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Performance, Emission and Combustion Characteristics of Biofuel and Diesel Blends in Yttria-Stabilized Zirconia Coated Diesel Engine

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ABSTRACT

This paper aims at a comparative study on performance , emission and combustion characteristics of two biofuel – Turpentine oil and Eucalyptus oil – and diesel fuel blends inYttria-Stabilized Zirconia Coated Diesel Engine. In first phase, the test is conducted between coated and uncoated engine using diesel as base fuel and the results are obtained. In the second phase, the test is repeated under the same condition using turpentine and eucalyptus oil blends as fuel in the coated engine. The results reveal that brake specific energy consumption for eucalyptus oil blends decreases by 3.54% compared to diesel fuel, whereas brake specific energy consumption for turpentine oil blends is slightly increased compared to eucalyptus oil blends and diesel fuel. Brake thermal efficiency of turpentine and eucalyptus oil blends is higher compared to diesel fuel in coated engine and uncoated engine. The heat release rate is higher for higher proportions of eucalyptus oil blend. At all loads, it is found that smoke density, unburnt hydrocarbon emission, carbon monoxide and oxides of nitrogen emission are significantly reduced in coated engine for eucalyptus and turpentine oil blends as compared to diesel fuel in coated engine. For all the tests, smoke density and unburnt hydrocarbon increase for all the blends in coated engine compared to uncoated engine, whereas turpentine oil blend is almost equal to the diesel fuel in uncoated engine.

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INTRODUCTION

Compression ignition (C.I.) engines are the most fuel-efficient engines ever developed for transportation purposes due, largely to their relatively high compression ratio and lack of throttling losses. C.I.engines operates with conventional diesel fuel derived from crude oil. C.I.engines operates with less fuel consumption and lower emissions of carbon monoxide and unburned hydrocarbon compared with gasoline engines (McDonnell, 1995), (Peterson, 1986). Dr.Rudolf Diesel first developed the diesel engine in 1895 and run with the variety of oils including vegetable oil. He said "the diesel engine could be run with vegetable oils as engine fuels may seen insignificant today, however these oils become in the course of time as important as petroleum and coal for production at present" (Bryant, 1976). In 1970's the petroleum crisis came out and vegetable oil- based alternative fuels became more attractive recently because of its environmental benefits and better quality exhaust emission (Alton, 2001). The cost of vegetable oils is the main reason which makes it handicap to commercialization of the product (Ramadhas, 2004). The vegetable oils are as 10% lesser calorific value than the diesel fuel. The main drawback of using the vegetable oils is their chemical properties such as high viscosity and low volatility of vegetable oil as compared to petroleum based fuels (Dorado, 2003). Due to these properties of vegetable oil, it leads to severe engine deposits, injector choking and piston ring sticking (Canakci, 2007). In order to overcome the above said problems, the vegetable oil can be used in four ways are direct use and blending, micro emulsion, Pyrolysis (Thermal Cracking) and tranesterification (Bhattacharyya,1994). In this analysis, two biofuels such as turpentine and eucalyptus oil are used as alternative fuel to conventional diesel fuel. The direct use and blending method is adopted.

2. Biofuel Production:

Biomass derived oil - Turpentine and Eucalyptus oil is used in this study. Turpentine oil had widely been used as commercial fuel. It is obtained from pine tree – by resin fraction. The distillation of pinus resin yields two products – turpentine and rosin. Turpentine is a yellowish, opaque, sticky volatile,

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combustible mixture of hydrocarbon isomers obtained either from pine gum or pine wood. Turpentine oil consists of 58-65% gamma – pinene, beta – pinene and other isometric terpenses. The turpentine oil absorbs active oxygen at 100°C and its properties can be retained for years if placed in dark place. The analysis properties of turpentine oil made it suitable for diesel engine operations. It was used in early engines without any modifications. But abundant availability of diesel fuel had stopped the use of turpentine oil in I.C.engines. As turpentine produces low polluting exhaust emission, it will be alternative fuel. The cost of the turpentine is slightly higher than the petro-fuels, but it would be least when compared to global emission management cost. Biomass derived eucalyptus oil is another chosen alternate to conventional diesel fuel. Eucalyptus oil is extracted from the leaves of the eucalyptus tree. Eucalyptus oil has a clear, sharp, fresh and very distinctive smell. And it is pale yellow in color and watery in viscosity. Eucalyptus oil production is perennial and not seasonal, as the eucalyptus leaves were available abundantly throughout the year. It is noted that Orange oil and Eucalyptus oil can be the potential candidate for the internal combustion engines (Ramesh, 1994). Both the oil is directly blending with the diesel fuel without any modification to the oil. Table 1 shows the fuel composition, variation of calorific value and viscosity for various properties of Eucalyptus, turpentine oil blends with diesel fuel.

Table 1: Fuel composition, Variation of calorific value and viscosity for various properties of fuel eucalyptus, turpentine oil blends with diesel fuel.

Sl. No.	Fuels	Fuels blended (% volume)	Viscosity (cst)	Calorific value (kJ/kg)	Density
1.	DF	100% diesel fuel	3	42700	0.827
2.	EOF 20	80% diesel fuel+20%Eucalyptus oil fuel	2.8	42814	0.841
3.	EOF 40	60% diesel fuel+40% Eucalyptus oil fuel	2.6	42928	0.854
4.	TOF 20	80% Diesel fuel + 20% Turpentine oil fuel	3.2	41616	0.846
5.	TOF 40	60% Diesel fuel + 40% Turpentine oil fuel	3.3	40532	0.864

3. Thermal Barrier Coating With Yttria- Stabilized Zirconia:

The reduction of polluting vehicle emission can be achieved by providing combustion of the fuel. Some researches assure that coating the combustion chambers with ceramic material reduce the polluting vehicle emission. The engine which has this inbuilt facility is called adiabatic (or) low heat loss engine. Coating of some parts of combustion chamber with low thermal conducting material increases the combustion temperature and reduces in the polluting emission (Qiu, 1996). The partially adiabatic engine minimizes the heat loss during normal running of the engines, decreases the load on the cooling system and also the power consumed by it. As a result, the efficiency of the engine is increased (Wacker, 1982).The combustion chamber temperature of ceramic coated engine is higher than the uncoated engine and this permit to use even low quality fuels. Since the heat loss which goes to the cooling system is reduced, the temperature of gas after combustion is increased. It enables the engine to start even at cold weather conditions and ensures noise reduction at engine operations because of the controlled combustion (Hejwowski , 2002). From various studies, it is noticed that improved engine performance and low polluting emission of vehicles are possible when some parts of the combustion chamber are coated with ceramic material (Sudhakar, 1984; Miyairi, 2007).The ceramic coating material suggested in this study is Zirconia ceramics. By controlling phase transition of the fabrication process, the desired Zirconia property can be achieved. Normally Zirconia becomes very strong and tough at room temperature. Understanding of the phase transitions is crucial to determine the required properties of Zirconia ceramics. The zirconium dioxide (ZrO_2) has a monoclinic crystallographic structure at ambient temperatures. Upon raising the temperature the oxide undergoes the phase transitions - from monoclinic to tetragonal at the phase transitions temperature of 1170^{o}C, from tetragonal to cubic at the transition temperature of 2370^{o}C and from cubic to liquid at transition temperature of 2680^{o}C The transformation from tetragonal to monoclinic phase, when temperature decreases approximately at 1170^{o}C , is quite disruptive and renders pure ZrO_2 unusable as it is a high temperature structural ceramic. This disruption is caused by 6.5% volume expansion upon the transformation from tetragonal to monoclinic phase change which could cause structural failure of any ceramic coating. However, ZrO_2 forms solid solutions with aliovalent oxides such as CaO, MgO, Y_2O_3 and other rare oxides of earth. This is obtained by through mixing of the powders - ZrO_2 and Y_2O_3 - and is pressed to form a solid body and sintering at the temperature adequately high to promote the inter-diffusion of the coatings. This solid solution (yttria-doped zirconia) behaves quite differently. The pure $ZrO_{2,}$ as the temperature phases, tetragonal and cubic, tend to be stabilized at temperatures lower than 1170^{o}C and 2370^{o}C, respectively. Hence, doping of the aforementioned aliovalent oxides serves as the stabilizing agent for the zirconia. With the addition of sufficient fraction of stabilizer, the cubic phase could be stabilized at the ambient temperature. The addition of 9% mole fraction of yttria (Y_2O_3) or more to ZrO_2 will result in fully stabilized zirconia (FSZ) which has the cubic structure at all temperature from ambient upwards. Addition of 6% mole fraction of Y_2O_3 or less generates partially stabilized zirconia (PSZ) which consists of the cubic matrix with dispersed tetragonal or monoclinic precipitates, or both, depending on the temperature in the process. Plasma spray process offers a flexible and relatively economic means for producing FGM. It has been used for many years to apply layered and graded deposits (bond coats) to enhance the survivability of engines. These graded coatings are applied to reduce discontinuities in thermal expansion coefficients in order to avoid mismatch- related failure in service. In this study, the effect of ceramic coating on cylinder head, valves and piston crown face are analyzed with respect to performance, emission and combustion characteristic of diesel engine. Before applying the thermal barrier coating in a manner of "functionally graded" onto the crown, cylinder head and valve a thickness of 300 microns of a new set of piston crown are to be machined off. Ceramic layers are made with partially stabilized zirconia with aluminum oxide (Al_2 O_3 ZrO_2), using plasma spray method, of thickness about 300 micron. The thickness of coating is selected within the optimum range of thickness 0.1–1.5 mm (Heywood, 1988). The Cylinder liner is not coated as it is very small area. The Combustion chamber geometry is maintained by machining the components before ceramic coating.

MATERIALS AND METHODS

A 5.2 KW four stroke single cylinder, direct injection, water cooled, constant speed (1500 rpm), vertical cylinder direct injection Kirloskar TV-1 diesel engine were used in the test. The compression ratio, injection pressure and timing of the engine were 17.5:1, 220 kg/cm^2 and 23^o bTDC and the experimental set up was shown in the figure 1.The engine was run for 30 min with diesel fuel to attain a normal working temperature. In first phase the test was conducted in the coated engine using diesel as base fuel and the results were obtained. In second phase of work, the test was repeated under the same conditions using eucalyptus and turpentine oil blends as fuel in the same coated engine (CE). The engine was maintained at the constant speed and all the measurements were repeated for a minimum of three times. Finally the average value of the three readings was taken for the calculation.

4.1. Error Analysis:

The Errors and uncertainties in the experiments can arise normally from selection of the instruments, condition, calibration, environment, observation, reading and test planning. The uncertainty analysis is needed to show the accuracy of the experiments. The various parameters like total fuel consumption, brake power, specific fuel consumption and brake thermal efficiency were calculated. Percentage uncertainty of this experiment is ± 2.26 %.

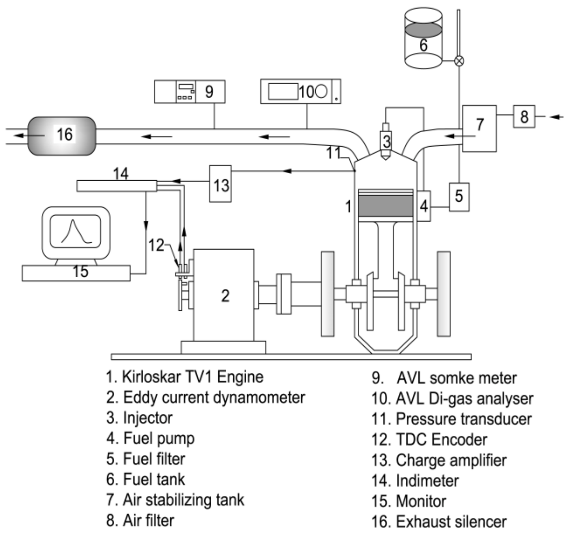

Fig. 1: Experimental setup.

RESULTS AND DISCUSSION

5.1 Performance Parameters:

5.1.1 Brake Thermal Efficiency:

Figure 2 shows the brake thermal efficiency (BTE) with brake power for the Eucalyptus (EOF), Turpentine (TOF) oil blends with diesel fuel (DF) in the coated engine. BTE of DF in coated engine (CE) is 29.79% which is 3.6 % higher than diesel fuel in uncoated engine(UE).The BTE of biofuel is higher by 4 – 5% than DF in CE .It can be seen that the improvement in BTE is more significant at higher brake power outputs. Due to the ceramic coating, there will be higher operating combustion temperature in the combustion chamber, which improves the combustion characteristics and this may assist in better vaporization of the fuel and hence effective combustion of fuel which improves the brake thermal efficiency (Assanis et.al., 1991). The BTE of TOF and EOF blends is higher by 4.5 % and 3.2% compared to DF.It is found that BTE of T40 blend is higher compared to other blends. This variation is due to the chemical composition and higher cetane number of TPOF blends, which promotes the combustion process and BTE is improved.

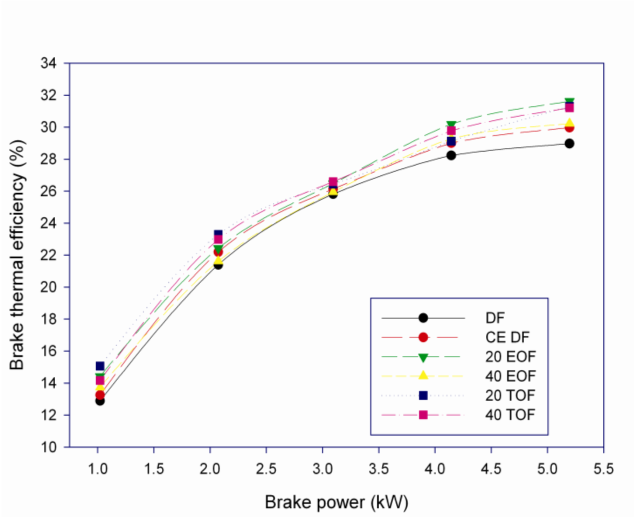

Fig. 2: Comparison of BTE of test fuels at different brake power.

5.1.2 Brake Specific Energy Consumption:

Brake Specific Energy Consumption (BSEC) is defined as the amount of energy given as input to develop one – kilowatt power (Dickey, 1989; Barie, 1981).BSEC is an important parameter rather than BSFC because it takes care of both mass flow rate and calorific value of the fuel (Canakci M, ,2005).Figure 3 shows the brake specific energy consumption against the brake power. BSEC values of the insulated engine are lower than the UE (Assanis, 1991; Sudhakar 1984). This is because of the higher surface temperatures of its combustion chamber. From the results it can be found that BSEC for the EOF blend is lesser by 3.05% than DF in CE. This occurs because of higher heating value of EOF and diesel blends. Because of this, it leads to lesser amount of energy consumption by the engine to maintain constant brake power. The high density and low viscosity of EOF blend is injected to the combustion chamber which results, the spray cone angle increases, which in turn enhances the mixture formation and hence better premixed combustion can be achieved. From this observation, it can be concluded that EOF blends requires less BSEC when compared to diesel fuel. However, the specific energy consumption for TPOF blends slightly increases by 1.03% compared to DF. This is due to the combined effect of lower heating value of fuel and high density of TPOF blends and hence larger amount of TPOF is supplied to maintain constant brake power output (Canakci M, 2005).Brake specific fuel consumption also follows the same trend.

5.2 Emission Parameters:

5.2.1 Carbon Monoxide (CO):

The CO emission, formed by the presence of oxygen during combustion is insufficient to form CO_2 (Heywood JB, 1988; Sayin C., Uslu K., 2008). Incomplete combustion of carbon leads to CO formation. Figure 4 shows the variation of CO for diesel fuel and various blends of TOF and EOF over the entire range of brake power. CO emission for diesel fuel in CE is 12.5% lesser compared to DF in UE. From the results it is found that at full load, TOF and EOF 40 blends are 42.8% lesser compared to DF in CE. The decrease in CO emissions in the CE is observed due to the increase in after-combustion temperature because of ceramic coating (Morel T, *et al*., 1986). Furthermore, expansion in the ceramic coating engine at the high temperature contributes to accelerated kinetics and more complete oxidation of CO. CO decreases because of the higher combustion kinetics and temperatures which promotes a more complete conversion of the fuel. Therefore, there is simultaneous increase and decrease in Carbon dioxide and CO. These can be explicited by the enrichment of oxygen in the blends (Lin CY, Lin HA, 2006). Moreover, another reason for reducing CO emission is lower cetane number of EOF and TOF blends.

5.2.2 Oxides of Nitrogen:

Figure 5 shows the variation in oxides of nitrogen **(**NOx) emission for various TOF and EOF blends as reference to diesel fuel. It is seen that there is decreasing tendency in NOx emission with the use of DF, TOF and EOF blends in CE as compared to the DF in the uncoated engine. It is known that NOx emissions are caused by higher combustion temperature in the cylinder. The NOx emissions for 40 TOF blend is lesser by 10.54% compared to 40 EOF blend and DF in CE. TOF produce lower combustion temperature due to their lower heating value and oxygen content. (Dennis N, *et al*.,1991). It is seen that about 10.54% of NOx emission with 19.2 % reduction in exhaust temperature is reduced for 40 TOF blend in coated engine.

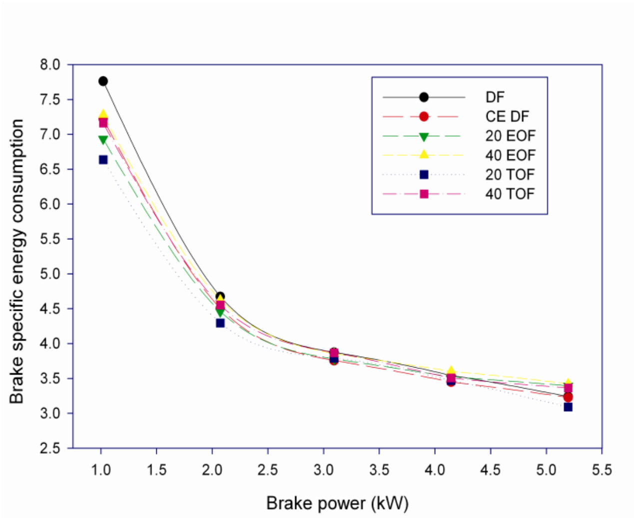

Fig. 3: Comparison of BSEC of test fuels at different brake power.

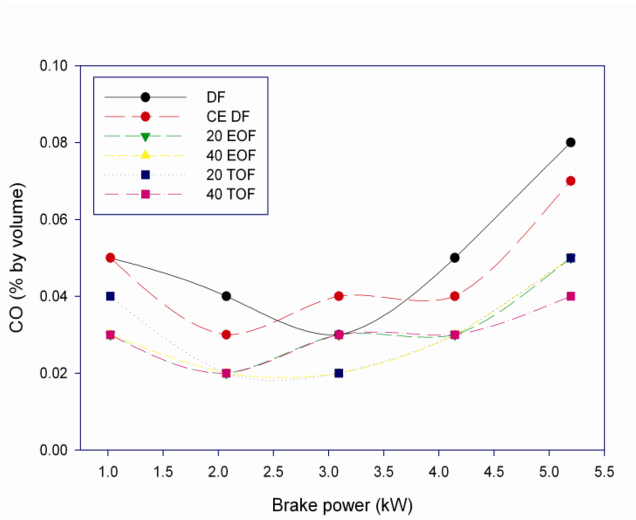

Fig. 4: Comparison of Carbon monoxide of test fuels at different brake power.

5.2.3 Smoke Density:

Figure 6 shows the variation of smoke density for diesel fuel and various blends of TOF and EOF blends over the entire range of brake power. From the results, it is found that smoke density is reduced with respect to increase in turpentine and eucalyptus oil fraction in the blends compared to DF in the CE. The reason for reduced smoke is due to higher heat release rate during diffusive combustion phase with increase in biofuel fractions. There is significant reduction of smoke emission for EOF and TOF blends compared to DF. This may be due to the higher oxygen content of blends (Lin CY, Lin HA, 2006). At full load smoke density of TOF blend is 27.7% and 38.2% lesser compared to EOF and DF in CE. The higher oxygen content in TOF blends compared to EOF leads to an improvement in diffusive combustion phase. However the smoke density for the CE is higher as compared to uncoated engine. The increase in the smoke density for coated engine may be due to long combustion duration.

5.2.4 Unburned Hydrocarbon (UBHC):

Figure 7 shows the influence of UBHC emission against brake power .The UBHC emission is increased in CE compared to uncoated engine. It is found that 38.8% increases for the diesel fuel in CE compared to uncoated engine. The same trend is observed by another researcher (Allidas, A.C, 1987). An UBHC contributor to the exhaust includes lubricating oil. Fuel escapes combustion by means of wall quenching of the flame, bulk quenching, valve overlap and lean mixing during the ignition - delay period. At lower loads the bulk quenching is dominant whereas at higher loads the oil cracking is dominant. From the results there is an average decrease in UBHC emissions for EOF and TOF blends is 39.1% and 47.2 % compared to base line DF in CE.

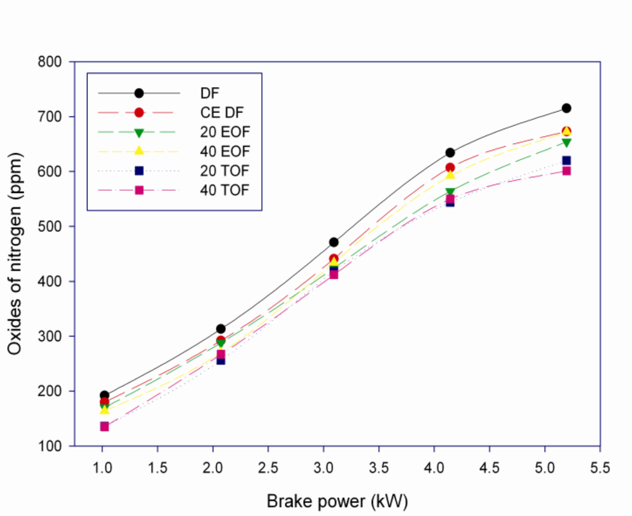

Fig. 5: Comparison of oxides of nitrogen of test fuels at different brake power.

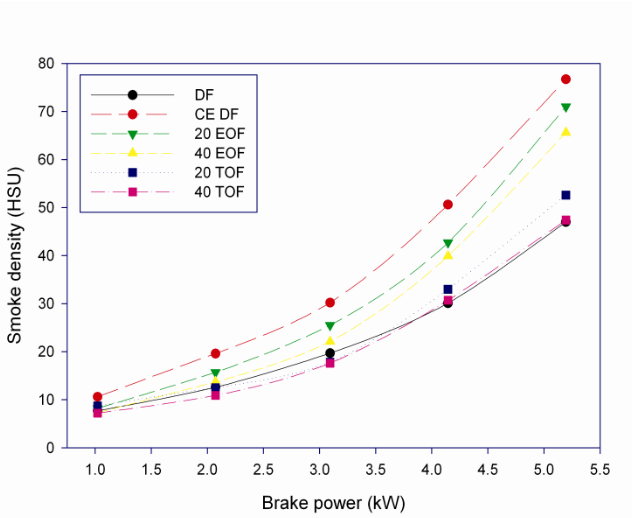

Fig. 6: Comparison of smoke density of test fuels at different brake power.

5.3 Combustion Analysis:

5.3.1 Heat Release Rate:

Figure 8 shows the heat release rate (HRR) of EOF and TOF blend and diesel fuel at varying crank angles from -30° to 90°. It has been observed that the heat release rate for diesel fuel in UE is lesser compared to CE and it is 99.109 kJ/m^3 deg & 95.488 kJ/m^3 deg respectively. For TOF 40 and EOF 40 blend the heat release rate is 94.052kJ/m^3deg and 180.289 kJ/m^3 deg for CE at full load. This shows that the HRR of TOF blend in CE is lower compared to EOF and DF. And also the occurrence of peak heat release rate for TOF 40 blend is advanced approx 4-5 degrees in CE. The rate of heat release of ceramic coated engine slightly shifted from the top dead center due to reduced premixed combustion. This could be attributed to lower internal energy and slow burning, because of lower calorific value and slight increase in density of TOF blends. The same trend is observed by the other researcher (Kamo.et.al. 1984). It is also noticed that in UCE & CE engine the heat release during the premixed combustion period is higher for EOF blends rather than the diesel fuel because of longer ignition delay (Huang Zuohua, *et al*., 2004).

5.3.2 Cylinder Pressure:

The figure 9 shows the P-θ diagram for a diesel fuel and various TOF and EOF blend. The various factors that affect the peak pressure are compression ratio and influence of combustion chamber design and combustion duration, fuel specific heat, energy content and quality. During the combustion of fuel, the energy release is used to generate internal pressure developed in the net calorific value of the fuel (Heywood, 1998). From the figure it has been observed that the TOF and EOF blends produces similar in-cylinder pressure patterns as compared to diesel fuel. The maximum cylinder pressure for TOF 40, EOF 40 blends and DF in coated engine is 76.98 bar, 73.54bar and 76.264 bar. It is found that the EOF and TOF blends produce peak pressure within 5 – 15 crank angle after TDC, due to its high burning rate at the initial stage. Thus it is concluded that the engine operation with these blends did not pose any problem related to knock, combustion (or) partial burn.

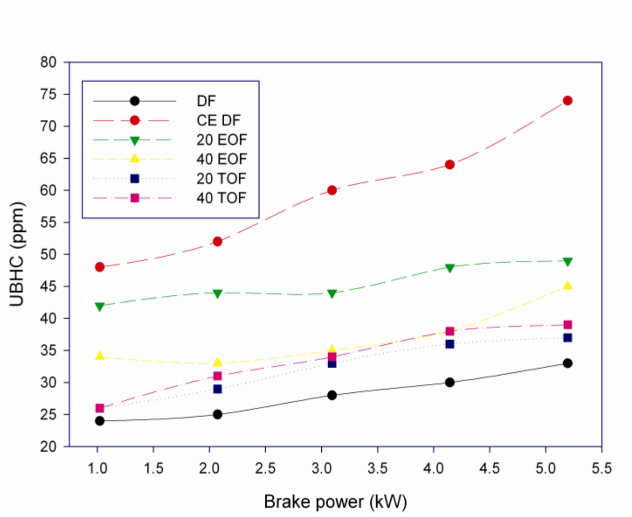

Fig. 7: Comparison of Unburned hydrocarbon emission of test fuels at different brake power.

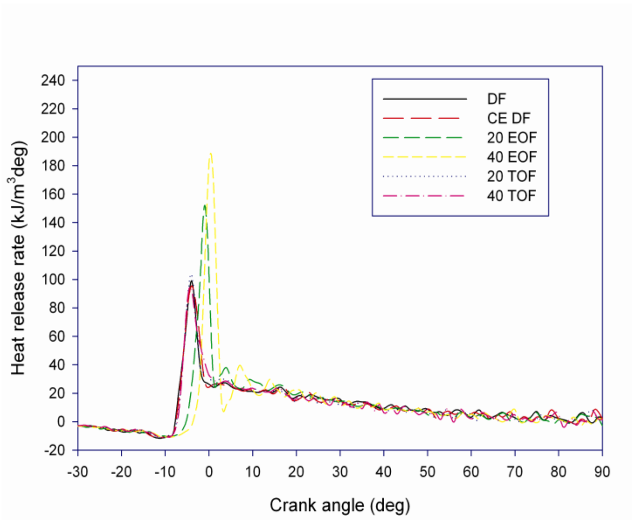

Fig. 8: Comparison of Heat release rate of test fuels at different brake power.

Table 2: Comparison of full load values for diesel, EOF and TOF blends.

Parameters	Diesel (UE)	Diesel (CE)	40 EOF	40 TOF
Bth (%)	28.969	29.971	30.217	31.2052
BSEC	3.2395	3.227	3.123	3.263
Smoke (HSU)	47	76.7	65.6	47.4
NOx (ppm)	715	673	672	601
UBHC (ppm)	33	74	45	39
CO (% by volume)	0.08	0.07	0.04	0.04
Cylinder pressure (bar)	74.305	76.264	73.54	76.19
Heat release rate (KJ /m^3)	99.109	95.488	180.289	94.052

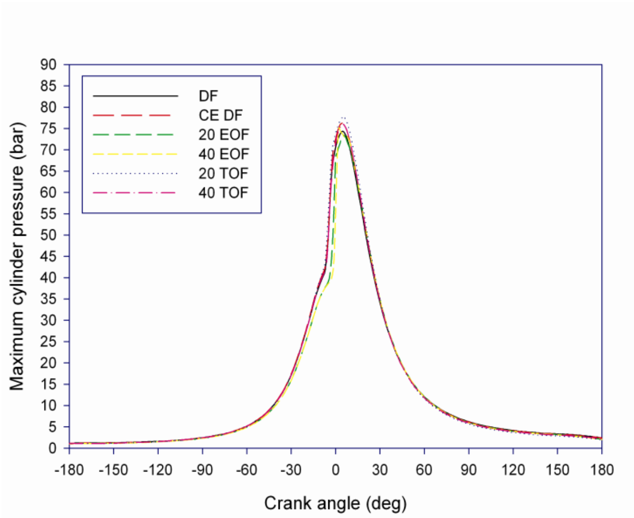

Fig. 9: Comparison of Cylinder pressure of test fuels at different brake power.

6. Conclusion:

Form the results, it is observed that performance, emission and combustion characteristics of the engine are affected positively with EOF and TOF blends. The results obtained at full load are given in the table-2.

It has been observed that

1) The BSEC for EOF blends decrease by 3.54 % compared to diesel fuel in the coated engine, whereas BSEC for TOF blends is slightly higher compared to EOF blends and DF.

2) The BTE of TOF and EOF blends is higher compared to DF in coated and uncoated engine.

3) EOF blends exhibits longer ignition delay and higher combustion duration compared to TOF blends and diesel fuel. The heat release rate is higher for higher proportions of eucalyptus oil blend. The HRR for 40 EOF blend is 180.29 kJ/m^{3}deg and DF is 99.109 kJ/m^{3}deg.

4) At all loads it is found that smoke density, UBHC, CO and NOx emission are significantly reduced for coated engine for EOF and TOF blends compared to DF in coated engine.

For all the fuel tests, the injector nozzle was inspected visually, there is no significant carbon deposits.

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