Performance studies and injection timing optimisation for LHR single cylinder diesel engine fuelled with biodiesel blends

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Abstract: Experimental investigations on engine performance, emissions and combustion characteristics using Waste Cooking oil Biodiesel (WCBD) and Dairy Scum oil Biodiesel (DSBD) blends (10, 20 and 30% by volume) were conducted in conventional and Low Heat Rejection (LHR) single cylinder, four stroke diesel engine at five different load conditions (0, 1.1,2.2,3.3 and 4.4 kW). Experiments were also conducted on LHR engine by varying injection timing (20°-Retarded, 23°- rated and 26°-advanced, before top dead centre). The results showed that biodiesel blended fuels have exhibited considerable improvement in Brake Thermal Efficiency (BTE) and significant reduction in exhaust emissions (except NO_x) at all loads conditions in LHR engine at advanced injection timing. Blend of 20% biodiesel of WCBD has shown better performance in LHR engine with advanced timing and BTE was increased by 10.84% compared to conventional engine at Brake Power (BP) of 3.3 kW. Desirability approach of Response Surface Method (RSM) was used to optimise Injection Timing (IT), % of blend and BP. Higher desirability of 0.96 was achieved at injection timing of 26° btdc, BP of 3.61 kW and blend of 18% for waste cooking oil biodiesel.

Key words: Performance, Biodiesel, Injection Timing, RSM, Optimisation

1. Introduction

Diesel engines use different types of fuels such as diesel, biofuel, biodiesel, biogas, CNG, hydrogen etc., for producing power. It is a choice of larger vehicle trucks, locomotives, ships and submarines due to their good fuel economy, higher thermal efficiency and capacity to produce higher power. Main problem(s) of diesel engines is their higher levels of harmful emissions such as particulate matter, Carbon monoxide (CO), Oxides of Nitrogen (NO_x) and Un-burnt Hydrocarbons (UBHC). Use of fuels like vegetable oils / biodiesel produces lower emissions compared to diesel fuel. Combustion of vegetable oils/blends will be incomplete due poor atomization because of higher viscosity resulting in loss of power [1, 2]. Viscosity of vegetable oil can be reduced by converting it into biodiesel by transesterification process [3]. Biodiesel is having similar properties as that of diesel and it is renewable, biodegradable, environmental friendly and non-toxic. It contains approximately 10-12% of oxygen by weight which aids in better combustion of biodiesel [4].

Waste Cooking Oil (WCO) is considered as one of the high value waste product. It is found that consumption of recycled cooking oil has great health and environmental risks due to undesirable levels of contaminants [5]. This used oil can be converted into value based biodiesel which is a better substitute to diesel fuel.

Dairy scum oil is also one of the potential biofuels which is being used as an alternate to diesel and is produced from dairy scum. It is estimated that a large dairy of 5-6 lakh litres milk capacity produces approximately 300-350 kgs of waste scum every day [22]. Most of the dairies dispose this scum to the waste disposal yard and which in turn results in environmental problems. If it is treated and converted as biodiesel it will improve country's economy.

Even after transesterification viscosity of biodiesel is higher than diesel and use of biodiesel in conventional engine results is poor performance. An approach in which heat energy is arrested in an engine cylinder by insulating parts like piston crown, cylinder head, combustion chamber walls, exhaust valves, etc., with a low thermal conductivity ceramic material which can withstand high temperature and minimize coolant heat loss is called Low Heat Rejection (LHR) engine [6]. Although number of ceramic materials have been used as coatings, amongst them Partially Stabilized Zirconia (PSZ) has proved good due to its physical properties like lower heat conductivity, higher mechanical strength, chemical stability and higher thermal expansion coefficient [6, 7, 8].

2. Methodology

The single cylinder, four stroke, 4.41 kW Kirloskar TAF1 diesel engine (Fig. 1) is converted into semi adiabatic (LHR) engine by coating the piston crown with 300 microns of PSZ by plasma spray technique and used for conducting the experiments. Experiments are conducted using Waste cooking oil biodiesel and Dairy scum oil biodiesel blends of 10, 20 and 30% by volume by varying injection timing (23^o btdc-rated injection timing, 20^o btdc-retarded injection and 26^o btdc-advanced injection). Load is applied from no load to full load in steps of 25% of maximum load using electric dynamometer to find performance (BP, BTE, Brake specific Energy Consumption-BSEC), combustion (cylinder pressure rise and Heat Release Rate-HRR) and emission characteristics

(CO, UBHC, NOx and Filter Smoke Number-FSN) of different blends tested. The AVL Digas 444 analyser is used for measuring exhaust gases and Filter Smoke Number is measured using AVL 415 variable sample smoke meter. Response Surface Method (RSM) is applied to optimise injection timing, brake power and % of biodiesel blend for the fuels tested. Surface plots are drawn to study the effects of variables like injection timing, BP and % biodiesel blend on engine responses such as BTE, BSEC, emissions and combustion parameters. Confirmation experiments are carried out at optimised values and results are compared with RSM models in order to validate the experimental results.

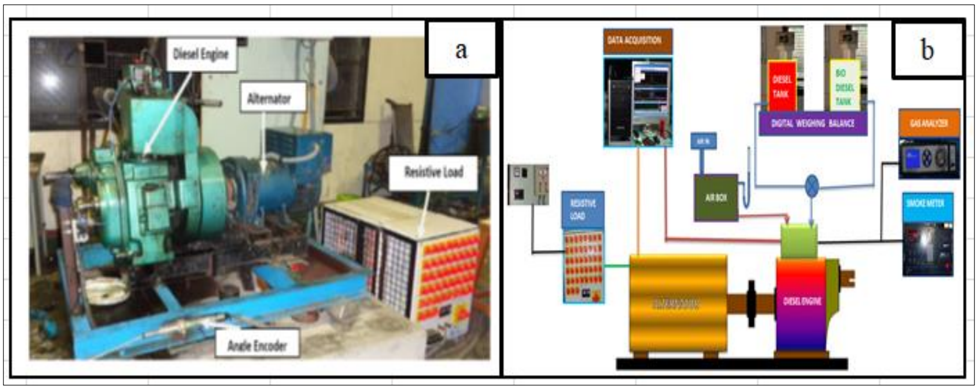

Fig 1 a) Engine test rig b) Schematic of experimental setup

3Results and Discussion

Fig 2 (a) and (b) indicates variation of BSEC with BP for the fuels tested in conventional engine. Amongst the blends (10, 20 and 30%) tested, 20% blend of WCBD showing lower BSEC at all load conditions compared to diesel (Fig 1, c

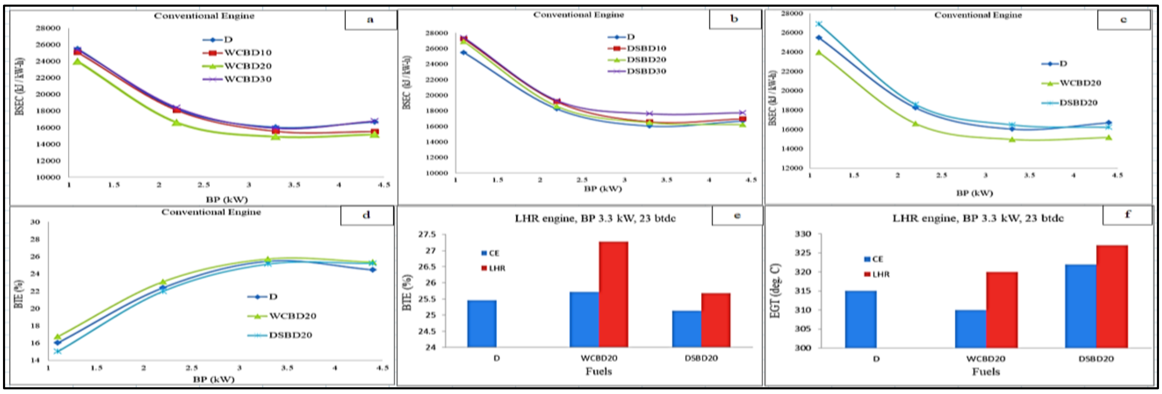

Fig 2 a) Variation of BSEC with BP for WCBD blends b) Variation of BSEC with BP for RSBD blends c) Variation of BSEC with BP for WCBD20 and DSBD20 d) Variation of BTE with BP for WCBD20 and DSBD20 e) Histogram showing variation of BTE in LHR engine f) Histogram showing variation EGT in LHR engine.

This may be probably because of addition oxygen present in biodiesel (being optimum at 20% blend) and higher cetane number of WCBD which will enhance the combustion reactions resulting in lower BSEC compared to other blends. The lower BSEC resulted in higher BTE as evidenced from Fig 1(d). Effect of LHR on BTE of 20% blends is shown in Fig 2(e). It is observed that all blends tested shows improved BTE in LHR engine compared to conventional engine. This could be because of higher in-cylinder gas temperature (Fig 1,f) due to coating which leads to better vaporization and combustion of biodiesel blends in the combustion chamber [9]. In addition, coating also helps in decrease of premixed burning of air-fuel mixture and increases diffusion burning period [10].

Experiments are conducted on LHR engine by varying injection timing for all biodiesel blends and results indicated that 20% blends of WCBD and DSBD have shown significant improvement in BTE at all load conditions with advanced injection timing of 26^{o} btdc compared to diesel as shown in Fig 3 (a, b and c). WCBD20 has shown higher percentage increase in BTE compared to DSBD20 because of its higher cetane number and calorific value.

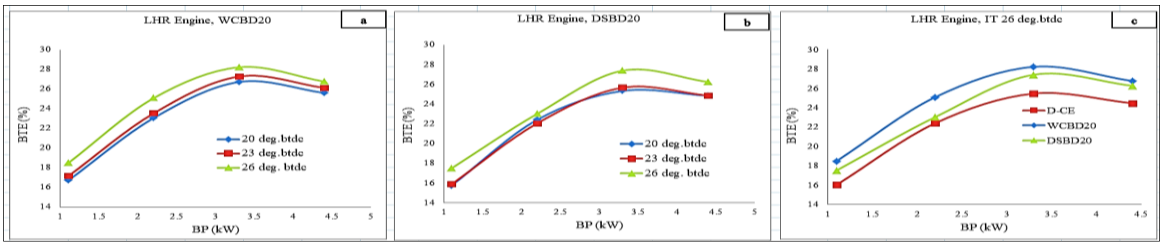

Fig 3 a) variation of BTE with BP for WCBD20 b) variation of BTE with BP for DSBD20 c) variation of BTE with BP in LHR engine at IT of 26^{o} btdc.

The reason for increase in BTE in LHR engine at advance timing (26^{o} btdc) could be due to longer residence time available for the fuel to undergo efficient combustion due to better pre-mix of fuel with air [11,12,13] and resulting in higher peak pressure and maximum heat rerelease rate as shown in Fig 4 (a)&(b) for WCBD20. Apart from this small amount of oxygen (in the form of water content) present in biodiesel will also enhance combustion.

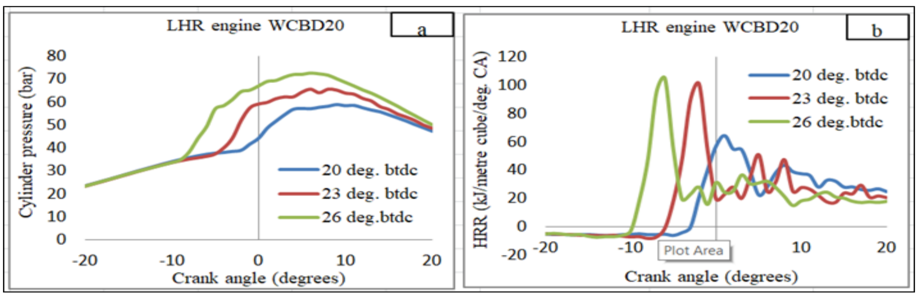

Fig 4 variation of a) cylinder pressure with crank angle b) HRR with crank angle

It is observed that CO, UBHC and FSN (except NO_x) are reduced in conventional and LHR engine for all the blends tested. The reduction in exhaust emissions could be due to higher in-cylinder temperatures (in LHR engine) and presence of inherent oxygen in the biodiesel which aids in improved combustion. Emissions of LHR engine with advance timing (except NO_x) are considerably reduced for all blends tested and the results of WCBD20 which is showing better performance amongst all are presented at 3.3 kW of BP.

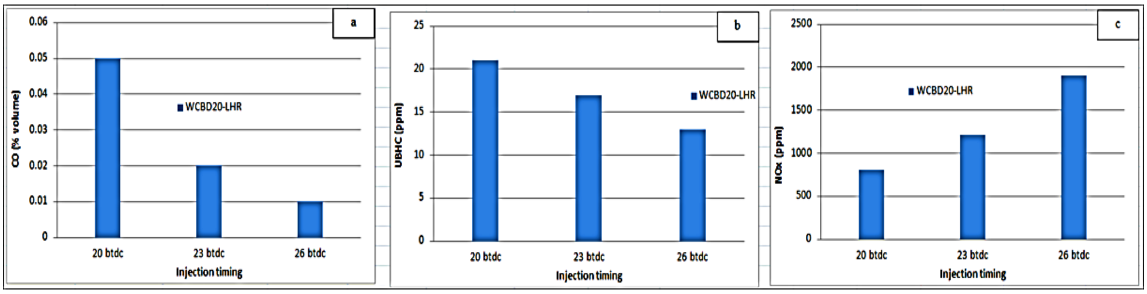

Fig 5 Variation of a) CO with injection timing b) UBHC with injection timing c) NO_X with injection timing at BP of 3.3 kW

Carbon monoxide emission reduction in LHR engine with advance injection timing (Fig 5, a) is mainly due to better oxidation reactions in the pre-mixed stage (early start of combustion) followed with prolonged combustion and improved after burning because of higher in-cylinder exhaust gas temperatures [12,13]. Un-burnt hydrocarbons emissions are decreased further in LHR engine (Fig 3, b) with early timing due to more residence time resulting in improved combustion efficiency. LHR effect also influences on UBHC reduction due to reduced quenching effect because of higher in-cylinder temperatures [14, 15, 16]. NO_X emission is increasing at early injection timing of 26^o btdc due to higher in-cylinder temperatures because of coating and longer combustion duration due to early injection timing. The effect of late injection (20^o btdc) in LHR engine resulted in decrease in performance compared to rated and early injection timing with all the blends tested due to reduced combustion duration, pressure rise and late heat release rate resulting incomplete combustion and loss of power [17]

4. Optimisation Criteria for WCBD blends

The experimental data is used in MINITAB 17 software package and optimal solution is obtained using desirability approach of RSM. The criterion for optimal solutions is obtained by defining goal set for each response (lower and upper limits), weights used and importance of the response. During desirability approach of optimisation, different best solutions with different composite desirability values are obtained. The solution having higher desirability value is considered. Higher desirability of 0.96 was achieved at 26° btdc injection timing, 3.61 kW of power output and 18% biodiesel blend. These parameters can be considered as optimum inputs for the engine chosen for conducting experiments having 4.41 kW of rated power running at 1500 rpm using waste cooking oil biodiesel

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5 Surface plots obtained by RSM analysis for WCBD blends

Fig 6 (a) shows a surface plot drawn between BTE, % blend and injection timing. From the plot it is observed that BTE increases with IT and found to be maximum at BP of 3.61 kW. Up to 20% blend BTE is increasing and beyond that it is showing decrease in trend. Probably this is due to higher percentages of blend consists of higher percentage of water which supresses the combustion and hence incomplete combustion and poor efficiency. Increase in BTE with blend and IT is evidenced from decrease in BSEC as observed from surface plot as shown in Fig 6(b)

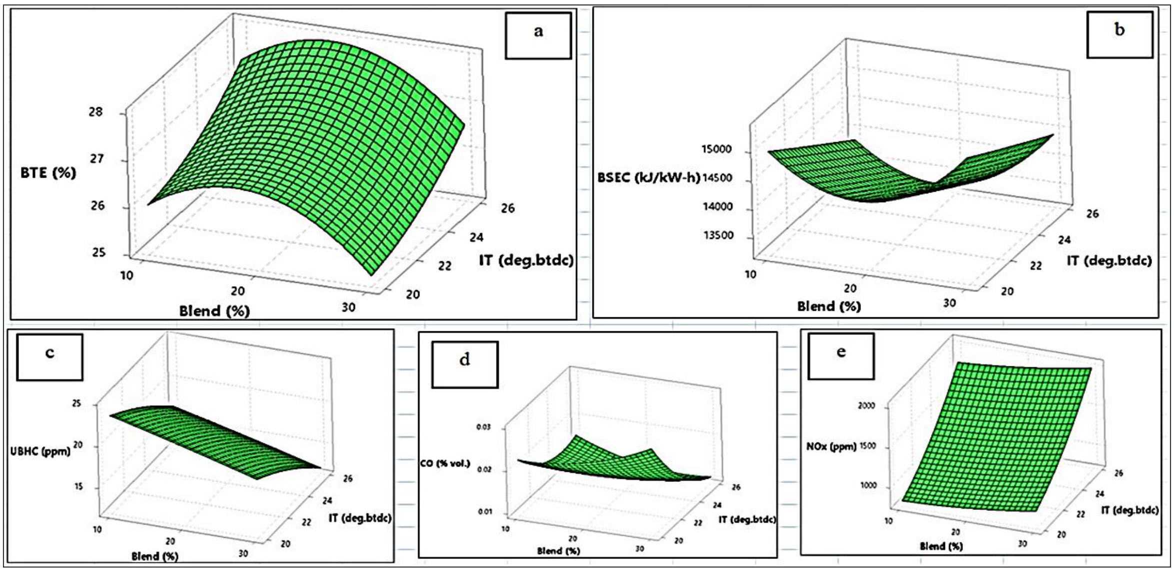

Fig 6 surface plot of a) BTE with blend and IT b) BSEC with blend and IT c) UBHC with blend and IT d) CO with blend IT e) NO_X with blend and IT

Fig 6 (c and d) shows surface plots of variation of UBHC and CO emissions with injection timing and percentage blend. From the plots it is noticed that UBHC and CO emissions decreases with advancing the injection timing. This is because of effect of higher in-cylinder gas temperatures in combustion chamber due to coating and advanced injection timing provides better oxidation reactions between carbon and oxygen molecules due to more residence time. UBHC and CO emissions are higher with retarded injection timing due to incomplete combustion because of late burning of fuel resulting in loss of power.

Fig 6(e) shows a surface plot drawn between NO_X, injection timing and percentage blend at optimum brake power of 3.61 kW. From the plot it is observed that NO_X emission is increasing with increase in percentage of biodiesel in the blend and advancing the injection timing. With injection timing advanced, cylinder peak pressure and temperature will rise quickly and this causes nitrogen to react with oxygen to form NO_X [55]. While at retarded injection timing, NO_X emission decreases because of late combustion of fuel due to late injection [52]. This decreases peak cylinder pressure which results in low peak temperatures and thus NO_X emission reduces

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6. Conclusion

i. Biodiesel blends of waste cooking oil and dairy scum oils are successfully used in conventional and LHR engine.

ii. Amongst the blends tested WCBD20 and DSBD20 have shown significant improvement of performance in LHR engine at advanced (26^o btdc) injection timing.

iii. Exhaust emissions (except NO_X) are reduced in conventional and LHR engine with biodiesel blends.

iii. Amongst WCBD20 and DSBD20, 20% blend of WCBD has shown higher BTE in LHR engine at 26^o btdc compared to diesel.

iv. Optimised injection timing of 26^o btdc, blend of 18% and BP of 3.61 kW was obtained for WCBD in LHR engine from desirability approach of RSM.

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