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Optimization of Injection Timing and Injection Duration of a Diesel Engine Running on Pure Biodiesel SME (Soya Methyl Ester)

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Abstract

This study was carried out to predict the impact of injection timing and injection duration on engine brake power and Nitrogen Oxides emissions in a diesel engine using biofuel Soya Methyl Ester (SME). Predictions were accomplished at three different injection timings 10˚, 5˚ Crank Angle (CA) before Top Dead Center (bTDC) and 0˚ CA at Top Dead Center (TDC) and four injection durations 20˚, 25˚, 30˚, 35˚ CA. The study was conducted using a simulation software (Diesel-RK). The predicted results showed that the powers produced by all the setups of the different injection timings are almost equal, but they differ in injection durations, e.g. the power at setup (10˚ CA-bTDC) duration 20˚ CA and 2500 rpm equal to 52 kW, at setup (5˚ CA-bTDC) duration 25˚ CA and same engine speed the power is equal to 51 kW, and at setup (0˚ CA-TDC) durations 30˚ the power is equal to 51 kW. The power in all setups are decreased as the injection duration increased, e.g. at setup 0˚ CA TDC durations 25˚, 35˚, and 40˚ CA and at 4000 rpm, the brake powers are equal 71, 65, and 59 kW respectively, thus the reduction percentages are 9% and 17% when compared to the 25˚ injection duration. The nitrogen oxides emissions decreased as the injection duration is increased, e.g. the emissions at setup (10˚ CA-bTDC) durations 25˚, 30˚, and 40˚ CA and at 2500 rpm are equal 852, 589, 293 ppm respectively, the reduction percentages are 30% and 72%. The variations of injection timing and injection duration have taken a weighty influence on engine performance and emissions. The results are considered as a novelty in the field of using pure biofuel Soya Methyl Ester in diesel engine according to our information.

Keywords

Pure Biofuel Soya Methyl Ester, Diesel Engine, Injection Timing, Injection Duration Optimization

1. Introduction

Biodiesel is a renewable and an alternative fuel like fossil diesel that can be produced from plant oils, animal grease, or restaurant used oil. Biodiesel is used in diesel engines as an alternative fuel or in any device that works on diesel fuel. Biodiesel physical properties are similar to those of fossil diesel [1] [2]. Biodiesel has ecological benefits, economically inexpensive and can be produced in bulky amounts without decreasing food supplies. Biodiesel shows a number of benefits such as better lubricity which decreases friction and retains equipment well lubricated. It also provides an effective combustion at high temperatures because it uses its own oxygen, and also reduces harmful emissions [3] [4] [5]. The chemical structure in biodiesel and fossil diesel is different, but has similar size of molecules, whereas biodiesel contains no sulfur. Biodiesel contains higher oxygen 10% to 12% more than fossil diesel. Also, biodiesel is greatly less toxic than fossil diesel, which is considered as an extra benefit [6].

2. Literature Review

The diesel engine performance is deeply affected by the injection system design and profile. In reality, the most distinguished advances attained in diesel engines resulted directly from excellent fuel injection system designs. Whereas the main objective of the fuel system is to provide fuel into the cylinders of a diesel engine, the difference in engine emissions, performance and noise characteristics depends mainly on how that fuel is supplied and delivered to the engine, so as the engine to use the fuel efficiently. The two main purposes of the fuel system are the injection of fuel, must be at an accurate time and sufficient duration, so it is essential to governor the injection timing. The other purpose concern to power requirements, the fuel system must deliver the correct amount of fuel, so it is important to control and metering the injection quantity [7]. The period of time at which the diesel fuel injected into the combustion chamber from the injector is known as injection duration, is the time taken between start of injection and end of injection and is associated with the quantity of fuel injection. Injection timing is the instant of entering the diesel fuel into the cylinder during the burning process [8]. When altering the timing of fuel injection, therefore will lead to change the combustion timing, injection timing has a strong impact on combustion process injection pressure and engine emissions. Some problems occur when the injection system is not properly adjustment, such as difficult starting, hot engine temperature, poor fuel economy, and also smoke during startups and acceleration [9]. The time injection is the most significant parameter to obtain great combustion efficiency, the leading causes to optimize the combustion process are ignition timing and valve opening timing, those in turn affect the engine performance. Crank angle (CA refers to the position of a piston as it moves inside the cylinder with respect to crank shaft rotation) controls essentially fuel injection timing at which combustion starts, thus the combustion efficiency changes as fuel injection advanced or delayed [10]. Delayed injection timing (starts later), in this case, the air pressure and temperature are a little higher, and this leads to ignition delay. Advanced injection timing (starts earlier), foremost pressure and temperature of air are lower, thus increase the ignition delay [11]. Consequently, injection timing has a strong influence on the delay of the ignition, and therefore on engine emissions and combustion because the engine maximum temperature and pressure changed. To improve combustion efficiency, injection duration could be reduced with high injection pressures and small nozzles, this is common in the modern Diesel engine [12]. The injector parameters affect the combustion pressure rate, heat release rate, pressure load and pressure oscillation which influences the combustion noise. Nozzle geometry, droplets diameter, mass flow, impulse and angle of spray are the important injection parameters since they are required for excellent fuel evaporation in the combustion chamber. Elements that intensely influence the injection and combustion process are injection pressure, fuel injection timing, the interaction between the fuel injects and airflow in the combustion chamber, the usage of multiple injections and the rate [13]. Therefore, an investigation about the variation of injection timing and injection duration linked to combustion process and exhaust gas emissions are necessary. Furthermore, it was required to discover the best injection timing.

2.1. Scope of Biodiesel as an Alternative Fuel

Therefore, in this paper, different injection timing for diesel engine using Biodiesel SME is chosen to optimize the engine performance and emissions. Biodiesel is the likely substitute diesel fuels, is act as an alternate fuel alike to fossil diesel. Biodiesel is able to produce from conventional vegetable oil, animal oil and fats, and unwanted cooking oil. Transesterification is known as a method of converting these oils to Biodiesel. The main likely source of appropriate oil, derives from oil crops such as soybean, rapeseed and palm. Soya Methyl Ester (SME) is a methyl ester derivative from soybean oil. Soy Methyl Ester characteristics are active solvency, volatile organic compounds are low, flashpoint is high, nonhazardous, and friendly with plastics, elastomers, most metals and other organic solvents [14]. Soy Methyl Ester uses as a lubricity element in diesel fuel for alternatives environmentally safe and acts as an economical cleaning agent [15].

There are many environmental benefits of biofuels, the main benefit can be referred to carbon neutral. The biofuels emit at low level a carbon in the form of carbon dioxide (CO_2), because the grows of oil crop take in an equal quantity of CO_2 as is released when the fuel is burned. According to information by the (NREL), biodiesel emits 75% less CO_2 than fossil fuel. Biofuels is a clean fuel when compared to the fossil fuels, produce no sulfur or aromatics during combustion, thus there's no hateful smell related to the biofuels burning. Biofuels are safer and decreases danger of environmental disasters, In Gulf of Mexico, in 2010, an underwater well of oil burst, it released millions of gallons of oil, causing an indefinite amount of damage [16]. The biofuels can supply a useful solution to the international petroleum crisis. Bioethanol and biodiesel are the two worldwide biofuels that might replace the fossil fuel. Similar as fossil fuels, biofuels have some environmental effects beside their impacts on greenhouse gas emissions [17]. Comparative to fossil fuels, however, the influences causing from refining, transporting and using biofuels are mostly significantly lesser. Furthermore, there are methods to develop the resource efficiency and impacts of these activities [18] [19]. One of the greatest significant challenges that face engines designers and manufacturers is to decrease the engine emissions by keeping or even improving the engine performance and fuel consumption. Present-day engine suffers from high exhaust emissions, low power output and comparatively high noise during combustion [20]. Different techniques have been carried out in the latest years to achieve the goal of reduction pollutant emissions and improve engine performance such as [21].

1) Directly affecting combustion efficiency

- Recirculation of exhaust gas (EGR).
- Improving the injection system.
- Modifying piston design and combustion chamber.

2) Exhaust gas treatment methods

- Particulate matter filters.
- Diesel oxidation catalysts (DOC) or selective catalytic reduction (SCR) systems.

The objective of this research is to investigate the effect of different injection timing and injection duration of diesel engine running biodiesel on brake power and NOx emissions using an engine simulation software. Examinations will be conducted to select the optimum injection timing condition, and followed by an investigation to find out the best injection duration. The best conditions are selected referring to the maximum obtainable brake power with lesser NOx emissions. To the best of our knowledge, no research was conducted to examine and optimize the best injection timing and injection duration when diesel engine use 100% biodiesel Soya Methyl Ester, we think it an important gap to be explored.

2.2. Research Approach

The study was performed by using diesel-RK simulation software. The selected operating conditions of the engine are as follow:

- At different engine speeds (1000, 1500, 2000, 2500, 3000 and 4000 rpm).
- At different injection timing 10˚ CA-bTDC, 5˚ CA-bTDC and 0˚ CA-TDC.
- At different injection duration 20˚, 25˚, 30˚, 35˚ and 40˚ CA.

3. Methodology

Diesel-RK Russian simulation software initiated in 1982 in the department of Internal Combustion Engines (Piston Engines), Bauman Moscow State Technical University (MSTU). The software was created as a research improvement tool in the field of internal combustion engines. According to the requests of manufacturing enterprises including largest IC engine manufacturers in Russia several computational improvements were done in the software to make it more powerful as an analytical tool [22].

Diesel-RK is a professional software product that can be used effectively by researchers and graduate students. The software has been continuously developed using advanced mathematical models of combustion in a diesel engine. Diesel-RK takes into consideration specific injection parameters and quality of fuel injection, dynamics of diesel fuel inject development, interaction of sprays with air swirl and with cylinder walls and direction of sprays in the combustion chamber [22]. The Diesel-RK software supports some types of engines such as DI Diesel engines, SI petrol engines, SI gas engines, Two-stroke engines and Dual fuel engines. Furthermore, Diesel-RK simulates the shape of combustion chamber, the injection location (central or non-central), numbers, bore and direction of injection, fuels including biofuels and biofuels-diesel mixture, character of injection shape and sprays interaction with cylinder wall [22].

3.1. Diesel Engine Specifications

The 4D56 engine is a four-cylinder, belt-driven, overhead camshaft diesel engine, which was a part of the “Astron” family introduced in 1990. As the first Turbo diesel to be offered in a Japanese passenger car. Until now it is still in production, but made into a modern power plant by putting a common rail direct injection fuel system into the engine. The investigations were performed in 4D56 engine with the specifications presented in **Table 1** [23].

3.2. Properties of Biofuel

Biofuel SME B100 can be used in many different concentrations. The most common are B5 (5% biodiesel), B20 (20% biodiesel) and B100 (100% biodiesel). Using pure biodiesel, a number of issues should be considered. Pure biodiesel contains less energy on a volumetric basis than pure diesel. Therefore, the higher the percentage of biodiesel (above 20%), the lower the energy content per gallon. To avoid engine operational problems, B100 must meet the specifications of ASTM D6751-15ce1, the properties of the biofuel (B100) are shown in **Table 2**.

The engine brake power and NOx emissions data, which were obtained as the result of the computer simulation processes are listed in **Appendix A**. The simulation program was run on the 4D56 diesel engine using Biodiesel SME fuel at different injection timings and durations, to calculate the engine performance and NOx emissions. Firstly, the Diesel-RK software effectiveness could be examined by compares the engine maximum output power (98 kW at 6400 rpm) when using diesel as a fuel, with the average power gained by the program at the same engine speed, which is equal to 103.2 kW. The program effectiveness percentage between those values is equal 95%, while the maximum brake power gained by the software is found at 7000 rpm and is equal to 105.5 kW. This is the justification of choosing the Diesel-RK software as a tool uses in this research.

Table 1. Specifications of 4D56 diesel engine [23].

S/No.	Specification	Value
1	Number of cylinders	4
2	Numbers of valve per cylinder	16
3	Combustion Chamber	Pentroof Type
4	Fuel System	Electronic Common Rail direct injection
5	Displacement, cm^3	2477
6	Bore × Stroke, mm	90 × 95
7	Compression Ratio	18:1
8	Max Output	98 kW at 6400 rpm
9	Max Torque	174 N.m at 4400 rpm
10	Number of injector per cylinder	1
11	Injector nozzle bore, mm	0.16
12	Number of spray hole/nozzle	3
13	Ambient parameters	1 bar, 313 K

Table 2. Properties of biofuel (SME B100).

S/No.	Quantity	Value
1	Composition (mass fraction)	C = 0.7731, H = 0.1188 and O = 0.1081
2	Low heating value (MJ/kg)	36.22
3	Cetane Number	51.3
4	Density at 323 K (kg/m^3)	885
5	Surface tension factor at 323 K (N/m)	0.0433
6	Specific vaporization heat (kJ/kg)	325
7	Fuel thermal specific capacity (J/kg. K)	1853
8	Molecular mass	292.2
9	Sulphur content	0.005%

4. Results and Discussions

4.1. Brake Power

In this section, a brief discussion will be carried out for all results obtained using simulation software. The most interesting parameter of the diesel engine that will be discussed is the engine Brake Power (bp). Brake power is an engine's power output after subtracting the losses caused by auxiliary components (gearbox, alternator, water pump, differential, and other). It is well known that injection timing affects the performance of engine. Injection timing is known as the starting time of injection of diesel fuel into the cylinder, while the injection duration is the interval of time from the start of injection to the end of injection during which the diesel fuel enters the combustion chamber through the injector.

The injection of biodiesel SME at different injection timings and different injection durations are shown in Figures 1-3. Injection timing at 10˚ CA-bTDC (10˚ before TDC) and at different injection duration (20˚, 25˚, 30˚, 35˚ and 40˚)

are shown (see **Figure 1**), while the injection timing at 5˚ CA-bTDC and at different injection duration (25˚, 30˚, 35˚, 40˚ and 45˚) are presented (see **Figure 2**), and the injection timing at 0˚ CA (at TDC) and at different injection duration (25˚, 30˚, 35˚, 40˚ and 45˚) are displayed (see **Figure 3**).

In the case of injection timing at 10˚ CA-bTDC and injection duration (20˚, 25˚, 30˚, 35˚ and 40˚) (see **Figure 1**), it seems clearly higher brake power obtained at injection timing 10˚ CA-bTDC and 20˚ duration (10˚-bTDC to 10˚ CA-aTDC) at all engine speeds when compared to other injection duration and at same timing. For example, at setup (10˚-bTDC to 30˚ CA-aTDC) which indicates to 40˚ injection duration and 3000 rpm the brake power is equal to 47.923 kW, at setup 10˚-bTDC to 10˚ CA-aTDC (which refer to 20˚ of injection duration) and 3000 rpm the brake power is found to be 61.073 kW, the increasing rate is about 27% when compared to the (−10˚ to 30˚ CA) setup, thus the brake power increases as the injection duration decreases from 40˚ to 20˚ injection duration.

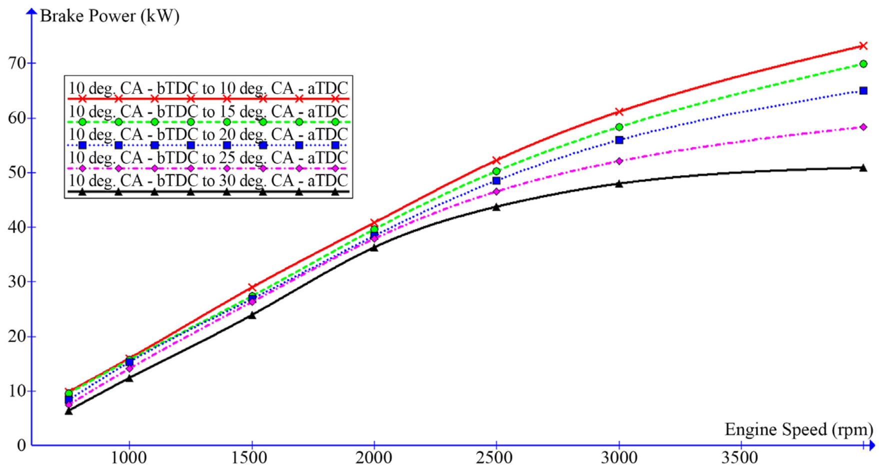

Figure 1. Brake power vs engine speed at timing 10˚ CA-bTDC and different injection durations.

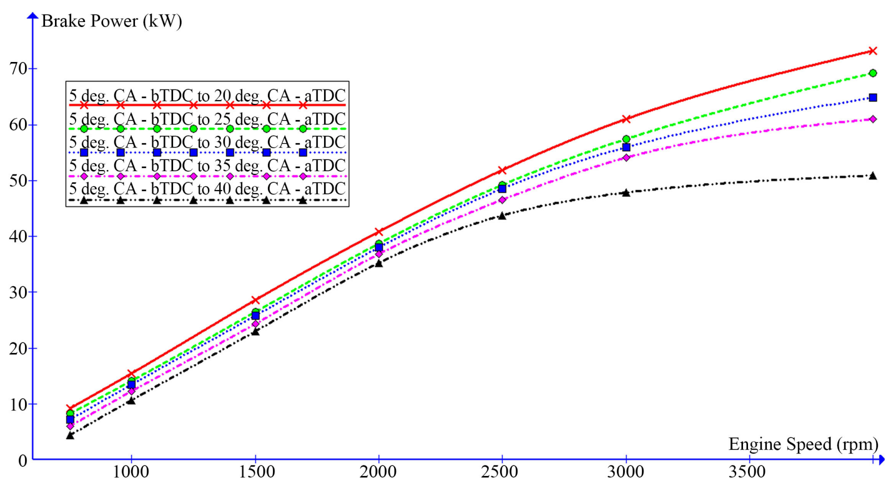

Figure 2. Brake power vs engine speed at timing 5˚ CA-bTDC and different injection durations.

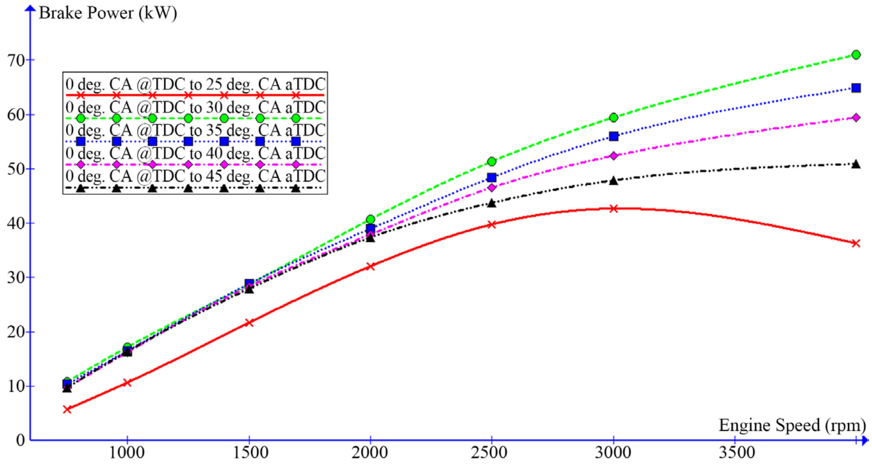

Figure 3. Brake power vs engine speed at timing 0˚ CA-TDC and different injection durations.

The setup 5˚-bTDC to 20˚-aTDC (25˚ of injection duration) obtains the best condition to generate brake power at all engine speeds when compared to the other setups (see **Figure 2**). The brake power at setups −10˚ CA to 20˚ and 5˚-bTDC to 20˚-aTDC (both obtain higher brake power) at 4000 rpm are equal to 73.267 kW and 73.277 kW respectively. The comparison concludes that the power gained when retarding injection timing 10˚ CA before top dead center with 30˚ injection duration at setup −10˚ to 20˚ CA equals to the power gained when retarding injection timing 5o CA before top dead center with injection duration 25˚ at setup 5˚-bTDC to 20˚ CA-bTDC. Little bit difference with 0˚ to 30˚ CA setup in brake power which is equal to 70.908 kW when compare to the earlier setups.

At low and mid-engine speeds the injection duration does not affect the value the brake power significantly (see **Figures 1-3**), which affects greatly during high speeds. For example, from **Figure 1**, at setup 0˚ to 40˚ (injection starting at 0˚ CA and 45˚ injection duration) and 1500 rpm the brake power is equal to 27.944 kW, while the brake power at the setup 0˚ to 30˚ and same engine speed is equal to 28.699 kW, about 2.7% increasing rate when compared to the 0˚ to 40˚ setup.

The three best attainable brake power gained from different injection timings and duration are shown in **Figure 4**. At the first condition, the injection timing starts at 10˚ CA before TDC and 20˚ CA injection duration. The second condition the injection timing starts at 5˚ CA before TDC and 25˚ CA injection duration, while in the third condition the injection starts at the top dead center 0˚ CA and the injection duration takes 30˚ CA. Referring to **Figure 4**, the maximum brake power that can be obtained from using biofuel SME in a diesel engine is by using the setups 10˚-bTDC to 10˚ (20˚ CA duration) and 5˚-bTDC to 20˚-aTDC (25˚ CA duration). The third setup 0˚-TDC to 30˚-aTDC (30˚ CA duration) achieved greater brake power at low engine speeds (less than 2000 rpm) when compared to the others, while generated less at high engine speeds (more than 2500 rpm), this reduction is due to the ignition delay (the injection starts at the peak pressure at TDC).

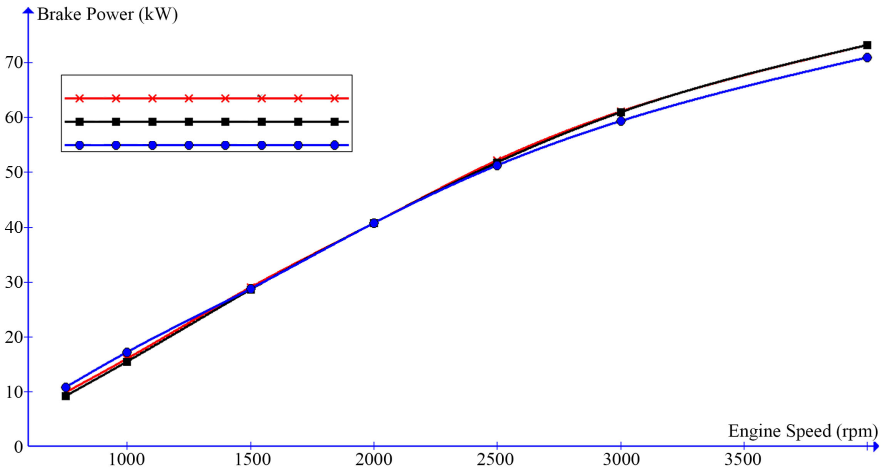

Figure 4. Brake power vs engine speed at timing 0˚ CA-TDC, 5˚ CA-bTDC and 10˚ CA-bTDC and different injection durations.

4.2. Nitrogen Oxides Emission

In low engine speeds, the operating conditions cause of high nitrogen oxides emissions. At low speeds (750 - 2500 rpm) and at all operating conditions, engine releases high rates of nitrogen oxides (see Figures 5-7). In low engine speeds, the time for NOx formation is available in addition of availability of excess fresh air (N_2 and O_2) high volumetric efficiency and the temperatures above 1800˚C, all these factors lead to increase the NOx production. On the other hand, the NOx emission is reduced considerably at high engine speeds, as a result of less amount of fresh air entering the cylinder, due to low volumetric efficiency, and less time available for NOx formation. For example, Figure 5 shows, at setup (0˚ CA-TDC to 25˚ CA-aTDC) and at 750 rpm the NOx is equal to 2267 ppm, in the case of 4000 rpm and same setup the NOx decreased to 686 ppm, reduction rate about 30% due to increase in engine speed.

The highest rate of emissions occurred in the shortage injection duration (0˚ CA to 25˚ CA-aTDC) equals to 25˚ CA when the injection starts at 0˚ CA (the piston at TDC) (see Figure 5), whereas the brake power at the same setup reached to its maximum value (see Figure 2). Therefore, a strong relation between the values of brake power and the formation of NOx emissions, as the power increase the NOx increase and vice versa. This phenomenon occurred clearly in all simulated setups (see Figure 6 and Figure 7). The second observation as the injection duration is increased the NOx formation is decreased, this due to reduction in combustion efficiency and hence leads to lessening the in cylinder temperature. For example, at setup (5˚ CA-bTDC to 20˚ CA-aTDC), the injection started at 5˚ CA before TDC and continued till 20˚ CA after TDC, therefore the injection duration is 25˚ CA, at this setup and at 3000 rpm the NOx emissions is equal to 995.6 ppm (see Figure 6). When increasing the injection duration to 30˚ CA, the emissions reduces to 848.25 ppm, more reduction in emission can be achieved at the maximum injection duration 45˚ CA which is reached to 342.4 ppm.

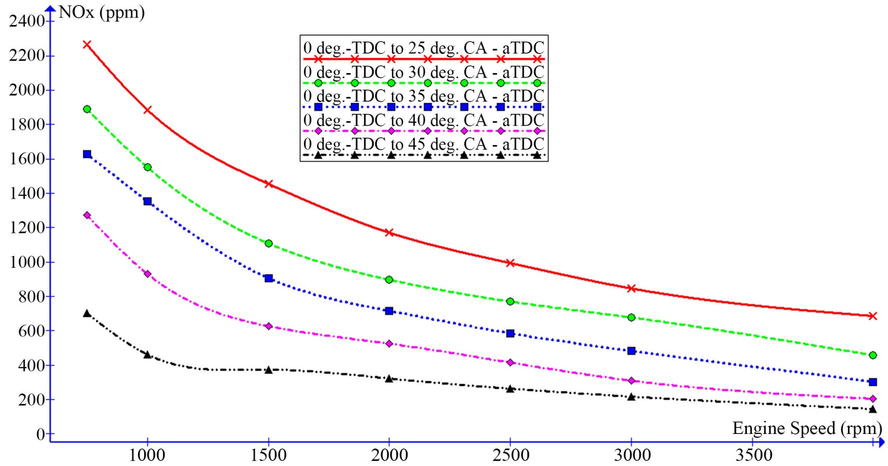

Figure 5. NOx emissions vs engine speed at 0˚ CA-TDC injection timing and different injection durations.

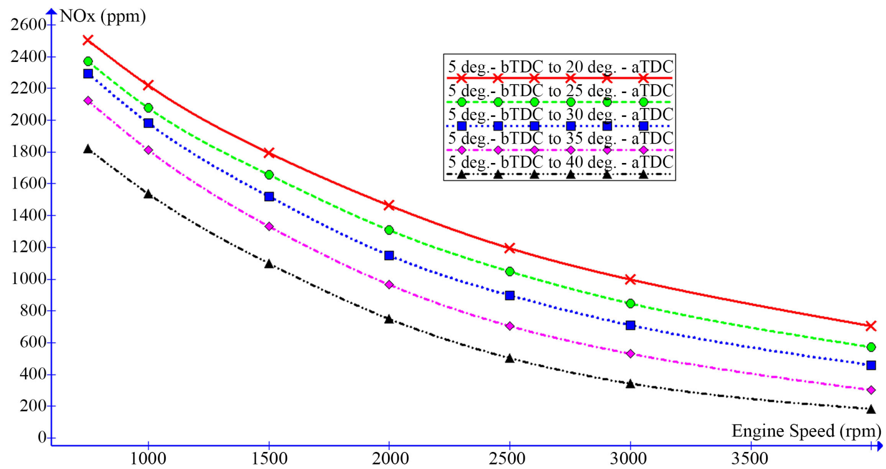

Figure 6. NOx emissions vs engine speed at 5˚ CA-bTDC injection timing and different injection durations.

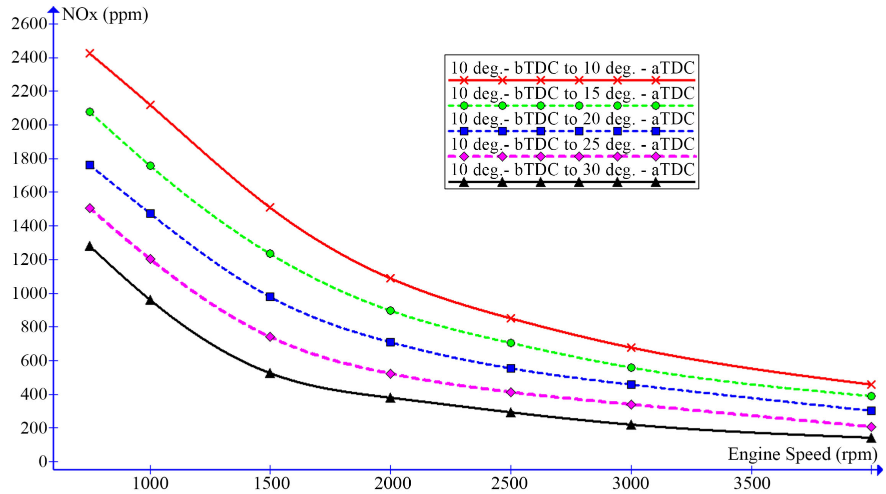

Figure 7. NOx emissions vs engine speed at 10˚ CA-bTDC injection timing and different injection durations.

A significant reduction in NOx emissions as the duration of injection increased (see Figures 5-7). The greater the injection duration the lesser the brake power the lesser the nitrogen oxides emissions (see Figures 1-3). The increasing of the injection duration far beyond definite limit some fuel will not get sufficient time to burn which is uneconomical and produces more emissions such as CO and UHCs as a result of incomplete combustion and excess injected fuel, while the nitrogen oxides decreases because the reduction of combustion efficiency. The optimum injection timing to obtain the great brake power is at the peak in-cylinder pressure, in case of less peak pressure (advanced or delay) leads to lower cylinder temperature and hence less brake power.

Figure 8 shows the maximum NOx emissions created by the three best setups regarding the brake power shown in Figure 4. The maximum NOx occurred at the setup 5˚ CA-bTDC to 20˚ CA-aTDC, while the best injection time setups to obtain extreme brake power started are at 5˚ CA-bTDC and 10˚ CA-bTDC (see Figure 4), therefore, the extreme brake power always accompanied by maximum NOx emissions. Figure 4 shows that the setup 10˚ CA-bTDC to 10˚ CA-aTDC can also achieve the same brake power as produced from setup 5˚ CA-bTDC to 20˚ CA-aTDC, but less amount of NOx formation created when compared to the setup 5˚ CA-bTDC to 20˚ CA-aTDC. Thus, the conclusion of this study is stated as, when the diesel engine used biofuel SME and after a deep investigation and discussion the injection profile 10˚ CA-bTDC to 10˚ CA-aTDC achieved the best brake power and less NOx emissions when compared to the other setups. Therefore, the best injection timing and injection duration of a diesel engine running on pure biodiesel SME is at 10˚ CA—before TDC and 20˚ CA duration respectively. The fuel injection starts at 10˚ crank angle before top dead center during the compression stroke, and ends at 10˚ crank angle after top dead center during the expansion stroke. The choosing process was based on the maximum power output and less quantity of NOx emissions.

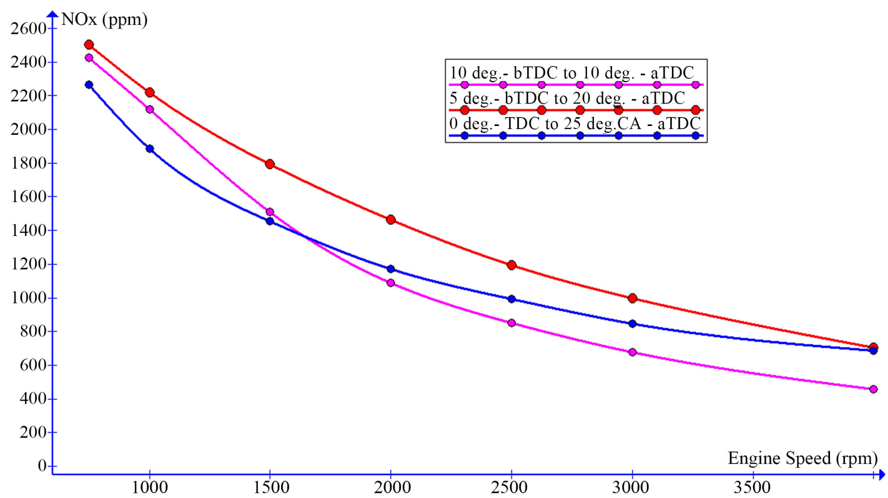

Figure 8. NOx emissions vs engine speed at different timing 0˚ CA-TDC, 5˚ CA-bTDC and 10˚ CA-bTDC and different injection durations.

5. Conclusions

Biofuels are renewable energy sources, prepared from carbon-based material, sugar or vegetable oils. Biofuels play a useful role in decreasing the emissions of carbon dioxide. The biofuels usage has grown-up quickly through the last years. This study is carried out to research the best injection timing and injection duration to obtain high engine performance and lesser nitrogen oxides emissions. Since the brake power is directly proportional to the emissions, Retarding or advancing the injection timing has an effect on the peak cylinder pressure. As the cylinder pressure increases, the combustion temperature tends to increase which result in more power and high NOx emissions. Additionally, there is an optimum injection timing that gives the best performance. From this investigation, the results can be summarized as follows:

1) The increase of brake power through advance fuel injection was due to high cylinder pressure and high heat rate.

2) Furthermore, the delay of the injection timing with suitable injection duration increases the engine brake power.

3) The NOx emission was reduced in the greater injection durations while the brake power decreased at those injection durations. Consequently, as the brake power increased the NOx emissions increased.

Therefore, to reduce the NOx emission it is recommending to introduce one of the techniques used to minimize the emissions to the engine fueled by biofuel such as Exhaust Gas Recirculation, oxidation catalysts (OC) or selective catalytic reduction (SCR) systems. Finally, the selection of the best injection timing and injection duration of diesel engine using 100% biofuel Soya Methyl Ester is considered as extra information in the field of using renewable energies.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

aTDC	After Top Dead Center o CA	NREL	National Renewable Energy Laboratory
bp	Brake Power kW	SCR	Selective Catalytic Reduction
bTDC	Before Dead Center o CA	SOI	Start of Injection
CA	Crank Angles o	SME	Soya Methyl Ester
CO_2	Carbon Dioxide ppm	ppm	part per million
DOC	Diesel Oxidation Catalysts	rpm	revolution per minute
EGR	Exhaust Gas Recirculation	HCs	Hydrocarbons
EOI	End of Injection	NOx	Nitrogen Oxides

Appendix (A)

Injection Duration Crank Angle (CA)	Engine Speed (rpm)	Brake Power (kW)	NOx Emissions (ppm)
10˚ CA-bTDC to 10˚ CA-aTDC	750	9.8	2424
	1000	15.9	2117
	1500	28.9	1511
	2000	40.8	1090
	2500	52.2	852
	3000	61.1	679
	4000	73.3	456
10˚ CA-bTDC to 15˚ CA-aTDC	750	9.5	2078
	1000	15.67	1757
	1500	27.4	1236
	2000	39.6	897
	2500	50.2	706
	3000	58.4	559
	4000	69.9	389
10˚ CA-bTDC to 20˚ CA-aTDC	750	8.3	1763
	1000	15.2	1473
	1500	26.8	980
	2000	38.4	755
	2500	48.5	589
	3000	55.9	457
	4000	64.9	301
10˚ CA-bTDC to 25˚ CA-aTDC	750	7.5	1507
	1000	14.0	1202
	1500	26.3	740
	2000	37.9	522
	2500	46.5	414
	3000	52.1	340
	4000	58.4	204

Continued

	750	6.3	1282
	1000	12.3	961
	1500	23.9	525
10˚ CA-bTDC to 30˚ CA-aTDC	2000	36.3	382
	2500	43.8	293
	3000	47.9	218
	4000	50.8	142
	750	10.2	2448
	1000	15.3	2180
	1500	28.6	1792
5˚ CA-bTDC to 20˚ CA-aTDC	2000	40.8	1464
	2500	51.8	1221
	3000	60.9	1025
	4000	73.3	706
	750	8.2	2372
	1000	14.1	2078
	1500	26.4	1656
5˚ CA-bTDC to 25˚ CA-aTDC	2000	38.7	1310
	2500	49.2	1048
	3000	58.4	824
	4000	70.3	571
	750	8.8	2292
	1000	16.4	1979
	1500	28.8	1520
5˚ CA-bTDC to 30˚ CA-aTDC	2000	39.9	1150
	2500	48.4	896
	3000	55.9	679
	4000	64.8	458
	750	5.9	2124
	1000	12.2	1773
	1500	24.4	1330
5˚ CA-bTDC to 35˚ CA-aTDC	2000	36.9	964
	2500	46.5	668
	3000	54.1	457
	4000	61.0	301
	750	5.7	1820
5˚ CA-bTDC to 40˚ CA-aTDC	1000	16.7	1539
	1500	25.9	1100
	2000	36.2	715

Continued

	2500	43.7	487
	3000	47.9	342
	4000	50.9	182
	750	5.7	2267
	1000	10.7	1887
	1500	21.6	1456
0˚ CA-TDC to 25˚ CA-aTDC	2000	32.0	1170
	2500	39.7	993
	3000	42.7	848
	4000	36.2	686
	750	10.2	1890
	1000	16.1	1552
	1500	28.7	1110
0˚ CA-TDC to 30˚ CA-aTDC	2000	39.7	897
	2500	50.2	770
	3000	58.4	678
	4000	69.9	458
	750	10.3	1626
	1000	16.4	1352
	1500	28.5	906
0˚ CA-TDC to 35˚ CA-aTDC	2000	38.9	715
	2500	48.3	585
	3000	55.9	481
	4000	64.8	301
	750	9.6	153
	1000	17.2	929
	1500	28.3	524
0˚ CA-TDC to 40˚ CA-aTDC	2000	37.9	522
	2500	46.5	414
	3000	52.4	310
	4000	58.4	204
	750	9.7	701
	1000	16.3	461
	1500	27.9	372
0˚ CA-TDC to 45˚ CA-aTDC	2000	37.3	382
	2500	43.8	293
	3000	47.9	217
	4000	50.9	142