EFFECT OF STEAM INJECTION ON NO_X EMISSIONS AND PERFORMANCE OF A SINGLE CYLINDER DIESEL ENGINE FUELLED WITH SOY METHYL ESTER

by

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Biodiesel attracts most of the researchers and automotive industries in recent years as an alternative fuel for diesel engines, because of its better lubricity property, higher cetane number, and less greenhouse gas emissions. The use of bio diesel leads to reduction in hydro carbons, carbon monoxide, and particulate matter, but increase in NO_x emissions. Increase in biodiesel blends in standard diesel leads to increase in NO_x emission. In this study, an attempt is made to reduce the NO_x emissions of a diesel engine fueled with pure soy methyl ester (B100) with low pressure steam injection. Experiments were carried out and studied for both standard diesel and pure biodiesel of soy methyl ester with steam injection ratio of 5, 10, and 15% on mass ratio basis of air in the inlet manifold. The present study has shown that around 30% reduction in NO_x can be achieved for the steam injection rate of 10% and considerable reduction for all other steam injection rates when compared to standard diesel and B100. It is also observed that steam injection having significant impact on reduction of other emissions such as HC, CO, and CO_2. The study also noted marginal improvement in the engine brake power, brake thermal efficiency and reduction in specific fuel consumption at part loads and minor increase during peak load operation for the low pressure steam injection on B100.

Key words: *diesel engine, soy methyl ester, steam injection, NO_x emission, specific fuel consumption*

Introduction

Internal combustion engines become an integral part of day to day life like transportation, power and agricultural sectors. The resources of petro diesel are declining day by day and their impact on environment needs an alternate energy source. Petro diesel releases large amount of pollutants like NO_2, CO, CO_2, HC, SO_2, particulate matter (PM), and a range of air toxics. The diesel engine has higher compression ratio, it has higher thermal efficiency, but the high compression ratio leads the higher combustion temperature and encourages the formation of nitrogen oxides (NO_x) emission as well as occurrences of knock [1].

Jinlin Xue, *et al*. [2] reviewed that the use of biodiesel leads to significant reduction in PM, HC, and CO emission with minimum power loss, increase in specific fuel consumption, and increase in NO_x emissions in diesel engines. This is mainly due to higher oxygen content

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Table 1. Worldwide production statistics of soybean

Country	Metric tons
USA	115,802,000
Brazil	107,000,000
Argentina	57,000,000
China	13,800,000
India	11,500,000
Paraguay	9,400,000
Canada	8,400,000

and higher cetane number, further higher load of engine also influences the NO_x emission. The use of biodiesel is feasible way to meet out the growing demands and is best substitute for diesel engines. Mostly the biodiesels are being produced from soybean, rapeseed, palm, and canola [3]. According to EPA Renewable fuel standards program regulatory impact analysis published in 2010, biodiesel from soybean oil reduces an average of 57% of greenhouse gases when compared to diesel. United States Department of Agriculture (USDA) estimates that the global soybean production in 2017-2018 will be 348.04 million metric tons [4]. Table 1 shows the worldwide production statistics of soybean of 2016-2017. Most of the investigations [5-7] are reported that higher blend ratio have more NO_x emission in the biodiesel based engine.

There are various approaches for reducing the biodiesel NO_x have been investigated such as retard injection timing, exhaust gas recirculation (EGR), and selective catalytic reduction (SCR), *etc.* [5]. Among these water injection technique is the simple way to reduce the NO_x by controlling the combustion temperature and pressure. It controls the unwanted emissions and also it improves the volumetric efficiency of the engine and hence it augments the output power. It is simple and efficient method to reduce the engine's susceptibility to detonation. The water absorbs large amounts of heat as it vaporizes, reducing peak temperature as a result it reduces the formation of NO_x and also reducing the amount of heat energy absorbed into the cylinder walls [8]. It was found that with correct water-to-fuel ratio during the intake provides maximum NO_x reduction without affecting engine power output, NO_x emissions reduce up to 33%, effective power and torque increases up to 3%, and specific fuel consumption (SFC) decrease up to 5% [9-11].

Based on literature reviews there is no ample work and study on the effect of low pressure steam injection along with pure biodiesel especially with soy methyl ester (SME). In the present study an attempt is made to reduce the NO_x in B100 with the adaption of low pressure steam injection in the inlet manifold of a diesel engine with SME. The experimental study also includes the impact of low pressure steam injection on engine performance parameters and emission characteristics.

Experimental set-up

The engine used for this experimental work is a single cylinder four stroke diesel engine, Kirloskar make water cooled engine having rated power of 3.7 kW and 1500 rpm constant speed. The engine was loaded with an eddy current dynamometer and is attached to a strain gauge type load cell for measuring applied load on the engine and is linked with the data acquisition system along with the computer. Engine cooling water inlet and outlet temperatures, exhaust temperature were measured using K-type thermocouples. The air flow rate to the engine is measured by using the mass air flow sensor and the fuel consumption was measured by using two optical sensors placed at either levels of burette. The steam rate is measured by a steam flow meter and is controlled by a flow control valve. A piezo-electric pressure transducer is mounted on engine head to measure combustion pressure. The schematic arrangement of experimental set-up is given in figs. 1 and 2, and specifications are detailed in tab. 2. The exhaust emissions (CO, unburned HC, O_2, NO_x, and CO_2) were measured using five gas (multi gas) analyzer (NETEL).

Experimental procedure

In this study, the saturated steam at pressure of 1.5 bar and temperature 110 °C is passed through inlet manifold in to the engine cylinder during the suction stroke without any engine modifications. Experiments were conducted on constant speed single cylinder four stroke diesel engine for various loads and various percentages of steam rates such as 5, 10, and 15% on mass ratio basis along with the air for pure biodiesel SME (B100). The performance and emission values of each loading were observed and compared with the standard diesel and B100 with steam injection.

Table. 2. Technical specifications of the engine test rig

Engine make	Kirloskar
Number of cylinders	Single
Cylinder bore [mm]	80
Cylinder stroke [mm]	110
Rated power BHP	5
Compression ratio	17:1
Rate speed [rpm]	1500 (constant)
Injection pressure	210 bar
Injection timing	23° BTDC
Type of loading	Eddy current dynamometer
Type of cooling	Water

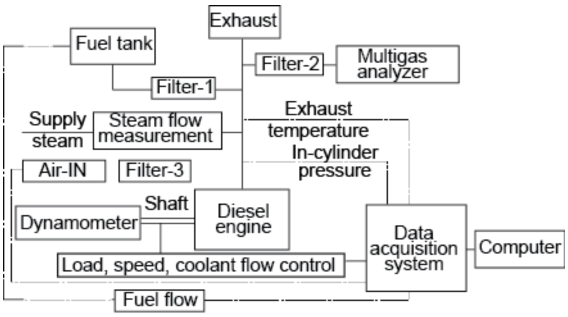

Figure 1. Schematic arrangement of experimental set-up

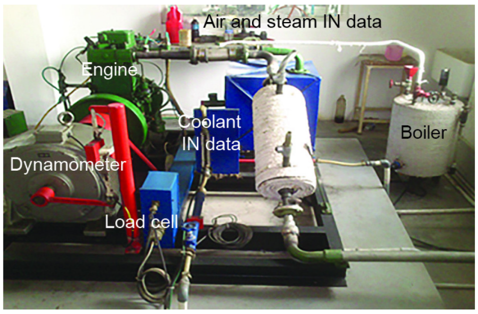

Figure 2. Actual experimental set-up with steam injection arrangement

The soybean biodiesel was produced by transesterification process. The raw soybean oil was purchased from local manufacturer. For transesterification process the standard procedure was followed. Adding raw soyoil of 1000 ml with 200 ml of methanol and 35 g of NaOH mixed well with help of magnetic stirrer. The mixer was heated 60 °C and is maintained for two hours, then it is allowed to settling of glycerin about 24 hours. After separating and washing the properties of bio diesel like density, flash and fire point, viscosity and calorific value were measured and is tabulated and compared with other fuels in tab. 3.

Table 3. Comparison of properties of soybean biodiesel with other fuels

Property	ASTM method	Diesel	SME	SFME	PME
Density [kgm^{-3}]	D1298	830	868	900	881
Flash point [°C]	D93	60	140	145	180
Cetane number	D613	42	50	48	50
Viscosity (CST)	D445	2.8	4.3	5.8	4.65
Gross heating value [$kJkg^{-1}$]	D4809	45000	39000	37800	38850

The engine and gas analyzer was tested and calibrated, and the engine was allowed to run for 10-15 minutes as trial run before the actual observations were made. In the present experimental study, the estimated uncertainties based on the error of the selected instruments for the thermal efficiency, SFC and brake power and emission characteristics are:

$$Y = X_1^2 + X_2^2 + X_3^2 + X_4^2 + X_5^2 + X_6^2 + X_7^2 = 1.6\%$$

Result and discussion

Performance parameters

Brake power

The effect of brake power with percentage of loading is shown in fig. 3. The brake power of the engine compared with standard diesel (DI) and pure biodiesel (B100) of SME at various steam rates. The brake power increases for standard diesel when compared with B100 at all loads. This is due to lower heating value of B100, but the addition of steam as 5% (B100 + S5) and 10% (B100 + S10) shows the improvement in brake power at all loads. When the steam rate increase there is a drop in brake power is observed. When steam rate increased as 15% (S15) the brake power decreases for B100, thus it reduces the performance of engine.

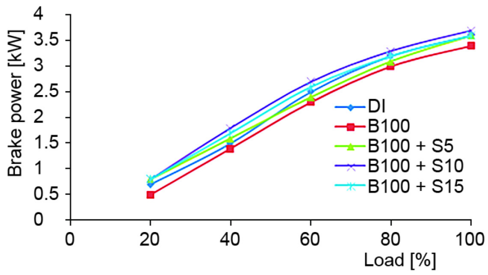

Figure 3. Variation of brake power with load

Brake thermal efficiency

The effect of brake thermal efficiency with percentage of load is shown in fig. 4. It is observed that the brake thermal efficiency (BTE)of the engine is higher for DI when compared with B100.This may be due to low heating value of pure bio diesel. But there is an improvement in BTE when steam is added to B100 at rates S5 and S10 for all loading conditions. This may be due to better vaporization and mixing process of steam with intake air [12]. When steam supplied at 15% (S15) there is a drop in the efficiency was observed for full and part loads for both diesel and B100. This may be due to when excess steam is allowed into the combustion chamber, it reduces combustion temperature and pressure.

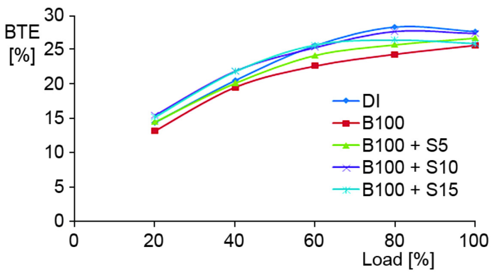

Figure 4. Effect of brake thermal efficiency with load

Specific fuel consumption

Figure 5 shows the variation of specific fuel consumption of the engine with and without steam injection for SME (B100) and various steam rates. As it observed from the figure SFC decreases as the load increases at all situations with and without steam injection. For B100 SFC increases when compared with pure diesel. This is due to lower heating value of B100. For B100, at full load about 14% increase in SFC is observed for steam rate of S15 when compared with pure diesel. At 80% of loading SFC shows the lower value for all steam rates and for steam rate of S10, SFC is closer to diesel, but less than that of B100. This may be due to improved vaporization and mixing of air and fuel drops by the introduction of steam injection [12].

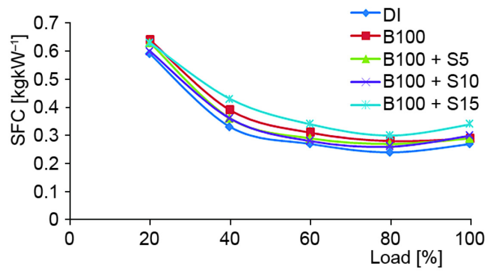

Figure 5. Variation of specific fuel consumption with load

Emission characteristics

Emission of NO_x

The formation of thermal NO_x is due to high temperature of combustion and high residence time of nitrogen and oxygen compounds inside the combustion chamber of the engine cylinder [13, 14]. Since the pure biodiesel has higher oxygen content, it has higher NO_x emission. Figure 6 shows the variation of NO_x emissions with percentage of loading for standard diesel and B100 along with steam injection rates. It can be observed that the NO_x increased at all loading conditions forB100 when compared with standard diesel and at full load conditions NO_x increases up to 12%.

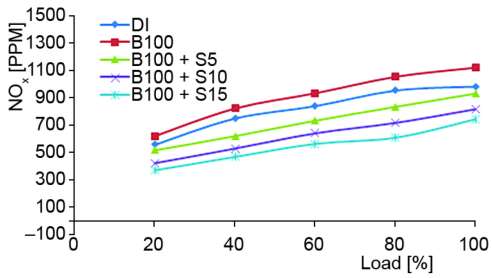

Figure 6. Variation of NO_x emission with load

At full load for steam rate of S5, S10, and S15 NO_x reduces as 16, 30, and 33%, respectively, for B100 when compared with without steam injection. The NO_x reduces up to 33% at full load conditions for higher rate of steam injection (S15). As it noted that the increase in steam injection rate decreases the NO_x emissions considerably. This is due to the reduction in combustion temperature, by the injection of steam into the combustion chamber which absorbs considerable amount of heat during combustion. The fine droplets of water absorbs the peak temperature of combustion and hence the nitrogen oxide emission decreases [8, 10, 12, 14].

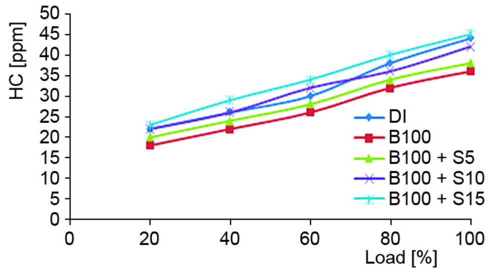

Figure 7. Variation of HC emission with load

Emissions of HC and CO

The variation of hydrocarbon and carbon monoxide emissions with percentage of load is shown in figs. 7 and 8, respectively.

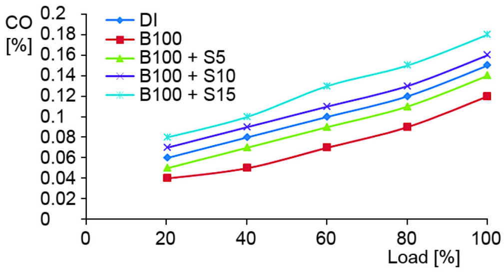

Figure 8. Variation of CO emission with load

Lower level of HC release is observed for B100 due to improved combustion efficiency. Increasing steam injection rate reduced the combustion capability of engines and produced increased level of HC emissions in steam injected condition compared to standard engine. Both HC and CO emissions are followed the same trend due to incomplete combustion nature of the steam injected engine. But in CO chart it is clear that lower rate of steam injection leads lower level of CO compared to standard diesel engine and significant reduction in CO is observed for B100.

Emission of CO_2

Figure 9 shows the CO_2 emission release for the current study, it is noted that the reduction in CO_2 is observed for B100 when compared to standard diesel. There was a marginal reduction in CO_2 emission for biodiesel while adding the steam. The reason may be incomplete combustion due to presence of steam which makes lean air/fuel ratio and reduction in combustion temperature.

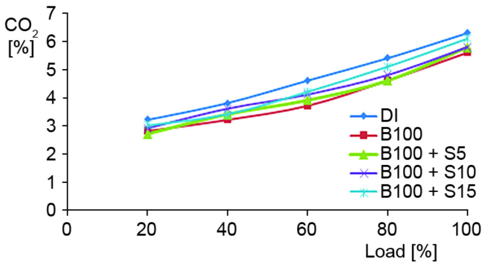

Figure 9. Variation of CO_2 emission with load

The increase in unburned hydrocarbons (HC) and carbon monoxide (CO) emissions and reduction in CO_2 is observed in the present study. This is due to presence of steam in the combustion chamber which reduces the combustion temperature as the water molecules absorbs more amount of heat and leads to more concentration of unburned HC and CO, subsequently CO_2 emission reduced.

Conclusions

In the experimental study the effect of low pressure steam injection on the diesel engine fueled with soybean methyl ester are studied and obtained the following key findings.

- The NO_x emissions reduced significantly (30%) for B100 while introducing low pressure steam injection (S10) with improvement in engine brake power.
- Increasing steam injection rate as 15% the HC and CO marginally and lower level of CO_2 and reduction in performance observed for B100 compared to all loading conditions.
- Reduction in HC and CO are observed for B100 when compared to standard engine.
- Increase in SFC is noted for increasing rate of steam injection and hence reduction in thermal efficiency of engine.
- The B100 leads to drop in engine power by small extent, increases in NO_x emission and decrease in HC and CO emissions when compared with standard diesel.
- Based on the performance measure results and emission characteristics, the optimum steam injection rate to be S10 for B100 operation for the present study conditions.

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