Experimental investigation of performance, emission and combustion characteristics of an indirect injection multi-cylinder CI engine fuelled by blends of de-inking sludge pyrolysis oil with biodiesel

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ABSTRACT

De-inking sludge can be converted into useful forms of energy to provide economic and environmental benefits. In this study, pyrolysis oil produced from de-inking sludge through an intermediate pyrolysis technique was blended with biodiesel derived from waste cooking oil, and tested in a multi-cylinder indirect injection type CI engine. The physical and chemical properties of pyrolysis oil and its blends (20% and 30% vol.) were measured and compared with those of fossil diesel and pure biodiesel (B100). Full engine power was achieved with both blends, and very little difference in engine performance and emission results were observed between 20% and 30% blends. At full engine load, the brake specific fuel consumption on a volume basis was around 6% higher for the blends when compared to fossil diesel. The brake thermal efficiencies were about 3–6% lower than biodiesel and were similar to fossil diesel. Exhaust gas emissions of the blends contained 4% higher CO_2 and 6–12% lower NO_x, as compared to fossil diesel. At full load, CO emissions of the blends were decreased by 5–10 times. The cylinder gas pressure diagram showed stable engine operation with the 20% blend, but indicated minor knocking with 30% blend. Peak cylinder pressure of the 30% blend was about 5–6% higher compared to fossil diesel. At full load, the peak burn rate of combustion from the 30% blend was about 26% and 12% higher than fossil diesel and biodiesel respectively. In comparison to fossil diesel the combustion duration was decreased for both blends; for 30% blend at full load, the duration was almost 12% lower. The study concludes that up to 20% blend of de-inking sludge pyrolysis oil with biodiesel can be used in an indirect injection CI engine without adding any ignition additives or surfactants.

Keywords: CI engine; De-inking sludge; Pyrolysis oil; Performance; Emission; Combustion characteristics.

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Abbreviations

BD	Biodiesel
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
CI	Compression Ignition
DS	De-inking Sludge
DSPO	De-inking Sludge Pyrolysis Oil
FD	Fossil Diesel
GC-MS	Gas chromatography-Mass spectrometry
HHV	Higher Heating Value
IDI	Indirect Injection
LHV	Lower Heating Value
PO	Pyrolysis Oil

1. Introduction

De-inking sludge (DS) consists mainly of fibres and paper fillers, and is a waste stream derived during the de-inking process of recycled paper at secondary fibre paper mills. De-inking sludge has the potential to be converted into useful biofuels. Typically, 160−500 kg of wet DS is produced for each ton of paper production in China [1]. In the UK, approximately 1 million tonnes of DS are produced annually [2]. Its typical heating value and moisture content are 2.8 MJ/kg (as received basis) and 58% (wt) respectively [3]. A number of larger mills (> 400,000 tpa) incinerate this sludge for energy recovery [4, 5]. However, due to the low calorific value of de-inking sludge, autonomous combustion systems cannot be sustained on this fuel alone, and therefore co-firing is essential [4]. A significant amount of sludge is disposed of by landspreading, landfilling or used as a cattle bedding medium [4]. Neither landspreading nor landfilling is an ideal option from both environmental and economic points of view. In this study, the use of DS-derived pyrolysis oil (PO) in an internal combustion engine is explored as a method of converting DS into a useful energy source.

Pyrolysis produces liquids, solids and gases from biomass and waste materials by processing them at moderate temperatures typically between 250−550ºC in the absence of oxygen. All these products have potential as fuels; in particular liquid fuels may power internal combustion engines [6, 7]. Today pyrolysis is the subject of much research and development [8]. Among the techniques of pyrolysis, fast pyrolysis is a modern technique for producing the maximum quantity of PO from biomass feedstocks such as wood or agricultural wastes. Slow pyrolysis is a traditional technique mainly used to produce charcoal [9−11]. Intermediate pyrolysis is a relatively new technique reported to produce low-tar oils from a wider variety of biomass or waste feedstocks [12, 13].

Techniques to produce liquid oil and gaseous products from DS have previously been investigated [1, 4, 14−17]. Yanfen and Xiaoqian [18] investigated the co-firing of DS with coal. Lou et al. [1] carried out bench scale pyrolysis of DS in a tubular furnace reactor at 800ºC under atmospheric pressure. The oil and gas yields were 24.4% and 29.78% respectively. These gas was composed of CO (31.6%), H_2 (17.71%), CH_4 (19.54%), CO_2 (21.53%) and C_2H_4 (9.62%) [1]. In another study DS was pyrolysed in a furnace at various reaction temperatures with a heating rate of 10ºC/min, at 500ºC the products were: PO 40%, gas 24% and charcoal 36% [14]. Chunbao and Lancaster [15] produced from DS oils with a heating value of around 35 MJ/kg with and without using catalyst by direct liquefaction in hot-compressed air. Zhang et al. [16] illustrated that gaseous product with high H_2 content and oil with high heating value (HHV) (~36 MJ/kg) could be produced using a

supercritical water treatment technique. Ouadi et al. [4, 17] recently demonstrated that POs with a low water content of 3−4% and HHVs of around 36−37 MJ/kg could be produced through intermediate pyrolysis of DS obtained from both a secondary fibre tissue and newsprint mill. Approximately 9% (wt) of the dry feed was converted into pyrolysis oil [17].

Although high energy value liquids can be produced from DS, there currently exists no literature to assess the actual viability of de-inking sludge pyrolysis oil (DSPO) as a fuel in compression ignition (CI) engines. The aim of this work is to investigate experimentally the feasibility of using blends of DSPO as a substitute to fossil diesel (FD) in a multi-cylinder indirect injection (IDI) CI engine. Pyrolysis oil produced by intermediate pyrolysis will be blended with biodiesel (BD) in varying proportions. Physical and chemical properties of the blends will be evaluated; and engine performance, exhaust gas emissions and combustion parameters will be measured in comparison to FD operation.

An off-the-shelf IDI type engine has been selected to operate on high viscosity DSPO blends. It is expected that, in the IDI engine, the turbulence created by the partial burning in the pre-chamber will help to combust the DSPO blend inside the main chamber by mixing the fuel and air more efficiently. Consequently, there will be reduced tendency for unburnt pyrolysis oil to remain in the main combustion chamber; and introduction of the unburnt oil in the crankcase and coke formation inside the piston-cylinder will be minimised. In addition, the use of an IDI engine may help to reduce the NO_x emission, as the combustion temperature in the main chamber is lower than in the direct injection type.

2. Materials and methods

2.1. Pre-treatment of DS and pyrolysis oil production

De-inking sludge was obtained from Aylesford Newsprint Paper Mill (SCA), UK. The moisture content of the DS as received was in the range of 33−35% (wt). The DS was dried externally by Envirosystems Ltd (UK) at a drying temperature of approximately $1000^{o}C$ in a rotary drum dryer, using air as the heating medium to reduce the moisture content to around 3% (wt). The DS was subsequently pelletised at Aston University using a 9PK-200 biomass pelletiser. The size of pellets produced was approximately 6 mm (dia) by 15 mm (length). Further details of the feedstock pre-treatment and the pyrolysis process are given by Ouadi et al. [4, 17].

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Intermediate pyrolysis trials with the pre-treated DS feedstock were carried out using a reactor known as a Pyroformer [4, 17, 19] – see Fig. 1. The Pyroformer is essentially an auger pyrolysis reactor with two counter-rotating screws which can process a feed at a rate of up to 20kg/hr [4, 17]. The reactor is heated externally by electrical heating strips. Feed enters at one end and moves through the screw conveyor system whilst being heated to the specified pyrolysis temperature. The solid residue exits at the opposite end of the reactor and pyrolysis gases, which are a mixture of condensable organic vapours and permanent gases, pass through an outlet pipe.

De-inking sludge pellets were fed into the pyroformer unit at a rate of 15 kg/hr. The reactor temperature was maintained at 450ºC. Steady state of the gas outlet temperature was reached after about 60 minutes. The total duration of the run lasted for 3 hours and consumed approximately 47 kg of DS feedstock. The mass balance revealed that approximately 9% (wt) of the feed converted into condensable volatile organic vapours, 1% (wt) aqueous phase, 11% (wt) converted into permanent gases consisting of mainly (CO, N_2, CH_4 and CO_2) and the remainder (~79% wt) was solid residue − mainly calcium based inert materials. For removal of entrained solid particulates the hot organic vapours and permanent gases were transferred into hot gas filter candles which were maintained at the reaction temperature to prevent condensate formation (Fig. 1). Next the gases entered a shell and tube water cooled condenser where the organic vapours were condensed. Water was used as the cooling medium. The permanent gases were then routed into an electrostatic precipitator for aerosol removal and then to a GC-TCD Hewlett Packard HP5890 for gas composition detection. The liquid collected consisted of aqueous and oil phases which were allowed to separate by settling under gravity; the aqueous phase was then removed from the oil. Thus the process yielded 9 kg of DSPO per 100 kg of dry feedstock. A total of 4 litres of steady-state DSPO was collected for engine testing.

2.2. *Blend preparation and characterisation*

2.2.1   De-inking sludge pyrolysis oil-biodiesel blends preparation

The GC-MS analysis revealed that the DSPO contained about 12% fatty acid methyl esters (see section 3.1). Note that esters blend readily with both FD and BD. Biodiesel used in this study was obtained from Brittania Oils Ltd (Birmingham, UK) and was produced from waste cooking oils. Blends containing 20% and 30% (v/v) DSPO were prepared with both BD and FD. Blends were prepared by mixing in an agitated tank without the addition of any surfactants and then allowed to settle for a period of 24 hours. DSPO with FD showed no phase

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separation but some solid deposition occurred after approximately 20 minutes. Deposits found may have been caused by the lack of affinity between chemical groups present in the DSPO−FD blend. In contrast, this did not occur when DSPO was blended with BD. Therefore the use of the DSPO-FD blend was not pursued further. The DSPO-BD blends were then filtered using a 1µm sock filter to remove fine solid particulates and dust prior to engine testing.

2.2.2. Characterisation

A Parr 6100 bomb calorimeter was used to measure the higher heating values. Canon Fenski u-tube viscometers and a thermostatic water bath (±0.1°C) were used to measure the kinematic viscosities according to ISO 3104 giving an accuracy of ±0.22%. The pH values were measured using a Fisher-brand pH meter and densities were measured using a hydrometer according to ASTM−D7544 and ASTM−D4809 standards respectively. Flash point was measured using a Setaflash series 3 plus closed cup flash point tester (model 33000-0) according to ASTM-D1655 standard. Elemental analysis to investigate the carbon, hydrogen, nitrogen, oxygen and sulphur content (% wt) was performed by an accredited laboratory using a Thermo EA1108 series elemental analyser. The lower heating value (LHV) was calculated from the HHV and hydrogen content. Water content was measured by Mettler Toledo V20 compact volumetric Karl-Fischer titration according to ASTM−E203 standard. GC-MS analysis was conducted using a Hewlett Packard HP 5890 Series II Gas Chromatograph with an automatic injector and auto sampler with a DB 1706 non-polar capillary column. Ash content was determined using a Carbolite furnace (model: AAF-1100) in accordance with ASTM-D482-03 standard. Acid number was measured using a Mettler Toledo G20 compact titrator as per standard ASTM-664-04. Carbon residue was determined in accordance with the ASTM-D524-09 standard test procedure using a Conradson carbon residue test apparatus.

2.3. *Engine test rig set-up*

Table 1 shows the specifications of the indirect injection water cooled CI engine selected for the study. The experimental set-up is shown in Fig. 2.

2.3.1. Fuel supply system and instrumentation

A dual-fuel supply system was designed so that the engine can be started and warmed up with FD (or BD) before switching to DSPO-BD blend after about 10 minutes (Fig. 2). At the end of each test run the engine was

reverted back to FD operation in order to remove the remaining DSPO-BD blend from the fuel supply and engine injection system. Additional filters were connected into the fuel supply system. The fuel supply tanks were placed at 3 m height for reliable fuel flow and to overcome the pressure losses in the additional fuel filters. Stainless steel piping and valves were used to avoid any corrosion or erosion. The radiator was by-passed by a header tank type HX (Bowman UK) supplied with tap water. The radiator itself and the fan were kept in place to enable comparisons of the engine performance with the rated figures provided by the manufacturer and cooling the engine accessories.

An eddy current dynamometer (Froude Hofmann AG80HS) was used to measure and adjust the engine load and speed (Fig. 2). The torque and speed accuracies of the dynamometer were ±0.4 Nm and ±1 rpm respectively. A five-gas emission analyser (Bosch BEA 850) and smoke opacity meter (Bosch RTM 430) were used to analyse the exhaust gas components and to measure the smoke intensity respectively. A graduated cylinder and stop watch were used to measure the fuel consumption rate (Fig. 2). K-type thermocouples were used to measure the temperatures of the exhaust gas, fuel inlet, lub oil and engine jacket water. A LabVIEW® data acquisition system was used to log the temperatures at the various locations. The engine was operated at different loads with a constant speed of 1500 rpm. A pressure sensor (Kistler 6125C11) and charge amplifier (Kistler 5064B11) were used to measure pressure in the cylinder nearest to the radiator end of the engine. Another pressure sensor (Kistler 4065A500A0) and amplifier (Kistler 4618A0) were used to measure the fuel line injection pressure. This sensor was installed on the fuel delivery line of the same cylinder. An optical encoder (Kistler 2614A) was installed for detection of the crank angle position. The amplifiers and the encoder electronics were connected to the 'KiBox' (Kistler, model 2893AK8) for data logging, which was connected to a PC through an ethernet port. KiBoxCockpit software was used to measure and analyse the various engine combustion parameters.

3. Results and discussion

3.1. *Fuel properties: de-inking sludge pyrolysis oil, biodiesel, blends and fossil diesel*

The moisture content and HHV of dried DS were approximately 3% (wt.) and 6.4 MJ/kg respectively. Table 2 shows physical and chemical properties of DSPO, BD, FD and DSPO-BD blends. The viscosity and flash point temperature of the DSPO were approximately 4 times and 2.5 times higher than that of FD. On the other hand, the viscosity of BD was about 2.7 times higher than that of FD. Flash point temperatures of the BD and DSPO were almost the same. With regard to LHV, Table 2 shows only small differences between DSPO and BD. In

contrast, LHV of DSPO was lower by about 17% than for FD. Density, acid number and carbon residue values of DSPO were considerably higher than those of FD and BD; in the case DSPO−BD blends these values were decreased significantly (Table 2). The carbon content in FD was 7–9% higher than in DSPO and in BD. Nitrogen and sulphur content in the DSPO was much higher than in the BD and in FD (Table 2). On the other hand, sulphur content was at trace levels in the DSPO-BD blends. In the DSPO, hydrogen content was lower by approximately 31% but oxygen content was higher by about 7 times than that of FD. Ash content was at trace levels in all fuels. The components from the GC-MS analysis of the DSPO were found to be: toluene (C_7H_8) 4%, ethyl benzene (C_8H_{10}) 13%, 1,3,5,7 cyclooctatetraene styrene (C_8H_8) 28%, phenol (C_6H_6O) 3%, 4-ethyl-2-methoxy phenol ($C_9H_{12}O_2$) 3%, 2-methoxy-4-propyl phenol ($C_{10}H_{14}O_2$) 1%, methylethyl/methylethenyl benzene (C_9H_{12},C_9H_{10}) 12%, 1,3-propanediyl-bis-benzene 1,1 ($C_{15}H_{16}$) 12%, and esters ($C_{17}H_{34}O_2$, $C_{19}H_{38}O_2$) 12%.

3.2. *Engine performance and exhaust emissions*

Engine performance and emission parameters when operating on DSPO-BD blends were assessed against those of FD and BD (B100) operation. Brake specific fuel consumption (BSFC) and thermal efficiencies results were better for 20% blends than for 30% blends (Fig. 3). At full load, BSFC was 14−18% and 4−8% higher than FD and BD respectively, when operated on both 20% and 30% DSPO-BD blends (Fig. 3a). As the LHVs of the DSPO blends are less than that of FD or BD, more fuel is needed for the same engine output. Similarly, as the viscosities of the DSPO-BD blends are higher than that of FD this leads to less efficient mixing of fuel and air. In contrast, the fuel consumptions were comparable when expressed in volume rather weight basis due to the higher densities the DSPO-BD blends; and this was almost similar when compared to BD in all load conditions, but higher by approximately 6% than FD at full load (Fig. 3b, Table 2). At low loads, the brake thermal efficiency from both blends were close to those from BD and 4% higher than FD, but at full load efficiencies were about 3−6% lower than BD and were closer to FD (Fig. 3c).

Emissions of CO_2 were almost the same for BD and DSPO-BD blends at all loads, but higher by about 4% than FD at higher load conditions (Fig. 4a). The amount of air intake (i.e. oxygen content) was constant throughout the engine test – so, at higher loads the fuel to air ratio decreased, and hence in the case of FD operation, CO emission increased sharply at full load (Fig. 4b) due to the lack of oxygen content in the mixture. In contrast to this, sharp increases in the CO emissions were not noticed in the case of DSPO-BD blends due to having lower carbon-to-oxygen ratio as compared to FD (Fig. 4b, Table 2). In general, at higher loads CO and CO_2 emissions

were higher with DSPO blends when compared with FD, as higher amounts of the DSPO blends were burned for the same engine output (Fig. 4a, 4b). Oxygen emissions were almost the same between DSPO blends and BD; but slightly lower for all three fuels when compared with FD (Fig. 4c). Higher combustion temperatures in CI engines generally give higher NO_x emissions. The presence of higher water content in the DSPO-BD blends (Table 2) lowered the combustion temperature which caused lower NO_x emissions (Fig. 5a). For 20% and 30% blends and at full load, NO_x emissions were decreased by about 12% and 6% respectively compared to FD (Fig. 5a). In addition, these observations were consistent with the higher density of 30% DSPO-BD blend (Table 2); the higher the density the more NO_x emitted. Exhaust temperature is important for poly-generation applications (e.g. CHP, tri-generation). Little difference was observed in exhaust gas temperatures among the four fuels tested (Fig. 5b). Smoke levels were similar at low load conditions for all four fuels; but at higher loads, the smoke opacity values of DSPO-BD blends were slightly lower than for FD and BD.

3.3. *Combustion characteristics*

Smooth engine operation was observed with the 20% DSPO blend; however, the engine experienced minor knocking when operated on the 30% DSPO blend, as evident from the pressure-crank angle diagram (Fig. 6a, 6b). The low cetane number of the 30% DSPO blend caused this behaviour. Typical cetane number of PO has been reported as 5.6; whereas cetane numbers of FD and typical BD are 47 and 45 respectively [20-22]. Peak cylinder pressures of 30% DSPO blend were about 6−13% and 5−6% higher respectively, when compared to BD and FD operation. The cylinder pressure profiles for 20% DSPO blend, BD and FD were almost similar, and only minor peak pressure variations were observed. At low loads, integral heat release from combustion was almost the same for all fuels; and at higher load conditions, the integral heat released by DSPO-BD blends were decreased but the peak burn rates were higher (Fig. 7a, 7b). At full load, the peak burn rate of the 30% DSPO blend was about 26% and 12% higher than with FD and BD respectively (Fig. 7b). Higher peak burn rates in the case of DSPO blends may have been caused by long ignition delay and short combustion periods. Total combustion duration is defined as the duration of the crank angle between 5% and 90% combustion. Ignition delay is related to the ignition quality (ie. cetane number) of the fuel. Compression ratio, engine speed, cylinder gas pressure, temperature of the air intake, and quality of fuel spray affects the ignition delay period [23]. Fig. 8a shows that, in the case of DSPO-BD blends the start of combustion was delayed compared to FD at most load conditions. Total combustion duration increased with engine load for all fuels. In all load conditions, the combustion duration was shorter for the 30% DSPO blend than for FD and BD. For the 20% DSPO blend, the

duration was shorter than for FD operation only at higher load conditions; no significant trends were observed between 20% DSPO blend and BD in this respect (Fig. 8b). The short duration in the case of DSPO operation may be explained by less efficient mixing with inlet air as compared to the FD and BD, leading to a smaller amount of air-fuel mixture effectively available for combustion. At full load, combustion duration of the 30% DSPO blend operation was almost 12% lower than for FD (Fig. 8b). In the case of engine testing with other types of pyrolysis oils [24, 25], long ignition delays and short combustion periods were also reported. Higher cylinder pressure and high heat release rates of pyrolysis oil combustion are also reported in the literature [26-28]. The fuel injection pressure was higher in the case of DSPO blends; at full load, it was higher by approximately 17% than FD.

4. Conclusions

A three-cylinder indirect injection CI engine, with nominal output 9.9 kW, has been tested with 20% and 30% de-inking sludge pyrolysis oil, produced by intermediate pyrolysis, blended with biodiesel. Performance, emissions and combustion characteristics were compared against FD and BD (B100) operation at constant speed of 1500 rpm. The physical and chemical properties of all four fuels were measured. With DSPO blends, full engine power was achieved. Between the 20% and 30% blends, there were few differences in the results from the engine tests. However when compared to FD and BD, there were a number of small but significant differences when using DSPO-BD blends:

i. At full load, the BSFC was increased by 6% on a volume basis and 14−18% on a weight basis when compared with FD; whereas, BSFC was only 4−8% higher on a weight basis when compared to BD operation.

ii. At full load, brake thermal efficiencies were about 3−6% lower than BD but were almost similar to FD.

iii. Compared to FD, CO_2 and NO_x emissions were increased by 4% and decreased by 6−12% respectively. At full load, CO emission of 30% DSPO blends was almost 10 times lower than FD operation.

iv. Compared to FD, peak cylinder pressures were about 5-6% higher for 30% blend and were almost the same for the 20% DSPO blend.

v. In the case of DSPO-BD blends, the start of combustion was delayed but the burn rate was high as compared to FD. At full load, the peak burn rates of 30% DSPO blend were 26% and 12% higher than the FD and BD operation respectively.

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vi.   Total combustion duration was decreased for both blends; for 30% blend, at full load the duration was decreased by 12% when compared to FD.

The cylinder gas pressure diagrams indicated stable engine operation with 20% DSPO blend, but the engine experienced some minor knocking in the case of 30% DSPO blend. This study concludes that up to 20% DSPO blended with biodiesel can be used successfully without addition of any ignition additives or surfactants. After three hours of operation no deterioration in engine condition was observed. However, some solid deposits were observed inside the fuel filters; these were probably caused by non-miscibility of the residual diesel with pyrolysis oil blends in the fuel supply system. Alternative fuel switching techniques such as running the engine with B100 before switching to DSPO blend may help to reduce the amount of deposits in the fuel system. Areas of future work include: (i) long term tests to assess engine durability, (ii) production of better quality pyrolysis oils by optimisation of the pyrolysis parameters, (iii) engine components and fuel supply modification including investigation into alternative fuel switching techniques, and (iv) engine testing using higher DSPO blends mixed with ignition additives. As the properties of PO change with temperature, cooling of the inlet fuel may also be investigated for better engine performance and to preserve the engine life.

The use of this alternative fuel would help reduce greenhouse gas emissions as well as waste sent to landfill. It is estimated that, if the UK's total annual production of DS were utilised, then as much as 50,000 tonnes per year of PO could be produced. Based on the total fossil diesel used in 2010, this would replace approximately 0.3 % of fossil diesel in the UK [29]. Furthermore, the DSPO potential is about 3% of total biofuels currently consumed in the UK transport sector [30]. Although DSPO can only make a minor contribution by itself, it is expected that similar use of other waste streams such as sewage sludge, municipal refuse and agricultural wastes will help to achieve significant reduction in fossil fuel usage in the UK and other countries. This would also contribute towards the EU's target of achieving 20% of energy from renewable sources by 2020.

REFERENCES

[1] Lou R, Wu S, Lv G, Yang Q. Energy and resource utilization of deinking sludge pyrolysis. Appl Energ 2012; 90: 46-50.

[2] WRAP. Final Report: A new approach to paper mill sludge. First American Scientific Corporation; 2007. Available at http://www.fasc.net/downloads/MSP002_Final_Report_April_2007.93790a39.pdf (accessed 27 Oct 2011).

[3] Gavrilescu D. Energy from biomass in pulp and paper mills. Env Engg Manag J 2008; 7(5): 537-46.

[4] Ouadi M, Brammer J, Hornung A. Sustainable energy from paper industry waste. Proc. Bioten Conf. on Biomass Bioenergy and Biofuels, 21-23 Sept 2010, Birmingham, UK; CPL Press: 267-78.

[5] Forestry Commission. UK biomass power stations. January 2011.

[6] Barth T, Kleinert M. Motor fuels from biomass pyrolysis. Chem Eng Technol 2008; 31(5):773-81.

[7] Jones SB, Holladay JE, Valkenburg C, Stevens DJ, Walton CW, Kinchin C et al. Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case. US Dept of Energy, Pacific Northwest National Laboratory; 2009.

[8] IEA Bioenergy. Better use of Biomass for Energy; 2009. Available at http://www.ieabioenergy.com/LibItem.aspx?id=6476 [accessed 14 Oct 2011].

[9] Bridgwater AV. Biomass Fast Pyrolysis. Therm Sci 2004; 8(2): 21-49.

[10] Demirbas A, Arin G. An overview of biomass pyrolysis. Energ Sourc, Part A: Recov, Utiliz, Env Eff 2002; 24: 471-82.

[11] Technologies. btg World. Available at http://www.btgworld.com [accessed 21 Aug 2011].

[12] Hornung A, Apfelbacher A, Sagi S. Intermediate pyrolysis: A sustainable biomass-to-energy concept- Biothermal valorisation of biomass (BtVB) process. J Sci Ind Res 2011; 70: 664-7.

[13] Hornung A, Apfelbacher A. Combined pyrolysis reformer. Available at http://www.astoninventions.com /downloads/flyers/combined_pyrolysis_reformer.pdf (accessed 12 Oct 2011).

[14] Strezov V, Evans TJ. Thermal processing of paper sludge and characterisation of its pyrolysis products. Waste Manage 2009; 29:1644-8.

[15] Xu C, Lancaster J. Conversion of secondary pulp/paper sludge powder to liquid oil products for energy recovery by direct liquefaction in hot-compressed water. Water Res 2008; 42: 1571-82.

[16] Zhang L, Xu C, Champagne P. Energy recovery from secondary pulp/paper-mill sludge and sewage sludge with supercritical water treatment. Biores Technol 2010; 101: 2713-21.

[17] Ouadi M, Brammer J, Kay M, Hornung A. Waste to Power. Tappi Journal 2012; 11(2): 55-64.

[18] Yanfen L, Xiaoqian M. Thermogravimetric analysis of the co-combustion of coal and paper mill sludge. Appl Energ 2010; 87:3526-32.

[19] Hornung, A. et al. The thermal treatment of biomass, GB Patent Application Number: GB 0808739.7: Application submitted: May 15, 2009. World Patent Applied for (WO 2009/138757; Nov 19, 2009).

[20] Qiang L, Wen-Zhi L, Xi-Feng Z. Overview of fuel properties of biomass fast pyrolysis oils. Energ Conv Managm 2009; 50: 1376-83.

[21] Ikura M, Stanciulescu M, Hogan E. Emulsification of pyrolysis derived bio-oil in diesel fuel. Biom Bioenerg 2003; 24 (3):221-32.

[22] Hossain AK, Davies PA. Plant oils as fuels for compression ignition engines: A technical review and life-cycle analysis. Renew Energ 2010; 35: 1-13.

[23] Mahanta P, Mishra SC, Kushwah YS. An experimental study of *Pongamia pinnata* L. Oil as a diesel substitute. Proc. IMechE Part A: J. Power Energ 2006; 220: 803-808.

[24] Solantausta Y, Nylund N, Gust S. Use of pyrolysis oil in a test diesel engine to study the feasibility of a diesel power plant concept. Biom and Bioenerg 1994; 7(1-6): 297-306.

[25] Frigo S, Gentili R, Tognotti L, Zanforlin S. Feasibility of using wood flash-pyrolysis oil in diesel engines. SAE Technical Paper (No. 982529); 1998.

[26] Murugan S, Ramaswamy MC, Nagarajan G. Assessment of pyrolysis oil as an energy source for diesel engines. Fuel Process Technol 2009; 90:67 -74.

[27] Honnery D, Ghojel J, Stamatov V. Performance of a DI diesel engine fuelled by blends of diesel and kiln-produced pyroligneous tar. Biom Bioenerg 2008; 32: 358-65.

[28] Shihadeh A, Hochgreb S. Diesel engine combustion of biomass pyrolysis oils. Energ Fuel 2000; 14: 260-274.

[29] Department of Energy and Climate Change. Chapter 3 - Petroleum. Digest of United Kingdom energy statistics 2011. http://www.decc.gov.uk/en/content/cms/statistics/publications/dukes/dukes.aspx [accessed 28 Apr 2012].

[30] Department of Energy and Climate Change. Section 6 – Renewables. Energy Trends March 2012. http://www.decc.gov.uk/assets/decc/11/stats/publications/energy-trends/3946-energy-trends-section-6-renewables.pdf [accessed 30 Apr 2012].

Table 1

Table 1

Specification of the experimental engine

Manufacturer	Lister Petter (UK)
Model/type	LPWS Bio3 water cooled
No. of cylinders	3
Bore/stroke (mm)	86/80
Rated speed (rpm)	1500
Continuous power at rated speed (kW)	9.9
Overload power at rated speed (kW)	10.9
Type of fuel injection	Indirect injection. Self-vent fuel system with individual fuel-injection pumps
Fuel pump injection timing	20° BTDC
Cylinder capacity (litre)	1.395
Compression ratio	1:22
Minimum full load speed (rpm)	1500
Continuous power fuel consumption at 1500 rpm	3.19 litres/hr (fossil diesel)
Glow plug	Combustion-chamber glow plugs
Exhaust gas flow	41.4 litres/sec at full loads at 1500 rpm
Jacket water flow at full load	33 litres/min (at 1500 rpm)
Maximum engine jacket water temperature (°C)	99 - 102

Table 2

Table 2

Measured properties of DSPO, BD, DSPO − BD blends and FD

Physical and chemical properties	DSPO	BD (B100%)	20% DSPO + 80% BD	30% DSPO +70% BD	FD
Kinematic viscosity (cSt) at 40°C	12.3	8.2	8.91	9.35	3.01
Flash point temperature (°C)	168	170	105	118	68
pH value @ 22°C	4.8	7.75	5.91	5.73	7.01
Acid number (mg KOH/g)	26.0	0.489	6.74	7.66	0.023
Density (kg/m^3) @ 22°C	980	890	906	920	832
Higher heating value (MJ/kg)	37.04	39.29	38.79	38.58	44.67
Lower heating value (MJ/kg)	34.91	36.49	36.22	36.08	41.87
Water content (% wt.)	4.00	0.37	0.94	1.70	0.06
Carbon residue (% wt.)	3.89	<0.01	0.316	0.518	0.059
Ash content (% wt.)	<0.02	<0.01	<0.01	<0.01	<0.01
Carbon (% wt.)	78.71	77.20	77.15	77.34	84.73
Hydrogen (% wt.)	10.08	13.21	12.11	11.80	13.20
Nitrogen (% wt.)	1.02	0.10	<0.10	<0.10	<0.10
Oxygen (% wt.)	10.08	9.39	10.54	10.66	1.40
Sulphur (% wt.)	0.55	<0.10	<0.10	<0.10	<0.10

Figure 1
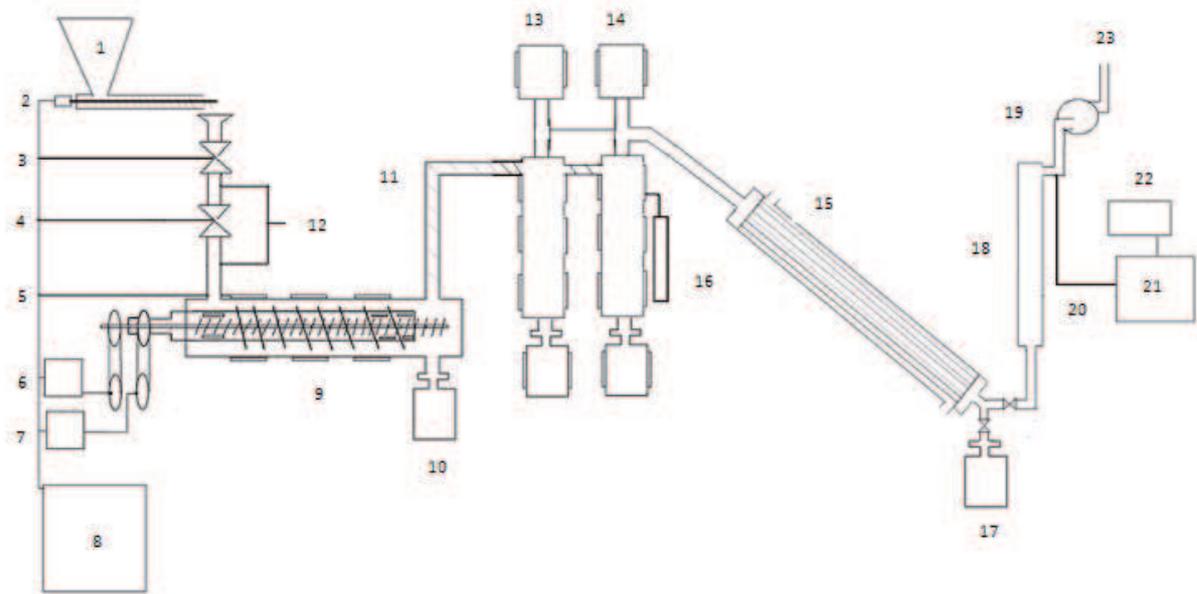
1 Feed Hopper, 2 Auger, 3 Actuating Value, 4 Actuating Valve, 5 Electric Heating Bands, 6 Electric Motor, 7 Electric Motor, 8 Main Control Board, 9 Pyrolysis Reactor, 10 Char Collection Vessel, 11 Heated Line, 12 N_2 Purge Line, 13 Heated Filter Candle, 14 Heated Filter Candle, 15 Shell and Tube Condenser, 16 Filter Candle Control Board, 17 Pyrolysis Oil Collection Vessel, 18 Electrostatic Precipitator, 19 Gas Suction Pump, 20 Gas Sampling Line, 21 Gas Chromatograph, 22 Computer, 23 Extraction Vent

Fig. 1. Schematic diagram of the intermediate pyrolysis used for the production of DSPO

Figure 2

Fig. 2. Schematic diagram of the engine test rig

1: Engine; 2: Dynamometer; 3: Smoke meter; 4: Exhaust analyser; 5: Exhaust data acquisition; 6: Exhaust gas discharge; 7: Dynamometer controller; 8: NI data acquisition for temperature; 9, 10: Kistler combustion analyser; 11: Jatropha/Karanj tank; 12: Diesel tank; 13: 3-way valve; 14: Vent screw; 15: Additional fuel filter; 16: Valve; 17: Fuel measurement; 18: Cold water flow to HX; 19: HX to cool jacket water; 20: Crank angle encoder; 21: Cylinder pressure transducer; 22, 23: Amplifier; 24: Injection pressure sensor; 25: NI DAQ; 26: Thermocouple

Figure 3

Fig. 3a - BSFC (wt.) vs. brake power
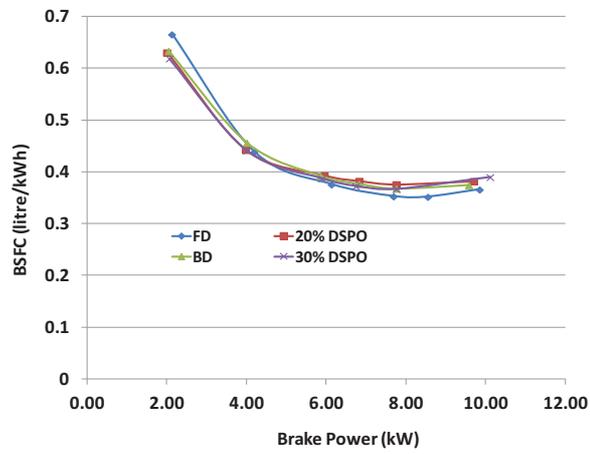
Fig. 3b - BSFC (vol.) vs. brake power
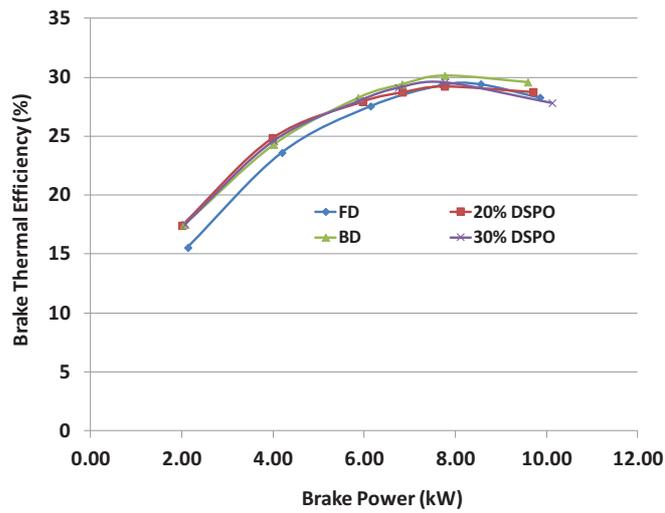
Fig. 3c - Thermal efficiency vs. brake power

Fig. 3. Comparative performance of fuel consumption and thermal efficiencies

Figure 4
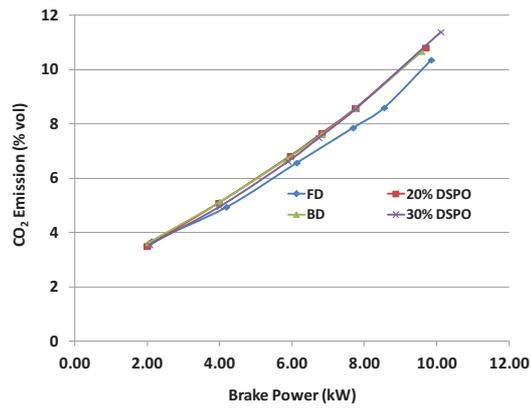
Fig. 4a - CO$_2$ emission vs. brake power
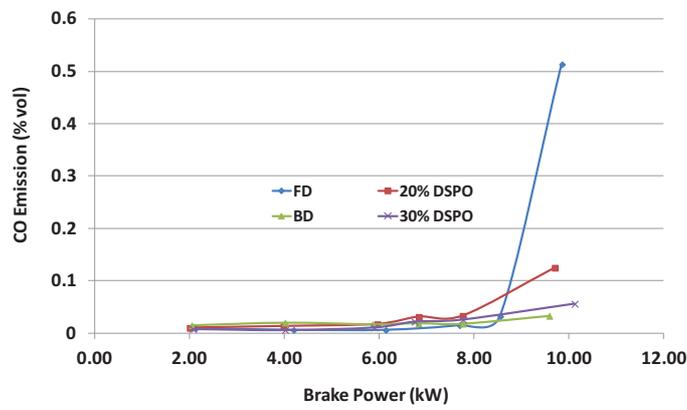
Fig. 4b - CO emission vs. brake power
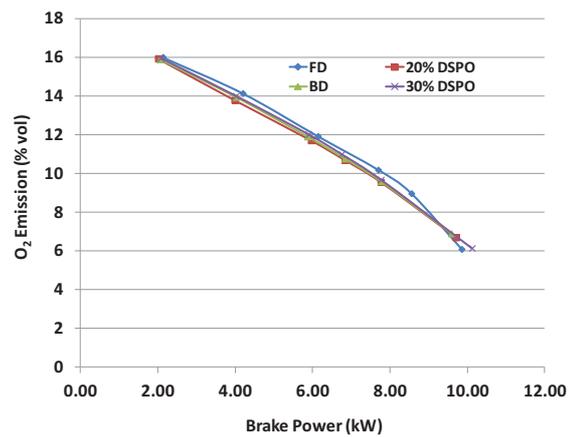
Fig. 4c - O$_2$ emission vs. brake power

Fig. 4. Comparison of exhaust emissions vs. brake load: DSPO-BD, FD and BD fuels
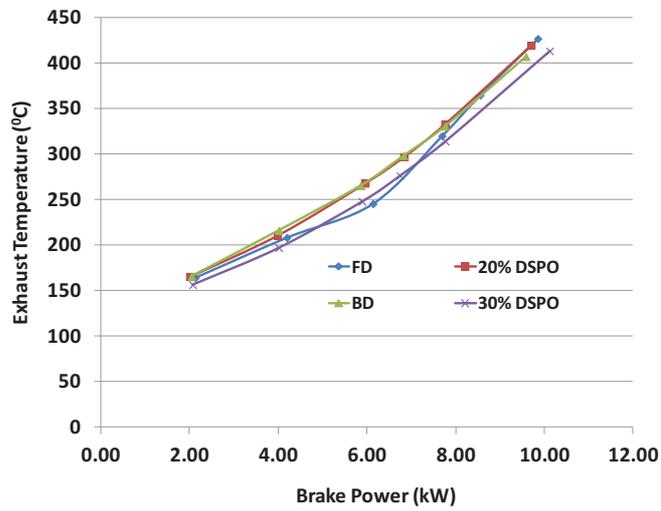
Figure 5
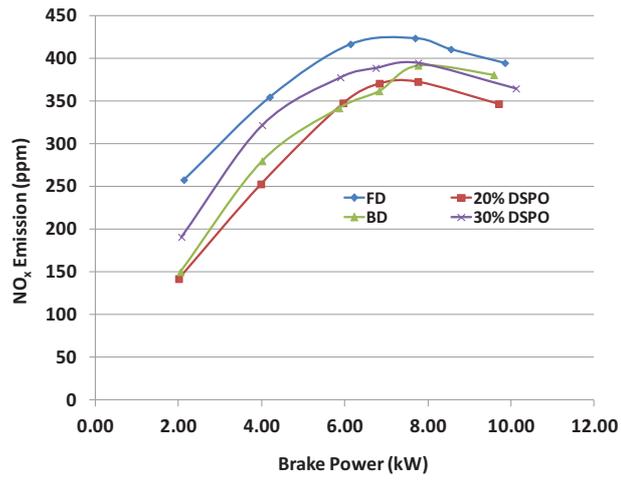
Fig. 5a - NO$_x$ emission vs. brake power

Fig. 5b - Exhaust gas temperatures vs. brake power

Fig. 5. Comparison of NO$_x$ emissions and engine exhaust gas temperatures

Figure 6
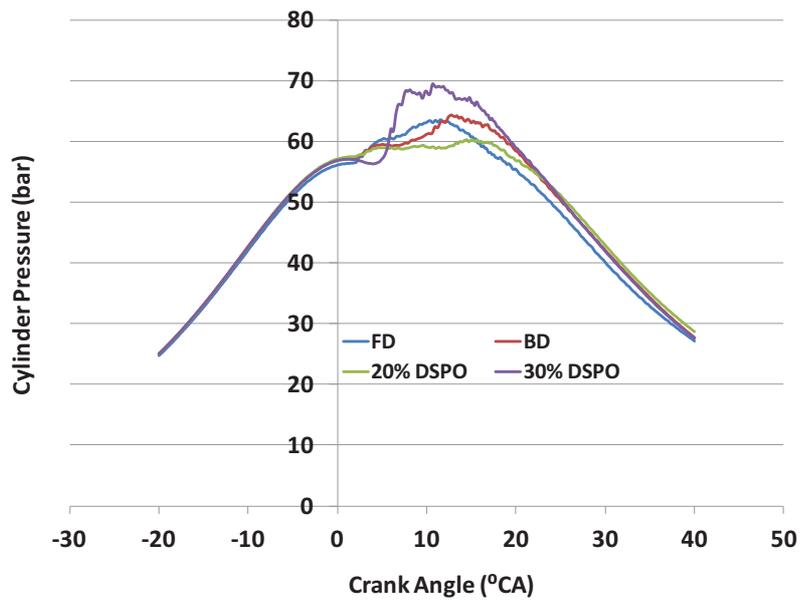
Fig. 6a – at full (100%) load
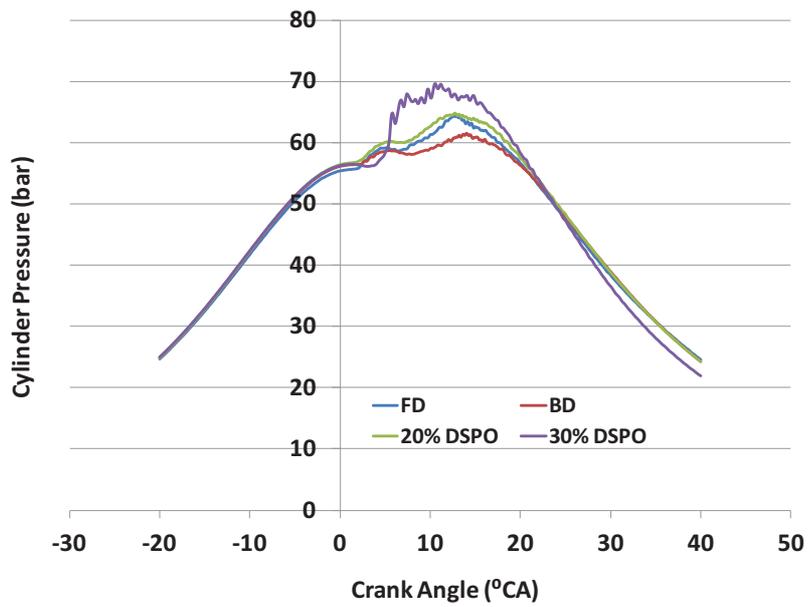
Fig. 6b – at 70% load

Fig. 6. Cylinder pressure vs. crank angle for various fuels

Figure 7
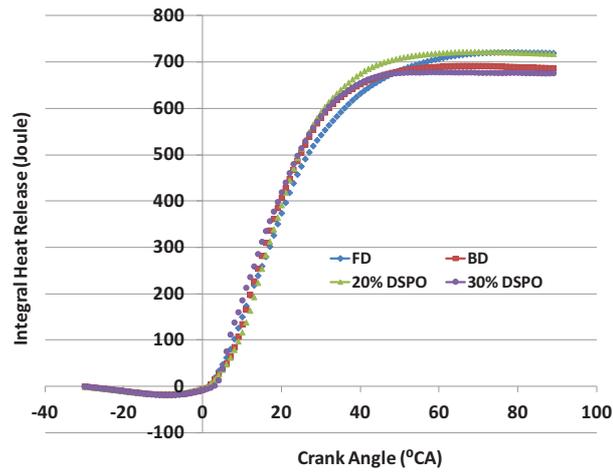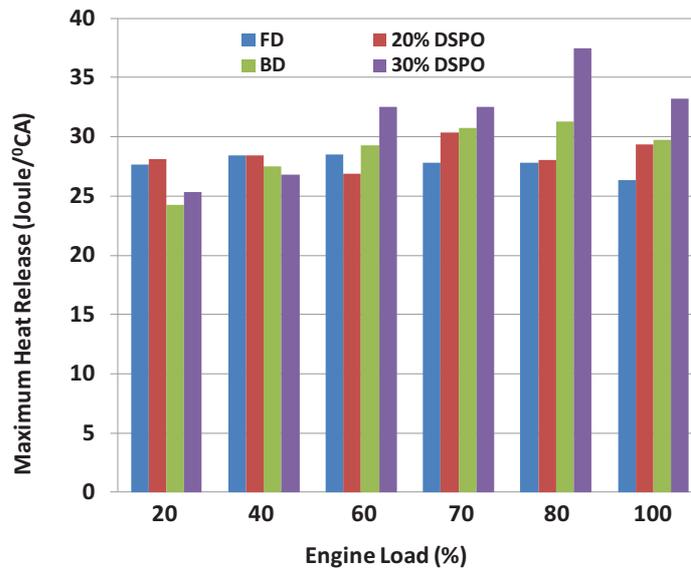

Fig. 7a – Integral heat release at full load

Fig. 7b − Maximum heat release rate at different loads

Fig. 7. Integral heat release and maximum heat release rates for various fuels
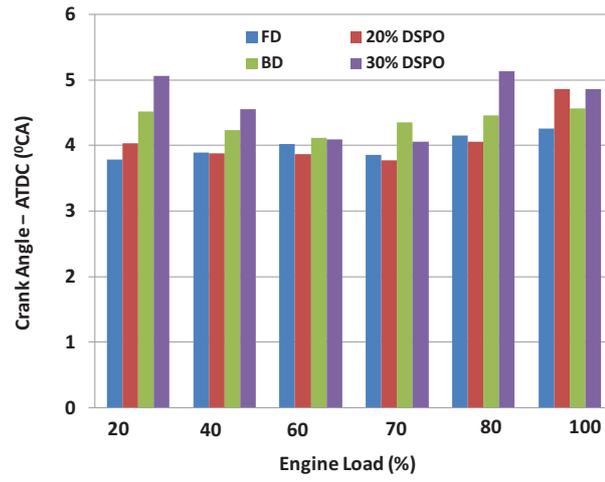
Figure 8

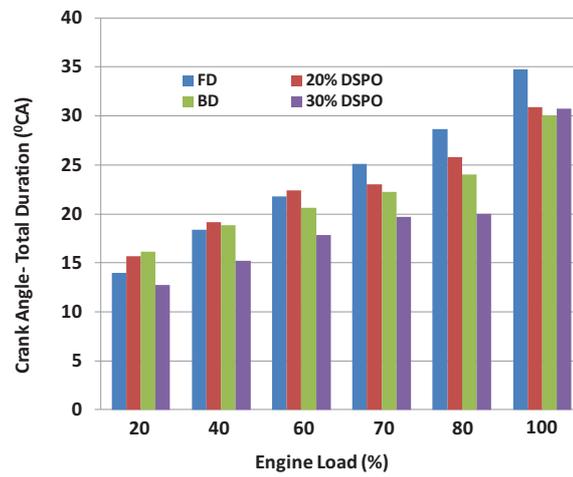Fig. 8a – Crank angle position at 5% combustion

Fig. 8b – Total combustion duration

Fig. 8. Combustion vs. engine loads for various fuels