Scientific Paper

Evaluation of mixtures of *Jatropha curcas* (L.) biodiesel in diesel engine banks

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Abstract

The objective of this study was to evaluate different mixtures of the biodiesel extracted from *Jatropha curcas* (L.) in diesel engine benchs, for their later use in agricultural transportation in Cuba. For such purpose, mixtures of diesel fuel were prepared with 5, 10, 15 and 20 % of this biofuel. The engines' performance, emissions of pollutant gases and combustion parameters were evaluated; likewise, the level of biodiesel content that can be included in the fuel mixture was defined. Among the most important results, an increase in the specific consumption of fuel was shown as the biodiesel percentage in the mixture and the pressure in the combustion chamber increased; as well as a decrease of the ignition delay time, due to the higher cetane number of the biodiesel compared with diesel. In the case of the fuel injection system, an increase of the injection pressure was recorded when using biodiesel. A reduction was shown of CO, NOx and CO_2 emissions when up to 20 % was mixed, for which it is considered to be an adequate percentage, although it is necessary to conduct engine durability tests.

Keywords: combustion, pollutants, density, viscosity

Introduction

At present, the use of renewable energy sources is a national security issue of for any country. Among the main reasons for their use is the accelerated consumption of fossil fuels at en exponential rate, along with the levels of pollution load, mainly of greenhouse gases (GHG), which generates the characteristic combustion of vehicles (Li *et al*., 2015; Ribas *et al*., 2016). For the transportation sector, one of the most effective variants is the use of alternative fuels, especially those derived from plant oils, such as biodiesel (Nitièma-Yefanova *et al*., 2017). This last one has as advantages that it is a fuel similar to diesel, it is biodegradable, and shows relatively high calorific content and high energy density (Tüccar *et al*., 2014).

Likewise, when small farmers use the land to produce biofuels, they have an opportunity to obtain profits and guarantee long-term security for the market of their harvests. The most adequate way for biofuel industry is to carry out biofuel production and consumption in rural areas and not at a higher scale. The *Jatropha curcas* (L.) plantations offer the possibility of intercropping, for which the used area can be utilized for food production, with mutual benefits, as it is observed in the experience of the BIOMAS-CUBA project[1].

On the other hand, the physical-chemical properties of biodiesel depend on an important number of indicators of the combustion process and of the engine performance, mainly due to the variation ranges in the composition of fatty acids that can be found even among different genetic *J. curcas* varieties (Piloto-Rodríguez *et al*., 2012).

Biodiesel B100 could be directly used in a diesel engine, with or without mixture of diesel fuel. Nevertheless, its generalization in the world has been marked by the use of both fuels, with 20-30 % of biodiesel in the mixture (Xu *et al*., 2017), even when studies are reported with higher percentage (Bhuiya *et al*., 2016; Dharma *et al*., 2017). This is due to the fact that with B100 problems can appear

[1] BIOMAS-CUBA: International project led by the Pastures and Forages Research Station Indio Hatuey, funded by the Swiss Development and Cooperation Agency (SDC).

in the engines, such as obstructions in the injection systems and the filters; the use of mixtures of the oil with diesel is also reported (Deshmukh and Patil, 2017).

In Cuba there is knowledge and experience of more than 10 years about the use of plant oils and their fuel mixtures, and of their effect on the decrease of GHG emission when these oils are used in vehicles, and are also valued as an alternative source of renewable energy and of import substitution (Toral *et al*., 2008).

Due to the above-explained facts, the objective of this study was to evaluate different mixtures of the biodiesel extracted from *J. curcas* in diesel engine banks, for their later utilization in local agricultural transportation.

Materials and Methods

The *J. curcas* biodiesel was extracted from a plantation of Guantánamo –Cuba–, for which the seeds harvested in one production were used; the viscosity and density of the biodiesel from the plant (B100) and of the reference diesel which is used in the banks and the mixtures, were also determined.

Physical and chemical characterization of the biodiesel. For determining the density a standard 25-mL pycnometer and a Kern analytical scale with an accuracy of 0,00001 g were used. In the case of the dynamic viscosity, a Rion VT 03-F viscometer was used; the temperature of 40 ºC and adequate agitation for the homogeneous formation of the mixture were guaranteed through an IKA RCT basic magnetic stirrer.

Tests in diesel engine banks. For the tests two facilities were used. The first one was composed by a monocylindrical engine which analyzed the performance of fuels in the combustion chamber. Trials were conducted with pure diesel and biodiesel (B100) in order to appreciate changes in the combustion related to the two fuel extremes (both components of each mixture). A Lister-Petter direct injection diesel engine was used, with the following technical characteristics: a cylinder, with 0,659 L of cylinder capacity, compression ratio 16,5: 1 and water cooling. The tests were conducted in stationary regime, that is, when the thermal status, speed regime and engine load did not vary with time. To measure the pressure in the combustion chamber, the engine had a Kistler (type 6067C) piezoelectric sensor installed into the cylinder.

These tests were conducted in November, 2017, and the experimental environmental conditions of reference were the following: ambient temperature remained between 28 and 30 ºC, atmospheric pressure between 1 001 and 1 004 hPa, and relative humidity around 70 %.

For the analysis of the exhaust gases a Testo 350x gas analyzer was used. The experiments in the monocylindrical engine were developed at 78 Nm of load, and the rotation frequency varied between 1 300 and 1 700 rpm.

The second engine used was a two-cylinder Lister-Petter one, which was formed by an engine-electrical generator bond. The generator has a control center in a metal cabinet with flexible wiring. The engine-generator set was fixed to the base through anti-vibrator shock absorbers. The main characteristics of the engine-generator pair were: two cylinders, direct injection and 1 800 rpm of rotation frequency. This facility had almost all the possibilities provided by the installation of the monocylindrical engine, except the measurements in the combustion chamber.

A Sartorius scale model EA6DCE-1 was installed, with an accuracy of ± 0,2 g, in order to determine the expense of hourly fuel. The measurement of this indicator was carried out by the gravimetric method, through which the fuel mass consumed or spent for a time of five minutes was determined.

The evaluated indicators were the specific fuel consumption (SFC) and the emissions of contaminating gases at different rotation frequency values of the engine and of load. The engine load was fixed and indirectly determined through the coupling to a bank of variable resistors existing in the facility.

In this engine four mixtures with 5, 10, 15 and 20 % biofuel (B5, B10, B15 and B20, respectively) were tested, as well as the reference diesel fuel, again. These experiments were conducted with a constant load of 1 800 rpm, a mean frequency for this engine and habitual in diesel engines, and work was done at four loads. All the tests were carried out on the same day, at an outer temperature of 21 ºC, 70 % of relative humidity and 1 016 hPa.

In the case of the analysis of the engine performance, as well as the measurements in the combustion chamber, they were developed from the completion of the engine work cycles, and, thus, corresponded to a large number of experimental data, because a cycle occurs in milliseconds and the trials in bank for each fuel last several minutes. This caused the results to be analyzed from the determination of the mean values, of performance as well as emissions, and through the standard deviation 5 % of uncertainty was determined. All the statistical analyses were carried out for a 95 % confidence interval.

The cetane number was determined from the fatty acid profile of the *J. curcas* oil, from which the biodiesel is produced (Piloto-Rodríguez *et al*., 2013).

Results and Discussion

The results of density and viscosity of fuels are shown in table 1. The regulations for biodiesel (ASTM D6751 and EN 14214) state that the dynamic viscosity must be below 6 mPa-s, while the biofuel density, between 860 and 900 kg/m^3.

In this case, biodiesel was within the established range of density and dynamic viscosity for both regulations. According to the values of dynamic viscosity and density for biodiesel (table 1), the analyzed one was also in the range of cinematic viscosity established by the regulation ASTM D 6751-07, below the maximum established limit of 6 mm^2/s. Nevertheless, in studies conducted by Tiwari and Sahu (2013) a viscosity of 4,8 mm^2/s (8,1 mPa-s) was determined with a density of 898,1 kg/m^3 (Barua, 2011).

From the composition of fatty acids (table 2) the cetane number of the biodiesel extracted from *J. curcas* was estimated, which was 47,55, higher than the value established for the Cuban diesel fuel (43). According to the regulation for biodiesel ASTM D 6751-07, the minimum value allowed for cetane is 47, for which the biodiesel was within the established limit.

If in the tests in the monocylindrical engine there are no significant differences in the performance of the two fuels that make up the mixtures, no important differences should be expected when they are prepared at a certain percentage and are introduced in the engine, because any mixture should show intermediate levels in the parameters analyzed in the combustion chamber. The comparison of the pressure diagram in the cylinder for diesel fuel and B100 at 1 300 rpm and 78 Nm is shown in figure 1.

There was a slight increase in the maximum pressure in the combustion chamber when B100 was used; for such reason, any intermediate mixture should experience a maximum in the pressure in an intermediate pressure value and, thus, even closer to that of diesel fuel which is the reference one, but higher than it. A similar performance in the maximum pressure in combustion chamber was reported for the *J. curcas* biodiesel by Sahoo *et al*. (2009), with an increase of 7,6 % at low and moderate engine loads when using B100.

The slight pressure increase in the cylinder when using biodiesel could be due to higher rate of the combustion process and a slight increase in its efficiency. Normally for biodiesel an opposed performance occurs, with a slight decrease of the cylinder pressure (Agarwal *et al*., 2003). Nevertheless, this depends on the engine, work conditions

Table 1. Viscosity and density values for the fuels.

Fuel	Dynamic viscosity η (mPa-s) at 40°C	Density (kg/m^3) at 15 ºC
Diesel	4-5	850,5
J. curcas biodiesel (B100)	6	870,1

Table 2. Fatty acid profile of the *J. curcas* oil.

Fatty acid	%
Palmitic (16:0)	13
Palmitoleic (16:1)	0,5
Stearic (18:0)	5
Oleic (18:1)	38
Linoleic (18:2)	26
Linolenic (18:3)	10
Myristic (14:0)	0,1

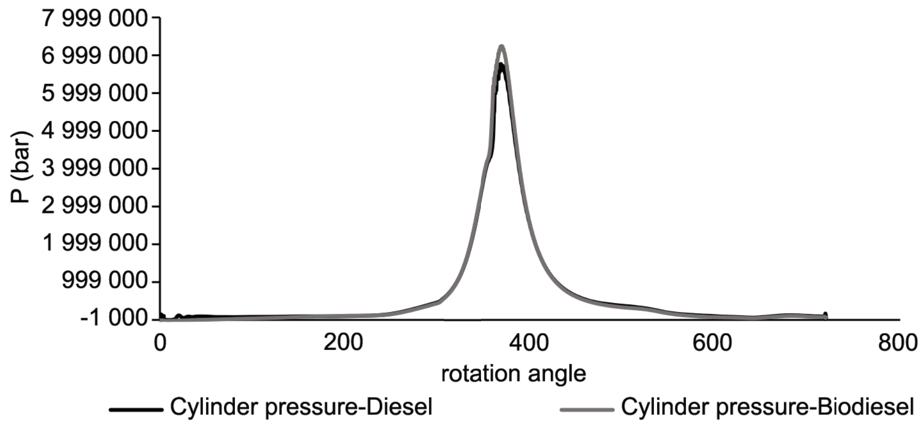

Figure 1. Pressure inside the cylinder for diesel and B100 at 1 300 rpm and 78 Nm

and cetane number of the fuel, and the performance can change completely with the engine load.

Figure 2 shows the diagram of first derivative against crankshaft angles; there was a slightly earlier start of combustion for the biodiesel extracted from *J. curcas* (B100) at 1 300 rpm and 78 Nm. This change is not numerically high, because it is in the order of 3º, but this is sufficient for it to exert influence on the engine performance, emissions and released heat. The increase of pressure in the cylinder could be influenced by the earlier start of combustion; this is a typical phenomenon of biodiesel, because it has a higher cetane number than diesel and, thus, the ignition delay time is reduced (Shahabuddin *et al*., 2013).

For the case of the injection pressure (fig. 3), there was a substantial increase when B100 was used instead of the diesel fuel. This result brings about that, although the mixtures that are used are under 30 % –and it decreases and approaches more the injection pressure to that of diesel fuel–, it is necessary to conduct a study about the influence of fuel change on the injection systems, because by generating higher injection pressure than the normal one for the injector, its useful life might be reduced to a certain extent or the required times to perform maintenance are likely decreased.

In literature an increase is reported in the injection pressure when using biodiesel, with an increase of up to 100 bar over diesel (Banapurmath *et al*., 2008). When biodiesel is injected, the pressure increase created by the pump is higher, due to its lower compressibility and faster propagation of the fluid through the injector, because of the higher rate

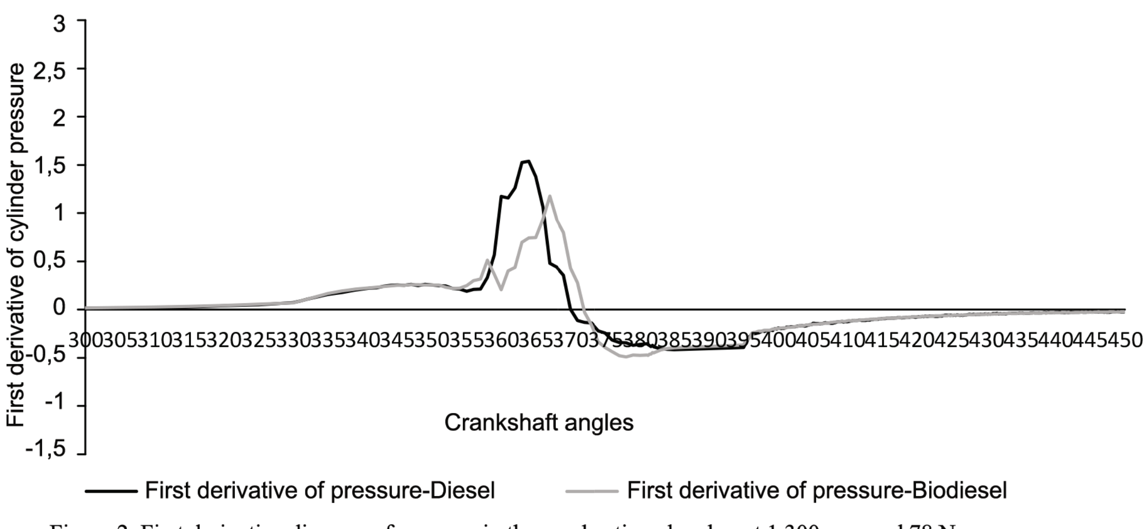

Figure 2. First derivative diagram of pressure in the combustion chamber at 1 300 rpm and 78 Nm.

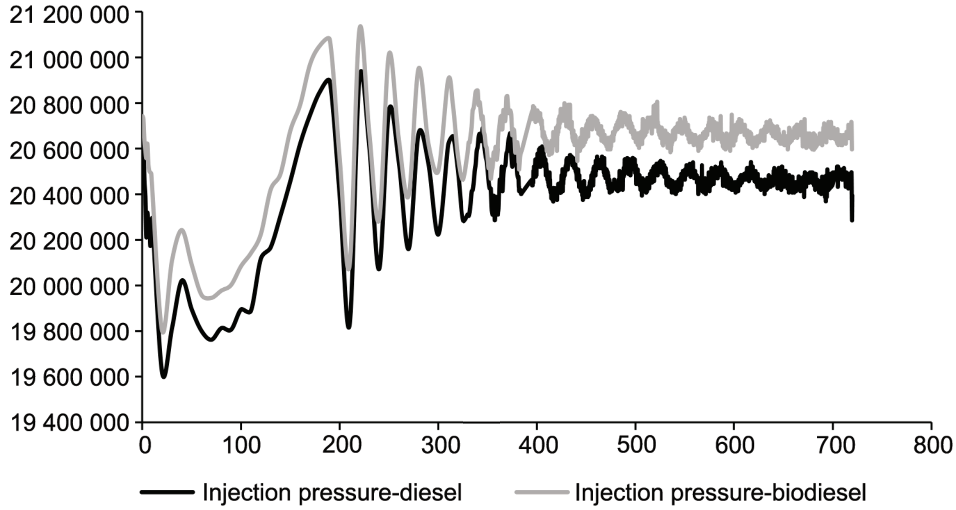

Figure 3. Fuel injection pressure at 1 300 rpm and 78 Nm.

developed by biodiesel. Additionally, its higher viscosity reduces leakage possibility in the injection system, which generates higher pressure (Lapuerta *et al*., 2008). For the case of the biodiesel extracted from *J. curcas* at 1 500 rpm and 78 Nm, a similar performance to the one at 1 300 rpm when combustion begins was observed; nevertheless, the differences were more stressed when using diesel fuel (figs. 4, 5 and 6).

The beginning of combustion was observed much earlier than in diesel fuel, phenomenon that was not so evident at 1 300 rpm (fig. 5). This explains, partly, the fact that there was higher maximum pressure in the combustion chamber when B100 was used with regards to diesel, because by advancing combustion more fuel was burned in the pre-mixture zone and higher combustion efficiency should also be expected, which does not mean it is favorable for the engine.

For the case of B100 at 1 500 rpm and 78 Nm, a similar performance was observed to the one at 1 300 rpm, when combustion started; however, the differences can be more stressed when using diesel fuel.

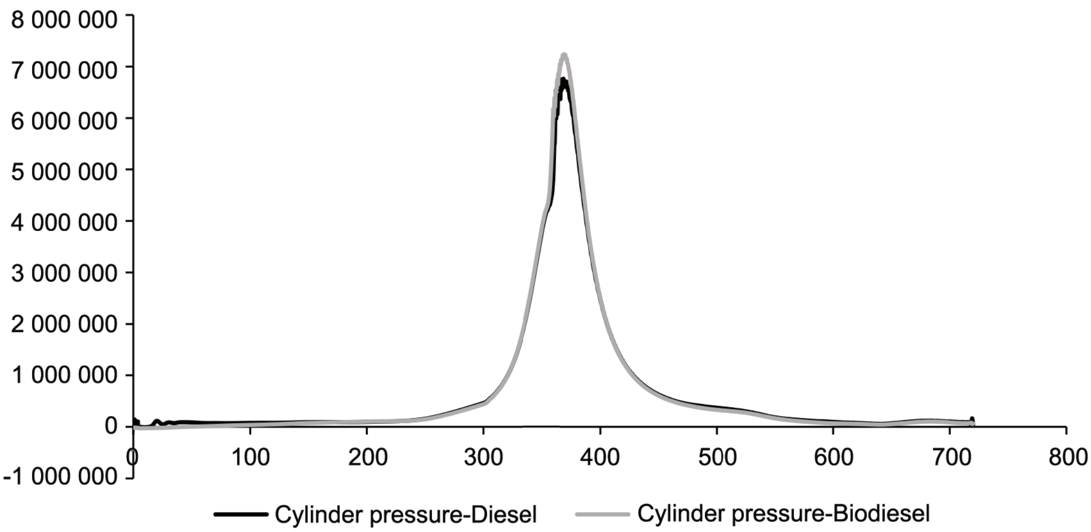

Figure 4. Pressure inside the cylinder for diesel and B100 at 1 500 rpm and 78 Nm.

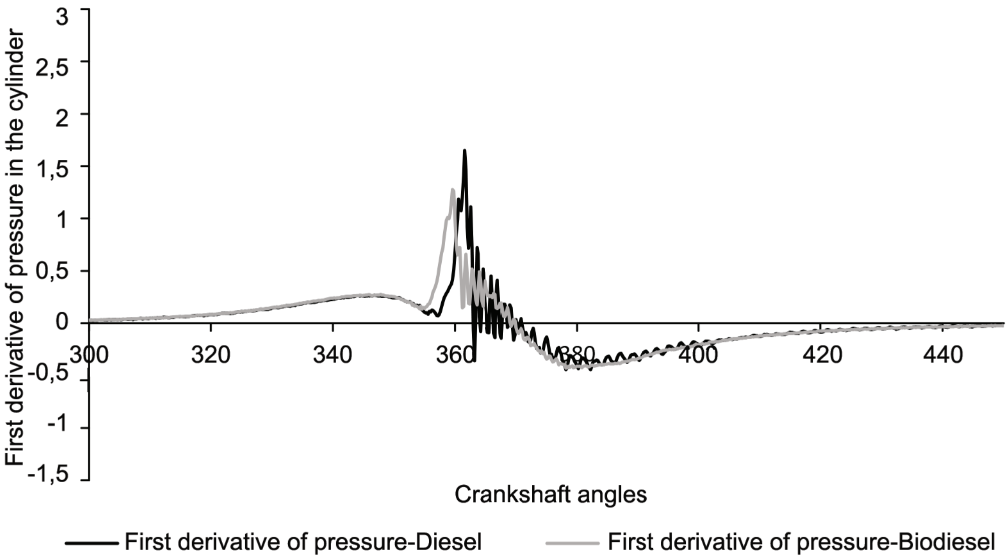

Figure 5. First derivative diagram of pressure in the combustion chamber at 1 500 rpm and 78 Nm.

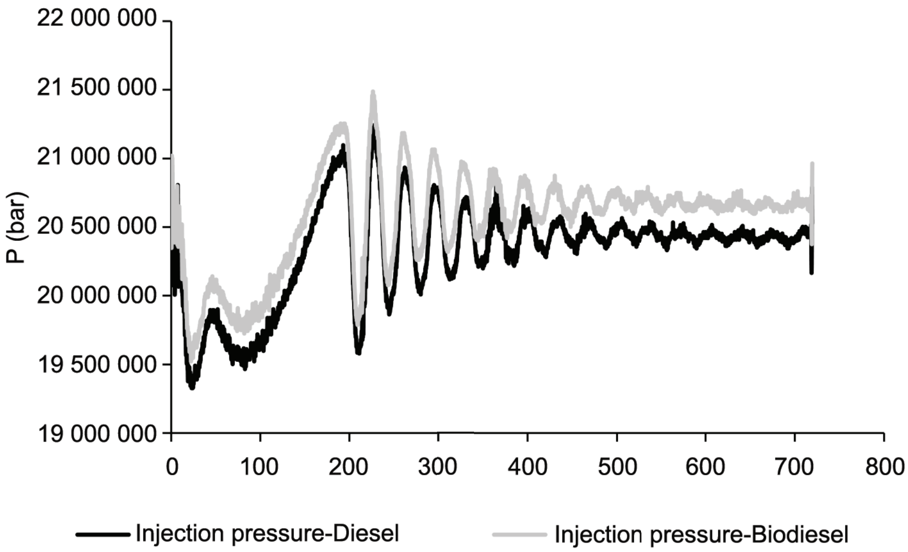

Figure 6. Pressure in fuel injection at 1 500 rpm and 78 Nm.

The tests at 1 700 rpm and 78 Nm showed a similar performance of the two fuels to the test at 1 500 rpm. From these results, it is clear that the mixtures that are introduced to the motor with up to 20 % biodiesel will have the performance described in this work, intermediate regarding all the analyzed parameters (taking the two pure fuels as extremes) and closer to that of diesel.

The results showed that the biodiesel extracted from *J. curcas* generated higher pressure in the injection and in the combustion chamber, and combusted faster.

The mixtures (B5, B10, B15 and B20) did not have significant differences regarding the specific fuel consumption (fig. 7).

The emissions of nitrous oxide (NOx) at different engine loads are shown in figure 8; in all the cases a decrease of these emissions was observed in the mixtures of *J. curcas* biodiesel with regards to the diesel. In the cases of extreme loads (low or

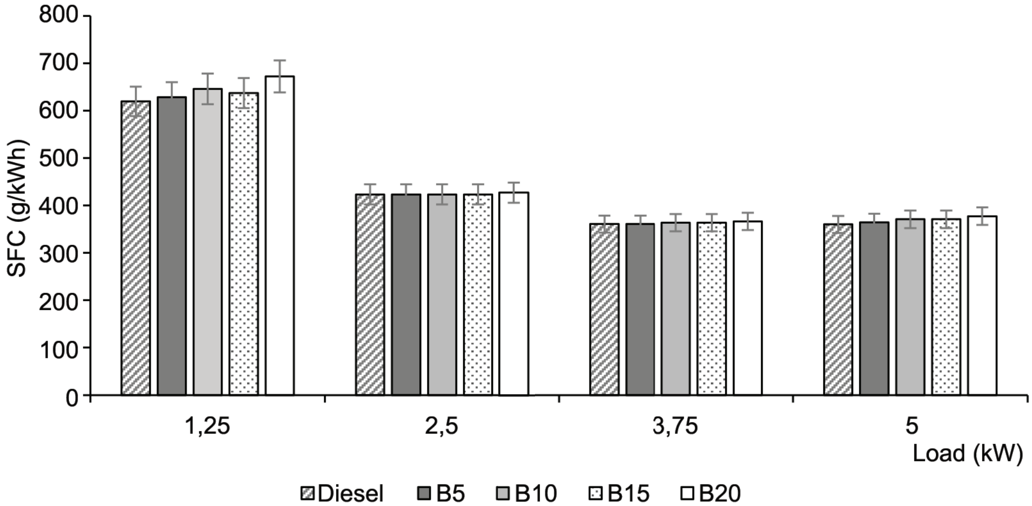

Figure 7. Performance of the specific fuel consumption for mixtures at 1 800 rpm.

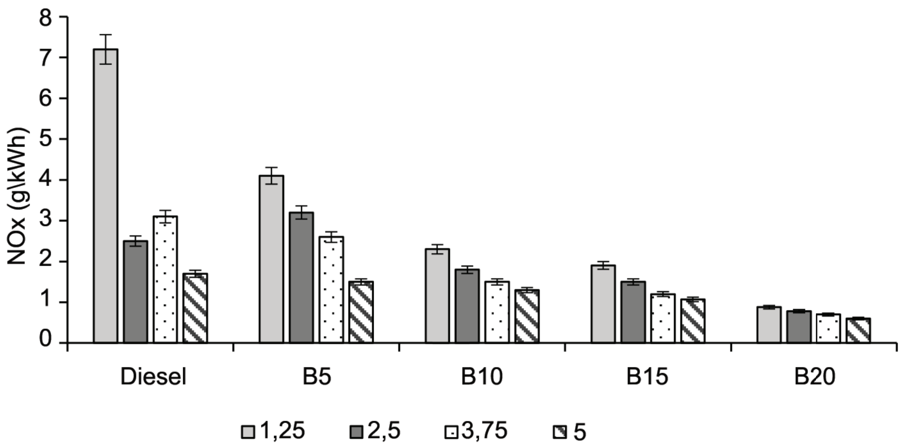

Figure 8. NOx emissions at different engine loads and 1 800 rpm.

highest) higher changes occurred. This result is logical, because at a low load the engine is fairly free and less fuel is consumed; while at high loads there is higher fuel demand; and in this case, by introducing more biodiesel in the system, there is a trend to reduce temperature in the combustion chamber (Piloto-Rodríguez, 2014).

The NOx emissions in an engine are determined by temperature in the combustion chamber, and it is known according to specialized literature that biodiesel tends to decrease this temperature and, thus, reduce NOx emissions (Piloto-Rodríguez, 2014). It is necessary to specify that the utilization of biodiesel can reduce the NOx emissions and contribute, this way, to the reduction of GHG emissions.

When comparing when diesel fuel, the mixture that decreased the most the emissions was B20, for which it could be expected that with higher biodiesel percentages they would be even more reduced; however, other factors should be considered, such as: lower combustion efficiency, due to the stressed increase of density and viscosity in the mixture; and even higher reduction of the calorific power, which would lead to an increase of SFC. Nevertheless, the fundamental element for not exceeding 20 % would be related to engine durability.

The NOx levels were below 6 g/kWh, which have been reported for this type of biodiesel, and below the norm Euro 4 (3,5 g/kWh), except when the engine worked at low load for diesel fuel and B5. The fact that the mixture does not exceed B20 is internationally established as the commitment in the reduction of pollutant load to the environment with as little affectation as possible for technology (Piloto-Rodríguez, 2014).

The results of carbon monoxide (CO) emissions are shown in figure 9. The reduction in CO emissions for the mixtures with biodiesel and, especially for the case of B20, occurs due to a more efficient combustion in the combustion chamber, because of the higher cetane number of biodiesel (Piloto-Rodríguez, 2014); if the combustion is efficient it should be more complete and, thus, less CO should be emitted. This result, along with the NOx reductions, is positive consequence of the analyzed mixtures. Lapuerta *et al*. (2008) also found a reduction in the CO emissions when using biodiesel. Hence the positive effect of the utilization of biofuel in fuel engines, as an alternative for GHG decrease.

Another important result with regards to the emissions was the decrease of carbon dioxide (CO_2) with the biodiesel percentage in the mixture (fig. 10) and an opposite performance with regards to the quantity of oxygen in the exhaust. A decrease of the temperature of exhaust gases also occurs, which is related to the lower calorific value of fuel, and as final result there is a decrease of CO_2 (Xue *et al*., 2011).

Concerning oxygen in the exhaust gases, as the biodiesel percentage in the mixture increased there was an increase of the oxygen content, just like when comparing the engine load increase (fig. 11). The increase in the oxygen content could be related to several factors, among them structural oxygen content in biodiesel (which is not present in diesel fuel) and the variation of the air-fuel ratio in the engine when changing the fuel type, which logically increases with the increase of the engine load, because there is higher quantity of air at the entrance.

The results of this study constitute the first ones in banks of the biodiesel produced in Cuba from

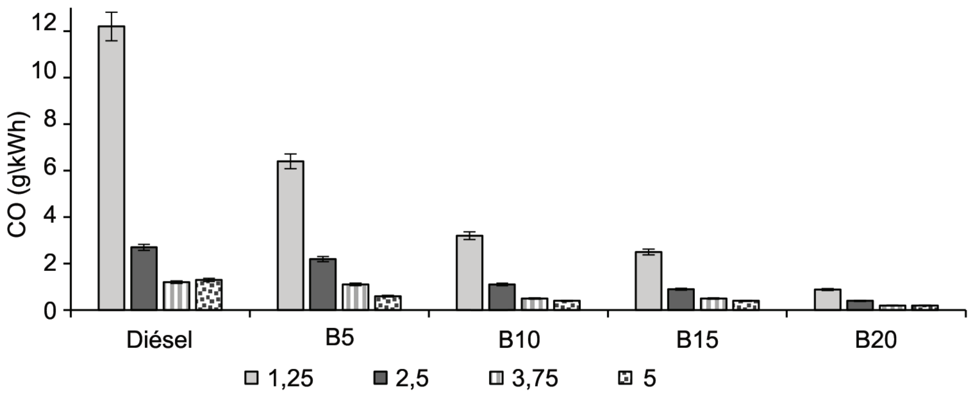

Figure 9. CO emissions at 1 800 rpm and different loads.

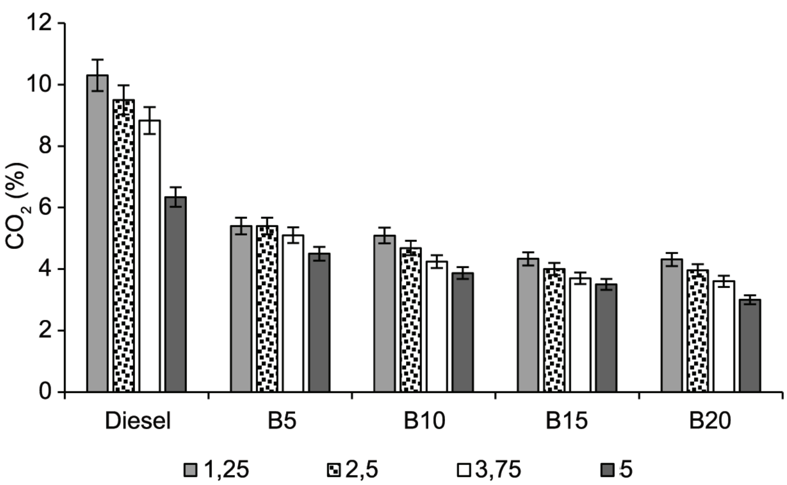

Figure 10. CO_2 emissions at 1 800 rpm and with variation in the engine load.

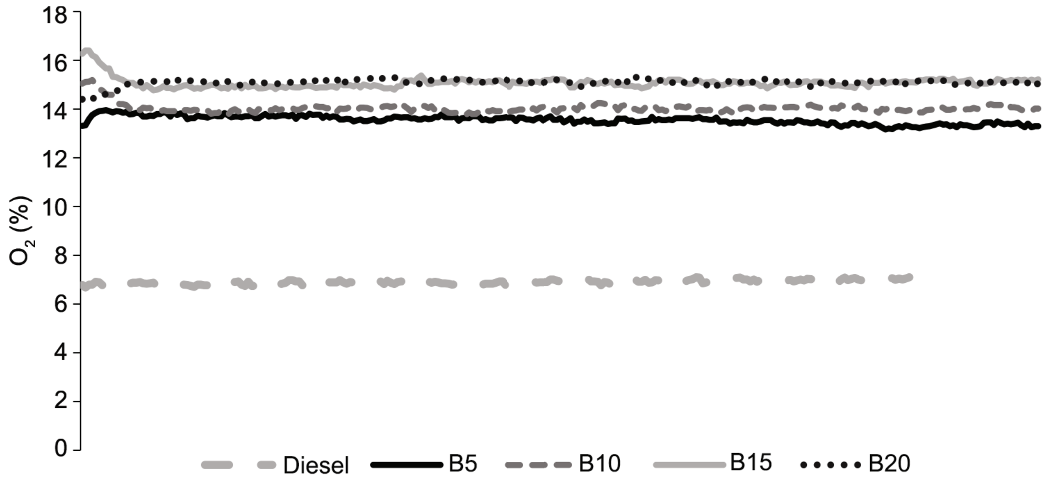

Figure 11. Oxygen content in the exhaust at 1 800 rpm and 1,25 Kw.

J. curcas, in different work regimes of the engine, and allow to establish strategies for the next trials, especially in the first stage of mixture percentage determination, before conducting long-duration essays in the engine. A remarkable reduction was found in the emissions of pollutant gases without compromising the engine performance, which allows to continue to a second stage of increase of biodiesel percentage in the mixture.

Conclusions

The *J. curcas* biodiesel combusted in less time than diesel fuel. An increase of pressure in the combustion chamber was observed for the case of the tests with a monocylindrical engine, and remarkably in the injection pressure of fuel with the mixtures. Likewise, a considerable reduction of the CO, CO_2 and NOx emissions occurred when the biodiesel mixed with diesel up to 20 % was used, with an increase of the dioxygen content in the exhaust.

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