oils. BTHE trend at 20% blend of biodiesel is as H20 > P20. For other blends, trend is similar to that for 20% bio - blend. As load increases, BTHE too increases, may be due availability of oxygen which helps in complete combustion of the fuel.

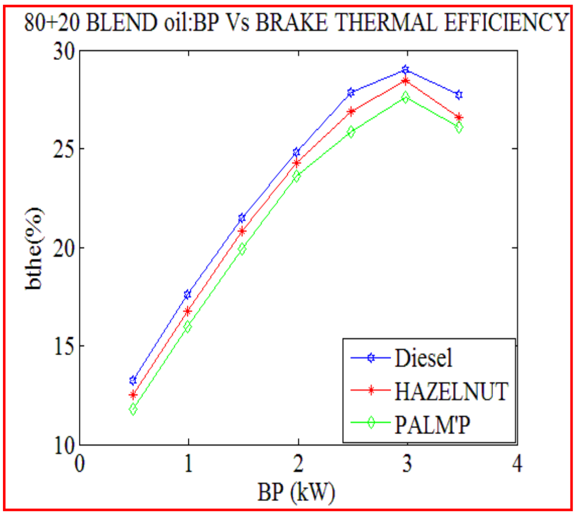

Fig.2: Brake Thermal Efficiency

B. Hydrocarbon (Hc) Emissions

HC emission of diesel is maximum compared with biodiesel blends at various loads tested (Fig. 3). Among biodiesels, Hazelnut showed minimum HC emissions than other oils. HC emissions trend at 20% blend of biodiesel is as H20 > P20, may be because all biodiesels contain oxygen, which favors better combustion when compared with diesel. Hence, HC emissions are very less for biodiesel. For other blends, trend is similar to that for 20% blend, as load increases, HC emissions increases.

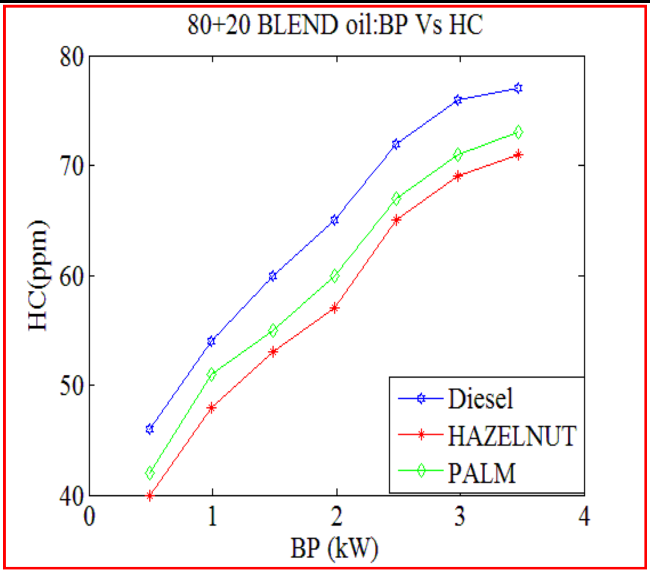

Fig.3: Hydrocarbon Emissions

C. NOX Emissions

Fig. 4 shows, the emissions nitrogen oxides (NOx) in ppm for the neat diesel fuel, and 20% blends of the two bio-fuel oils with diesel fuel, at different loads. It is observed that the NOx emission by all bio-diesel blends are higher than corresponding diesel fuel. The lower cetane number of bio-diesels blends (higher ignition delay) may play a role in this increase, apart from the delicate distribution of the fuel–air 'packets' inside the sprays as influenced by the fuel bound oxygen.

Out of all biodiesels blends Hazelnut bio-diesel blend is showing minimum NOx emissions than other oils. NO_x emissions trend at 20% blend of biodiesel is as H20 > P20, may be due to the low cetane number of biodiesel , which lead to ignition lag and causes to accumulate large amount of un burned mixture of air and bio-fuel. This accumulated charge after reaching the self ignition condition will burn at a time causes better combustion than diesel. As a result, the adiabatic flame temperature or maximum temperature inside cylinder is more in case of biodiesels than diesel. Hence, this catalyzes reactions for oxidation of nitrogen and hence NOX emissions are more for biodiesels. For other blends, trend is similar to that for 20% blend. As load increases, NOX emission increases. However, emissions are less when compared with 20% blend.

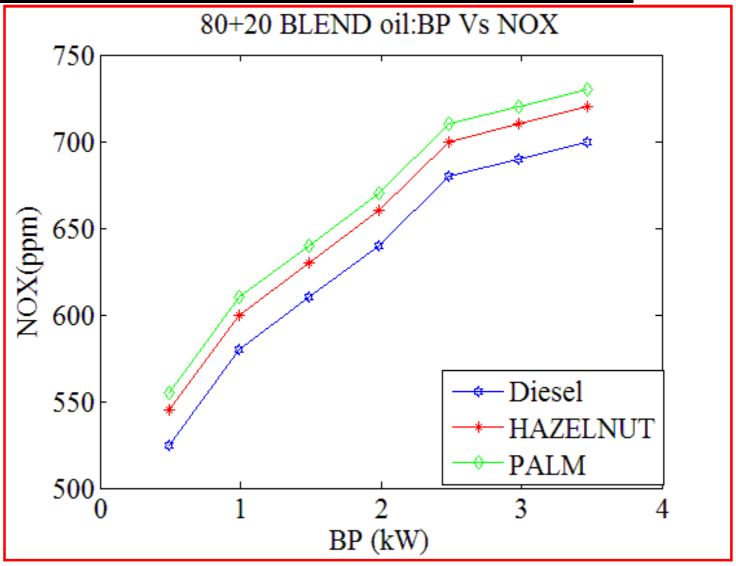

Fig.4: NO_X

D. Co Emissions

Fig. 5 shows CO emission of diesel is maximum compared with biodiesel blends at various loads tested (Fig. 3). Among biodiesels, Hazelnut showed minimum CO emissions than other oils. CO emissions trend at 20% blend of biodiesel is as H20 > P20, may be because all biodiesels contain oxygen which favors better combustion when compared with diesel. Hence, CO emissions are very less for biodiesel. For other blends, trend is similar to that for 20% blend, as load increases, CO emissions increases.

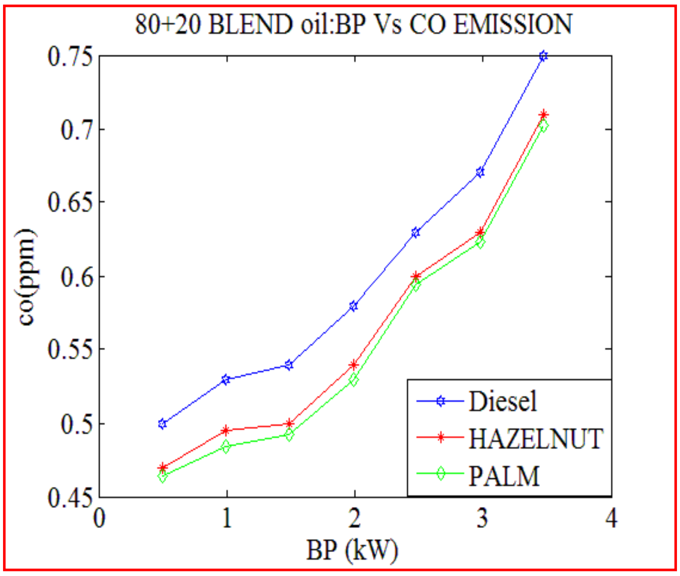

Fig.5: CO Emissions

E. Smoke Density

Fig.6 shows the smoke density for the neat diesel fuel, and 20% blends of the four vegetable oils with diesel fuel, at different loads. One can observe that the density of all bio-fuel blends is higher than the ones for the corresponding neat diesel fuel.

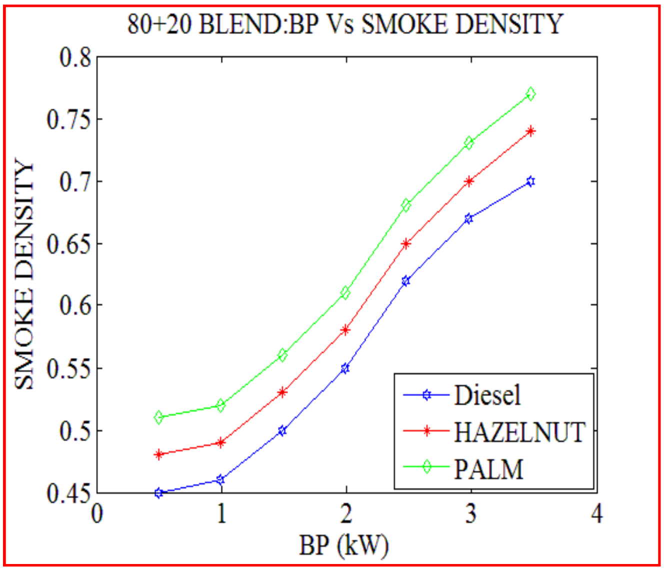

Fig.6: Smoke Density for the Neat Diesel Fuel

F. Brake Specific Fuel Consumption

Fig. 7 shows the brake specific fuel consumption (b.s.f.c.) expressed in kg/kW h (kilograms per kilowatt and hour) for the neat diesel fuel, and blends of 20% of two bio-fuels and neat diesel fuel at different loads. The mass flow rate of fuel blend is calculated from the respective volume flow rate value which is measured and the density of the fuel blends which is computed by considering the densities of the fuel using and the ratio of fuel blends involved in the experimental work. Since the evaluation of work is made on the constant speed and same load which is translated in to the same engine power, and these values are proportional to the mass flow rate of fuel. It is to be observed that the air mass flow rate remains same under the same operating conditions.

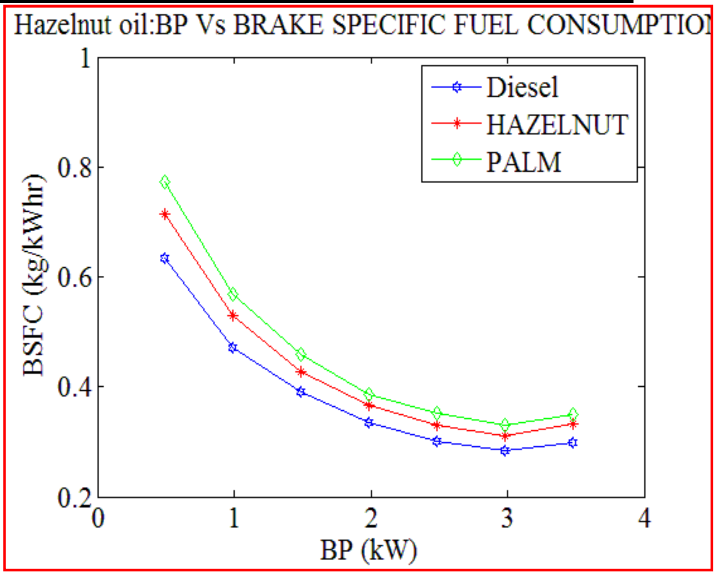

Fig.7: Brake Specific Fuel Consumption

G. Exhaust Gas Temperatures

Exhaust gas temperature Exhaust gas temperature (EGT) varied with load and the results for different fuels are presented in Figure 8. EGT of all the tested fuels increased with load. EGT of B20 was higher than that of diesel fuel at the highest load due to the blends' higher viscosities, which resulted in poorer atomization, poorer evaporation, and extended combustion during the exhaust stroke. As the amount of bio-fuel content increases (B20, B25) then viscosity also increases, and, as a result, EGT of the blends was higher than that of diesel fuel due to deterioration in combustion and more fuel being oxidized.

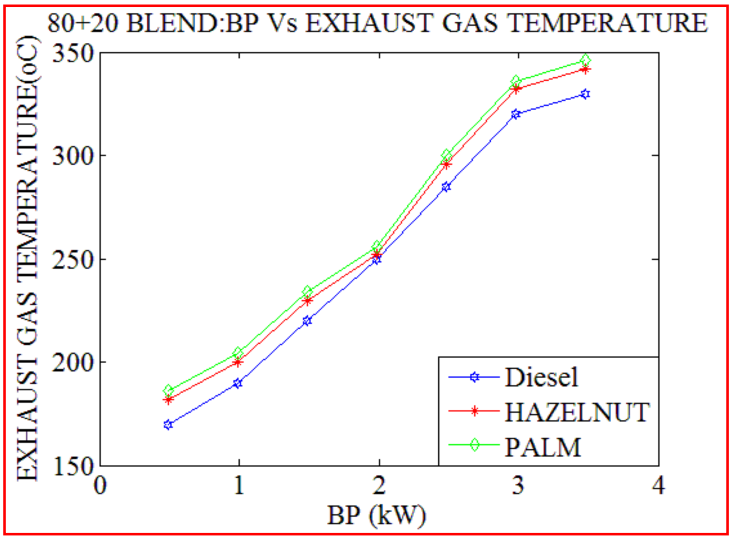

Fig.8: Exhaust Gas Temperatures

VII. SUMMARY AND CONCLUSIONS

An experimental investigation is conducted to evaluate and compare the performance and exhaust emission levels of two different bio-fuels viz. Hazelnut and palm as supplements in the diesel fuel at blend ratios of 20/80 (by vol.), in a fully instrumented, single-cylinder, four stroke single cylinder direct injection, diesel engine.

A series of tests have been performed by using the above each of fuel blends, providing the engine working at different loads. In each test, exhaust gas, exhaust smokiness, temperatures and exhaust regulated gas emissions such as carbon monoxide (CO), nitrogen oxides (NOx) and total unburned hydrocarbons (HC) are analyzed. Brake thermal efficiency and brake specific fuel consumption were computed from measured fuel volumetric flow rate and calorific values.

The exhaust smoke density was increased by the use of bio-diesel blends as fuel when compare with neat diesel fuel, hazelnut bio-diesel blends are performing better when compared with remaining all bio-fuels blends prepared from hazelnut and crambe.

There is a marginal increase in NOx emission with the use of hazelnut bio-diesel blend and crambe bio-diesel blend as a fuel when compare with the NOx emission released from the engine with conventional diesel as fuel. Out of all bio-fuels prepared in the present study hazelnut bio-diesel blend HB20 is giving lower as compared with remaining blends.

The CO emissions were decreased noticeably with the use of bio-diesel blends as fuel in conventional engine when compare with CO emission from the same engine with diesel as, this is also decreasing as the percentage of bio-diesel increase in the blend.

The HC emissions were decreased noticeably with the use of bio-diesel blends as fuel in conventional engine when compare with HC emission from the same engine with diesel as, this is also decreasing as the percentage of bio-diesel increase in the blend.

Brake Thermal efficiency of an engine operated with diesel is showing marginal decrease in BTHE when compared with BTHE from the same engine but with conventional diesel as fuel.

REFERENCES

[1] Rakopoulos CD, Giakoumis EG. Diesel engine transient operation – principles of operation and simulation analysis. London: Springer; 2009.

[2] Pulkrabek WW. Engineering fundamentals of internal combustion engines. 2nd ed. New Jersey: Pearson Prentice-Hall; 2004.

[3] Levendis YA, Pavlotos I, Abrams RF. Control of diesel soot, hydrocarbon and NOx emissions with a particulate trap and EGR. SAE paper no. 940460; 1994.

[4] Larsen C, Oey F, Levendis YA. An optimization study on the control of NOx and particulate emissions from diesel engines. SAE paper no. 960473; 1996.

[5] Komninos NP, Rakopoulos CD. Numerical investigation into the formation of CO and oxygenated and noNOxygenated hydrocarbon emissions from isooctane- and ethanol-fueled HCCI engines. Energy Fuels 2010; 24:1655–67.

[6] Miyamoto N, Ogawa H, Nabi MN. Approaches to extremely low emissions and efficient diesel combustion with oxygenated fuels. Int J Engine Res 2000;1:71–85.

[7] Pepiot-Desjardins P, Pitsch H, Malhotra R, Kirby SR, Boehman AL. Structural group analysis for soot reduction tendency of oxygenated fuels. Combust Flame 2008;154:191–205.

[8] Rakopoulos CD, Michos CN, Giakoumis EG. Studying the effects of hydrogen addition on the second-law balance of a biogas-fuelled spark ignition engine by use of a quasi-dimensional multi-zone combustion model. Proc Inst Mech Eng, Part D, J Autom Eng 2008;222:2249–68.

[9] Abu-Jrai A, Rodriguez-Fernandez J, Tsolakis A, Megaritis A, Theinnoi K, Cracknell RF, et al. Performance, combustion and emissions of a diesel engine operated with reformed EGR. Comparison of diesel and GTL fuelling Fuel 2009;88:1031–41.

[10] [10] Barlow RS, Karpetis AN, Frank JH, Chen J-Y. Scalar profiles and NO formation in laminar opposed-flow partially premixed methane/air flames. Combust Flame 2001;127:2102–18.

[11] Hansen AC, Kyritsis DC, Lee CF. Characteristics of biofuels and renewable fuel standards. In: Vertes AA, Blaschek HP, Yukawa H, Qureshi N, editors. Biomass to biofuels – strategies for global industries. New York: John Wiley; 2009.

[12] Rickeard DJ, Thompson ND. A review of the potential for bio-fuels as transportation fuels. SAE paper no. 932778; 1993.

[13] Hansen AC, Zhang Q, Lyne PWL. Ethanol–diesel fuel blends – a review. Bioresour Technol 2005;96:277–85.

[14] Rakopoulos CD, Antonopoulos KA, Rakopoulos DC, Hountalas DT, Giakoumis EG. Comparative performance and emissions study of a direct injection diesel engine using blends of diesel fuel with vegetable oils or bio-diesels of various origins. Energy Convers Manage 2006;47:3272–87.

[15] Rakopoulos CD, Rakopoulos DC, Giakoumis EG, Dimaratos AM. Investigation of the combustion of neat cottonseed oil or its neat bio-diesel in a HSDI diesel engine by experimental heat release and statistical analyses. Fuel 2010;89:3814–26.

[16] Rakopoulos CD, Antonopoulos KA, Rakopoulos DC. Experimental heat release analysis and emissions of a HSDI diesel engine fueled with ethanol–diesel fuel blends. Energy 2007;32:1791–808.

[17] Rakopoulos DC, Rakopoulos CD, Kakaras EC, Giakoumis EG. Effects of ethanol– diesel fuel blends on the performance and exhaust emissions of heavy duty DI diesel engine. Energy Convers Manage 2008;49:3155–62.

[18] Rakopoulos DC, Rakopoulos CD, Hountalas DT, Kakaras EC, Giakoumis EG, Papagiannakis RG. Investigation of the performance and emissions of a bus engine operating on butanol/diesel fuel blends. Fuel 2010;89:2781–90.

[19] Agathou MS, Kyritsis DC. An experimental comparison of non-premixed biobutanol flames with the corresponding flames of ethanol and methane. Fuel 2011;90:255–62.

[20] Barlow RS, Ozarovsky HC, Karpetis AN, Lindstedt RP. Piloted jet flames of CH4/ H2/air: experiments on localized extinction in the near field at high Reynolds numbers. Combust Flame 2009;156:2117–28.

[21] Rakopoulos CD, Kosmadakis GM, Pariotis EG. Evaluation of a combustion model for the simulation of hydrogen spark-ignition engine using a CFD model. Int J Hydrogen Energy 2010;35:12545–60.

[22] Graboski MS, McCormick RL. Combustion of fat and vegetable oil derived fuels in diesel engines. Prog Energy Combust Sci 1998;24:125–64.

[23] Demirbas A. Biodiesel fuels from vegetable oils via catalytic and non-catalytic supercritical alcohol transesterifications and other methods: a survey. Energy Convers Manage 2003;44:2093–109.

[24] Srivastava A, Prasad R. Triglycerides-based fuels. Renew Sustain Energy Rev 2000;4:111–33.

[25] Papayannakos N, Rakopoulos CD, Kyritsis S, Lappas A, Chatzigakis A, Chlivinos G, et al. Pilot production and testing of bio-diesel produced from Greek feedstocks. In: Frangopoulos C, Rakopoulos C, Tsatsaronis G, editors. Proc of the 19th Int Conf 'ECOS 2006', vol. 3, Crete, Greece, July 12–14, 2006, p. 1489–97.

[26] Canakci M, Erdil A, Arcaklioglu E. Performance and exhaust emissions of a biodiesel engine. Appl Energy 2006;83:594–605.

[27] Rakopoulos CD, Antonopoulos KA, Rakopoulos DC, Kakaras EC, Pariotis EG. Characteristics of the performance and emissions of a HSDI diesel engine running with cottonseed oil or its methyl ester and their blends with diesel fuel. Int J Vehicle Des 2007;45:200–21.

[28] Rakopoulos CD, Rakopoulos DC, Hountalas DT, Giakoumis EG, Andritsakis EC. Performance and emissions of bus engine using blends of diesel fuel with biodiesel of sunflower or cottonseed oils derived from Greek feedstock. Fuel 2008;87:147–58.

[29] Benjumea P, Agudelo J, Agudelo A. Effect of altitude and palm oil biodiesel fuelling on the performance and combustion characteristics of a HSDI diesel engine. Fuel 2009;88:725–31.

[30] Bueno AV, Velasquez JA, Milanez LF. Heat release and engine performance effects of soybean oil ethyl ester blending into diesel fuel. Energy 2010. doi:10.1016/j.energy.2010.07.030.

[31] Barsic NJ, Humke AL. Performance and emissions characteristics of a naturally aspirated diesel engine with vegetable oil fuels. SAE paper no. 810262; 1981.

[32] Fort EF, Blumberg PN, Staph HE, Staudt JJ. Evaluation of cottonseed oils as diesel fuel. SAE paper no. 820317; 1982.

[33] Jacobus MJ, Geyer SM, Lestz SS. Taylor WD, Risby TH. Single-cylinder diesel engine study of four vegetable oils. SAE paper no. 831743; 1983.

[34] Zubik J, Sorenson SC, Goering CE. Diesel engine combustion of sunflower oil fuels. Trans ASAE 1984;27:1252–6.

[35] Rakoqoulos CD. Comparative performance and emission studies when using olive oil as a fuel supplement in DI and IDI Diesel engines. Renew Energy 1992;2:327–31.

[36] Shaheed A, Swain E. Combustion analysis of coconut oil and its methyl esters in a diesel engine. Proc Inst Mech Eng, Part A 1999;213:417–25.

[37] Agarwal D, Agarwal AK. Performance and emissions characteristics of Jatropha oil (preheated and blends)

in a direct injection compression ignition engine. Appl Therm Eng 2007;27:2314–23.

[38] Bajpai S, Sahoo PK, Das LM. Feasibility of blending Karanja vegetable oil in petro-diesel and utilization in a direct injection diesel engine. Fuel 2009;88:705–11.

[39] Haldar SK, Ghosh BB, Nag A. Studies of comparison of performance and emission characteristics of a diesel engine using three degummed non-edible vegetable oils. Biomass Bioenergy 2009;33:1013–8.

[40] Rakopoulos CD, Giakoumis EG. Second-law analyses applied to internal combustion engines operation. Prog Energy Combust Sci 2006;32:2–47.

[41] Rakopoulos CD, Antonopoulos KA, Rakopoulos DC, Hountalas DT. Multi-zone modeling of combustion and emissions formation in DI diesel engine operating on ethanol–diesel fuel blends. Energy Convers Manage 2008;49:625–43.

[42] Rakopoulos CD, Antonopoulos KA, Rakopoulos DC. Development and application of a multi-zone model for combustion and pollutants formation in a direct injection diesel engine running with vegetable oil or its bio-diesel. Energy Convers Manage 2007;48:1881–901.

[43] Rakopoulos CD, Antonopoulos KA, Rakopoulos DC. Multi-zone modeling of diesel engine fuel spray development with vegetable oil, bio-diesel or diesel fuels. Energy Convers Manage 2006;47:1550–73.

[44] Abolle A, Kouakou L, Planche H. The viscosity of diesel oil and mixtures with straight vegetable oils: palm, cabbage palm, cotton, groundnut, copra and sunflower. Biomass Bioenergy 2009;33:1116–21.

[45] Varde KS. Bulk modulus of vegetable oil-diesel fuel blends. Fuel 1984;63:713–5.

[46] Heywood JB. Internal combustion engine fundamentals. New York: McGraw- Hill; 1988.

[47] Glassman I. Combustion. 2nd ed. Orlando: Academic Press; 1987.

[48] Stradling R, Gadd P, Singer M, Operti C. The influence of fuel properties and injection timing on the exhaust emissions and fuel consumption of an Iveco heavy duty diesel engine. SAE paper no. 971636; 1997.

[49] Ferguson CR. Internal combustion engines. New York: Wiley; 1986