Experimental Investigation on Performance, Combustion and Emission Characteristics of a Low Heat Rejection Engine using Rapeseed Methyl Ester and Diethyl Ether

S. Krishnamani*, T. Mohanraj and K. Murugumohan Kumar

Department of Mechanical Engineering, SASTRA University, Thirumalaisamudram, Thanjavur - 613401, Tamil Nadu, India; tmraj@mech.sastra.edu, krishnamani@mech.sastra.edu, murugumohan@mech.sastra.edu

Abstract

Background/objectives: Today, as a result of limited fuel resources and stringent emission standards, the methyl ester fuel has been focused on alternative fuels for I.C engine. Methyl ester fuels can be effectively used in low heat rejection engines (LHR), in which the surface temperature of the combustion temperature is increased by providing a thermal barrier coating. The main objective of our work is to reduce the engine exhaust emissions like HC and CO using diethyl ether in low heat rejection engine. Methods/Statistical Analysis: In this work, engine components like piston crown, cylinder head, and liner, inlet and exhaust valves of a diesel engine were coated with the ceramic material lanthanum zirconate by plasma spray technique. The effects of rapeseed methyl ester (biodiesel) produced by transesterification method and its blends with Diethyl ether (10% and 20% by volume) were studied in the low heat rejection engine. Findings: The thermal efficiency is found to be higher for diesel and biodiesel in the LHR engine. The results indicate that, B10 (10% Diethyl ether & 90% Biodiesel) and B20 (20% Diethyl ether & 80% Biodiesel) shows lower thermal efficiency compared with that straight biodiesel in low heat rejection engine. Applications/Improvements: Significant improvements were observed in engine exhaust emissions like CO and HC (except NOx) for all the diethyl ether blended biodiesel fuel in LHR engine. The higher oxygen content in the blended fuel reduces CO and HC emissions by 10% and 18% respectively compared to biodiesel in LHR engine.

Keywords: Brake Thermal Efficiency, Combustion Characteristics, Lanthanum Zirconate, Low Heat Rejection Engine, Rapeseed Methyl Ester, Transesterification

1. Introduction

The use of alternative fuels is very important in the current energy scenario because it is a fundamental source for economic improvement of any country1. The alternative fuel plays an important role to meet the energy requirements and emission standards in the field of internal combustion engine. Many studies affirmed that the usage of raw vegetable oil as a fuel creates sticking of piston rings, injector nozzle choking and dilution of crank case oil. Although, the problems could be fixed by the chemical treatment (transesterification) of vegetable oil, still the biodiesel faces some challenges to be used as diesel substitutions in I.C. engines. The major disadvantages of biodiesel usage in diesel are its higher viscosity and poor volatility. As the diesel is regulated for diesel fuel alone, running the diesel engine with biodiesel requires some engine modifications like increasing the compression ratio, changing the geometry of the combustion region and thermal blockade of the engine.

*Author for correspondence
components\textsuperscript{2-4}. Ceramic coatings applied to the combustion chambers of diesel engine are desired to reduce the transfer of heat from the in-cylinder gas to the cooling system. The heat to work conversion efficiency of the engine is improved by applying ceramic coating on the components of the engine using various techniques. Plasma spray coating is the method followed to apply suitable coating for diesel engine\textsuperscript{5-7}. The direct injection diesel engine was converted into low heat rejection engine by employing a thermal blockade coating made from lanthanum zirconate. It is observed that there is an improvement in BSFC in the order of 4.16% lower with coated engine compared to the baseline diesel engine operation. HC emissions are observed to be low with all fuels with LHR engine related to baseline fuel operation. But there is a slight increase in NOx emission with coated engine\textsuperscript{8}. The low heat rejection (LHR) engine operated with diesel and biodiesel and performance and heat transfer analysis could be correlated with heat transfer models. The studies like Annad's combined heat transfer model and Wiebe's heat transfer model was employed to determine the deliverance rate of heat and extended zel’dovich mechanism is used for predicting NO emissions. The models have been validated against the experimental data obtained from the engine. It is observed that highest peak pressure for LHR engine fuelled with diesel is due to highest and early heat release rate. It is noticed that, for conventional engine there is a marginal decrease in maximum pressure with diesel and biodiesel compared with LHR biodiesel. The heat rejected by the LHR engine is reduced due to ceramic coating and reduction of heat varies from 30 to 40%. It is concluded that, all the restored heat cannot be converted into useful work output but there is a gain in work conversion efficiency due to lower loss of heat energy\textsuperscript{9}. The experimental work shows that, a DI diesel engine aspirated with Dimethoxymethane (DMM)-diesel blends shows increased performance with higher thermal efficiency and decreased exhaust emissions. Smoke and CO emission decreases due to faster premixed combustion and diffusion combustion stages. The diesel engine fuelled with 30 % DMM blended with diesel gives satisfactory fuel efficiency and emission levels\textsuperscript{10}. The experimental studies on characteristics of C.I engine operated with n-butane blended DME fuel shows that, the power output and consumption of fuel were improved at higher loads and extremely higher hydrocarbon emissions were observed with addition of n-butane fuel. The CO emissions are quite comparable with diesel fuel\textsuperscript{11}. The research work on a turbocharged DI diesel engine shows that, the oxygen –enriched air and EGR techniques were used to produce lower NOx and smoke emissions than conventional diesel engine under same fuel quality and quantity. The results shows that at full load and 1600 r.p.m of engine speed, the optimum NOx emission can be achieved with 30-40 % EGR rate and intake oxygen density was improved from 21.5-22.5%. It is concluded in numerical simulation results that oxygen enriched combustion can suppress the formation of poly-cyclic aromatic hydrocarbon (PAH) and smoke emissions\textsuperscript{12}. The optimization of fuel injection timing is very important for low heat rejection engine. It was observed that for the actual injection timing of 20° before TDC, the consumption of fuel to power for thermal blockade coated engine was around 6% less than the actual engine\textsuperscript{13}. By changing the fuel injection timing for LHR engine, both BSFC and nitric oxide emission were decreased by 2% and 11% when compared to conventional diesel engine and the most favorable injection timing for multi-cylinder DI engine with thermal barrier coating was 18° before TDC. The NOx emissions from the direct injection diesel engine could also be effectively controlled by providing selective catalytic converter in the engine exhaust system\textsuperscript{13,14}.

The aim of the paper is to examine the effect of Rapeseed Methyl ester and diethyl ether as substitute fuel for the ceramic coated engine on engine combustion and emission characteristics.

2. Materials and Methods

2.1 The Experimental Setup and Arrangements

The tests were conducted in a single cylinder, DI diesel engine coupled with eddy current dynamometer. The experimental setup is shown in the Figure 1. The experiment was executed with variable load and the engine develops a brake power of 3.72 kW at constant speed of 1500 rpm. The static fuel injection timing of 23° before TDC and fuel injection pressure of 200 bar is maintained throughout the experiment. The engine specifications are shown in Table 1. The fuel consumption rate was measured on volume basis using measuring burette and stop watch. The test engine cooling system is a water cooling system and the supply of water to the engine is regulated.
by a control valve. The intake air temperature and exhaust gas temperature is measured by k-type thermocouples. The pressure transducer, inbuilt analog and digital converter and amplifier with data acquisition system were used to record in-cylinder pressure data. The exhaust emissions like CO, HC and NOx were measured using exhaust gas analyzer.

### 2.2 Biodiesel Preparation

Biodiesel is biodegradable, non-toxic could be used as a substitute fuel for diesel engine. The non-edible oil (Rapeseed oil) is converted into biodiesel (Rapeseed Methyl ester) by transesterification process. The transesterification of Rapeseed oil includes heating of oil, addition of methoxide solution [KOH + Methyl alcohol], mixture stirring, and glycerol separation, water washing.

---

**Table 1. Engine Specifications**

| Engine Details       | Specifications                                      |
|----------------------|-----------------------------------------------------|
| Engine Make          | COMET                                               |
| Type                 | Single Cylinder, four stroke, Direct injection      |
| No. of Cylinders     | 1                                                   |
| Bore                 | 87.5mm                                              |
| Stroke               | 110mm                                               |
| Displacement Volume  | 661 cc                                              |
| Compression Ratio    | 17.5:1                                              |
| Maximum power        | 3.72kW                                              |
| Engine Speed         | 1500 rpm                                            |
| Dynamometer          | Eddy current                                        |
| Fuel Injection Timing| 230 before TDC                                      |
| Fuel injection Pressure| 200 bar.                                           |
and heating for removing the stains of water. This process reduces the viscosity of the oil and increases the cetane number of the fuel. In this research work, the rapeseed oil is heated to the temperature of 55°C and then it is treated with methoxide solution [KOH and methanol] and the mixture is simultaneously stirred using the magnetic stir bar. After 60 minutes of stirring and heating, the mixture is allowed to cool and settle for the period of 24 hours. After the settlement, the dark layer of glycerin on the bottom of the flask was observed with separated biodiesel on top as shown in Figure 2. The biodiesel is then transferred to separator funnel and washed with distilled water. After the settlement, water is drained out and biodiesel is heated and filtered to remove the water content. The prepared biodiesel is employed in LHR engine for the experimental investigation. The properties of rapeseed Methyl ester and baseline fuel were compared and shown in the Table 2.

2.3 Preparation of Ceramic Coat
On account of poor thermal conductivity, Lanthanum Zirconate (La\textsubscript{2}Zr\textsubscript{2}O\textsubscript{7}) has been used as a thermal blockade coating material for diesel engine components. The ceramic material was coated to the layer of 0.5mm thickness using plasma spray coating process. The d.c. plasma torch generates plasma jet from a flowing gas heated by electric arc. The plasma torch operates with N\textsubscript{2}-H\textsubscript{2} gas mixtures resulting in temperature around 900K-1000K and the plasma jet velocity ranges around 1300m/s at the nozzle exit. The electric arc ionizes the gas and it requires the power level of around 80kW. The coating material is taken in the form of powder into the plasma jet. The thermal blockade coating is laminated to a thickness of 0.3mm over the NiCrAl bond coat of thickness 0.2mm over the substrate material. The plasma spray process is mainly used for coating oxide ceramics. Thus the engine components are coated with ceramic material and employed in the engine to conduct test with diesel and biodiesel.

3. Results and Discussions

3.1 Brake Thermal Efficiency
The variation of brake thermal efficiency with respect to load for different proportions of Di-ethyl ether (DEE) with biodiesel (rapeseed methyl ester) were considered for the present analysis was shown in Figure 3. The brake thermal efficiency was higher with biodiesel when compared with blends in LHR engine. The lower energy content of the diethyl ether results in the reduction of thermal efficiency for all the blended fuels. It is observed that, the thermal efficiency of biodiesel in LHR engine is 1.28% and 3.51% higher than the 10% and 20% diethyl ether-biodiesel blended fuel respectively at full load condition.

3.2 Brake Specific Fuel Consumption
The variation of brake specific fuel consumption with load is shown in Figure 4. It can be seen that the fuel consumption per hour for the blend fuel is marginally higher than that for biodiesel in LHR engine. This is due to the difference in heating values of the fuel and the variation in energy consumption. The specific fuel consumption increases by 18% and 48% corresponding to 10 % and 20 % DEE-biodiesel blended fuel operation respectively compared to biodiesel operation at maximum load condition. A similar trend can be noticed at other loads as well.

Table 2. The Properties of Diesel and Biodiesel

| Properties                  | Diesel Fuel | Rapeseed methyl ester |
|-----------------------------|-------------|------------------------|
| Density (kg/m\textsuperscript{3}) | 830         | 890                    |
| Calorific value (kJ/kg)     | 44,000      | 37,000                 |
| Kinematic Viscosity @20\degree C (cST) | 2.9         | 6                      |
| Cetane Number               | 45-50       | 45-59                  |
3.3 Oxides of Nitrogen Emission

Figure 5 shows the variation of NO\textsubscript{x} with brake power in LHR engine. The NO\textsubscript{x} emissions of 10 % and 20 % of DEE-Biodiesel blends increases compared to biodiesel under all operating conditions. The formation of NO\textsubscript{x} is strongly dependent on the temperature, local concentration of oxygen and duration of combustion. The NO\textsubscript{x} emission of the blended fuel of 10 % and 20 % are 1020 ppm and 1067 ppm respectively at full load condition. The increase in NO\textsubscript{x} emission is due to the enhancement of oxygen level of diethyl ether and higher intense of heat release in the premixed combustion phase of Diethyl ether-biodiesel blends.
3.4 Hydrocarbon Emission

Figure 6 compares the HC emissions of the blended fuel operation with neat biodiesel in LHR engine. It can be seen that the HC emissions of DEE-biodiesel blended fuel operation is lower than that in the case of neat biodiesel operation. This is due to the oxygen content in the blended fuel which can results in more complete combustion, thus reducing the emission of unburned hydrocarbon. The HC emissions are reduced by 5% and 18% corresponding to 10 % and 20 % of DEE-Biodiesel blended fuel operation respectively compared to neat biodiesel at the maximum load condition. A similar trend can be noticed at other loads as well.
3.5 Carbon Monoxide Emission

Figure 7 shows the variation of carbon monoxide with brake power. The CO emissions are reduced significantly by 4% and 10% corresponding to 10% and 20% DEE-biodiesel blended fuel operation respectively compared to neat biodiesel at maximum load condition. This is due to better combustion of the blended fuel and oxygen concentration of the diethyl ether. At other loads also a similar trend can be noticed.

![Figure 7. The Variation of Carbon Monoxide with brake power.](image)

3.6 Pressure Variation

Figure 8 shows the in-cylinder pressure for the engine running on DEE-biodiesel blends and neat biodiesel at full load condition. The maximum pressure of the blended fuel for 10 % and 20 % is 69 bar, 68 bar respectively at full load and 74 bar for neat biodiesel fuel. The peak pressure for the blended fuel and diesel occurs at 5 crank angle degrees after TDC. The higher pressure for the biodiesel fuel is due to more amount of fuel taking

![Figure 8. The Variation of pressure with crank angle.](image)
part in the uncontrolled combustion leading to longer ignition delay.

3.7 Heat Release Rate

The heat release rate at full load is shown in Figure 9. Biodiesel had a less intense premixed combustion phase but a slightly longer diffusive combustion phase. The less intense premixed combustion phase may be due to shorter ignition delay of diesel compared with that of DEE–biodiesel blends. The higher heat release rate for the blended fuel is due to the higher availability of oxygen content and higher cetane rating of diethyl ether resulting in early combustion of the fuel.

4. Conclusion

The performance, combustion and emission characteristics of low heat rejection engine fueled with biodiesel (Rapeseed methyl ester) and diethyl ether–biodiesel blends have been investigated. The results depicts that the brake thermal efficiency, specific fuel consumption and exhaust emissions are function of diethyl ether–biodiesel blends. The following conclusions are made from this investigation:

1. The brake thermal efficiency of the biodiesel is marginally higher than that of diethyl ether–biodiesel blends at all load conditions. This may be due to lower energy content of the diethyl ether blends results in higher fuel consumption. The maximum thermal efficiency for biodiesel at full load condition is 26.13% whereas for diethyl ether blends of B10 and B20 are 23.79% and 21.45% respectively. The brake thermal efficiency of diesel fuel at full load condition is 31.5%.

2. The hydrocarbon emissions and CO emissions are comparatively low for blended fuels at all the load conditions in LHR engine. The oxygen content in the diethyl ether and higher surface temperature of the engine combustion chamber promotes complete combustion of the fuel in LHR engine.

3. The NO\textsubscript{x} emissions for the blended fuel are higher when compared with biodiesel in LHR engine. This may be due to higher rate of heat release during premixed combustion stage and higher cetane rating of diethyl ether enhances early heat release rate.

It has been depicted from the results that, the HC and CO emissions except NO\textsubscript{x} are less compared to straight biodiesel in LHR engine and engine performance was comparatively higher for the low heat rejection running with straight biodiesel than the engine operating with diethyl ether/biodiesel blends.

5. References

1. Zhu R, Wang X, Miao H, Gao J. Performance and Emission Characteristics of Diesel engine fuelled with

---

Figure 9. The Variation of heat release rate with crank angle.
Diesel-Dimethoxymethane (DMM) blends. Journal on energy and fuels. 2009; 23(1):286-93.
2. Lee S, oh S, Choi Y, Kang K. Performance and emission characteristics CI engine operated with n-butane blended DME fuel. Applied Thermal Engineering. 2011; 31(11-12):1929-35.
3. Agarwal AK, Dhar A. Experimental Investigation on Performance, Emission and Combustion Characteristics of karanja oil blended fuel in DICI Engine. Renewable Energy. 2013; 52:283-91.
4. Zhang W, Chen Z, Li W. Influence of EGR and Oxygen enriched air on diesel engine NO-smoke Emission & Combustion Characteristics. Applied Energy. 2013; 107:304-14.
5. Rajendra Prasad B, Tamilporai P. Analysis of Combustion, Performance & Emission characteristics of Low heat rejection engine using biodiesel. International Journal of Thermal Sciences. 2010; 49(12):2483-90.
6. Kumar DV, Ravi Kumar P, Santhosa Kumari M. Prediction of performance and Emission of a biodiesel fuelled lanthanum Zirconate DI diesel engine using artificial neural Networks. Procedia Engineering. 2013; 64:993-1002.
7. Buyukkaya E, Cerit M. Experimental study of NOx emissions and Injection timing of low heat rejection diesel engine. International Journal of Thermal Sciences. 2008; 47(8):1096-106.
8. Cinar C, Can O, Sahin F, Yucensu S. Effects of Pre mixed diethyl ether on combustion and Exhaust emissions in a HCCI-DI diesel engine. Applied thermal Engineering. 2010; 30(4):360-65.
9. Zheng Z, Yao M. Numerical Study on the Chemical reaction kinetics of n-heptane for HCCI combustion process. Fuel. 2006; 85(17-18):2605-15.
10. Kim DS, Lee CS. Improved emission Characteristics of HCCI engine by various premixed fuels and cooled EGR. Fuel. 2006; 85(5-6):695-704.
11. Anand R, Mahalakshmi NV. Simultaneous reduction of NOx and smoke from diesel engine with EGR and diethyl ether. Journal of Automobile Engineering. 2007; 221(1):109-16.
12. Ma J, Lu X, Hung Z. An experimental study of HCCI-DI combustion and emission in a diesel engine with dual fuel. International Journal of Thermal Sciences. 2008; 47(9):1235-42.
13. Navaneethakrishnan P, Vasudevan D. Experimental Study on Performance and Exhaust Emission Characteristics of a C.I. Engine Fuelled with Tri Compound Oxygenated Diesel Fuel Blends. Indian Journal of Science and Technology. 2015 Jan; 8(4):307-13.
14. Selvam M, Vigneshwaran, Irudhayaraj R, Palani S. Emission Control Diesel Power Plant for Reducing Oxides of Nitrogen through Selective Catalytic Reduction Method using Ammonia. Indian Journal of Science and Technology. 2016 Jan; 9(1):1-7.