Experimental Studies on a Diesel Engine Fueled with Wood Pyrolysis Oil Diesel Emulsions

R.Prakash, R. K.Singh, and S.Murugan

Abstract—**This paper describes the combustion, performance and emission parameters of a diesel engine fueled by wood pyrolysis oil (WPO) diesel emulsion with Diethyl ether (DEE) as an ignition improver. Experimental studies were carried out in a single cylinder, four stroke, air cooled, and DI diesel engine with three fuels that were WPO diesel emulsion, WPO diesel emulsions with addition of 2% and 4% DEE. The results were compared with the diesel fuel data, analysed and it is presented in the paper. The brake thermal efficiency is found to be higher by 6.34, 9.5 and 9.3 percentages for WPO diesel emulsion, WPO diesel emulsions with 2% and 4% DEE respectively when compared with diesel fuel at full load. The percentage reduction in NO emissions of about 19.21, 28.38 and 34.81 were noticed for the above said fuels.**

Index Terms—**Diesel engine, emission, ignition improvers, performance, pyrolysis, surfactant.**

I. Introduction

Many alternative fuels for compression ignition engines were introduced in the last two decades for replacement of diesel fuel. Liquid alternative fuel from biomass has a great scope especially in agriculture based countries and developing countries. Biomass can be converted into useful energy by adopting different techniques such as dry combustion, anaerobic digestion, bio photolysis, pyrolysis, liquefaction, gasification, hydrolysis and solvent extraction [1]. Out of this, pyrolysis has a few advantages such as simple and low pressure operation, negligible waste product and high conversion efficiency of the order of 83%. Pyrolysis is the thermal decomposition process of waste substances in the absence of oxygen or little presence of oxygen. Pyrolysis of biomass may yield solid, liquid and gaseous products [2]. Biomass resources can be used for energy production includes a wide range of materials such as forest residues, energy crops, organic wastes, agricultural residues etc., Agricultural waste, a readily available biomass that is produced annually worldwide has to be utilized effectively [3].

Use of bio-oil in diesel engines is far more limited. Bio-oil, which is produced by fast pyrolysis of lignocellulosic biomass [4], is an oxygenated renewable fuel with a low cetane number [5]. The problems arise when attempting to use this fuel in diesel engines [6] are more specifically due to its higher viscosity and acidity, tars and fine particles it often contains and the formation of char and solid residues during its combustion [7]. Flash pyrolysis oil was used by Solantausta et al. [8] as an alternative fuel in a small diesel power plant. The engine tests revealed that the injector nozzle coking occurred fastly and the bore of the cylinder pressure transducer was clogged by fueling with flash pyrolysis oil. An experimental study was conducted to determine the feasibility of using flash pyrolysis oil of wood in diesel power plants [9]. The study includes the spray analysis, engine tests, thermo gravimetric analysis (TGA), single-drop reactor tests and corrosion tests. The engine was found to have difficulties such as build up of carbonaceous injection system fault and engine seizing. Char generation was noticed in a TGA apparatus and in the single droplet atmospheric reactor. Fast erosion of steel components in the diesel engines was also noticed when it was fueled with WPO. Experiments were performed in a single cylinder diesel engine with blends of WPO with different percentage of oxygenated compounds and micro emulsions of WPO in diesel fuel [10]. Lower NO emissions were observed with increasing the percentage of WPO. Hydro carbon emissions were also found to be lower than diesel up to 30% WPO and beyond that, it increased. Carbon monoxide emissions were more due to the poor self ignition characteristics of WPO.

Major problem with the WPO is its miscibility with diesel fuel. The problem of immiscibility can be solved by upgradation of pyrolysis oil by emulsification process. Emulsion is one of the techniques used for mixing two different fuels, one with a hydroscopic nature. An emulsion was prepared for pyrolysis oil with diesel fuel using a surfactant ranging from 0.8 to 1.5% by volume. The stable emulsion was prepared using two surfactants namely hypermer and CANMET (5). Alahmer et al. [11] have studied the performance of a variable speed diesel engine operating with diesel water emulsion. It was observed that a surfactant could be used to stabilize water in diesel mixture which cannot be maintained by natural mixing of diesel with water because of their different densities and forces of surface tension. Surfactants reduce the surface tension forces so that they permit two different densities of liquid to form a stable emulsion. Emulsion prepared with an addition of Tween 20 surfactant 2% by volume with six different percentages of water as fuels were tested in a diesel engine. It was observed from the results that the 5% by volume of water diesel emulsion gave an optimum brake power and a brake thermal efficiency compared with the other water diesel emulsions. Many surfactants such as Ampholak, Armotan, Carbopol, Hypermer, Tween 20, and Span 20 have been reported to form stable emulsions [10]-[12]. In the present investigation Polysorbate 20 [Tween-20] was used to prepare an emulsion

Manuscript received October 25, 2011, revised December 20, 2011. This work was supported by the Department of Science and Technology, Government of India under Grant No. SR/S3/MERC/061/ 2009.

R.Prakash and Prof. S.Murugan are with the Mechanical Engineering Department, National Institute of Technology, Rourkela, Orissa, 769 008 India. (e-mail: prakasu2000@yahoo.com; mail: recmurugan@yahoo.co.com)

Prof. R.K.Singh is with the Chemical Engineering Department, National Institute of Technology, Rourkela, Orissa, 769 008 India. (email: rksingh@nitrkl.ac.in)

of WPO with diesel. The emulsion of WPO and diesel was used as fuel in a single cylinder, air cooled, direct injection diesel engine with addition of different percentages of ignition improver. The results are compared with diesel fuel operation and presented.

II. Materials and Methods

A. Production and Fuel Properties of WPO

The properties of WPO is compared with diesel fuel and given in Table 1.

TABLE I: Comparison of WPO With Diesel

Properties	ASTM Standard	Diesel	WPO
Specific gravity at 15 ℃	ASTM D 4052	0.83	1.156
Net calorific value[MJ/kg]	ASTM D 4809	43.8	20.58
Flash point[℃]	ASTM D 93	50	66
Fire point[^{o} C]	ASTM D 93	56	108
Pour point[℃]	ASTM D 97	30	2
Carbon residue[%]	D 2500-05	0.1	12.85
Kinematic viscosity at 40 ℃[cSt]	ASTM D 445	2.58	13
Moisture content [wt %]	-	0.025	15-30
Ash [wt%]	-	0.13	0.01

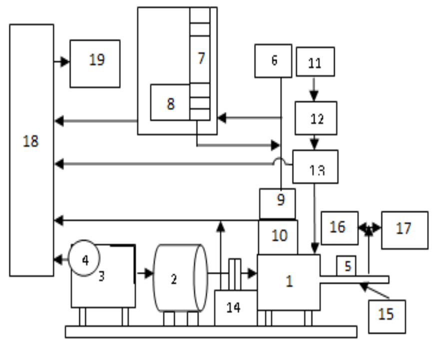
WPO used in the present investigation was obtained from vacuum pyrolysis process of soft wood (pine wood). The softwood obtained from the packing container boxes were taken as feed stock. The pyrolysis process for deriving WPO was carried out at 500 ^{o}C. The products of pyrolysis in the form of vapour were sent to a water cooled condenser and the condensed liquid was collected in a container.

B. Emulsification of WPO and Diesel

Emulsification of WPO and diesel was performed with a help of homogenizing unit. Energy input for homogenizing can be given by either shaking or stirring [13]. The surfactant Polysorbate-20 commercially known as Tween-20 having hydrophilic-lithophilic balance (HLB) number 16.7 was used as an emulsifier to emulsify WPO and diesel. For the preparation, first the surfactant was added to the diesel and then the pyrolysis oil was added. The resultant mixtures were shaken well to make a stable emulsion. Three percentages by volume of surfactant was used to emulsify 10% of WPO with 90% of diesel fuel. Then, the resultant emulsion was used as a fuel for the diesel engine to study its combustion, performance and emission characteristics.

C. Experimental Setup

Figure 1 shows the schematic diagram of the experimental setup. The engine was coupled to an alternator to provide the loading. A control panel located near the engine helps to operate the alternator to provide the load to the engine by a load switch. The exhaust gas temperature was measured with the help of a temperature thermocouple fitted on the exhaust pipe. Fuel was admitted from fuel tank to the engine through a fuel filter and fuel pump. The fuel consumption was measured with the help of a burette and a fuel sensor. Air enters to an air filter and then to air box. Air intake was measured by air flow sensor that was fitted in the air box. A speed sensor was connected near the flywheel of engine to measure the speed. The exhaust pipe had a provision to access the probes of an AVL 444 exhaust gas analyser that measures unburnt hydrocarbon (HC), carbon monoxide (CO) and nitric oxide (NO) emissions. HC and NO emissions were measured in ppm and CO is measured in percentage. An AVL 437 C diesel smoke meter was used to measure the smoke density of the engine exhaust.



1. Engine	6. Fuel tank	11. Air filter	16. Gas analyser
2. Alternator	7. Burette	12. Air box	17. Smoke meter
3. Control panel	8. Fuel sensor	13. Air flow sensor	18. Data acquisition system
4. Load switch	9. Fuel filter	14. Speed sensor	19. Computer
5. Thermocouple	10. Fuel pump	15. Exhaust pipe	

Fig. 1. Schematic diagram of the experimental setup

TABLE II: Specifications of the Test Engine

Make/Model	Kirloskar TAF 1
Brake power, [kW]	4.4
Rated speed, [rpm]	1500
Bore [mm]	80
Stroke [mm]	110
Compression Ratio	17.5:1
Nozzle Opening Pressure [bar]	200
Injection Timing [^{o}CA]	23

Data collected like fuel consumption, speed, air flow and exhaust gas temperature for the corresponding loads were fed to the data acquisition system and displayed in the monitor of the computer. The combustion analysis was performed in the experiment with the help of Kistler pressure transducer fitted on the cylinder head of the engine and crank angle encoder fitted to the output shaft. The specifications of the engine used are given in Table 2. Initially experiments were conducted with WPO emulsion only. The WPO emulsion exhibited a longer ignition delay (ID). In order to reduce the ID an ignition improver was added. Diethyl ether (DEE) is considered as an ignition improver. It is renewable in nature. The cetane number of DEE is above 125. Therefore, it was chosen for addition with WPO emulsion. All the tests were carried out by starting the engine with diesel fuel only. After running the engine with different emulsions, again the engine was run with diesel fuel to flush out the emulsion present in the fuel line.

III. Results and Discussion

A. Combustion Parameters

1) Ignition Delay

Ignition delay is the time delay between the start of injection and start of combustion, which is expressed in terms of degrees crank angle. For the conventional diesel fuels, ignition delay correlates with cetane number. Fig. 2 depicts the variation of ignition delay with brake power for all the fuels tested. The WPO emulsion exhibits longer ignition delay than conventional diesel fuel. This may be due to the poor ignition quality of the WPO [14]. When the DEE is added to the emulsion the ignition delay reduces considerably.

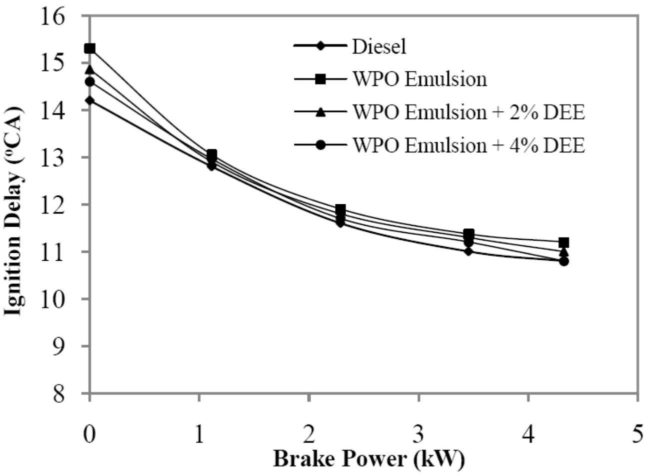


Fig. 2. Variation of ignition delay with brake power

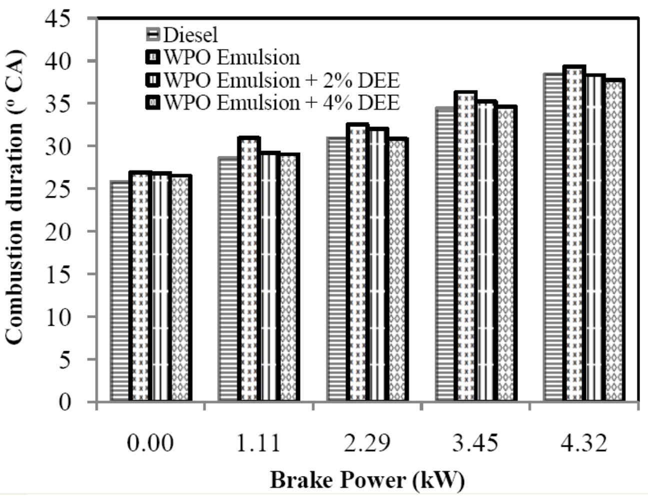


Fig. 3. Variation of combustion duration with brake power

This may be due to high cetane number of DEE which reduces the ignition delay. Addition of DEE at 2% and 4% with WPO emulsion reduces the ignition delay by about 0.34 ^{o}CA and 0.6 ^{o}CA when compared with WPO emulsion. However, the ignition delay is marginally higher than diesel.

2) Combustion duration

Fig. 3 shows the variation of combustion duration with brake power. Combustion duration is the time between start of combustion and end of combustion. From the heat release rate curve, the crank angle at which there is a sudden rise in heat release was taken as the start of combustion. End of combustion was determined from cumulative heat release rate curve. It was taken as the point where 90% of heat release had taken place. The combustion duration is higher (39.3 ^{o}CA) for WPO emulsion compared with diesel (38.4 ^{o}CA), WPO emulsion with 2% DEE (38.3 ^{o}CA) and WPO emulsion with 4% DEE (37.7 ^{o}CA) at full load. The increase in combustion duration is due to longer ignition delay of WPO emulsions.

It can be observed that the combustion duration decreases with DEE addition, which indicates faster heat release which leads to high thermal efficiency than WPO emulsion as indicated in the section 3.2.1. DEE (ignition improver) forms a number of ignition centres in the combustion chamber before the ignition of WPO emulsion which may result in reduced combustion duration [15].

B. Performance Parameters

1) Brake Thermal Efficiency

Fig. 4 shows the variation of the brake thermal efficiency with brake power for different WPO and diesel emulsions.

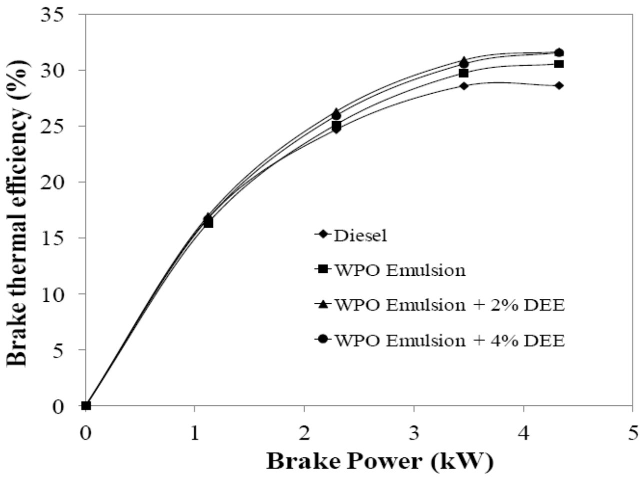


Fig. 4.Variation brake thermal efficiency with brake power

The brake thermal efficiency is higher for the emulsions compared to that of diesel at all loads. Addition of DEE to WPO emulsion will decrease the viscosity of blends and may result in improvement in the shape of fuel spray and atomization. These finer fuel droplets tend to mix thoroughly with air and hence improving the combustion [16]. It can be observed from the figure that the brake thermal efficiency of diesel fueled operation at full load is 28.64%. In case of WPO-diesel emulsions the brake thermal efficiencies of three blends WPO emulsion, WPO emulsion with 2% DEE and WPO emulsion with 4%DEE at full load are 30.58%, 31.66% and 31.58% respectively. The thermal efficiency of the WPO-diesel emulsions is higher than diesel due to improved combustion due to presence of oxygen. The percentage increase in the brake thermal efficiency was 6.34, 9.5 and 9.3 for WPO diesel emulsion, WPO diesel emulsions with 2% and 4% DEE respectively. Brake thermal efficiency was reduced slightly at 4% DEE addition may due to the cooling effect of DEE.

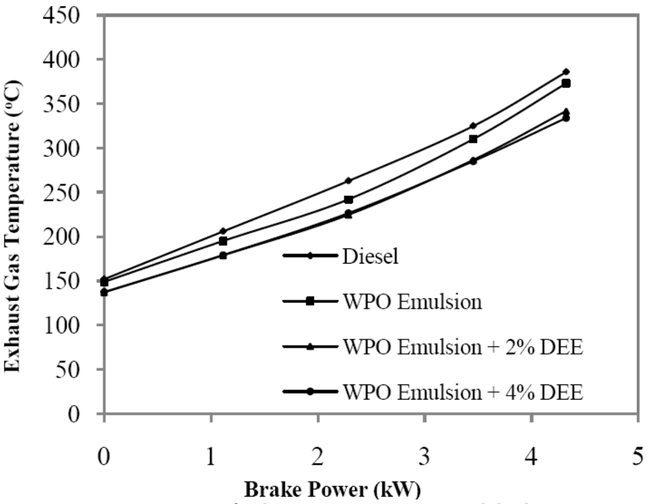


Fig. 5. Variation of exhaust gas temperature with brake power

2) Effect on Exhaust Gas Temperature

Exhaust gas temperature measured from the engine is an indication for the conversion of heat into work. It is observed from Fig. 5 that the exhaust gas temperature varies from 152 ^{o}C at no load to 386 ^{o}C at full load for diesel operation.

It is evident from the figure that the exhaust gas temperatures of the different WPO diesel emulsions are lower than diesel fuel operation. For WPO emulsion, the exhaust gas temperature varies from 148 ^{o}C at no load to 373 ^{o}C at full load. The reason may be due to lower calorific value of the emulsions when compared with diesel fuel and quenching effect of WPO due to water content present in WPO (9). Further the exhaust gas temperature reduces with the addition of DEE and the reason may be the higher latent heat of vaporization of DEE absorbs the heat of combustion [17].

C. Emission Parameters

1) NO emission

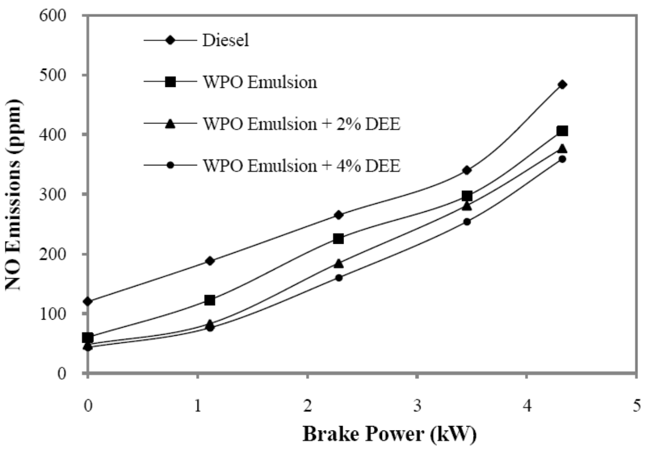


Fig.6. Variation of NO emission with Brake Power

Fig. 6 shows the formation of NO at various brake power for the different emulsions and diesel fuel. Nitric oxide constitutes more than 90% of the oxides of nitrogen in an engine exhaust [18]. The formation of oxides of nitrogen is due to thermal root leading to thermal NO, hydrocarbon fragment related root leading to prompt NO and fuel bound nitrogen that results fuel bound NO. Two principles factors that affect formation of NO are temperature and oxygen fraction [19]. NO emissions are lower for WPO diesel emulsion due to more water content in the WPO which may reduce the combustion temperature. Addition of DEE reduces the NO emissions further since the DEE has high cetane number and hence the reduced ignition delay lowers the mass of fuel accumulated before combustion. This lowers the initial combustion rate and also the actual injection timing is retarded. This decreases the peak temperature and lowers NO level [20].

It is observed that the percentage reduction in NO emissions was 19.21, 28.38 and 34.81 for WPO diesel emulsion, WPO diesel emulsions with 2% and 4% DEE respectively when compared with diesel fuel at full load.

2) CO emissions

A comparison on CO emissions among diesel, WPO emulsion and WPO emulsion with DEE is shown in the Fig.7.

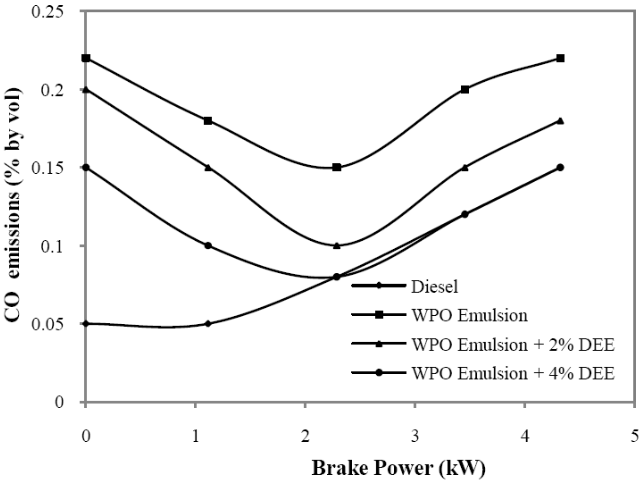


Fig. 7. Variation of CO emission with Brake Power

The CO emission is an indication for incomplete combustion of fuel air mixture that takes part in the combustion. The low volatility of WPO emulsions affects the atomization process, resulting in local rich mixtures, which produces higher CO emission. However, the addition of DEE with WPO emulsions results in reduced CO emission. The ignition improver (DEE) forms a number of ignition centres in the combustion chamber which will result in complete combustion. This may result in reduced CO emissions [15]. There is a significant difference in the CO emissions between diesel and WPO based fuels at low loads than at full load.

iii) Unburned Hydrocarbon emission

Unburnt hydrocarbon is the direct result of incomplete combustion in the combustion chamber [21]. Diesel exhaust hydrocarbons are composed of fuel molecules pyrolysis products of fuel compounds and partially oxidized hydrocarbons [22].

It can be observed from the Fig. 8 that the hydrocarbon emissions increases by 14.28% and 7.14% for WPO diesel emulsion and with 2% DEE addition whereas, HC emissions decreases by 28.57% for WPO diesel emulsions with 4% DEE addition. Unburnt hydrocarbon emissions are more in the case of WPO diesel emulsions due to more water content which leads to longer ignition delay and incomplete combustion. Introduction of diethyl ether drastically lowers the HC level due to improved oxidation. However, the HC level is higher than base diesel fuel operation.

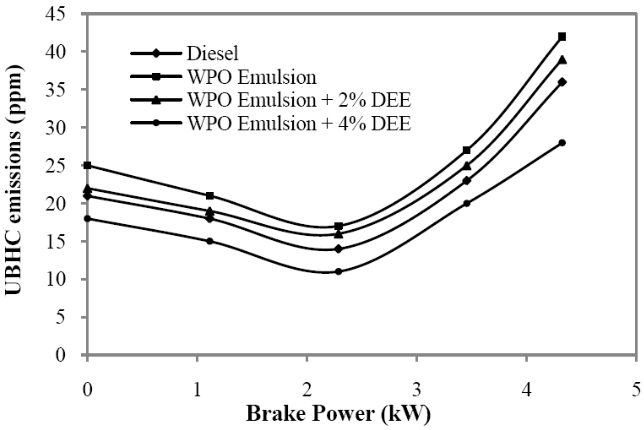


Fig.8. Variation of HC emission with brake power

IV. Conclusion

Preliminary tests were conducted with an emulsion of WPO-diesel in a single cylinder diesel engine and the following results were obtained from the experimental study:

- The WPO emulsions exhibits longer ignition delay than conventional diesel fuel.
- The combustion duration is higher for WPO emulsion compared with diesel at full load. It is observed that the combustion duration decreases with DEE addition.
- Percentage increase in the brake thermal efficiency was 6.34, 9.5 and 9.3 for WPO diesel emulsion, WPO diesel emulsions with 2% and 4% DEE respectively, which is higher than diesel fuel operation.
- The exhaust gas temperatures of different WPO diesel emulsions are lower than diesel fuel operation.
- It is observed that the percentage reduction in NO emissions was 19.21, 28.38 and 34.81 for WPO diesel emulsion, WPO diesel emulsions with 2% and 4% DEE respectively.
- The CO emissions of WPO-diesel emulsions are slightly higher than diesel fuel due to reduction in gas temperature.
- The hydrocarbon emissions increases by 14.28% and 7.14% for WPO diesel emulsion and with 2% DEE addition whereas, HC emissions decreases by 28.57% for WPO diesel emulsions with 4% DEE addition.

So it can be concluded that the WPO can be used in the diesel engines in the form of fuel emulsions along with some ignition improver addition.

References

[1] G. D. Roy, *Non-Renewable energy sources*, Khanna publications, 2004.

[2] D. Chiaramonti, A. Oasmaa, and Y. Solantausta, "Power generation using fast pyrolysis liquids from biomass," *Renewable and Sustainable Energy Reviews*, Vol 11, pp. 1056-1086, 2007.

[3] H. B. Goyal, D. Seal, and R.C. Saxena, "Bio-fuels from thermochemical conversion of renewable resources- A review," *Renewable and Sustainable Energy Reviews*, Vol. 12, pp. 504- 517, 2008.

[4] A.V. Bridgwater, A. J. Toft, and J. G. Brammer, "A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion," *Renewable and Sustainable Energy Reviews*, Vol. 6, pp. 181–248, 2002.

[5] M. Ikura, M. Stanciulescu, and E. Hogan, "Emulsification of pyrolysis derived bio-oil in diesel fuel," *Biomass Bioenergy*, Vol. 24, pp. 221–32, 2003.

[6] G. Lopez Juste and J. J. Salva Monfort, "Preliminary test on combustion of wood derived fast pyrolysis oils in a gas turbine combustor," *Biomass Bioenergy*, Vol. 19, pp.119–28, 2000.

[7] A. Shihadeh and S. Hochgreb, "Diesel engine combustion of biomass pyrolysis oils," *Energy Fuels*, Vol 14, pp. 260–74, 2000.

[8] Y. Solantausta, N. O. Nylund, M. Westerholm, T. Koljonen, and A.Oasmaa "Wood-pyrolysis oil as fuel in a diesel-power plant," *Bioresource Technology*, Vol. 46, pp.177- 188, 1993.

[9] S. Frigo, R. Gentilli, L.Tognotti, S. Zanforlin, and G. Benelli, "Feasibility of using flash pyrolysis oil in diesel engines," *SAE pape*r 982529, 1998.

[10] C. Bertoli, J.D. Alessio, N.D. Giacomo, M. Lazzaro, P. Massoli, and V. Moccia, "Running light-duty DI diesel engines with wood pyrolysis oil," SAE paper 2000-01-2975, 2000.

[11] A. Alahmer, J. Yamin, A. Sakhrieh, and M. A. Hamdan, "Engine performance using emulsified diesel fuel," *GCREEDER 2009*, Amman Jordan, March 31st – April 2nd 2009.

[12] D. Chiaramonti, M. Bonini, E. Fratini, G. Tondi, K. Gartner, A. V. Bridgwater, H. P. Grimm, I. Soldaini, A. Webster, and P. Baglioni, " Development of emulsions from biomass pyrolysis liquid and diesel and their use in engines – Part 1: Emulsion production," *Biomass and bioenergy*, Vol. 25, pp. 85-99, 2003.

[13] Z. Qi, C.Jie, W. Tiejun, and X.Ying, "Review of biomass pyrolysis oil properties and upgrading research," *Energy Conversion and Management*, Vol. 48, pp. 87-92, 2007.

[14] Y. Solantausta, N. O. Nylund, and S. Gust, "Use of pyrolysis oil in a test diesel engine to study the feasibility of a diesel power plant concept," *Biomass and Bioenergy*, Vol. 7, pp. 297-306, 1994.

[15] V. Edwin Geo, G. Nagarajan, and B. Nagalingam, "Studies on improving the performance of rubber seed oil fuel for diesel engine with DEE port injection," Fuel, Vol. 89, pp. 3559–3567, 2010.

[16] S. Sivalakshmi and T. Balusamy, "Research on di-ethyl ether as an oxygenated additive with biodiesel in CI engine," P*EA-AIT International Conference on Energy and Sustainable Development*: Issues and Strategies (ESD 2010), Thailand, 2010.

[17] N. K. Miller Jothi, G. Nagarajan, and S. Renganarayanan, "Experimental studies on homogeneous charge CI engine fueled with LPG using DEE as an ignition enhancer," *Renewable Energy*, Vol 32, pp. 1581–1593, 2007.

[18] P. Degobert, Automobiles and pollution, Editions Technip publishers, 1995.

[19] H. S. Mukunda, Understanding Combustion, Universities Press [India] Private Limited Publication.

[20] K. A. Subramanian and A. Ramesh, "Use of diethyl ether along with water-diesel emulsion in a DI diesel engine," SAE paper 2002-01-2720, 2002.

[21] V. Ganesan, *Internal combustion engines*, TMH Publication, 2008.

[22] B. P. Pundir, *Engine Emissions–Pollutant formation and advancement in control technology*, Narosa publications, 2007.