Performance of a Thermally Insulated Constant Speed Diesel Engine with Dioxane Blended Fuels

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GJRE Classification (FOR)
A.B 090201. 091302. 091305

***Abstract*- Dioxane (1,4 Dioxane) An Ether Derived From Alcohol Has Favorable Properties As An Alternative Or Blend Stock For Diesel Fuels. This Work Presents The Comparative Analysis Of Performance, Emission And Combustion Characteristics Of A Single Cylinder Direct Injection Diesel Engine Fuelled With Various Mixtures Of Dioxane And Conventional Diesel Fuel With And Without Thermal Barrier Coating. Results Show Addition Of Dioxane With Diesel Has The Potential To Reduce Smoke Density With Slight Increase In Nox And Drop In Fuel Economy For A Normal Engine While, Increase In Efficiency, Increase In Cylinder Pressure, Reduction In Nox And Reduction In Maximum Heat Release Rate Were Observed When The Engine Components Were Replaced With Zirconia-Alumina Plasma Spray Coated Components.**

I. Introduction

Due to the shortage of petroleum product and its increasing cost, efforts are on to develop alternative fuels especially to diesel oil for full or partial replacement. The most promising substitutes for petroleum fuels are the alcohols but are not suitable for compression ignition (CI) engines because of its low cetane number and non miscibility. The addition of oxygen containing compounds to diesel fuel has been proposed as a method to complete the oxidation of carbonaceous particulate matter and associated hydrocarbons. In addition, many oxygenates have high cetane number and their association with diesel results in high cetane number and hence lower exhaust emissions. Due to this advantages, there is growing interest in the introduction of oxygenates into diesel fuel.

Di methyl ether (DME) was considered as an ignition-improving additive to methanol powered diesel engines [1]. However, DME is a gaseous fuel and therefore requires that a vehicle be adopted for gaseous operation [2]. In addition, the fuel delivery infrastructure is not currently suitable to distribute large quantities of a gaseous fuel. For these reasons, there is interest in new liquid compression ignition fuels or fuel additives, which have high cetane rating and reduce particulate emissions and at the same time they are compatible with current vehicle technology and fuel delivery infrastructure. Some oxygenated compounds like ethers or methyl carbonates have been tested as additives to improve the performance of diesel fuels [3]. Particularly 1,2-diemthoxyethane, 1,2- dimethoxypropane, butyl ether, 2-methoxyethyl ether, 2- ethoxyethyl ether, pentyl ether and dibutoxymethane [4,5].

Bailey et al. [6] suggest DEE as a potential replacement fuel for CI Engines. The molecular weights of DEE are low; the molecules have high hydrogen to carbon ratios and a low number of carbon-to-carbon bonds. All these properties lower the tendency of forming solid carbon particulate during combustion. The molecules contain oxygen, which also suppress the formation of soot. The molecular bonds break up to radicals at reasonable activation energy, which leads to high cetane numbers.

P. Mohanan et al.,[7] studied the effect of DEE on the performance and emissions of a four-stroke direct injection diesel engine and found that 5% DEE can be blended with diesel fuel to improve the performance and to reduce emissions of the diesel engine even though experiments were carried out successfully up to 25% DEE blend. Gong Yanfeng et al.,[8] proved 15% of 2-methoxyethyl acetate (MEA) can be used to decrease exhaust smoke as a new oxygenated additive of diesel with marginal increase in efficiency.

Zhenkun Lin et al., [9] studied combustion intermediates of a cyclic oxygenated hydrocarbon, 1,4-dioxane at low pressure with an equivalence ratio of 1.80 and found no aromatic intermediates, that was a prominent difference between the fuel-rich flames of 1,4-dioxane and previously studied non cyclic oxygenated hydrocarbons.

C. Sundar Raj et al [10] formed a stable ethanol-diesel blended fuel with the help of 1, 4 dioxane additive, and analyzed the performance, emissions and combustion data for an evaluation of different oxygen content based on ethanol content on a single cylinder DI diesel engine and concluded that 10% addition of 1,4 dioxane by virtue of its properties is capable to stabilize 30% ethanol addition with 60% diesel by volume, and can be used as a blended fuel with diesel in a compression ignition engine with significant reduction in exhaust emissions as compared to neat diesel without any engine modifications.

Approximately one third of the heat released by the combustion of the fuel in a diesel engine is dissipated to the cooling medium. If this can be reduced by thermally insulating the piston crown, cylinder head then the gases in the cylinder will lose less heat and hence, there will be a possibility for extracting more work. The state of art of Thermal barrier coating (TBC) provides the potential for higher thermal efficiencies of the engine. The objective is not only to reduce cylinder heat rejection and thermal fatigue protection of underlying metallic surfaces, but also

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for possible reduction of engine emission. Ceramics have unique thermal, mechanical, chemical and electrical properties, but their high fabrication cost, brittleness and size and shape limitations as monolithic components restrict many potential applications. Plasma spray is one of the methods that offer a flexible and relatively economic means for producing coated engine components.

Banapurmath, N R and Tewari, P G[11] made an attempt to utilize the low volatile Honge oil and Honge oil methyl ester (HOME) in a CI engine to study the performance, combustion, and emission characteristics with a ceramic coating of partially stabilized Zirconium (PSZ) on combustion chamber elements and found improvement in brake thermal efficiency and reduction in emissions. M. B. Beardsley et al [12] demonstrated thermal efficiencies of 54% by single cylinder engine testing on coated engines. Prasad. R et al [13] used PSZ coating on the piston crown face and reported a 19% reduction in heat loss through the piston. P.Ramu and C. G Saravanan [14] studied the effect of ZrO_2-Al_2O_3 and SiC coating on diesel engines and observed less NOx emission for coated engines. They also found that addition of small quantity of 2-methoxyethyl (MEA) has the potential of reduce NOx, cylinder pressure and heat release rate. C. Sundar Raj et al [15] reported 7% increase in efficiency with considerable amount of smoke reduction for 20% ethanol–diesel with 10% dioxane on ZrO_2-Al_2O_3 coated engine.

Based on the previous studies the objective of this paper is to study the combustion and emission characteristics of a diesel engine driven by dioxane and diesel blends with TBC (WC) and without TBC (WOC) and to compare the results with sole fuel

II. Fuel Properties

1, 4 dioxane a new oxygenate is investigated in this study. The hydrocarbon moieties of these molecules constitute the hydrophobic portion of the structure due to their strong affinity over diesel fuel while the two oxygen atoms form very strong hydrogen bond with ethanol as shown in Figure 1, therefore it is non ionic and can form a stable, homogenous emulsion with ethanol also.

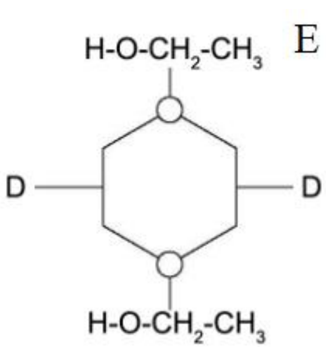

Figure 1 representation of a micelle between the Dioxane, diesel (D) and Ethanol (E)

General fuel properties of 1, 4 dioxane, diesel and the tested values of 50% dioxane and 50% diesel blend (Dy50) are presented in Table 1. It can be seen that, as a compression ignition fuel, dioxane has several favorable properties for on board storage.

Table 1Chemical properties of Diesel, 1, 4 Dioxane

	Molecular Formula	Molecular weight	Density at 20 °C (×103kg/m2)	Boiling point (°C)	Flash point (°C)	Viscosity (mPa s)	Cetane Number	Calorific Value (KJ/Kg)	% of oxygen by weight
Diesel[a]	CxHy	190–220	0.829	180 – 360	65 – 88	3.35	45 – 50	42500	0
Dioxane[b]	$C_4H_8O_2$	88	1.034	101	12	1.20	50	-	36

a. Table on Gasoline and Gasohol from Alcohols and Ethers, API Publication 4261, Second Edition (July1988)

b. United States Environmental Protection Agency, Retrieved on 2006-02-02

III. Preparation of Coating

Commercially available ZrO_2 and Al_2O_3 ceramic headstock powders (Sulzer Metco) with particle sizes ranging from 38.5 to 63 µm and Ni-20Cr-6Al-Y metal powder (Sulzer Metco NiCrAlY-9) with particle size ranging from 10 to 100 µm were used. The surfaces were grit blasted using 400 mesh Al_2O_3 powder. The substrates were grit blasted until a surface roughness of alumina (Ra-4) was achieved. The grit blasted substrates were ultrasonically cleaned using anhydrous ethylene alcohol and dried in cold air prior to coating deposition. A NiCrAlY bond coat of about 150 µm was air plasma sprayed on to the substrate. ZrO_2 of 150 µm was deposited over the bond coat and Al_2O_3 was sprayed over ZrO_2 coat. The thickness of Al_2O_3 was also150 µm. Air plasma spray system (Ion Arc 40 KW) was used to deposit the coating. No air cooling on the back side of the substrates was applied during the spraying process.

IV.Experimental Setup and Procedure

Experiments were conducted on a, single-cylinder, air-cooled, direct injection diesel engine developing a power output of 5.2 kW at 1500 rev/min connected with a water

Cooled eddy current dynamometer. The engine was operated at a constant speed of 1500 rpm and standard injection pressure of 220 bar. The specification of the engine is given in table 1. The fuel flow rate was measured on volume basis using a burette and a stop watch. K-type thermocouple and a digital display were employed to note the exhaust gas temperature.

Table 1 Engine specification

Type	Vertical, Water Cooled, Four Stroke
Number of Cylinder	One
Bore	87.5 mm
Stroke	110 mm
Compression Ratio	17.5:1
Maximum Power	5.2 Kw
Speed	1500 Rev/min
Dynamometer	Eddy Current
Injection Timing	23° Before TDC
Injection Pressure	220 Kgf/cm2 , Direct Injection

Smoke level was measured using a standard AVL437C smoke meter. The gas to be measured is fed into a chamber with non reflective inner surfaces. Light produced by an incandescent bulb scatter on the photo cell from reflections or diffused light inside the chamber. The system converts the current delivered from the photocell in to a linear function of the received light within the operating temperature range. The absorption coefficient is calculated in accordance with ECE-R24 ISO 3173 with an accuracy of 0.025 m-1. The equipment has a microprocessor controlled program sequence to check the measurement process and to store such values as pressure, temperature, opacity, absorption.

Exhaust emissions of unburned hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO2), oxygen(O2), oxides of nitrogen(NOx) were measured on the dry basis. A Non Dispersive Infrared (NDIR- AVL-444 digas) analyzer was used. The exhaust sample to be evaluated was passed through a cold trap (moisture separator) and filter element to prevent water vapour and particulates from entering into the analyzer. The analyzer was periodically calibrated according to the instructions of the manufacturer. Hydrocarbons and NOx were measured in parts per million (ppm) hexane equivalents and carbon monoxide, carbon dioxide and oxygen emissions were measured in terms of percentage volume. The accuracy and the measuring range of the analyzer is given in table 2

Table 2 Accuracy and measuring range of AVL-444 digas analyzer

Measured Quality	Measuring Range	Resolution	Accuracy
CO	0~10 vol%	0.01 vol%	< 0.6 vol % $\pm 0.03\ vol$
CO_2	0~20 vol%	0.1 vol%	< 10 vol % $\pm 0.5\ vol$
HC	0~20000 ppm vol	≤ 2000:1 ppm Vol	< 200 ppm vol % $\pm 10\ ppm\ vol$
O_2	0~22 vol%	0.01 vol%	< 2 vol % $\pm 0.1\ vol$
NOx	0~5000 ppm vol	1 ppm Vol	< 500 ppm vol % $\pm 50\ ppm\ vol$
Engine Speed	400~6000 min^{-1}	1 min^{-1}	$\pm$1% of ind. value
Oil temperature	-30~125^{0}C	1^{0}C	$\pm$4^{0}C
Lambda	0~9.999	0.001	Calculation of CO, CO_2, HC, O_2

AVL Combustion analyzer with 619 Indi meter Hardware and Indwin software version 2.2 is used to measure in cylinder pressure, heat release rate, IMEP etc., It consists of inbuilt analog to digital convertor, charge amplifier with PC interface. In cylinder was measured with a water-cooled piezoelectric transducer. The transducer was mounted flush on the cylinder head surface for avoiding passage effects. A piezoelectric transducer produces a charge output, which is proportional to the in cylinder pressure. The charge output was supplied to the inbuilt charge amplifier of the AVL combustion analyzer where it was amplified for an equivalent voltage. A 12-bit analog to digital converter(A/D Converter) was used to convert analog signals to digital form. The A-D converter had external and internal trigging facility with sixteen single ended channels. Data from 100 consecutive cycles can be recorded. Recorded signals were processed with specially developed software to obtain combustion parameters like peak pressure, maximum rate of pressure rise, heat release rate etc. The schematic experimental setup is shown in Figure 2

Base data was generated with standard diesel fuel. Subsequently five fuel blends of dioxane with diesel ranging from 10 to 50% by volume, namely (Dy10, Dy20, Dy30, Dy40 and Dy50) were prepared and tested. Readings were taken, when the engine was operated at a constant speed of 1500 rpm for all loads. Parameter like engine speed, fuel flow and the emission characteristic like NOx and smoke were recorded. The performance of the engine was evaluated in terms of brake thermal efficiency, brake power, brake specific fuel consumption from the above parameters. The combustion characteristics like cylinder pressure and heat release rate were noted for different blends. The experiments were repeated for the same fuels after thermally insulated the engine with a thin layer ZrO_2 – Al_2O_3 coated piston, cylinder liner, head and bottom of the valves and the results were compared

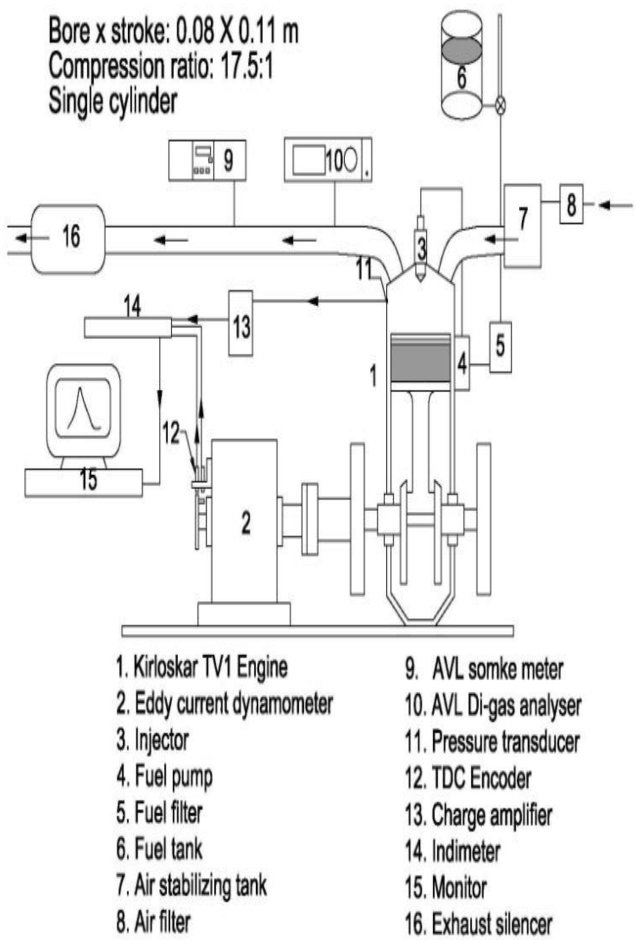

Figure 2. Experimental setup

V. Results and Discussion

As dioxane is having oxygen in its structure, more amount of fuel can be burnt in a given amount of air and hence the BSFC decreases for the blends compared with baseline fuel up to 10% dioxane addition. But, the heat value of the fuel mixture for higher blends decreases as the heat value of dioxane is less than diesel. Hence in order to maintain the same power, more fuels are consumed. As a result, BSFC will increase as the blended fuels with high dioxane concentration are used. Fig.3 shows the BSFC for different dioxane additions with and without thermal insulation. Decrease in BSFC is observed on TBC engines due to substantial reduction in combustion chamber heat transfer and reduced friction due to increased wall temperature as indicated by R. H. Thring [16].

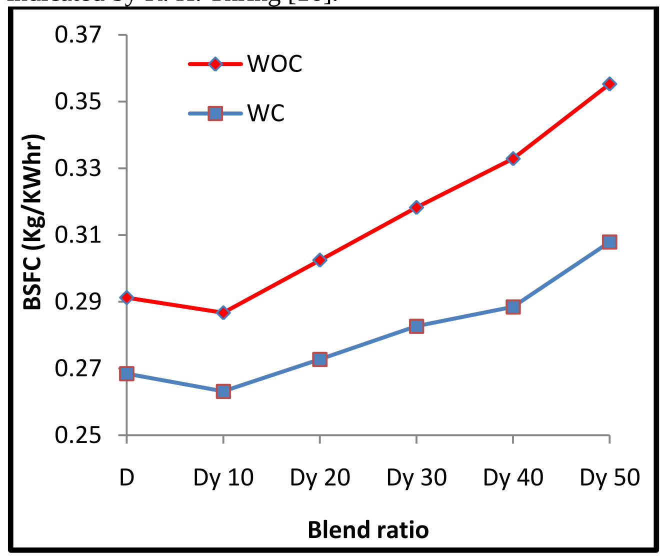

Figure 3. Brake specific fuel consumption for different dioxane blends at full load

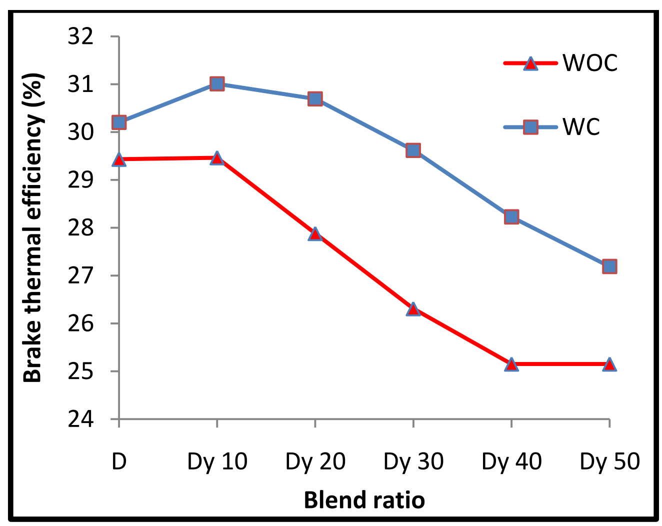

Figure 4. Brake thermal efficiency for different dioxane blends at full load

TBC engine improved the brake thermal efficiency of sole fuel by 3.8% when compared to the standard engine due to the in cylinder heat transfer reduction and increase in combustion duration as indicated by Ramu and Saravanan [14].The presence of oxygen due to dioxane in the oxygenated fuel, improve the combustion, especially diffusion combustion and hence increase the brake thermal efficiency. Figure 4 compares the effect of oxygenated fuel blend on the brake thermal efficiency for the standard and TBC engine. The maximum Brake thermal efficiency occurs for B10 blend ratio on the standard engine. The brake thermal efficiency decreases with increase in dioxane quantity as it reduces total heat value of the mixture. TBC engine recoded higher efficiency than the sole fuel at normal onditions of the engine up to B30 blends and thereafter decreases, hence B30 is considered as optimum blend for a TBC engine.

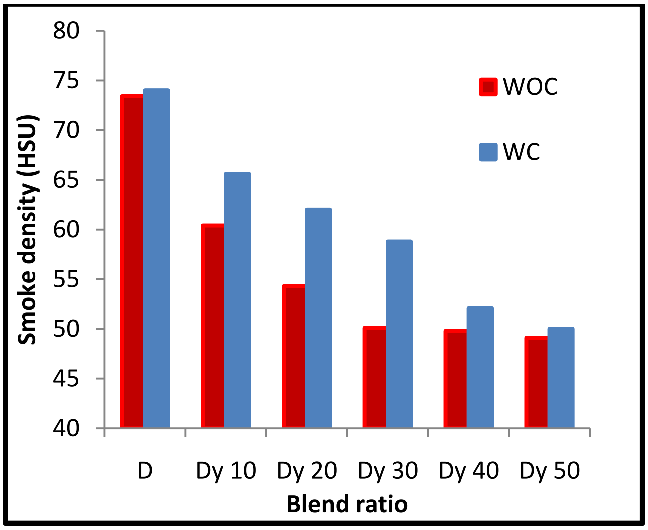

Figure 5. Smoke density for different dioxane blends at full load

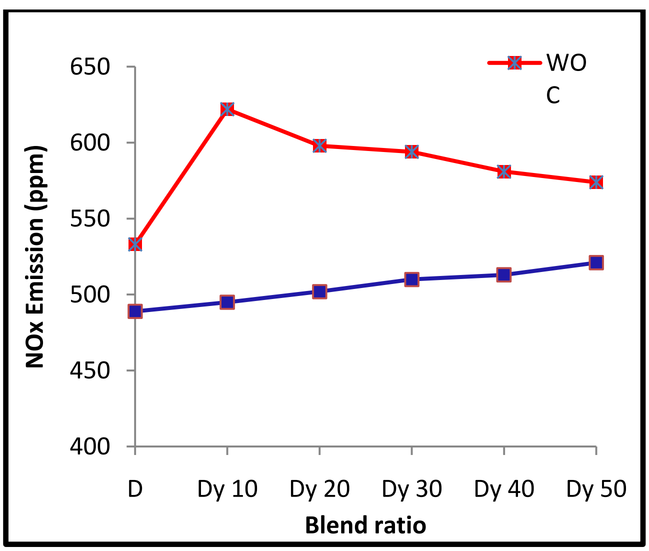

Figure 6 NOx emission for different dioxane blends at full load

The variation of smoke density for different dioxane blends at peak load is shown in figure 5. The addition of dioxane, decrease the smoke density. The improvement of smoke emission can be explained by the enrichment of oxygen owing to dioxane. Since the smoke is mainly produced in the diffusive combustion phase, the addition of oxygenated fuel leads to an improvement in diffusive combustion. The results reveal that the tendency to generate soot from the fuel-rich regions inside diesel diffusion flame is decreased by dioxane in the blends. The increase in smoke density for TBC engine may be due to the increase in combustion duration as shown in figure 10.

Fig.6 shows the emission of NOx for different dioxane blends at full load for the standard and TBC engine. Nitrogen oxides emissions are predominately temperature phenomena. In principle, the maximum temperature, residence time, and oxygen concentration in the mixture have a dominant effect on NOx emission. 20% increase in NOx emissions were observed for Dy10 blends. Higher blends show suppressed NOx emission due to retarded ignition timing with an increase in mixing fraction of dioxane. It was predicted that NOx emission increases, because flame temperature of the mixed fuel becomes higher due to advanced homogeneity for a TBC engine. But TBC significantly reduced NOx emissions as the maximum heat release rate occurs in the expansion stroke due to the mixing effect of low flash components.

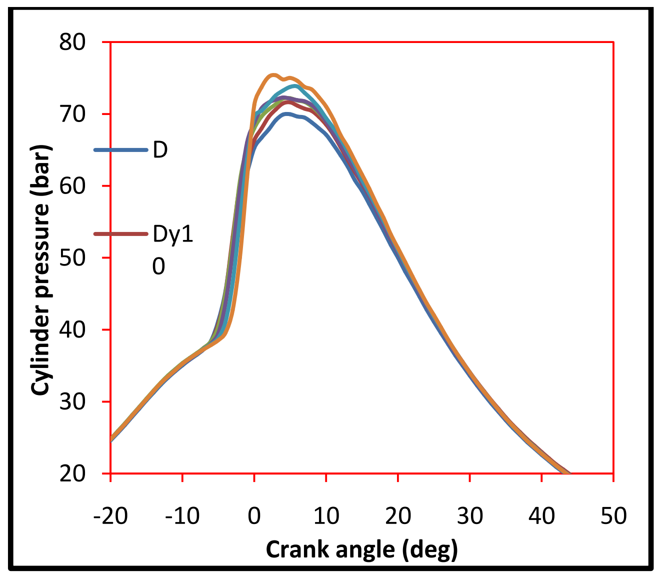

Figure 7 Cylinder pressure against crank angle

Dioxane contain oxygen molecule that increase the spray optimization and evaporation. Hence it improves the combustion process of the engine. Fig. 7 illustrates cylinder pressure traces of dioxane blended diesel fuels. It is found that at the same engine speed and maximum load, the ignition delay for the oxygenated blend is higher (the pressure rise due to combustion starts later) than the corresponding one for the neat diesel fuel case, while there is a slight increase in the maximum pressure. C.D. Rakopoulos et al. (2007)[17] obtained the same result for 15% ethanol but with no appreciable difference in the maximum pressure due to the lower cetane number of ethanol. In this case, the increase in pressure is due to the presence of the dioxane which improves the cetane number of the mixture. One can observe from figure 8 that TBC decreases the ignition delay for the oxygenated fuel due to the increasing gas temperature and hence increases the cylinder pressure. It can also be seen that for the oxygenated fuel on TBC engine higher pressure region change sharply as with diesel engine, but the durations of the higher pressure period is shorter than that of diesel engine.

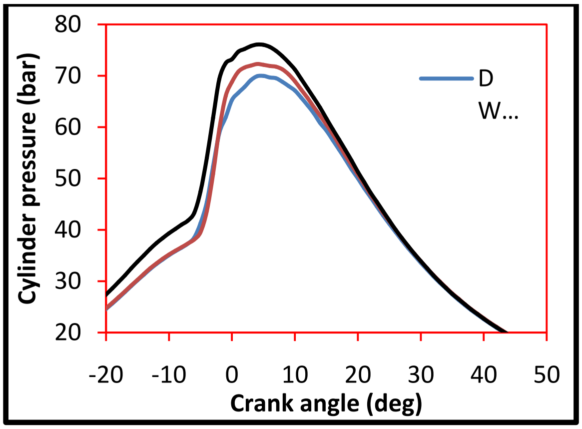

Figure 8 Comparison of Cylinder pressure against crank angle for Dy30 blends

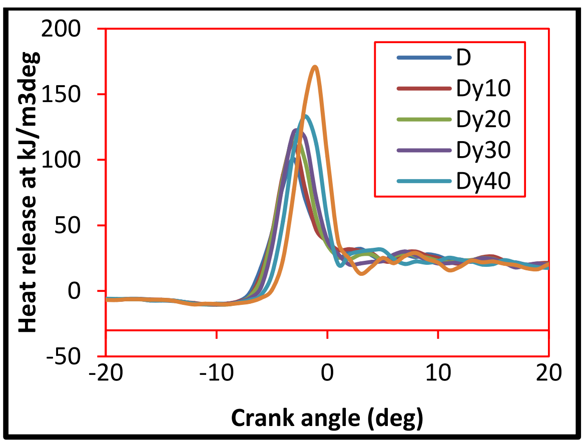

Figure 9. Heat release rate against crank angle

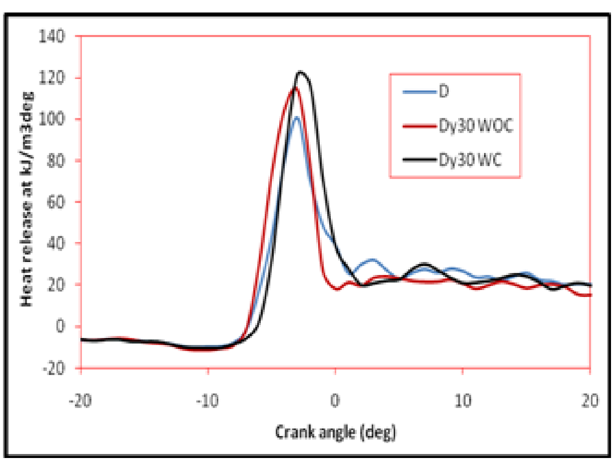

Figure 10 Comparision of heat release rate for Dy30 blends for the engine WC and WOC

One can again observe, from the figure 9, that the ignition delay for the oxygenated blend is higher than the corresponding one for the neat diesel fuel case, while its premixed combustion peak is much higher and sharper. It is the lower flash point of dioxane that causes the increase of ignition delay and so the increased amount of 'prepared' fuel for combustion after the start of ignition and is reflected in cylinder pressure. But C.D. Rakopoulos et al. (2007) [17] not experienced any increase in cylinder pressure for 15% ethanol (without any cetane improver) probably because of the counteracting effect of later combustion in a lower temperature environment. It can be seen that for the engine without thermal insulation heat release rate curves of the oxygenated fuel blends and sole fuel shows similar curve pattern although the rate of heat release for the Day 50 shows higher heat release than sole fuel. The reason is the rate of diffusion combustion of the oxygenated fuel increasing the heat release rate – consequently oxygenated fuel has controlled rate of pre-mixed combustion. The heat release rate is further increased for TBC engines due to increased pre-mixed combustion as shown in figure 10.

VI. Conclusion

The results of the present study may be summarized as follows The Brake specific fuel consumption increase with increase in dioxane, TBC decreases BSFC due to decrease in ignition delay.

Dy10 performs almost equivalent to sole fuel. Whereas, 2.5% improvement of brake thermal efficiency was observed for Dy10 blend when compared to sole fuel for TBC engines Smoke reduction is 19% Dy10 at peak load for the normal engine. Slight increase in smoke is observed for the coated engines.

All blends shows increase in NOx emission when compared to sole fuel at all engine conditions. TBC decreases the NOx emissions The peak pressure and heat release rate for blends are higher than sole fuel and is maximum for coated engines On the whole it is concluded that Dy10 blends can be used as fuel in a compression ignition engine with improved performance and significant reduction in exhaust emissions except NOx as compared to neat diesel and that can be controlled by other techniques like turbo charging, Exhaust gas recirculation etc. The dioxane ratio can further be improved in thermally insulated conditions.

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VIII. Abbreviations

BSFC	- Brake Specific Fuel Consumption
DEE	- Diethyl Ether
D	- Diesel
Dy	- 1, 4 Dioxane
DME	- Dimethyl Ether
HSU	- Hatridge Smoke Unit
TBC	- Thermal Barrier Coating
WC	- With Coating
WOC	- Without Coating