Performance and Emission analysis of optimal DEE blended Pongamia pinnata L. biodiesel fuelled to EGR coupled Low Heat Rejection (LHR) Diesel Engine

1* Vamsi Krishna K, 2 Sastry GRK, 3 Murali Krishna MVS 4Jibitesh Kumar P

1* Research Scholar, Mechanical Engineering Department, NIT Agartala, Tripura state, India
2 Associate Professor, Mechanical Engineering Department, NIT Agartala, Tripura state, India
3 Professor, Department of Mechanical Engineering, CBIT, Hyderabad, Telangana state, India
4 Research Scholar, Production Engineering Department, NIT Agartala, Tripura state, India

*Corresponding Author E-mail: masikrish@gmail.com

Abstract. To enhance the engine thermal efficiency and simultaneous decrease of emissions, an experimentation was done with 10% constant rate of exhaust gas recirculation (EGR) coupled low heat rejection (LHR) diesel engine developed via 8 YSZ (8% mol. yttria-stabilized zirconia) ceramic material coated cylinder head and liner fuelled by optimal blend B85A15 by vol. (Karanja based biodiesel 85% + additive diethyl ether 15%). Experiments were carried out on the regular engine (RE) and LHR engine fuelled by test fuels (diesel and blend B85A15) at different loads (0%, 20%, 40%, 60%, 80% and 100%) and Injection timings (300 BTDC to 340 BTDC). From the results, it was found that advancement of injection timing significantly improved all the investigated parameters except NOx for both the engines and in comparison the optimum results were 6.5% enhancement in brake thermal efficiency (BTE) with the reduction of 4.5% in brake specific energy consumption (BSEC), 44% in particulate matter density and 18.5% in NOx emissions found for LHR engine fuelled by B85A15 at 330 BTDC with an 80% load compared to RE with diesel. The optimum configuration of RE found to be diesel fuel at injection timing 310 BTDC with 80% load.

1. Introduction
The great thought and experiment with peanut oil as fuel in compression ignition engine done by Rudolf Diesel in 1990 hints the coming future fossil fuel crisis and necessity of developing the alternate such as biofuels. The investigation [1] on thermal balance of a conventional diesel engine shows only around 30% of useful work. Globally, the current consumption of crude oil was over 11 billion tonnes per year and the deposits will probably last until 2052 [2]. Biodiesel widely acknowledged [3, 4] as environmentally friendly fuel and potential alternative to diesel as all the properties were within the standard limits of ASTM D6751 and EN 14214 and also most of its properties directly depends on the type of source feedstock. The yield of biodiesel from Pongamia pinnata oil by dual step process [5] was 96.6% to 97%. Experimental investigation [6] on engine fuelled by Karanja biodiesel and its blends resulted in reduced emissions of carbon monoxide (CO), smoke and engine noise, but increased oxides of nitrogen (NOx). The influence of DEE on combustion, performance and emission characteristics [7]
of Karanja biodiesel blend fuelled to diesel engine found that high viscosity, cold starting problems and NOx emissions significantly reduced and the optimum results obtained with 15% DEE-Karanja biodiesel blend. The study [8] done on unmodified compression ignition (CI) engine fuelled by blends of additive diethyl ether blended and karanja biodiesel results in enhancement of peak in-cylinder pressure and heat release rate along with significant reduction in NOx and CO₂ emissions. The study [9] found that application of EGR in a compression ignition engine fuelled by biodiesel resulted in a reduction of NOx emissions without any significant effect on particulate matter emissions and brake specific energy consumption and also the optimum rate of EGR assistance was found to be 15%. Investigation of low heat rejection diesel engine developed via different thermal barrier materials showed enhanced combustion and performance parameters [10, 11].

2. Materials and Method

2.1. Fuels: B85A15 and neat Diesel

The optimum blending ratio of additive diethyl ether (DEE) with Karanja based biodiesel was found to be 15% by volume and hence the same was done to improve combustion, performance and emission characteristics. The test fuels used in the experimentation with LHR engine and RE were straight diesel and blend B85A15 (Karanja oil-based biodiesel 85%+Additive diethyl ether 15%) by vol. The significant properties of the fuels were given in table 1.

| Test fuels          | Density at 30°C (kg/m³) | Viscosity at 45°C (mm²/s) | Cetane number | Calorific Value (MJ/kg) | Flash point (°C) | Oxygen content (wt. %) |
|---------------------|-------------------------|---------------------------|---------------|-------------------------|------------------|------------------------|
| Diesel              | 820                     | 2.8                       | 49            | 43                      | 75               | 0                      |
| Karanja Biodiesel   | 880                     | 4.7                       | 56            | 39.5                    | 180              | 12.2                   |
| Diethyl ether (DEE) | 715                     | 0.35                      | 125           | 35.5                    | -40              | 21.5                   |
| Blend B85A15        | 855.2                   | 4.04                      | 66.3          | 38.9                    | 147              | 13.59                  |

2.2. Development of Low Heat rejection (LHR)

From the literature, it was known that maximum optimal coating thickness of YSZ on diesel engine components must be below 0.5 mm (500 microns). Initially, care was taken to strictly maintain the dimensions of the cylinder head and liner unaltered. The inner portion of the cylinder head was coated with YSZ ceramic powder material of thickness 400 microns via the Plasma spray coating process. The details of the plasma spray coating used were given in table 2. In ‘figure 1’, the alphabets A and B represents the YSZ ceramic coating and the cylinder head inner portion respectively. In a similar way, the outer portion of the cylinder liner was coated with YSZ ceramic powder material of thickness 400 microns. In ‘figure 2’ the alphabets C and D represents the YSZ ceramic coating and the outer portion of cylinder liner respectively. The properties of 8 YSZ ceramic powder material were taken from [12].

| Table 2. Plasma Spray Coating details |
|---------------------------------------|
| Plasma gun                            |
| Voltage (V)                           | 55                          |
| Current (A)                           | 400                         |
| Distance of Spray (inch)              | 2                           |
| Gas Pressure (hydrogen in Psi)        | 35                          |
| Gas Pressure (Argon in Psi)           | 85                          |
| Feed rate of Powder (g per minute)    | 36 to 40                    |
Table 3. Details of Experimentation engine test rig

| Engine make              | Kirloskar, India            |
|-------------------------|----------------------------|
| Type                    | Four Stroke Diesel Engine  |
| Rated Power             | 5 kW @ 1500 rpm            |
| Number of cylinders × cylinder position | One × Vertical position  |
| Stroke × Bore           | 110 mm × 90 mm             |
| Method of cooling       | Water cooled               |
| Fuel injection system   | In-line and direct injection |
| Compression ratio       | 18:1                       |
| Recommended injection timing & Pressure | 30°bTDC × 190bar |
| Number of holes of injector and size | 3 × 0.25mm |
| Type of combustion chamber | Direct injection type     |
| Type of Loading         | Electrical Dynamometer     |

2.3 Experimentation

‘Figure 3’ shows the engine setup used for the experimentation and its specifications were given in table 3. The load on the engine was applied via dynamometer of Eddy current type. The measurement of fuel consumption was done via a three-way valve and a calibrated burette arrangement. The particulate matter density (HSU %) and NOx concentration (ppm) in emissions were measured by AVL Hartridge Smoke meter and NOx analyzer respectively. An exhaust gas recirculation system with a control valve arrangement was coupled to the engine to enable the flue gases to flow and mix with the fresh air at the inlet manifold. Injection timing was varied via copper shims mechanism of 0.3 mm size placed between the pump body and the engine frame. Initially, investigation on performance and emission parameters like BTE, BSEC, particulate matter density and NOx emissions of a regular diesel engine fuelled by diesel were carried out at different loads (0% to 100%) and injection timing (30° BTDC to 34° BTDC) and then with blend B85A15. A similar investigation was carried out with LHR engine and compared with the results of RE.
3. Results and Discussions

3.1. Performance characteristics

‘Figure 4’ shows brake thermal efficiency (BTE) of the regular engine (RE) fuelled by diesel and B85A15 at different loads (0%, 20%, 40%, 60%, 80% and 100%) and significant injection timings (30° BTDC to 34° BTDC). Advancement of injection timing significantly increased the BTE of RE fuelled by both the test fuels. It was found that irrespective of injection timings and loads the blend B85A15 showed a mean decrease of 2 to 3% in BTE compared to diesel. This BTE decrease of RE with blend might be due to the inherent low calorific value, poor atomization and vaporization that leads to insufficient combustion of the blend. The optimum configuration of RE found to be diesel fuel at injection timing 31° BTDC with an 80% load.

‘Figure 5’ shows brake thermal efficiency of LHR engine fuelled by test fuels diesel and B85A15 at different loads and significant injection timings. It was found that B85A15 fuelled to LHR engine showed enhancement in BTE with advancement in injection timing and the optimum was 6.5% obtained at 33° BTDC with 80% load compared to RE fuelled by diesel at 30° BTDC. The chief reasons for BTE enhancement of LHR engine with blend might be due to thermal barrier coating on engine components provides ample hotness in the combustion chamber via which better fuel blend vaporization and complete combustion. The high compression ratio 18:1 along with sufficient combustible environment
in the combustion chamber of LHR reduces the ignition delay. Accumulation of more amount of vaporized fuel before TDC due to the advancement of injection timing moves the cylinder peak pressure closer to TDC consequently enhancement in BTE.

‘Figure 6’ shows the BSEC of RE and LHR fuelled by B85A15 and diesel at significant injection timings with 80% load. Advancement of injection timing improved the BSEC of LHR with blend and RE with diesel respectively. In comparison, the LHR engine with B85A15 showed significant improvement compared to RE with diesel at all injection timings. The optimum improvement was 4.5% found at 33° BTDC compared with RE fuelled by diesel at 31° BTDC. The reasons for this BSEC improvement of LHR with blend might be due to the ample hot environment in the combustion chamber of LHR helps to overcome the high viscosity problem and suits better for blend rather than diesel. Enhancement in thermal efficiency of LHR fuelled by blend consequently BSEC decrease. Advancement in injection timing helps in early combustion phase in the cycle which ensures complete fuel combustion and peak pressures moves closer to TDC. The higher oxygen content in the blend (13 to 14%) exhibits its optimum efficacy under LHR conditions. The 10% EGR assistance doesn’t show any penalty on BSEC.

![Figure 6. BSEC of RE and LHR at 80% load and significant Injection Timings](image)

3.2. Emission characteristics

‘Figure 7’ shows particulate matter density in emissions of LHR engine and RE fuelled by diesel and B85A15 at significant injection timings with a full load (100%) measured via AVL Hartridge smoke meter in terms of HSU%. Light extinction principle was involved in measuring the particulate matter density (smoke opacity). From the results, it was found that LHR engine fuelled by B85A15 showed lower particulate emissions for all the injection timings irrespective of the load and the optimum was 41% at 31° BTDC compared to RE fuelled by straight diesel at 33° BTDC. The reasons for this might be the low availability of oxygen with diesel at higher load whereas ample amount of oxygen content (13 to 14%) with the blend B85A15. Advancement in injection timing ensured more amount of vaporized fuel to accumulate before TDC due to which complete burning of fuel and particulates reduction along with higher BTE. The fuel density which known to have a direct influence on particulate matter emissions reduced significantly due to the blending of 15% diethyl ether (DEE) additive to biodiesel might be a major factor in this reduction. The existence of ample hot environment in the combustion chamber of LHR along with high compression ratio ensured proper fuel evaporation and effective fuel burning.
‘Figure 8’ shows the NOx levels in emissions of RE and LHR fuelled by B85A15 and diesel at significant injection timings with a full load. It was found that at all injection timings the NOx emissions of LHR engine were lower compared to RE due to 10% constant rate of EGR assistance. The optimum reduction in NOx emissions of LHR fuelled by B85A15 was 18.5% at 33° BTDC compared to RE with diesel at advanced injection timing 34° BTDC. Also, out of all operations, the lowest was 850 ppm (particulates per million) found at injection timing 30° BTDC for EGR assisted LHR fuelled by B85A15 and the highest was 1260 ppm for RE fuelled by B85A15 at advanced injection timing 34° BTDC. This might be due to the effective control of oxygen availability by EGR via recirculating exhaust gases to the inlet manifold of the combustion chamber and thus enhancing mixture heat capacity. Advancement of injection timing increased the NOx emissions since more availability of fuel resident time that provokes NOx chemistry to takes place.

4. Conclusions

An experimentation on low heat rejection (LHR) diesel engine developed via 8 YSZ ceramic coated cylinder head and liner coupled with optimum constant rate (10%) EGR fuelled by a blend of B85A15 (Karanja based biodiesel 85%+ additive diethyl ether blended 15%) by vol. was done to investigate performance and emission parameters like BTE, BSEC, particulate matter and NOx emissions at different load (0 to 100%) and injection timing (30° BTDC to 34° BTDC). The whole process was carried out at a constant high compression ratio 18:1 and fuel injection pressure 190 bar. From results, the following conclusions are drawn:

At manufacturer specified injection timing with low load, the LHR diesel engine fuelled by B85A15 showed satisfactory performance with improved emission characteristics compared to regular diesel engine fuelled by diesel and whereas at advanced injection timing with higher load condition it showed significant improvement in all the investigated parameters. The optimum was an enhancement in BTE by 6.5% with a reduction in BSEC by 4.5%, particulate matter by 44% and NOx by 18.5% found at 33° BTDC with 80% load. The optimum configuration of LHR engine found to be blend B85A15 at 33° BTDC with 80% load and of RE was straight diesel at 31° BTDC with 80% load. Hence a feasible and promising alternate found for a regular diesel engine fuelled by fossil diesel.
References

1. Taymaz, Imdat. "An experimental study of energy balance in low heat rejection diesel engine." *Energy* 31.2 (2006): 364-371.
2. https://www.ecotricity.co.uk/our-green-energy/energy-independence/the-end-of-fossil-fuels
3. Knothe, Gerhard, and Luis F. Razon. "Biodiesel fuels." *Progress in Energy and Combustion Science* 58 (2017): 36-59.
4. A.E. Atabani, A.S.Silitonga, H.C.Ong, T.M.I.Mahlia, H.H.Masjuki, Irfan Anjum Badruddin, H.Fayaz "Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production" Renewable and Sustainable Energy Reviews 18 (2013) 211–245.
5. Malaya Naika , L.C. Meherb , S.N. Naikb , L.M. Dasa “Production of biodiesel from high free fatty acid Karanja (Pongamia pinnata) oil” BIOMASS AND BIOENERGY 32 (2008) 354–357.
6. Nabi, Md Nurun, SM Najmul Hoque, and Md Shamim Akhter. "Karanja (Pongamia Pinnata) biodiesel production in Bangladesh, characterization of karanja biodiesel and its effect on diesel emissions." *Fuel processing technology* 90.9 (2009): 1080-1086.
7. Iranmanesh, M., Subrahmanyam, J., and Babu, M., "Potential of Diethyl Ether as a Blended Supplementary Oxygenated Fuel with Biodiesel to Improve Combustion and Emission Characteristics of Diesel Engines," SAE Technical Paper 2008-01-1805, 2008, https://doi.org/10.4271/2008-01-1805
8. Das, D., Anoop Kumar, and A. Yadav. "Evaluation of performance, emission and combustion characteristics of a CI engine fueled with karanja biodiesel and diethyl ether blends." *Biofuels* (2016): 1-6.
9. Agarwal, Deepak, Shailendra Sinha, and Avinash Kumar Agarwal. "Experimental investigation of control of NOx emissions in biodiesel-fueled compression ignition engine." *Renewable energy* 31.14 (2006): 2356-2369.
10. Abedin, M. J., et al. "Combustion, performance, and emission characteristics of low heat rejection engine operating on various biodiesels and vegetable oils." Energy conversion and management 85 (2014): 173-189.
11. V.S. MuraliKrishnaM, V.R.SeshagiriRaoV, KishenKumarReddyT, V.K.MurthyP “Performance evaluation of medium grade low heat rejection diesel engine with carbureted methanol and crude jatropha oil” Renewable and Sustainable Energy Reviews 34(2014)122–135.
12. https://www.americanelements.com/8-yttria-stabilized-zirconia-114168-16-0

Keywords
Exhaust gas recirculation, Low heat rejection, Yttria-stabilized zirconia, Regular engine, Injection timing, Pongamia pinnata L. (Karanja) biodiesel and Additive Diethyl ether (DEE)

Nomenclature

| Abbreviation | Description |
|--------------|-------------|
| LHR-         | Low Heat Rejection |
| RE-          | Regular Engine   |
| DEE-         | Diethyl Ether    |
| B85A15       | Biodiesel 85%+Additive diethyl ether 15% |
| EGR-         | Exhaust Gas Recirculation |
| YSZ-         | Yttria Stabilized Zirconia |
| BTE-         | Brake Thermal Efficiency |
| BSEC-        | Brake Specific Energy Consumption |
| BTDC-        | Before Top Dead Center |
| NOx-         | Nitrogen Oxide   |