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To cite this article: M Aldhaidhawi *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **518** 032024

IOP Conf. Series: Materials Science and Engineering **518** (2019) 032024 doi:10.1088/1757-899X/518/3/032024

Engine performance and emission formation of a diesel engine fueled with biodiesel B15 at different injection timings

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Abstract. Biodiesel could now be considered as an alternative fuel for compression ignition engines and it can be used directly or in blends with diesel without engine modification. Biodiesel is non-toxic, contains no aromatics is sulphur-free, biodegradable and an oxygenated and renewable fuel. In the present work, a numerical study was performed to determine the engine performance and exhaust gas emissions of a direct injection DI, four-cylinder, diesel engine by using pure diesel and biodiesel B15 fuel (15% sunflower oil mixed with 85% diesel, by volume) operating at different fuel injection timings. The results were acquired at engine speed 3000 rpm under full load conditions. A comparison between the numerical results and experimental data regarding the in-cylinder pressure was done in order to check the usefulness of this model. The results have shown that the engine performance of biodiesel B15 was slightly lower than that of pure diesel fuel. Concerning gas emissions; lower soot emission, higher NOx emissions of biodiesel B15 were obtained compared to those of diesel fuel at same operating conditions.

1. Introduction

Today, in most countries; biodiesel fuel is obtained from vegetable oils or animals fat and is one of the alternative fuels suitable for a diesel engine that could be used in pure form or as a mix with diesel fuel at a different volumetric percentage. Biodiesel B5 (5% biodiesel mixed with 95% diesel fuel, by volume) is used as a regular fuel in most countries, at the gas station pump. The international development specifications for a wide variety of products (ASTM) approved B5 for safe operation in any CI engine [1,2,3,4]. Biodiesel's high oxygenation (10-12% O2, in content) could benefit the combustion process, which leads to improvement of the engine performance and a reduction of exhaust gas emissions [5-6]. Biodiesel has a higher cetane number than diesel fuel which leads to a reduction of chemical ignition delay. However, there is drawback of biodiesel is viscosity. Biodiesel has 2-3 times higher viscosity value compared to that of diesel fuel which has an effect on spray pattern, break up and penetration [7,8].

Kannan [7] experimentally studied the effect of a mix with 40% waste cooking palm oil (WCO) methyl ester, 50% diesel and 10% ethanol on engine performance, combustion characteristics and emissions of a four-stroke, single cylinder, DI diesel engine. The experimental study was done at two injection timings (25.5° and 28° before top dead center (bTDC), at different injection pressures (220 bar to 300 bar, increment 20 bar). The results have shown that the optimum engine performance registers at injection pressure equal to 240 bar and injection timing of 25.5° bTDC when fueled with biodiesel-diesel-ethanol blend. The brake thermal efficiency was improved by 2%, while brake specific fuel consumption (BSFC) decreased up to 0.9 MJ/kWh when using biodiesel-diesel-ethanol blend than that of pure diesel fuel. Concerning exhaust gas emissions, CO, CO2, NOx, and smoke emissions were decreased in comparison to those of diesel fuel.

With the same objective, Gumus [9] investigated experimentally the effect of fuel injection pressures (18, 20, 22, and 24 MPa) of different biodiesel blends (B5, B20, B50 and B100) in a naturally aspirated, single cylinder, air cooled, DI diesel engine, with emphasis on BSFC and exhaust gas emissions. The results were acquired at engine speed 2100 rpm at different engine loads and have showed an increase in BSFC of biodiesel blends (B20, B50, and B100) when injection pressure is increased. In terms of emissions, CO, UHC and smoke opacity were decreased, while the CO2 and NOx emissions increased when using biodiesel at higher injection pressure.

In the last two decades, several studies tried to simulate the internal combustion engine with higher accuracy models operating on biodiesel and its blends. However, engine models can be used to better understand the combustion process, emissions formation and spray configuration, due to the fact that the experimental studies were more expensive and needed a lot more effort than numerical studies.

The effect of concentrated biodiesel blends (B50 and B100) on diesel engine emission formation at a constant engine speed of 2400 rpm under 10%, 50% and 100% engine load has been numerically studied by [10]. A model was created and analysed by using 3-D CFD simulation software KIVA4 coupled with CHEMKIN II. The results were at first compared with experimental data and have showed a good agreement, with a maximum deviation of up to 5% on the peak cylinder pressure. At all engine loads that were selected, biodiesel (B50 and B100) produced lower CO, smoke and UHC emissions, and an increase of NOx emissions compared to diesel fuel.

The effect of injection timing on engine performance and emissions of a GW4D20, four-cylinder, DI-diesel engine with common rail injection system fueled with isopropanol (B5, B10, B15 and B20, by volume) has been experimentally studied by Liu et al. [11] concluding that the isopropanol can significantly improve the engine soot and CO emissions. The combustion duration and peak fire pressure were decreased when using isopropanol, while the brake specific fuel consumption BSFC was increased.

The aim of this study is to numerically analyse the effect of the fuel injection timing (2°, 4°, 6°, 8° and 10° bTDC) on diesel engine performance and exhaust gas emissions of biodiesel B15 at constant engine speed 3000 rpm under full load operating conditions by using AVL BOOST 2016 code.

2. Experimental setup

In this study, a diesel engine with four-cylinder, four-stroke, naturally-aspirated and a direct injection DI coupled with an eddy-current dynamometer and a load controller was used (see Figure 1). Table 1 shows the main engine specifications. Numerous devices were installed to measure engine output parameters. The exhaust and intake temperature were measured by using a type K thermocouple. A Kistler 6061B pressure transducer with a sensitivity of 25 pC/bar was used to measure the in-cylinder pressure. The fuel system was modified by used tow tanks for multiple fuels operation, allowing the engine to be alternatively fueled with diesel and biodiesel B15 fuel. In the calculations, the experimental analysis was repeated three times and the average was considered for each parameter. An IMR 1000 Gas Analyser was used to analyse the exhaust gasses produced by the test engine. The engine performance, combustion characteristic, and pollutant emissions were registered at an engine speed of 3000 rpm under full load operating conditions and different injection timings (10, 8, 6, 4 and 2 before top dead centre bTDC).

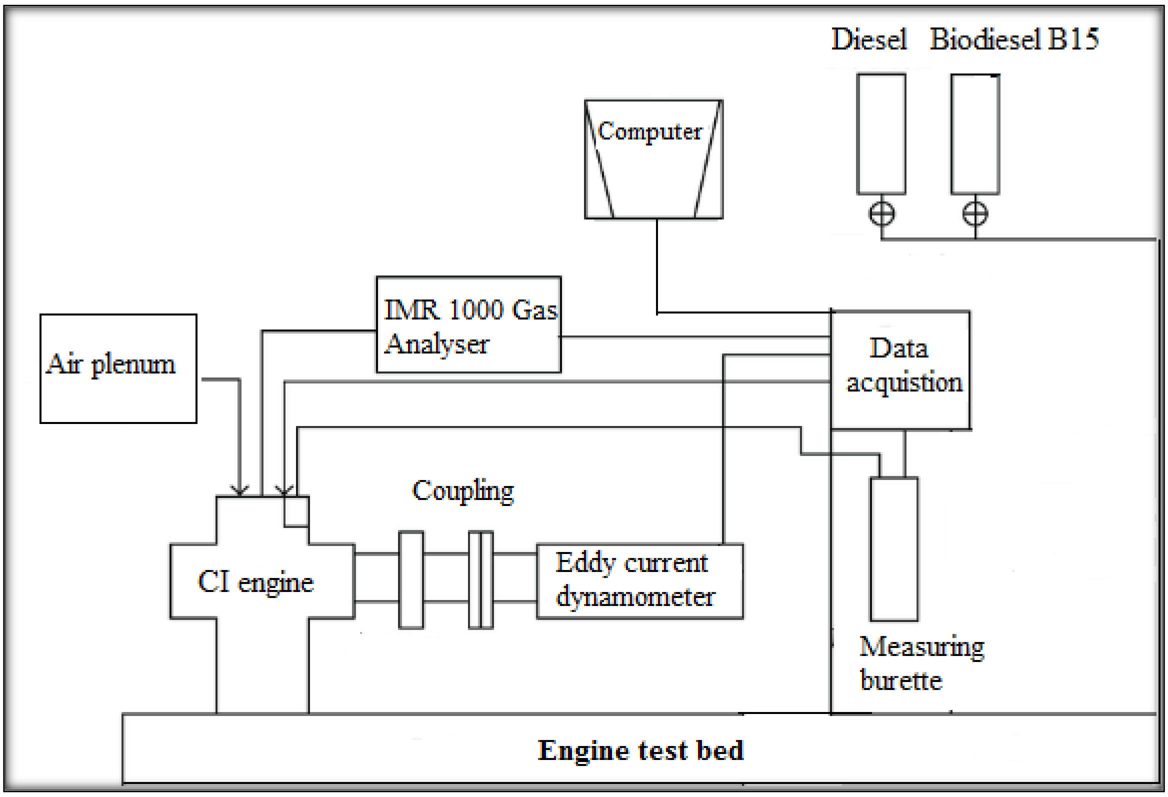

Figure 1. Schematic layout of the test engine bench.

Table 1. The main engine specifications

Engine characteristics	details
Kubota diesel engine	4-stroke
No. of cylinders	4 in line, vertical
Bore x stroke (mm)	95 x 105
Displacement (cm^3)	3500
Fuelling system	Direct injection (DI)
Maximum brake torque (Nm) at 2000 rpm	245
Rated power (kW) at 3000 rpm	65
Compression ratio	18:1

3. Numerical simulation

Today, AVL BOOST code is considered one of the most trusted programs for internal combustion engine simulation when working either with spark or compression ignition. This program predicts the engine performance, combustion characteristics and emissions formation of the engine fueled with different types of standard fuels. All engine components such as the intake and exhaust manifolds, engine cylinders, engine block, air filter, etc. were selected based on the real values of the test engine. All these components are linked together, in the program interface, by pipes as shown in Figure 2. The start and rate of fuel injection and air mass were experimentally measured and implemented in the program. For the combustion sub model, the vibe; two zones were selected, while the Woschni 1978 heat transfer was chosen as a sub model.

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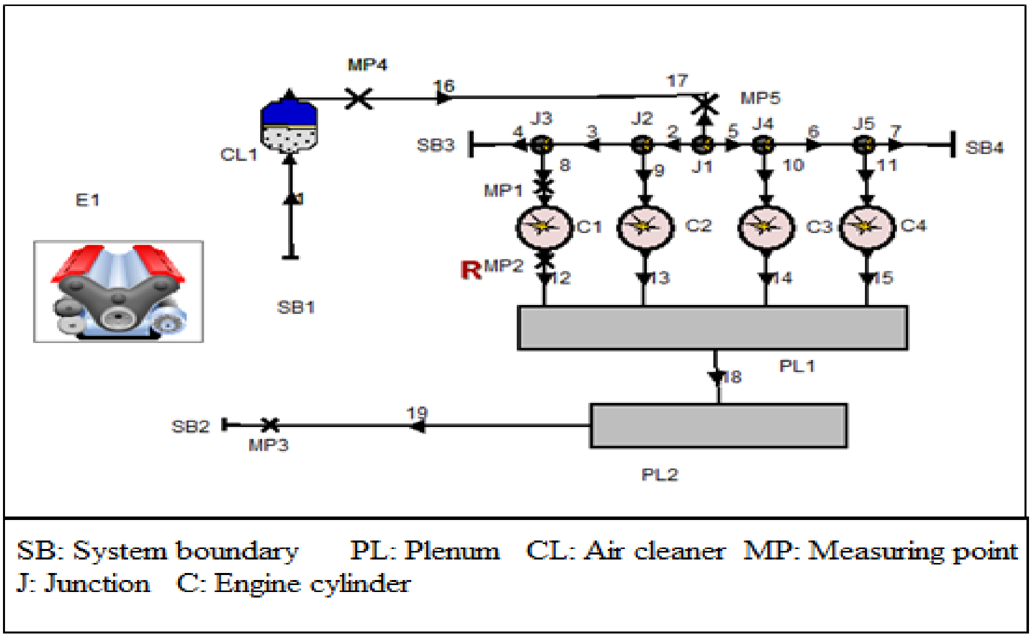

Figure 2. Schematic of the engine symbolic model by AVL Boost.

4. Simulation validation

To check the usefulness of this model, a comparison between the numerical results and experimental data regarding the in-cylinder pressure was done. Figures 3 and 4, represent the cylinder pressure as a function of the crankshaft position and were experimentally obtained and numerically simulated at engine speed 3000 rpm under full load operating conditions for diesel and biodiesel B15. As shown in these figures, there is a good agreement between the experimental and simulation cylinder pressure traces with a relative error in peak fire pressure up to 2.6%.

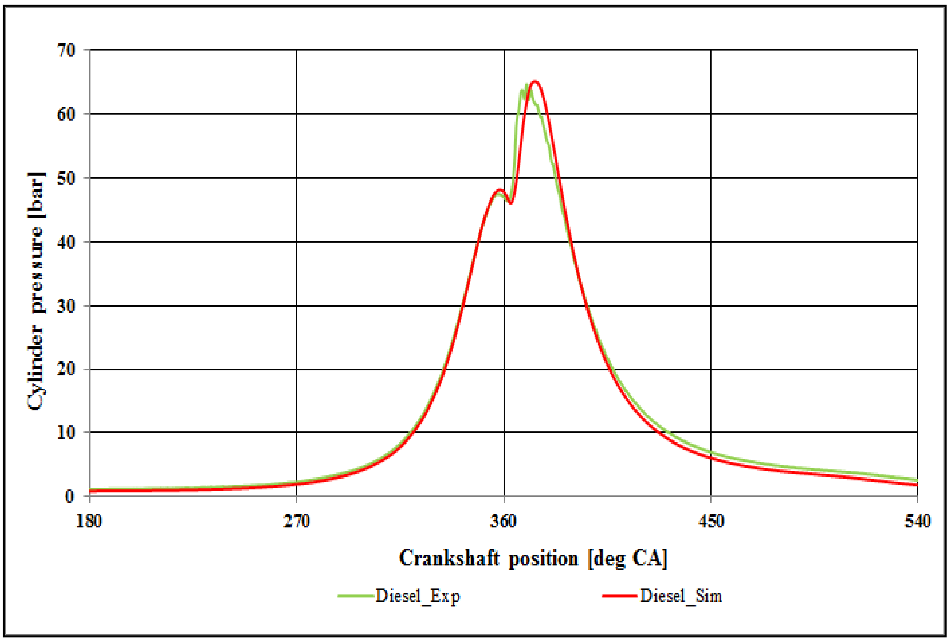

Figure 3. In-cylinder pressure vs. crankshaft position at full load, and engine speed 3000 rpm, for diesel fuel.

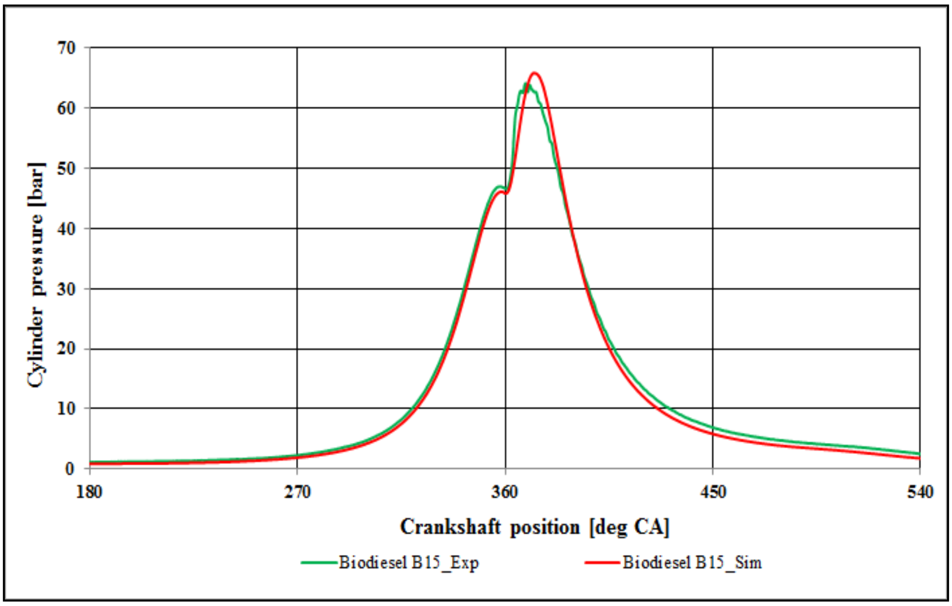

Figure 4. In-cylinder pressure vs. crankshaft position at full load, and engine speed 3000 rpm, for biodiesel B15 fuel.

5. Results and discussion

5.1. Effective power

Figure 5, presents the effective power variation, obtained numerically, with respect to the injection timings (2°, 4°, 6°, 8° and 10° bTDC) of diesel and biodiesel B15 fuels at an engine speed of 3000 rpm under full load operating conditions. It's clear in this figure that in all operating conditions, biodiesel B15 produces lower effective power than diesel fuel. This reduction may be due to the fact that biodiesel has higher viscosity and lower volatility than diesel fuel which lowered the fuel vaporization resulting in a less volatile combustion process. Similarly, Qzturk [4] found that effective power reduced when using biodiesel blends at all operating conditions.

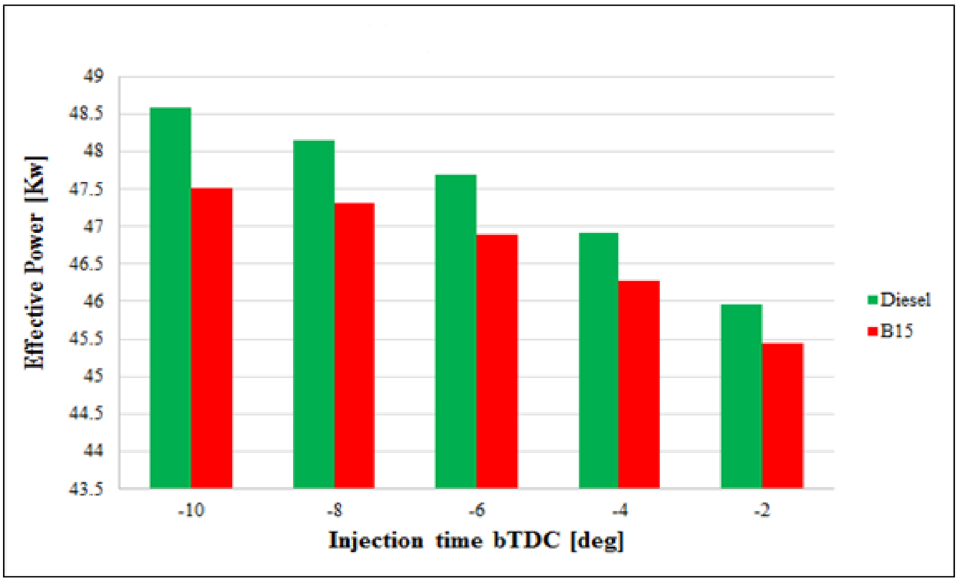

Figure 5. Effective power vs injection timing for diesel and biodiesel B15, engine speed 3000 rpm at full load conditions.

5.2. Effective torque

The effective torque as a function of injection timing for a compression ignition engine fueled with diesel and biodiesel B15 at a constant engine speed 3000 rpm and full load conditions were numerically obtained and are presented in Figure 6. The maximum torque when using biodiesel B15 was 189 Nm, register at injection timing 10 bTDC, while maximum torque of diesel fuel was 192 at the same injection timing. In general, biodiesel B15 has lower effective torque than diesel fuel at all injection timings. In the same vein, [8, 9] in them work notes that the biodiesel fuel shaped slightly lower effective torque than diesel fuel.

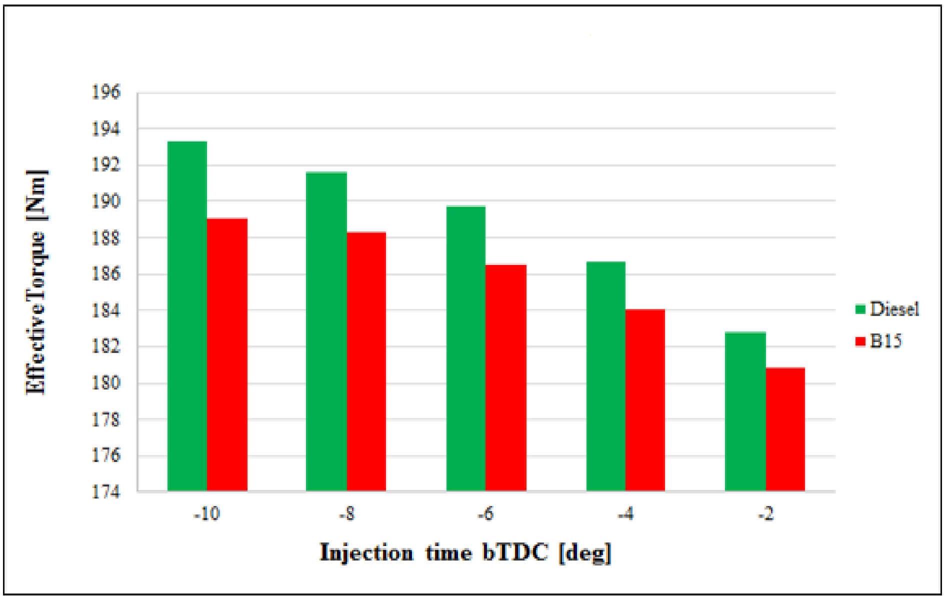

Figure 6. Effective torque vs injection timing, engine speed 3000 rpm at full load conditions.

5.3. Brake specific fuel consumption

Brake specific fuel consumption (BSFC) for internal combustion engines determines the fuel efficiency, and is calculated as follows:

$$\text{BSFC} = \frac{the\ fuel\ consumption\ rate\ in\ grams\ per\ second\ (g/s)}{power\ produced\ \ (watt)}$$

Figure 7 shows the variation of BSFC with respect to injection timing at engine speed 3000 rpm under full load operating conditions of a diesel engine fueled with diesel and biodiesel B15. As shown in this figure, biodiesel B15 produced higher brake specific fuel consumption than diesel fuel at all operating conditions, and this may be because biodiesel has higher viscosity, lower heating value and higher density than diesel fuel, this means that more fuel must be consumed to produce the same effective power when using diesel. Similarly, studies [11, 12] found that biodiesel and its blends produced slightly higher BSFC than diesel fuel at all operating conditions

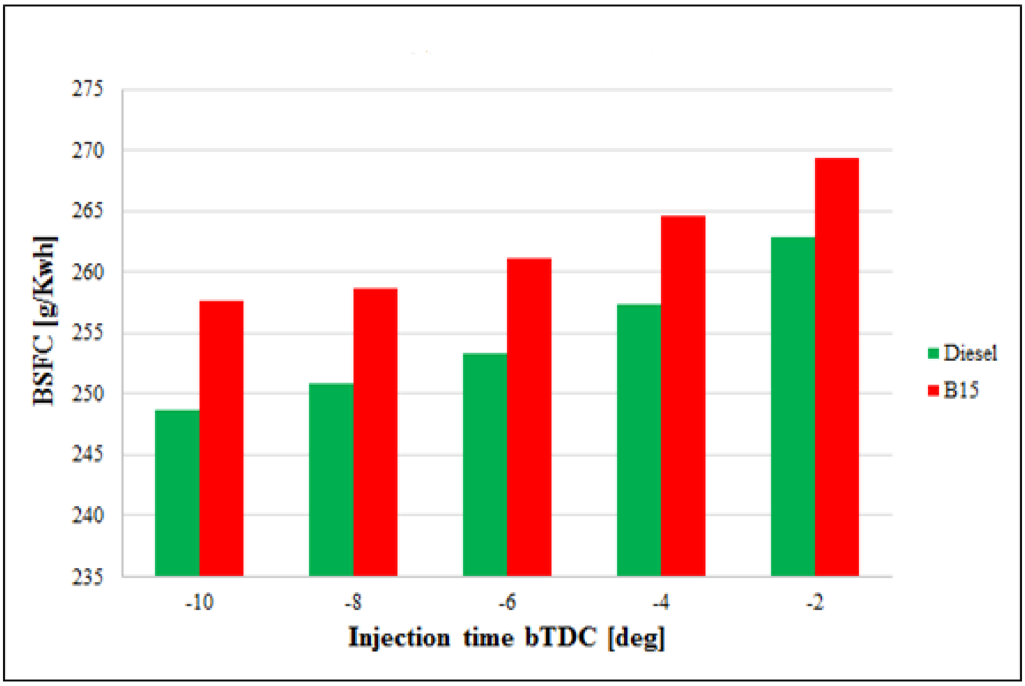

Figure 7. Brake specific fuel consumption (BSFC) vs injection timing, engine speed 3000 rpm at full load conditions.

5.4. Brake thermal efficiency

The evaluation of brake thermal efficiency of the diesel engine, fueled with diesel and biodiesel B15 at different injection timings and an engine speed of 3000 rpm under full load operating conditions, is presented in Figure 8. from this figure, biodiesel B15 produced slightly higher brake thermal efficiency than that of diesel fuel in most operating conditions. Due to the fact that biodiesel has a high oxygen content (10-12%) this leads to improvements in the combustion process thus resulting in an increase in brake thermal efficiency, as clearly shown in Figure 8.

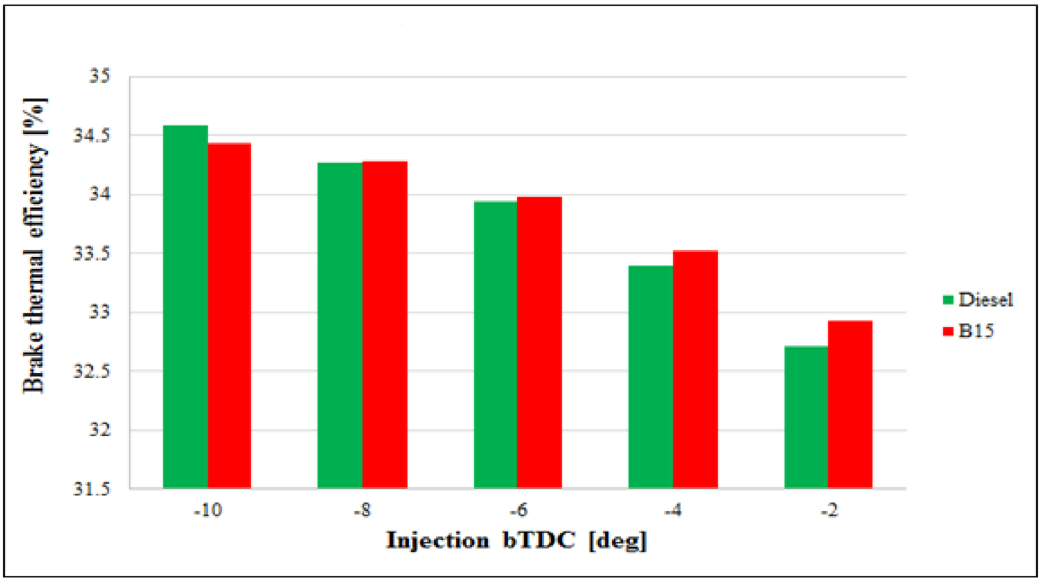

Figure 8. Brake thermal efficiency vs injection timing, engine speed 3000 rpm at full load conditions.

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5.5. Soot emission

Figure 9, shows the effect of diesel and biodiesel B15 on soot emission which was numerically determined under full load operating conditions and an engine speed of 3000 rpm at different injection timings. As shown from the figure, for all injection timings, the soot emission was significantly reduced when engine operating on biodiesel B15 than to those of diesel fuel. This reduction could be explanation by the fact that biodiesel is an oxygenated fuel (has 10-12% oxygen content), leading to an improvement of the combustion process and a reduction of the soot emissions. These results are similar to those reported by [3, 5, 6].

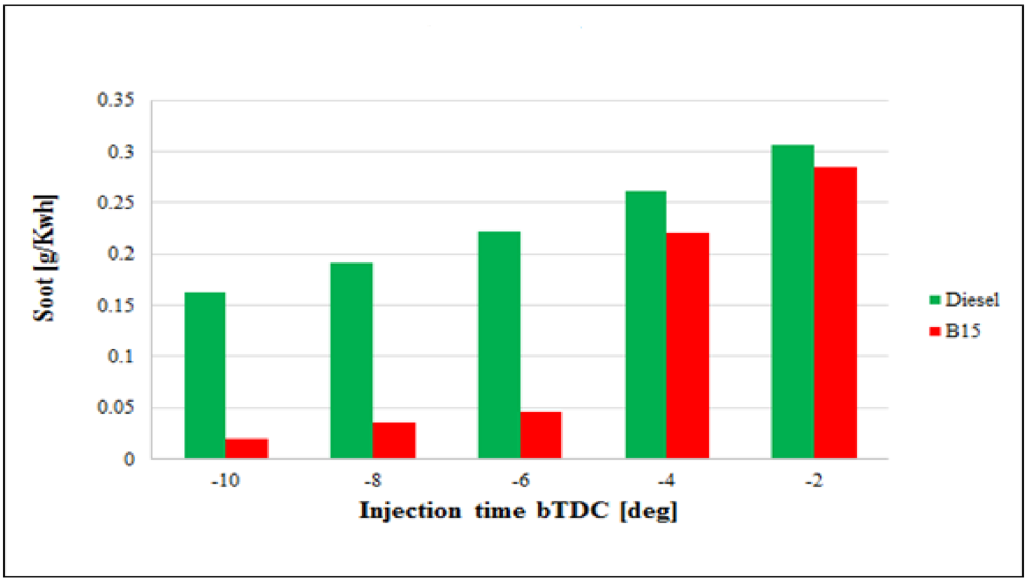

Figure 9. Soot emission vs injection timing, engine speed 3000 rpm at full load conditions.

5.6. Nitrogen oxide emissions (NOx)

The nitrogen oxide formation inside combustion chamber is affected by three main factors: local gas temperature, oxygen concentration and residence time. Figure 10, shows the NOx emissions as a function of the injection timing for both test fuels at the same operating conditions. As shown from the figure, biodiesel B15 produced higher NOx emissions than diesel fuel. The explanation of this behavior is due to the lower soot concentration of biodiesel which leads to decrease in the radiation heat transfer coupled with the higher oxygen content of biodiesel B15 which, in turn, leads to increases in NOx emissions. Several studies have reached similar conclusions related to NOx when using biodiesel and its blends as fuel in compression ignition engines [11, 12, 13].

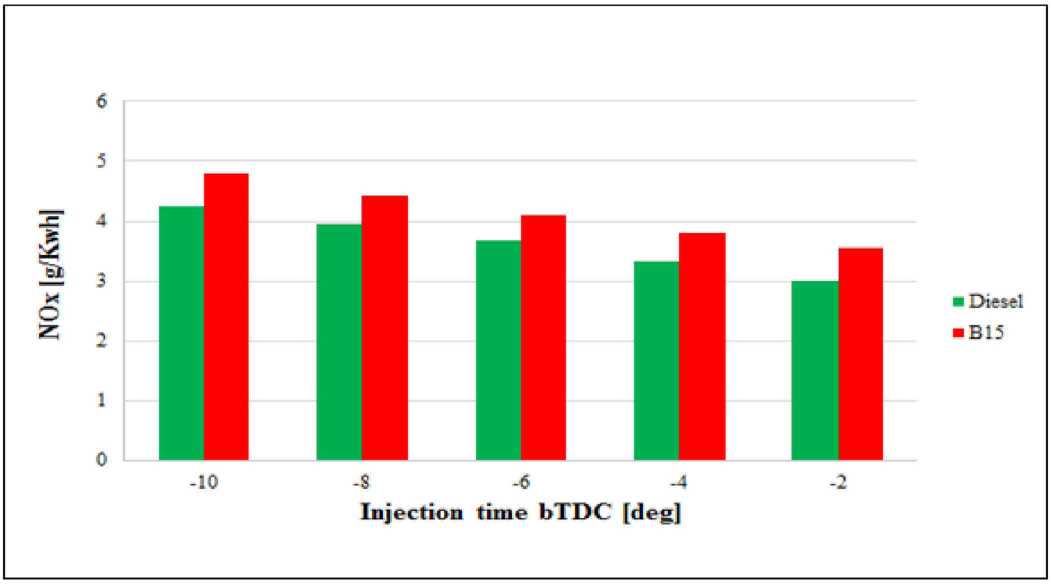

Figure 10. NOx emission vs injection timing, engine speed 3000 rpm at full load conditions.

6. Conclusion

According to the numerical study, the results show that effective power and effective torque was lower, while BSFC was higher when using biodiesel B15 in comparison with diesel fuel, at all injection timing. Brake thermal efficiency was improved with biodiesel B15 when using a retarded injection timing. Concerning exhaust gas emissions, biodiesel B15 produced lower soot emission, while the NOx emissions were higher when compared to diesel fuel.

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Acknowledgments
The authors of this paper acknowledge the AVL Advanced Simulation Technologies team for their significant support.