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Computational Investigation of Performance and Emission Characteristics of Diesel Engine Running on Soybean Biodiesel with Varying Injection Timing

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***Abstract*— On account of the energy crisis and search for possible next generation alternative fuel, biodiesels have emerged as a popular choice for research in case of diesel engines. The characteristics of biodiesel are similar to diesel and thus they have been the subject of research for many years. Efforts are being made to increase the Brake Thermal efficiency and decrease the NO_x emissions from diesel engines when running on biodiesels. For this, extensive experimentation is required which is cost ineffective and exhaustive. This work investigates the performance and emissions of a single cylinder diesel engine running on Soybean Biodiesel by varying the Injection Timing via the numerical approach using Diesel-RK software. Simulations were carried out for three different injection timings of 23°, 26°, and 29° bTDC for Soybean Methyl Ester (SME), at different load conditions in terms of brake power and constant speed of 1500 rpm and the results have been compared with those of baseline diesel fuel. The predicted results show better engine emission characteristics for the advancement of injection timing except NO_x emissions while engine performance is better for retardation of timing except PM and Smoke emissions. The performance of diesel fuel is better than Soybean biodiesel, while SME exhibits low Smoke and PM emissions.**

Keywords*— *Biodiesel, SME, Injection Timing, Simulation, Diesel-RK software.

I. INTRODUCTION

The transportation sector is an important unit which affects the economy of a nation. Most of the vehicles used today, be it commercial passenger cars, buses, motorcycles, or heavy-duty vehicles such as trucks and locomotives are reliant on fossil fuels such as Petrol and Diesel as an energy source. However, these fuels being a product of petroleum are non-renewable and will become scarce in the near future. Further, the emissions from engines using these fuels cause serious environmental problems of air pollution. Thus, extensive research has been going on in the field of alternative fuels. In the case of compression ignition engines, such as those running with diesel fuel, biodiesel has emerged as an important alternative [1].

Biodiesel has emerged as a promising alternative due to its favorable properties which are quite close to that of diesel fuel. Further, diesel engines can be run while fuelled with biodiesel with little or no modification. Biodiesels contain oxygen in their chemical structure, which enhances the combustion characteristics. However, reports indicated that usage of biodiesels results in high NO_x emissions [2]. Also, under similar operating conditions, BSFC is more in the case of biodiesels. Thus, research is going on for establishing the compatibility of biodiesel for present diesel engines.

In diesel engines, the fuel is injected some moments before the piston reaches top dead centre (TDC) position. The timing of injection is reported in terms of crank angle and is known as Injection Timing. This has a significant effect on the combustion, performance, and emissions, and one of them is NO_x, where retardation of injection timing has resulted in the decrease of NO_x emissions [3].

Experimental studies have reported significant results about the effect of injection timing, where the advancement has led to improvement in engine performance except NO_x emissions [4]. In another study, injection timing advance led to a considerable decrease in CO, HC, and smoke emissions [5]. Also, a study with waste plastic oil reported increase in BTE with retardation of injection timing [3], and a similar trend was observed for the study with Mahua oil methyl ester [6].

Thus, many experimental studies have been done on biodiesel as an alternative fuel, but the case of injection timing has not been addressed much. Furthermore, the reported studies are largely experimental in nature, which takes time and is expensive. Therefore, in this work, a commercially available engine simulation software Diesel-RK has been used to simulate the performance and emission characteristics of the engine with varying injection timings of 23°, 26°, and 29° bTDC for Diesel No. 2 (B0) and Soybean Methyl Ester (SME) (B100) fuels.

II. DIESEL-RK SIMULATION MODEL

Diesel-RK is intended for full-cycle thermodynamic simulation of IC Engines and is used for combustion, performance, and emission analysis. It has advanced RK model which can be used to predict the performance and emissions over the whole operating range [7] and also provides simulation capability for biofuels and their blends with diesel [8]. In this work Diesel-RK has been used since its agreement with actual experimental data is reported to be very good [7], and recalibration of the model is not necessary for different operating modes of the engine [9]. Also, several studies have reported the validity of the model to be used for IC Engine simulation [10], [11]. Diesel-RK is intended for full-cycle thermodynamic simulation of IC Engines and is used for combustion, performance, and emission analysis. It has advanced RK model which can be used to predict the performance and emissions over the whole operating range [7] and also provides simulation capability for biofuels and their blends with diesel [8]. In this work Diesel-RK has been used since its agreement with actual experimental data is reported to be very good [7], and recalibration of the model is not necessary for different operating modes of the engine [9]. Also, several studies have reported the validity of the model to be used for IC Engine simulation [10], [11].

III. PROPERTIES OF FUEL AND METHODOLOGY

Soybean Methyl Esters (SME) or Soybean biodiesel can be produced via transesterification process of soybean vegetable oil using a catalyst. This transforms the large branched molecular structure of oil to smaller straight-chained hydrocarbon structure for combustion in regular diesel engines and also reduces the viscosity of the oil. Further, soybean biodiesel has excellent lubricity and contains very small quantities of phosphorous and sulphur. Thus, SO_2 emissions are almost negligible. Important properties of Soybean biodiesel are given in Table 1 with those of diesel for comparison.

The simulation is based on a single cylinder engine whose specifications are taken from [12] and are mentioned in Table 2. Performance parameters such as BSFC, BTE, and emission parameters such as EGT, NO_x, CO_2, PM, and Smoke emissions have been calculated for three different injection timings at variable loads in terms of brake power at a constant speed of 1500 rpm for both the fuels. The results are discussed in sections that follow.

TABLE I. PROPERTIES OF FUEL

Property	**SME (B100)**	**Diesel No. 2**
Cetane Number	51.3	48
Calorific Value (MJ/kg)	36.22	42.5
Molecular mass	292.2	190
C	0.7731	0.87
H	0.1188	0.126
O	0.1081	0.004
Sulphur Fraction	0.005	0
Flash Point (°C)	168	63

TABLE II. ENGINE SPECIFICATIONS

Manufacturer	Kirloskar
Model	DAF-8
Type	4 Stroke
Rated Brake Power (bhp/kW)	8/5.9
No. of cylinder	One
Bore x Stroke (mm)	95 x 110
Compression Ratio	17.5
Cooling System	Air-cooled
Cubic capacity	0.78 Litres
Inlet Valve Open	4.5° bTDC
Inlet Valve Closed	35.5° aBDC
Exhaust Valve Open	35.5° bBDC
Exhaust Valve Closed	4.5° aTDC
Fuel Injection Timing	26° bTDC

IV. RESULTS AND DISCUSSION

The results of simulation for Diesel (B0) and SME (B100) are reported and discussed in this section. Among performance parameters, the variations of BSFC and BTE are plotted with Brake Power (% of Rated Power) with different injection timings. Among emission parameters, the variations of EGT, NO_x, CO_2, Smoke and PM emissions have been presented in similar fashion.

A. Variation of Brake Specific Fuel Consumption

The variations of BSFC with Brake Power (% of Rated Power) for injection timings of 23°, 26°, and 29° bTDC are shown in Figure 1. It is seen that BSFC increases with advancement and decreases with retardation of injection timing for both the fuels. In the case of full load (rated power), the BSFC increased by 1.71% for diesel and 4.93% for SME by the advancement of injection timing by 3° CA from the standard setup of 26° bTDC. Also, the BSFC decreased by 3.74% for SME by retardation of timing by 3° CA. Retarding the injection timing decreases the ignition delay period, thus leading to less accumulation of fuel and decreasing overall fuel consumption. On the comparison between the two fuels, it is seen that BSFC for diesel is always lower than that of SME for all loads and injection timings. This is due to the lower calorific value of SME and thus more fuel is needed to produce the same power. Therefore, the variation shows lowest BSFC for retarded timing (23° bTDC) and highest BSFC for advanced timing (29° bTDC) for diesel as well as for SME. Similar trends were reported in an experimental study [13].

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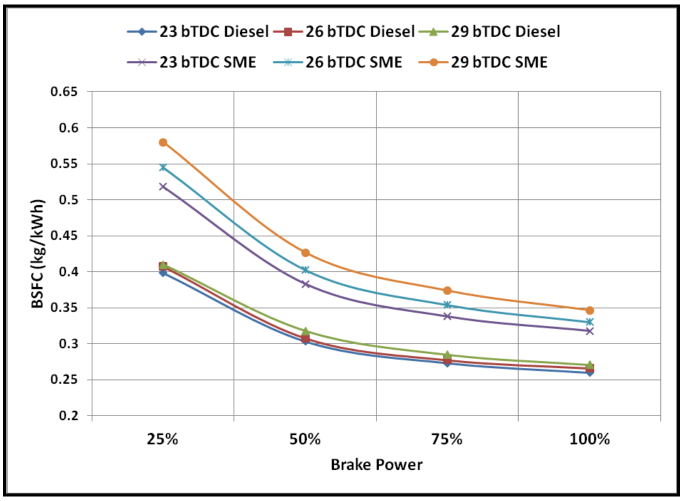

Fig. 1 Variation of Brake Specific Fuel Consumption

B. *Variation of Brake Thermal Efficiency*

The variations of BTE with Brake Power (% of Rated Power) for injection timings of 23°, 26°, and 29° bTDC are shown in Figure 2. It shows that thermal efficiency decreases with advanced injection timing and increases with retarded timing for both the fuels. For full load condition, BTE increased to 32.57% from 31.84% for Diesel while it increased to 31.27% from 30.1 % for SME for retarded injection timing from 26° bTDC to 23° bTDC. Also, it decreased from 31.84% to 31.31% for Diesel while it decreased from 30.1% to 28.69% for SME for advanced injection timing from 26° bTDC to 29° bTDC. Retarding the injection timing decreases the ignition delay period which results in combustion continuing up to the power stroke leading to better thermal efficiency [14]. It can be observed that Diesel exhibits better BTE than SME for all injection timings. This is due to lower calorific value and higher density of SME than diesel which results in lower thermal efficiency. Thus, BTE is highest for retarded injection timing of 23° bTDC and lowest for advanced injection timing of 29° bTDC for both the fuels.

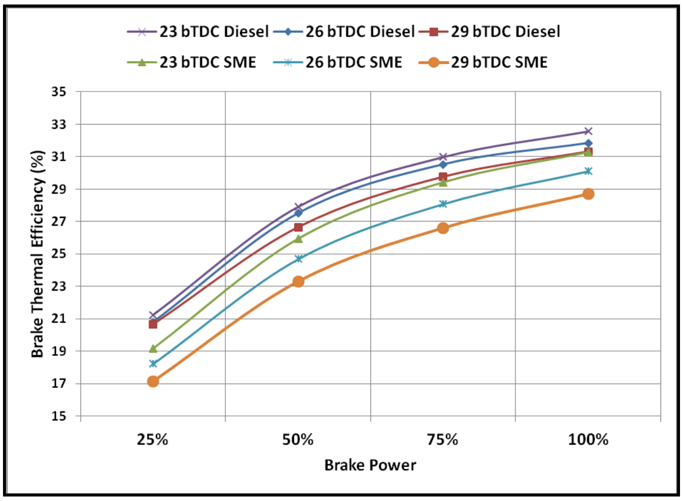

Fig. 2 Variation of Brake Thermal Efficiency

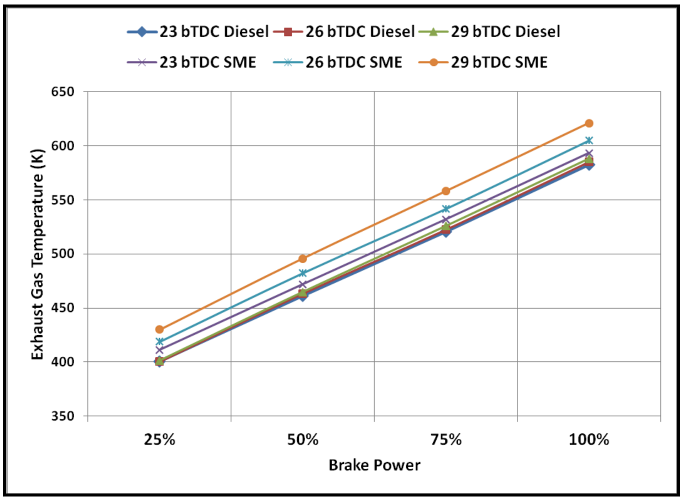

Fig. 3 Variation of Exhaust Gas Temperature

C. *Variation of Exhaust Gas Temperature*

The variations of Exhaust Gas Temperatures for the respective cases are shown in Figure 3. A similar trend is seen for both the fuels where exhaust gas temperature slightly increases with advanced injection timing. As stated earlier, advanced injection timing increases the ignition delay, leading to higher fuel consumption and consequently higher cylinder temperatures. However, the increase in EGT is much more in the case of SME than Diesel. This is primarily due to the presence of oxygen in the chemical composition of SME biodiesel which leads to better combustion process. Thus, maximum EGT is observed for SME for 29° bTDC injection timing.

D. *Variation of NO_x Emissions:*

The variations of NO_x emissions for the three injection timings are shown in Figure 4. It is seen that NO_x emissions increase with advanced injection timing and decrease with retarded injection timing for both diesel and SME. As stated earlier, the increase in ignition delay due to timing advancement increases the cylinder temperatures and provides favourable conditions for NO_x formation. For the advance of 3° CA in injection timing, NO_x emissions increased by 7.65% and 15.03% for diesel and SME respectively for full load condition. On the other hand, NO_x emissions decreased by 11.63% and 15.82% for diesel and SME respectively by retarding injection timing by 3° CA. If both fuels are compared for same injection timing at the same load, it is clear that NO_x emissions are predominantly higher for SME than those of diesel. This is due to oxygen-rich chemical composition of SME biodiesel. Further, all biodiesels emit higher NO_x emissions than diesel due to the presence of oxygen in their molecules. The predicted trends match qualitatively with experimental results reported in the literature [3], [15].

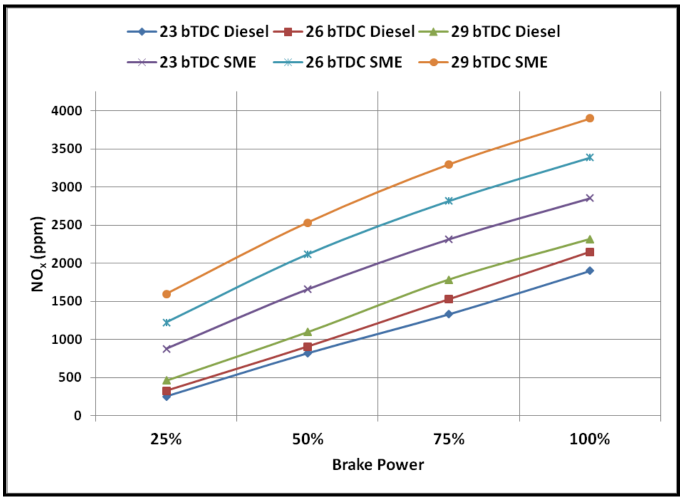

Fig. 4 Variation of NO_x Emissions

E. *Variation of CO_2 Emissions*

The variations of CO_2 emissions under varying injection timing are shown in Figure 5. CO_2 emissions follow increasing trend with advancement and decreasing trend with retardation of injection timing for both diesel and SME. Clearly, injection timing advance increases the delay period which provides longer time for combustion, hence efficient combustion occurs which increases CO_2 emissions while decreasing CO emission. Advance in injection timing decreases the thermal energy lost due to incomplete combustion products since CO emissions are reported to be decreased [16]. It is to be noted that CO_2 emissions are more for SME than diesel with highest emissions occurring for SME at 29° bTDC injection timing. This is again due to oxygen rich composition of biodiesels leading to better combustion.

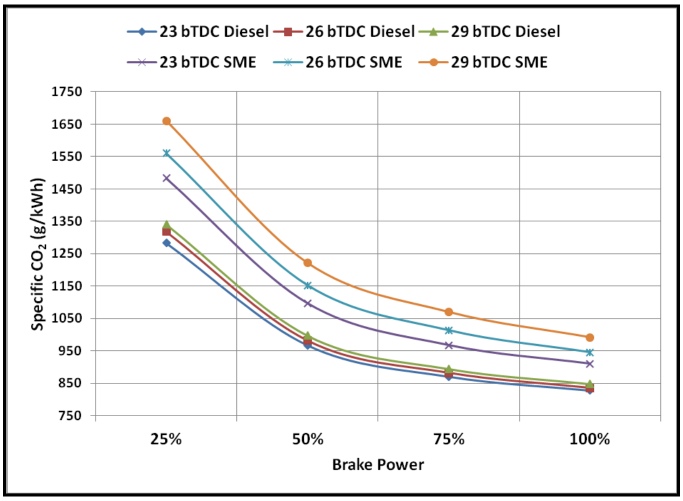

Fig. 5 Variation of CO_2 Emissions

F. *Variation of Specific PM and Smoke Emissions*

The variations of Specific Particulate Matter (SPM) and Smoke (in terms of Bosch Smoke Number) emissions are shown in Figures 6 and 7 respectively. The trend shows that there is a decline in both SPM and Smoke emissions with the advancement of injection timing for either diesel or SME. The primary reason is the increase in ignition delay as a result of timing advance which provides more time for combustion, hence enhancing combustion efficiency and reducing incomplete products in the exhaust. Also, these emissions are much lesser for SME than diesel for same operating conditions. Thus, SME burns more cleanly than diesel due to its inherent oxygen content leading to efficient combustion. Lowest Smoke and PM emissions are for 29° bTDC injection timing for both diesel and SME, the lowest being for soybean biodiesel. Similar observations were reported in other experimental studies [15].

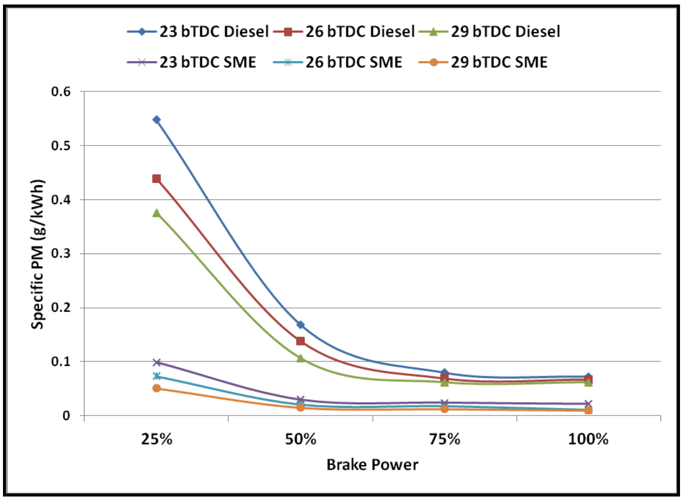

Fig. 6 Variation of Specific PM Emissions

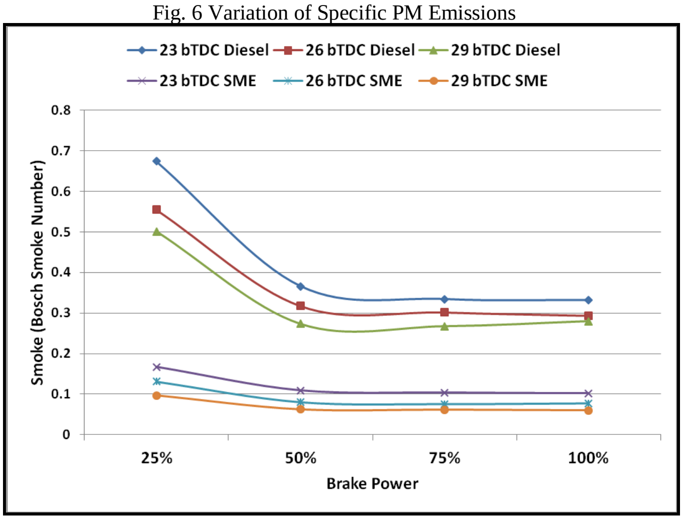

Fig. 7 Variation of Smoke Emissions

V. SUMMARY & CONCLUSION

The numerical investigation was conducted for a single cylinder four stroke diesel engine to study the effect of injection timing on performance and emission characteristics when the engine was run with diesel and Soybean biodiesel. Simulation method was chosen as it reduces manpower, exhaustive experimentation, and time for a research study. A commercially available software Diesel-RK based on multi-zone fuel spray combustion model was chosen for this approach since it is user-friendly, freely available, and experimental studies have validated its use for ICE simulation. Following conclusions were drawn from this study:

- Injection timing influences engine performance and emission characteristics since it affects the ignition delay period.
- Retarding the injection timing has improved performance characteristics of the engine such as BTE and BSFC for both diesel and soybean biodiesel. Further, significant reductions in NO_x emissions are seen for both fuels. However, it has resulted in an increase of SPM and Smoke emissions due to less time available for combustion resulting in incomplete products in exhaust.
- On the other hand, advanced injection timing has resulted in improved emission characteristics of the engine such as low PM, and Smoke emissions while decreasing the engine performance slightly.
- Comparing the two fuels, diesel gives better performance than soybean biodiesel and emissions of CO_2 and NO_x are lower, while the usage of Soybean biodiesel results in lower Smoke and PM emissions.
- Soybean biodiesel can be used with advanced injection timing to reduce smoke and PM emissions with slight decrease in performance, while NO_x emissions are taken care of by Exhaust Gas Recirculation technique or with retarded injection timing to reduce NO_x emissions, while PM and Smoke are taken care of by exhaust after-treatment system, thus providing a two-fold strategy for trade-off between performance and sustainability to the end user.

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