Energies **2015**, *8*, 3047-3057; doi:10.3390/en8043047

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Combustion Analysis of a Diesel Engine Running on Different Biodiesel Blends

Enrico Mattarelli, Carlo Alberto Rinaldini * and Tommaso Savioli

Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia,
Via Vivarelli 10, 41125 Modena, Italy; E-Mails: enrico.mattarelli@unimore.it (E.M.);
tommaso.savioli@unimore.it (T.S.)

* Author to whom correspondence should be addressed; E-Mail: carloalberto.rinaldini@unimore.it;
Tel.: +39-059-205-6152; Fax: +39-059-205-6126.

Academic Editor: Tariq Al-Shemmeri

Received: 13 February 2015 / Accepted: 27 March 2015 / Published: 20 April 2015

Abstract: Rape-seed biodiesel is an interesting option to address the problem of decreasing availability of conventional fossil fuels, as well as to reduce the CO_2 emissions of internal combustion engines. The present paper describes an experimental campaign carried out on a current production 4-cylinder, 4-stroke naturally aspirated diesel engine, running on standard diesel fuel and on three different blends of rape-seed biodiesel (20%-50%-100%). Performance, emissions and in-cylinder pressure traces were measured at full load. It was found that the influence of rape-seed biodiesel in the fuel blend is not constant at each operating condition. However, as the biodiesel content increases, full load performance tends to drop, in particular brake specific fuel consumption (maximum worsening: +18%), while soot emission goes down. The maximum improvement observed in terms of soot concentration is 37.5%, at 1200 rpm. The combustion analysis revealed that the main differences among the fuels occur in the first phase of combustion: the burn rate is slower for biodiesel blends at low speeds, and faster at high.

Keywords: biodiesel; diesel engine; combustion; soot; rapeseed

---

1. Introduction

Many papers indicate biodiesel as a valid replacement of diesel oil for Compression Ignition (CI) engines [1–4]. In comparison to fossil diesel oil, biodiesel presents several advantages: first of all, it is a renewable energy source; second, the environmental impact in terms of CO_2 is strongly attenuated by the amount of carbon dioxide absorbed by the plants during the growing process [5]; third, some emissions, such as soot, are generally lower than in fossil fuel, as reported in [6,7]. The main downside is the requirement of new fuel systems, complying with the specific features of biofuels; furthermore, many authors found an increase in nitrogen oxides (NO_x) emissions running on biodiesel [8–10], even if sometimes no changes in NOx emissions where reported [11].

Finally, different studies report that the engine power output may be negatively affected by the presence of biodiesel because of its lower lower heating value [12–14], even if, in some cases, the power loss was lower than expected as reported, for example, in [15,16]. Some authors even found an increase in power or torque running on biodiesel or biodiesel blends; the surprising benefit was supposed to be related to a shorter ignition delay time [17] or to the higher density and viscosity [18].

From this brief review, it is evident that the biodiesel composition, its production process and its physical properties such as density and viscosity may have different effects on engine combustion depending on engine characteristics and operating conditions.

The present paper describes the experimental campaign carried out on a current production indirect injection, naturally aspirated diesel engine, running on standard diesel fuel and on three different blends of rape-seed biodiesel (20%-50%-100%). Experimental tests were carried out at a dynamometer bench, measuring engine performance and emissions parameters at full load. Particular attention was paid to the combustion process, measuring the in-cylinder pressure traces.

The engine used for tests was chosen on the basis of the following considerations. First of all, a current production engine (see Experimental Setup section) was selected, instead of a research engine. In this way, it is possible to get more straightforward information about the applicability to real cases. Moreover, thanks to the accurate and comprehensive calibration done by the manufacturer, the experimental campaign can be more easily carried out over the whole range of operating conditions. As far as the combustion system is concerned, indirect injection with a full mechanical control was preferred to more sophisticated solutions for the following reasons:

(1) Even if, especially in the last years, there is an increasing number of studies on engine performance and emissions using biodiesel, only few of them pertain indirect injection diesel engine;
(2) The injection system is much more robust, and it can easily tolerate unconventional fuels;
(3) Many small capacity industrial engines are of this type, and there is a strong interest, at least in Europe, in operating these power plants with biodiesel: rules and constraints are much less stringent than in the automotive field, enabling an immediate application and, moreover, many countries provide significant subsidies for the use of biofuels in internal combustion engines [19].

2. Fuel Features

The biodiesel investigated in the present study is a commercial fuel derived from rape-seed oil. The fuel technical features are reviewed in Table 1. Four different blends of biodiesel and Standard

Diesel (SD) fuel are considered: B20 (20% of biodiesel, 80% of SD), B50 (50% of biodiesel, 50% of SD), B100 (100% biodiesel). SD will be referred to also as B00.

From the engine point of view, the rape-seed biodiesel has features similar to but not identical to SD. As it can be deduced from Table 1, the B100 density is slightly higher (882 *vs.* 840 kg/m^3, +5%), and the heating value is lower (37.5 *vs.* 42.5 MJ/kg, −11.8%). Considering the same mass of injected fuel, biodiesel brake performance (torque and specific fuel consumption) are expected to worsen, due to the reduced heating value. This reduction becomes smaller when considering the same volume of injected fuel, thanks to the recovery due to the higher density of biodiesel (the lower heating value, referred to the fuel volume, is 33 *vs.* 35.7 MJ/L, −7.6%). As the biodiesel molecule contains oxygen, the stoichiometric air to fuel ratio is lower than in SD (12.5 *vs.* 14.5, −13.6%). As a result, the relative air-to-fuel ratio increases, considering the same fuel rates. This is the main reason for the reduction of soot expected at full load when using biodiesels instead of SD. The C/H ratio of the rape-seed biodiesel is almost identical to SD (1.80 *vs.* 1.87), thus the composition should not affect the CO_2 emissions very much.

In general, all the combustion patterns are affected by the fuel nature, in a way that is very difficult to predict, as the fuel influence is related to the specific combustion/injection system and operating conditions (speed, load, ambient conditions, setting of injection parameters, *etc.*).

Concerning the physical properties, the rape-seed biodiesel presents a kinematic viscosity value at the high end of the SD range. However, there are many other physical parameters to be considered, in order to assess the compliance of biodiesel with an injection system designed for SD. As an example, biodiesels may be more aggressive on the injection system components, or leave deposits that may obstruct the fuel flow. The assessment of these issues is far beyond the scope of this study, however during the experimental tests it was necessary to change the fuel filter just after the use of B100. Even if this is not a final evidence, it is a clear hint suggesting that this type of biodiesel must be employed with care on conventional engines.

Table 1. Main properties of the rape-seed biodiesel compared to standard diesel oil.

Properties	Biodiesel	Diesel fuel (EN 590:1993)
Density [kg/m^3]	882	820–860
Viscosity [mm^2/s @ 40 °C]	4.6	2.0–4.5
Lower heating Value [MJ/kg]	37.5	42.5
Lower Heating Value [MJ/L]	33.0	35.7
Mass Composition	77% C 12% H 11% O	87% C 13% H
Stoichiometric Air/Fuel ratio	12.5	14.5

3. Experimental Setup

The engine employed in the study is a Lombardini 4 cylinder, naturally aspirated, indirect injection, Diesel engine [20]. The engine main characteristics are shown in Table 2.

Table 2. Engine main characteristics.

Cylinders	4-in line
Total displacement	1372 cm^3
Bore	75 mm
Stroke	77.6 mm
Compression Ratio	22.8:1
Injection system	Indirect injection with injector pump on head
Applications	Excavator, Dumper, Roller, Generation Set

At the test bed (Figure 1), the engine was coupled to an Eddy-current dynamometer (Apicom FRV 400, Cento (FE), Italy) while the Apicom Horus [21] software has been used for control and data acquisition.

The volumetric fuel consumption of the engine at each operating point was measured by means of a simple but accurate device, specifically designed and built in-house (a graduated burette with check valves).

Smoke is measured by the Dismoke 4000 opacimeter (AVL, Graz Austria) [22] while gas emissions are not reported in this paper because a detailed emission analysis will be the subject of a separate paper. The Dismoke 4000 measure the soot concentration in terms of light absorption (k-value) with a resolution of 0.01 m^{-1} (measurement range: 0–99.99 m^{-1}).

Figure 1. The Lombardini engine at the test bed.

Finally, pressure traces are measured by means of a Kistler 6058A piezo-electric transducer (Winterthur, Switzerland) [23], installed in the pre-chamber of cylinder #1 in place of the glow plug, and of an optical encoder. The raw signals are processed by a high frequency acquisition system based on the Alma Automotive Indicating Software [24], providing the cycle-averaged pressure traces, and calculating a number of combustion parameters (rate of heat release, fraction of fuel burned, *etc.*).

The experimental procedure consisted in testing each fuel at seven steady points at full load varying speed from 1200 to 3000 rpm by 300 rpm steps. Load is defined by the pedal position; since the injection pump is mechanical, for any fuel blend the injected volume depends only on engine speed. The maximum care was devoted to keep the same testing conditions, in particular the temperatures of fuel and engine lubrication oil. Furthermore, each measure is repeated at least twice, at different times.

4. Results and Discussion

4.1. Engine Performance and Emissions

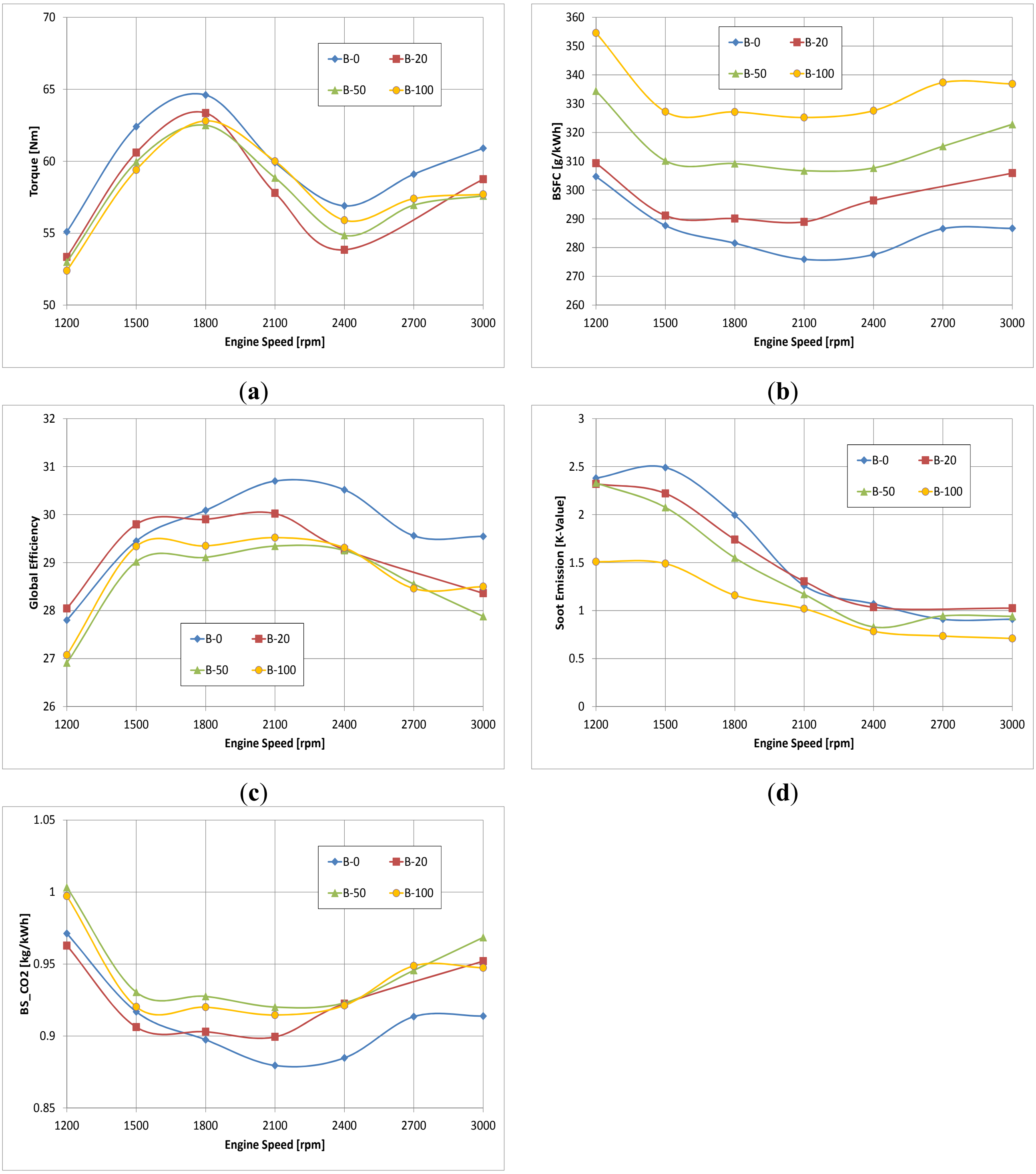
As it was envisioned, the presence of biodiesel slightly reduces the torque output at full load (Figure 2a). However, it may be noticed that the dependence on biodiesel percent is not linear, and under some operating conditions (as an example at 2100 and 2400 rpm) B100 yields better performance than B20. Furthermore, the maximum difference of torque, visible at 1200 rpm, between B0 (or SD) and B100, is lower than the difference in terms of lower heating value per volume (5.5% *vs.* 7.6%). All these evidences suggest that the fuel composition alters the combustion patterns in a way that depends on operating conditions.

Trends are clearer in the BSFC graph (Figure 2b): as the percent of rape-seed fuel increases, specific fuel consumption also increases. The maximum difference may be found at 2100 rpm: between B0 and B100 the BSFC worsening is 18.1%. Such a result may be explained considering that the effect of the lower heating value, reducing power, is added to the higher density, increasing the fuel mass flow rate.

The difference in terms of combustion reflects on the global fuel conversion efficiency (ratio of brake power to the product of fuel mass flow rate and fuel lower heating value, Figure 2c): B0 is always better than the biodiesel blends, except at 1200-1500 rpm, where 20% biodiesel seems to improve a little bit the indicated cycle.

Another clear influence of biodiesel is found on soot emission (Figure 2d): as the biodiesel content increases, soot concentration decreases, except at high speed (2700–3000 rpm). At 1200 rpm, between B0 and B100 the soot concentration reduction is 37.5%. This figure becomes 33.9%, if the specific soot (mass flow rate of soot to brake power) is considered. The benefit of biodiesel visible at almost every speed may be ascribed to the presence of oxygen in the fuel composition, increasing the value of the local relative air-fuel ratio [25]. The different behavior at 2700–3000 rpm is explained by a change in the combustion patterns. It is observed that B20 does not yield the expected advantages in terms of soot: only at 1500–1800 rpm the specific soot (the ratio of soot mass flow rate to brake power) is improved a little bit (8%–11%), while at all the other conditions there is a worsening up to 17% (3000 rpm).

Finally, the specific values of CO_2 are shown in Figure 2e). As for other biofuels, even if a small increase (up 7%) of carbon dioxide was measured for all the biodiesel blends (except at 1200–1500 rpm for B20), the global effect remains positive, because of the larger credit achieved during the rape-seed growth.



(**a**) (**b**)

(**c**) (**d**)

(**e**)

Figure 2. Engine performance and emission as a function of rotational speed (**a**) torque; (**b**) Brake Specific Fuel Consumption; (**c**) global efficiency; (**d**) soot emissions; (**e**) CO_2 specific emissions.

4.2. Combustion Analysis

The combustion analysis has been carried out analyzing the pressure traces acquired in the prechamber of the cylinder #1 during engine testing. The difference between prechamber and cylinder pressure is neglected. At each operating condition 100 consecutive cycles were acquired and the data reported represent the average values. Figure 3 shows the parameters used to analyze combustion: the peak of in-cylinder pressure (Figure 3a), the angular duration of combustion from 0 to 10% (MFB10%—Figure 3c), the angular duration of combustion from 0 to 50% (MFB50%—Figure 3d), and the angular duration of combustion from 0 to 90% (MFB90%—Figure 3e). Also the standard deviation of the in-cylinder peak pressure has been calculated (Figure 3b), as an index of the cycle-to-cycle variation. Figure 4 reports the combustion heat release and in-cylinder pressure as a function of crank angle for different engine rotational speed.

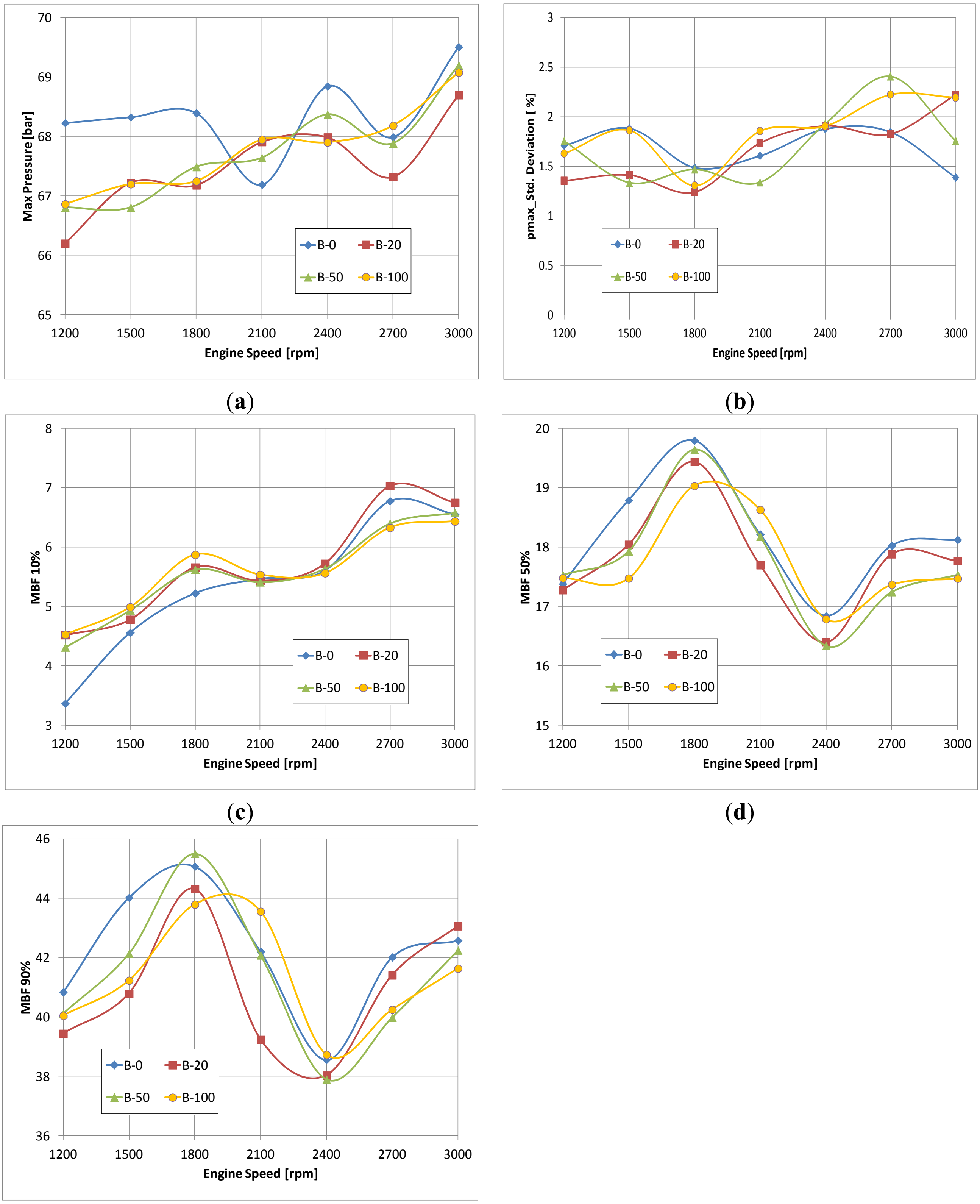
As far as the max in-cylinder pressure is concerned (Figure 3a), it is possible to note that at low rpms diesel values are always higher, revealing a smother combustion start for biodiesel blends; this behavior is visible also in Figure 4.

The standard deviation of the in-cylinder peak pressure (Figure 3b) is less than 3%, meaning that the cycle-by-cycle variation is always close to the typical values for this type of engines and that the combustion is regular running both on diesel oil and biodiesel blends.

One of the most interesting graphs is the one showing MBF10%. Here, the percent difference between SD and biodiesels is large: at 1200 rpm, between B0 and B100 the increase of duration is more than 32%. Such a difference tends to shrink as engine speed increases, and at high speed (2700–3000 rpm) an inversion may be observed. As combustion progresses (MBF = 50% and 90%), the differences among the fuels become smaller and more difficult to understand.

The explanation of this behavior can be found considering that the fuel features governing the first phase of combustion are the viscosity and the auto-ignition retard. The former is more important at low speed, when injection pressure is relatively low (simple mechanical injection), and vaporization more difficult; the latter becomes relevant at high speed, when burn rate is controlled also by chemical kinetics. Biodiesel blends feature a higher viscosity and a lower auto-ignition retard, thus combustion is slower at low speed, faster at high. The evidence supporting this theory is provided by Figure 4, where pressure traces and rate of heat release are shown at both ends of the engine speed range.

Finally, even if the in-cylinder pressure analysis shows some differences in the combustion process depending on engine speed, the combustion process seems to take place in a similar way changing the fuel, confirming the feasibility of the feeding the engine with the tested rapeseed biodiesel blends.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 3. Combustion parameter as a function of engine rotational speed (**a**) in-cylinder peak pressure; (**b**) in-cylinder peak pressure standard deviation; (**c**) crank angle for 10% mass fraction burn; (**d**) crank angle for 50% mass fraction burn; (**e**) crank angle for 90% mass fraction burn.

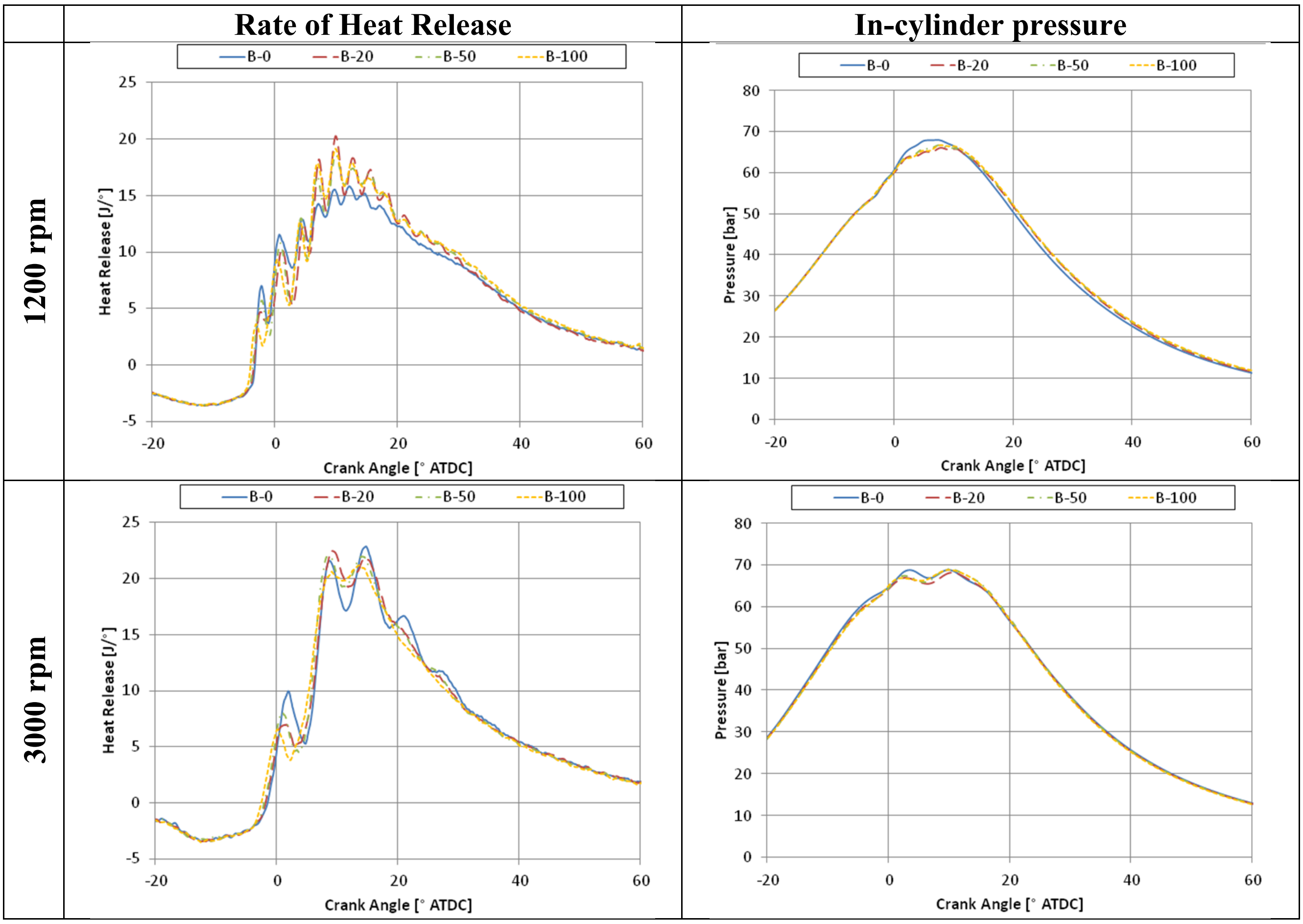


Figure 4. Combustion heat release and in-cylinder pressure as a function of crank angle for different engine rotational speed.

5. Conclusions

Four different blends (0, 20%, 50% and 100%) of rape-seed biodiesel and Standard Diesel fuel (SD) have been compared running experimental tests on a naturally aspirated, high speed, indirect injection diesel engine. The rape-seed biodiesel used for the test, in comparison with SD, has a slightly higher density (+5%), a lower Lower Heating Value (−11.8%) and a lower stoichiometric air to fuel ratio due to the presence of oxygen in its molecule.

The tests have been carried out at seven different engine speeds, full load. The experimental results show that:

- The presence of biodiesel slightly reduces the torque output;
- As the percent of rape-seed fuel increases, specific fuel consumption also increases; the maximum BSFC increment has been equal to 18%;
- Global fuel conversion efficiency of engines running on SD is always higher except at low rotational speeds, whereas b20 seems to improve the indicated cycle;
- As the biodiesel content increases, soot concentration decreases; at 1200 rpm, between b0 and b100 the soot concentration reduction is 37.5%;
- Biodiesel blends present a small increase of carbon dioxide emissions that is largely compensated by the credit achieved during the rape-seed growth.

The in-cylinder pressure analysis shows slight differences in the first phase of combustion, depending on engine speed: at low rpms the presence of biodiesel seems to speed up combustion whereas, at high rpms, the situation is reversed; after the first combustion phase, the differences among the fuels become smaller. The indicated analysis allowed the authors also to verify that the combustion process takes place always regularly, as the cycle-by-cycle variation are quite small for all the tested blends.

Acknowledgments

This research was funded by the Fondazione Cassa di Risparmio di Modena in the project “Soluzioni innovative per la riduzione delle emissioni di anidride carbonica dei motori a combustione interna” (Innovative solutions for reduction of carbon dioxide emission in internal combustion engines).

Author Contributions

All authors contributed equally to this work. All authors planned the experimental procedure, discussed the results and contributed to the manuscript at all stages. C.A. Rinaldini and T. Savioli performed the engine experiments and E. Mattarelli led the results analysis/discussion and the development of the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Puhan, S.; Gopinath, A.; Nagarajan, G. Combustion, performance and emission characteristics of a DI CI engine using biodiesel with varied fatty acid composition. *Int. J. Renew. Energy Technol.* **2009**, *1*, 81–100.
2. Zhang, N.; Huang, Z.; Wang, X.; Zheng, B. A comparative study of two kinds of biodiesels and biodiesel-DEE blends in a common rail diesel engine. *SAE Int. J. Fuels Lubr.* **2011**, *4*, 96–109.
3. Kannan, G.R.; Anand, R. Biodiesel as an alternative fuel for direct injection diesel engines: A review. *J. Renew. Sustain. Energy* **2012**, *4*, 012703.
4. Said, M.F.M.; Said, M.; Aziz, A.A. Modelling of diesel engine fuelled with biodiesel using engine simulation software. *AIP Conf. Proc.* **2012**, *1440*, 307–313, doi:10.1063/1.4704231.
5. Igbum, O.G.; Eloka–Eboka, A.C.; Ubwa, S.T.; Inambao, F.L. Evaluation of environmental impact and gaseous emissions of biodiesel fuels and blends of selected feed–stocks. *Int. J. Glob. Warm.* **2014**, *6*, 99–112.
6. Frijters, P.J.M.; Baert, R.S.G. Oxygenated fuels for clean heavy-duty engines. *Int. J. Veh. Des.* **2006**, *41*, 242–255.
7. Sahoo, P.K.; Das, L.M.; Babu, M.K.G.; Arora, P.; Singh, V.P.; Kumar, N.R.; Varyani, T.S. Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine. *Fuel* **2009**, *88*, 1698–1707.
8. Chauhan, B.S.; Kumar, N.; Cho, H.M. A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends. *Energy* **2012**, *37*, 616–622.

9. Tesfa, B.; Gu, F.; Mishra, R.; Ball, A. Emission characteristics of a CI engine running with a range of biodiesel feedstocks. *Energies* **2014**, *7*, 334–350.
10. Hansen, A.C.; Gratton, M.R.; Yuan, W. Diesel engine performance and NO_x emissions from oxygenated biofuels and blends with diesel fuel. *Trans ASABE* **2006**, *49*, 589–595.
11. Canakci, M. NO_x emissions of biodiesel as an alternative diesel fuel. *Int. J. of Veh. Des.* **2009**, *50*, 213–228.
12. Carraretto, C.; Macor, A.; Mirandola, A.; Stoppato, A.; Tonon, S. Biodiesel as alternative fuel: Experimental analysis and energetic evaluations. *Energy* **2004**, *29*, 2195–2211.
13. Kim, H.; Choi, B. The effect of biodiesel and bioethanol blended diesel fuel on nanoparticles and exhaust emissions from CRDI diesel engine. *Renew. Energy* **2010**, *35*, 157–163.
14. Xue, J.; Grift, T.E.; Hansen, A.C. Effect of biodiesel on engine performances and emissions. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1098–1116.
15. Ozsezen, A.N.; Canakci, M.; Turkcan, A.; Sayin, C. Performance and combustion characteristics of a DI diesel engine fueled with waste palm oil and canola oil methyl esters. *Fuel* **2009**, *88*, 629–636.
16. Aydin, H.; Bayindir, H. Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. *Renew. Energy* **2010**, *35*, 588–592.
17. Song, J.-T.; Zhang, C.-H. An experimental study on the performance and exhaust emissions of a diesel engine fuelled with soybean oil methyl ester. *J. Automob. Eng.* **2008**, *222*, 2487–2496.
18. Al-Widyan, M.I.; Tashtoush, G.; Abu-Qudais, M. Utilization of ethyl ester of waste vegetable oils as fuel in diesel engines. *Fuel Process. Technol.* **2002**, *76*, 91–103.
19. Kutas, G.; Lindberg, C.; Steenblik, R. *Biofuels—At What Cost?: Government Support for Ethanol and Biodiesel in the European Union*; International Institute for Sustainable Development: Geneva, Switzerland, 2007.
20. Lombardini Group. Available online: http://www.lombardinigroup.it/homepage (accessed on 10 April 2015).
21. Api Com. Available online: http://www.api-com.it/About-us/index/ENG/ (accessed on 10 April 2015).
22. AVL GMBH. DiCom4000 User Manual; AVL GMBH: Graz, Austria, 2007.
23. Alma Automotive. Available online: http://www.alma-automotive.it/ (accessed on 10 April 2015).
24. Kistler Holding AG. Available online: http://www.kistler.com/ (accessed on 10 April 2015).
25. Venkanna, B.K.; Reddy, C.V.; Wadawadagi, S.B. Performance, emission and combustion characteristics of direct injection diesel engine running on rice bran oil/diesel fuel blend. *Int. J. Chem. Biol. Eng.* **2009**, *2*, 131–137.