EXPERIMENTAL INVESTIGATION OF THE IGNITION DELAY AND GASEOUS EMISSIONS OF DIFFERENT DIESEL AND BIODIESEL BLENDS ON A VARIABLE COMPRESSION RATE ENGINE

Vinicius M. Olivares, viniciusolivares@gmail.com
Nauberto R. Pinto, nauberto@lmt.coppe.ufrj.br
Marcelo J. Colaço, colaco@ufrj.br
Albino J. K. Leiroz, leiroz@ufrj.br
Nisio C. L. Brum, nisio@ufrj.br
Federal University of Rio de Janeiro - UFRJ
Department of Mechanical Engineering - POLI / COPPE
Cx Postal 68503 - Rio de Janeiro, RJ 21941-972, Brazil

Abstract. *It is well known that vehicular emissions are the main agents contributing to the urban polution in the major cities around the world. It is also known that trucks and buses fleets, mainly based on Diesel engines, have been growing in recent years. Thus, there is a need to investigate ways to reduce the emissions of such engines, in order to minimize the damages to the environment. The use of biofuels, as a renewable energy source, has been investigated and is a reality in many countries as a way to promote a decrease in such emission levels. The objective of this work is to investigate different blends of biodiesel and diesel fuels in a variable compression rate engine, in order to verify the emissions levels, as well as the ignition delay, both as a function of the compression ratio and the time of injection.*

Keywords: internal combustion engines, biodiesel, emissions, ASTM/CFR.

1. INTRODUCTION

It is known that vehicle fleets are the agents with the greatest influence on urban pollution. It is also known that the number of trucks and buses around the world has been growing year after year. Under this scenario, governmental agencies have been issuing increasingly restrictive emission legislations. Thus, it is of fundamental importance to investigate fuels less harmful to the environment, or to investigate ways how to burn the actual fuels in a manner that they would cause less damages to the environment.

It is worth noting that the Brazilian government, since 2005, introduced the biodiesel fuel in the Brazilian energy matrix. Also, since 2010 diesel fuels sold in Brazil contains 5% of biodiesel in volume. Moreover, other governments like the United States have made commitments to increase the use of bioenergy (UNEP, 2009).

According to the ANP (Brazilian National Agency of Petroleum, Natural Gas and Biofuels) and ASTM (American Society for Testing and Materials), biodiesel is a fuel composed of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats. It is produced by reacting a vegetable oil or animal fat with an alcohol (methanol or ethanol) in the presence of a catalyst. This reaction also generates biodiesel glycerin (Biodieselbr, 2012a).

In recent years, the Brazilian production of biodiesel has grown: it has more than doubled between 2008 and 2010 (1.1 billion liters to 2.4 billion liters), leaving Brazil as one of the largest producers in the world (ANP, 2011).

In Brazil the main raw materials are soy and tallow, with the central part of the country emerging as a major national producer. Although palm oil has a greater productivity, soybean production has become more economically viable in Brazil and therefore represents more than 80% of national production (ANP, 2011).

Some physical characteristics of the biodiesel, such as viscosity and cetane number, must be controlled during its production in order to reach values close to diesel oil (Biodieselbr, 2012b).

It is reported in the literature (Brazil, 2004; Scholl and Sorensons, 1993; Choi and Reitz, 1999; McCormick et al, 2005) that certain mixtures of diesel with vegetable oil esters have a performance comparable to commercial diesel fuels, as well as lower emission levels of hydrocarbons and particulate matter. However, a possible side effect of low levels of particulate is the higher emission of nitrogen oxides (Scholl and Sorensons, 1993; Choi and Reitz, 1999; McCormick et al, 2005), which could restrict their use in accordance with the strict emission legislations. Fortunately, there are some ways to balance the emissions of particulates and nitrogen oxide, such as optimizing the variation of the time of injection (Scholl and Sorensons, 1993; Choi and Reitz, 1999; McCormick et al, 2005), changing the size of the injection device (Scholl and Sorensons, 1993), using pulsed injection (Choi and Reitz, 1999) and using additives such as EHN (McCormick et al, 2005). Such alternatives significantly decrease nitrogen oxide emissions and, in the example of EHN, increase the cetane number of the fuel.

On the engine side, the increasingly more restrictive emissions legislation has promoted the search for the optimization of current engines, especially when they should be used with different blends of biofuels. Some studies have considered the use of thermal barrier coatings, particularly in the combustion chamber in order to simulate engine adiabatic conditions. This could reduce emissions and improve engine performance (Buyukkaya, 2008; Kojima and Nishiwaki, 1994; Prasad and Samria, 1990). Recent advances also focused on the use of materials with gradual variation of thermophysical properties in order to reduce the discontinuity between the different material layers (Buyukkaya, 2008).

Studies with medium size diesel engines (Bittle et al, 2010), using pure diesel or pure biodiesel fuels, were made considering different loads and speeds. Such studies showed that the ignition delay in engines with biodiesel is smaller than in diesel engines. The same behavior is observed with respect to the duration of combustion in medium loads, probably due to the higher burning diffusion rate. However, such characteristic was not observed at low loads. It is expected that this faster rate of diffusion have strong influence on the increase in emissions of NOx.

Bunce et al (2011) performed an analysis using biodiesel from soybean, where the air-fuel ratio and the exhaust gas recirculation were optimized, in order to verify a possible reduction in NOx emissions This study concluded that a decrease in the NOx emission of B100 is possible through a decrease in the air-fuel ratio as well as an increase in the exhaust gas recirculation.

Another study (Fang et al, 2008) with different blends of biodiesel soy products came to the conclusion that the delay in the fuel injection reduces NOx formation regardless of the composition of the mixtures. The same behavior could be obtained also by decreasing the combustion temperature. This study analyzed also HCCI (Homogeneous Charge Compression Ignition) and PCCI (Premixed Charge Compression Ignition) engines.

Pimentel (2002) analyzed some combustion parameters in an ASTM/CFR Engine fueled with palm oil “in natura”. It was found that the parameters that most influence the engine performance are the fuel consumption and the time of fuel injection. It was also observed that the CO and HC emissions were lower when using palm oil “in natura” when compared to Diesel fuel.

The present study aims to analyze the behavior of the ignition delay and gaseous emissions of a diesel engine operating with different blends of diesel and biodiesel, for various compression ratios and injection timings.

2. EXPERIMENTAL APARATUS

For this study we used an ASTM/CFR Cetane engine, manufactured by WAUKESHA Co., located in the Thermal Engines Laboratory of the Federal University of Rio de Janeiro (LMT - UFRJ).

This test bench was chosen mainly due to its possibility of varying the compression ratio, fuel consumption rate, time of injection, and air temperature, along several other variables.

2.1. Engine

The engine is a single-cylinder four-stroke compression ignition with indirect injection and variable compression ratio. It has multiple fuel reservoir systems. The engine operates on a fixed speed controlled by a synchronous electric motor. Below are listed some technical and geometrical data of the engine:

- Diameter of cylinder: 83 mm
- Piston stroke: 114 mm
- Volume of pre-combustion chamber: 4.291×10^{-5} m^3
- Piston Speed: 3.42 m / s
- Engine speed: 900 rpm
- Engine weight: 399.16 kg (880 lb)
- Weight of the complete test bench: 1247.38 kg (2750 lb)
- Compression ratio: variable between 8:1 and 36:1 (limited to 15:1 due to mechanical limitations of the engine)

2.2. Instrumentation and Control Systems

2.2.1. Temperature Measurement

The engine itself has a temperature sensor for the lubricating oil and thermometers to enable the temperature control at some points, such as:

- Intake air temperature: can be controlled by a thermostat on the dashboard of the motor, which is connected to an electrical resistance installed in the intake manifold;
- Cooling water temperature of the engine block: the engine operates with two channels of cooling water, an open circuit to cool the injection nozzle and one closed circuit to the engine block.

2.2.2. Ignition delay and injection timing measurements

The engine is equipped with a pressure sensor installed inside the combustion chamber, as well as a position sensor installed on the flywheel. By taking the angular difference between the injection angle and the start of the combustion, the engine acquisition system (Fig. 1) calculates the ignition delay. The same system also measures the start of injection angle by using the information of the position sensor and a needle lift sensor installed at the fuel nozzle. The start of injection can be controlled by a mechanical system while the engine is running.

Figure 1. Engine ignition delay data acquisition system

2.2.3. Fuel flow rate

The engine has three fuel tanks, which make possible the test of three different fuels. During the tests of this work the fuel flow rate was set to 13 ± 0.2 ml/min. This flow rate was chosen to be the same used in the ASTM/CFR Cetane test (ASTME, 1985). For each different fuel blend used in this work, the fuel pump mechanism was adjusted to give this exact fuel flow rate.

2.2.4. Gaseous emissions measurement

In this work a TESTO 350XL gas analyzer was used, which uses a nondispersive infrared analyzer (NDIR) and electrochemical sensors, to measure NOx, CO_2, CO, O_2 and SO_2.

3. EXPERIMENTAL METHODOLOGY

3.1. Preparation of the fuel

The objective of this paper is to analyze the following blends of Diesel and biodiesel: B5, B20 and B60. To obtain these blends a mixture of commercial diesel S500 (B5) and palm oil biodiesel (B100) was employed. Chemical analysis carried out showed that the characteristics of biodiesel used, with the exception of the acid index (0.7 mg KOH/g where the limit is 0.5 mg KOH/g) were in agreement with the standards of Brazilian National Agency of Petroleum (ANP)

The volume fractions for B20 and B60 fuels were calculated based on the density of each component. For B20, the mixture had 84.2% of B5 and 15.8% of B100, while for B60 the mixture had 42.1% of B5 and 57.9% of B100.

The density was calculated by weighing 500 ml of fuel in a calibrated burette. With this procedure, we obtained a density of 833.4 g/l for B5 and 865.8 g/l to B100. After the blend, the B20 and B60 blends had densities of 838.5 g/l and 852.3 g/l, respectively.

Prior to the use of such mixtures in the engine, they were allowed to stand for one week in the lab in order to verify if there were stability problems, as a possible phase separation, which was not observed.

3.2. Test Procedure

The tests were performed using a fuel blend per time. Initially the fuel pump was adjusted to give the required flow rate (13 ± 0.2 ml/min), then the cetane number was measured according to the ASTM standards (ASTME, 1985). Finally the compression ratio and injection timing values were varied and the ignition delay values were recorded. The cetane numbers found were 46.1 for B5, 47.4 for B20, and 52.5 for B60.

Emissions measurements were performed after the initial tests and already in possession of all data and settings of the engine. For each emission measuring point, initial-test engine operational conditions were reproduced and measurements were taken after system stabilization.

For simplification purposes and prevention of problems with the ASTME/CFR engine, all auxiliary variables such as temperature of the inlet air and fuel flow, among others were kept constant and equal to those used in the standard procedure of the engine (ASTM, 1985). The values of the compression ratios, fuel blends, and the injection timing were defined as follows:

- Fuel blends: the blends B5 (diesel with 5% of biodiesel by volume, which is mandatory by law in Brazil), B20 and B60 were used.
- Compression ratio: in order to simulate more accurately the effects of using biodiesel in diesel engines, three compression ratios were chosen. Initially, the objective was to analyze high compression ratios, but due to some

mechanical limitation of the engine used, low values were used. Initially a compression ration of 15:1 was used, which correspond to the maximum compression ratio possible for the engine used, due to some mechanical limitations. Once this ratio was determined, two others were used: 14:1 and 13:1.

- Injection timing: Initially the use of angles of 13° (the same angle used in the ASTM/CFR Cetane testing), 10° and 7° before top dead center (BTDC) as the injection angles was intended, as they are within the range used in indirect injection diesel engines (ASTM, 1985). However, after performing some initial tests with Marine Diesel, which has no addition of biodiesel, it was noted that this choice would lead us to obtain some conditions where the start of combustion could occur after top dead center (TDC), a fact shown in Figure 2 (in this figure, 0° is the TDC), which would be undesirable from the viewpoint of engine performance. Therefore, the injection timings were changed to 13°, 11° and 9° before TDC.

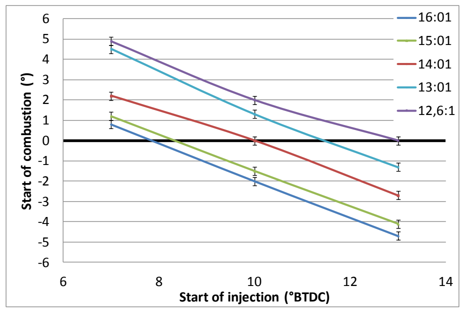

Figure 2. Start of combustion as a function of start of injection for several compression ratios.

3.3. Test planning

To prevent unnecessary use of fuel and reduce the time of testing, the sequence of tests, for each blend, was defined as follows:

- Start the test using standard conditions for cetane number determination, according to the ASTM standard (using the injection timing of 13° BTDC and compression ratios below 13:1);
- The next step is to increase the compression ratio to 13:1, then to 14:1 and finally to 15:1 with the injection timing fixed in 13° BTDC;
- Once the compression rate reaches 15:1, change the injection timing to 11° BTDC and then to 9° BTDC;
- After finishing the measurements for the compression ratio 15:1, decrease the compression ratio to 14:1, making measurements with injection timings of 9° BTDC and then 11° BTDC;
- Next, decrease the compression ratio to 13:1 with the injection timing of 11° BTDC and then finally change the injection timing to 9° BTDC.

These steps, when followed correctly, drastically reduced the duration of the tests.

4. RESULTS AND DISCUSSION

This section will present and analyze the results of the ignition delay, the start of combustion, and the gaseous emissions as a function of the injection timing and compression ratio for different fuel blends.

It is noteworthy that no repeatability analysis of tests was conducted. The measurement errors were based on the engine manual (ASTM, 1985) and on the technical information of the gas analyzer. For the ignition delay and start of combustion an error of 0.2 crank angle degrees was adopted. As for emissions, an error of 5% of the measured values for both NOx and for CO was considered.

4.1. Ignition Delay

Figure 3 shows the variation of the ignition delay as a function of the injection timing for three different compression ratios, considering the B5 blend.

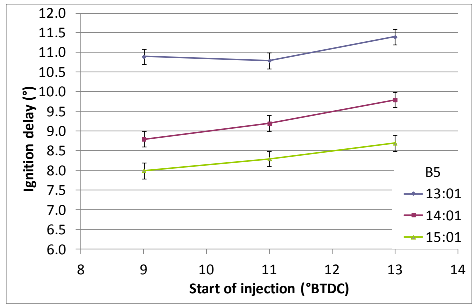

Figure 3. Ignition delay as a function of start of injection for three compression ratios using B5.

Results in Fig.3 show that for the same injection timing, the higher the compression ratio the lower is the ignition delay. This happens because increasing the compression ratio also raises the temperature and pressure in the combustion chamber, which enhances the atomization of the fuel and increases the density of air, reducing the minimum temperature of auto ignition. It can be seen further that starting the injection earlier causes an increase in the ignition delay, since the temperature and pressure in the combustion chamber will be lower than when injecting the fuel later. In this graph, the only exception regarding these conclusions was the variation in the injection timing from 9° to 11° BTDC for the compression ratio of 13:1. One possible reason is that by being a low compression ratio for compression ignition engines, this variation is not relevant in practice.

Figure 4 shows the same analysis for B20 and B60 blends. From the analysis of Figure 4, it can be observed that the behavior of the ignition delay when changing the injection timing and the compression ratio for the blends B20 and B60 is similar to the one presented in Figure 3 for the blend B5. Comparing these two figures is also possible to verify that there is a decrease in the ignition delay as we increase the volume fraction of biodiesel on the blend. This happens because pure biodiesel has higher cetane number than pure diesel and thus a lower ignition delay.

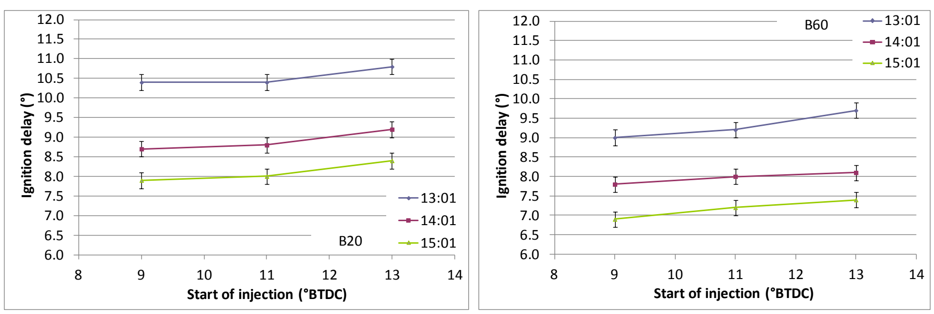

Figure 4. Ignition delay as a function of start of injection for three compression ratios using B20 and B60.

4.2. Start of combustion

Figure 5 shows the variation of the start of combustion as a function of the compression ratio and the injection timing for the blend B5. From the analysis of this figure it is possible to verify that as the compression ratio increases, the start of combustion occurs earlier. This happens because the ignition delay also decreases as explained from the analysis of Figure 3. It is worth to mention that injecting the fuel earlier (advancing the injection timing) can be used to start the combustion before the top dead centre in the case of a poor fuel.

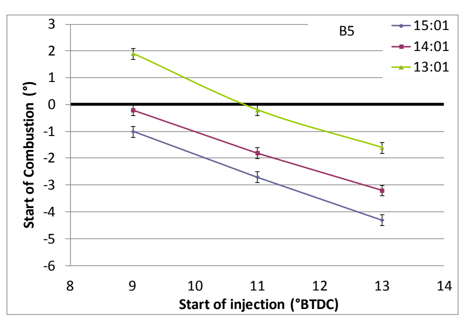

Figure 5. Start of combustion as a function of start of injection for three compression ratios using B5.

Figure 6 show the same analysis, but for the blends B20 and B60. It is clear that, since the blend B20 has a lower ignition delay, combustion starts earlier for this blend when compared to B5. Such behavior is more noticeable for the blend B60, as also reported in Figure 6.

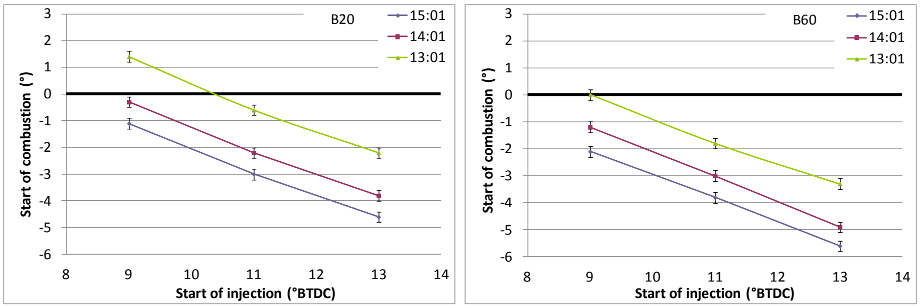

Figure 6. Start of combustion as a function of start of injection for three compression ratios using B20 and B60.

4.3. NOx emissions

The behavior of NOx emissions for a fixed fuel flow rate of 13 ml/min with a compression ratio of 13:1, for blends B5 and B20, is shown in Figure 7. Through the analysis of results depicted in Figure 7, it appears that B20 presents higher NOx emissions when compared to the B5 (up to 12% for the injection timing of 9° BTDC). One reason for this behavior is probably the fact that B20 has a higher concentration of biodiesel, which has Oxygen in its formulation. Thus, such Oxygen could facilitate the formation of NOx, according to the kinetics of formation of such pollutant (Heywood, 1988).

The use of earlier injection timings also increases NOx emissions (growth of up to 41.5% in the case of increasing the injection timing from 9° to 13° BTDC for B20). One possible explanation is the fact that earlier injection timings cause an anticipated start of combustion, with higher temperatures and pressures inside the combustion chamber. Thus, according to the kinetics of formation of NOx (Heywood, 1988), such high temperatures could facilitate its formation.

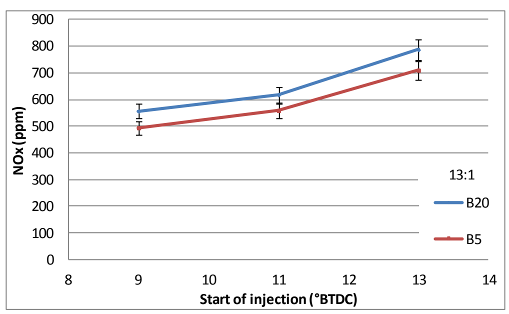

Figure 7. NOx emissions as a function of start of injection for B5 and B20, for a compression ratio of 13:1.

Figure 8 show the same analysis, but for compression ratios of 14:1 and 15:1, using B20 and B5. Observing this figure, one can notice the same behavior presented for Figure 7, regarding the variation of NOx emissions with respect to compression ratio and injection timing.

It was also found that there is a reduction (reduction of less than 10% at most points, by modifying the compression ratio from 13:1 to 14:1 or from 14:1 to 15:1) in NOx emissions when increasing the compression ratio. It was expected that higher compression ratios would increase the NOx emissions due to the higher temperature in the combustion chamber. However, other factors probably caused an inverse behavior as, for example, the duration of the combustion.

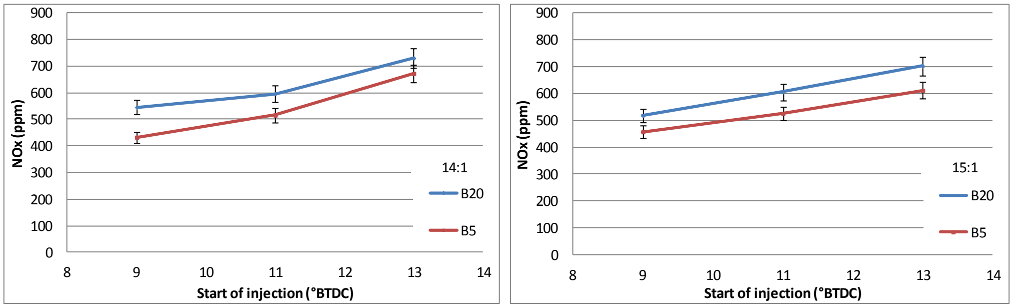

Figure 8. NOx emissions as a function of start of injection for B5 and B20, for compression ratios of 14:1 and 15:1.

4.4. CO emissions

Figure 9 shows the CO emissions as a function of the injection timing and the fuel blend for a compression ratio of 14:1, whereas figure 10 show the same analysis for compression ratios of 15:1 and 13:1. Analyzing them, it is noted that emissions of CO were higher for B5 (on average 81% higher for the 14:1 compression ratio and 52% for the compression ratio of 15:1). The reasons for the lower CO emissions when burning B20 are similar to that related to NOx emissions. The fact that B20 has a lower ignition delay and therefore starts the combustion earlier compared to B5, can provide a more complete combustion, especially due to the excess of oxygen.

Stating the injection earlier also decreases the CO emissions up to 31.5% in some cases (in the case of B5 for a compression ratio of 14:1, when the injection timing goes from of 9° BTDC to 13° BTDC) since higher temperatures and pressures are achieved in the combustion chamber, thus favoring a more complete combustion.

For the compression ratio of 15:1 (Figure 10), note that with the injection starting 13° BTDC, the CO emissions for both fuels, contrary to expectations, did not decrease. One possible reason is that as the engine operates at low speed (900 rpm), with the advance of injection, at such compression ratio, the combustion starts too early, which might dissociate CO_2.

For a compression ratio of 13:1, the behaviors are different from the others. One possible explanation for this is that such compression ratio has higher ignition delays, making the vaporization of the fuel occur at lower temperatures and pressures.

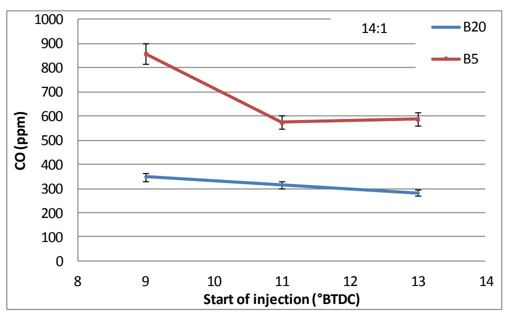

Figure 9. CO emissions as a function of start of injection for B5 and B20, for a compression ratio of 14:1.

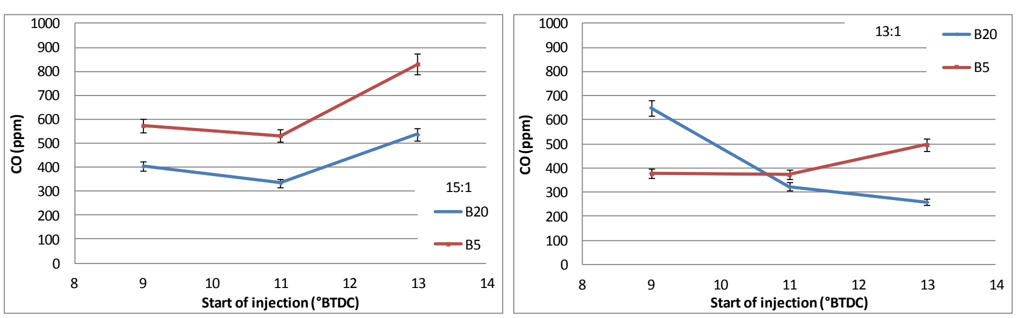

Figure 10. CO emissions as a function of start of injection for B5 and B20, for compression ratios of 15:1 and 13:1.

5. CONCLUSIONS

The objective of this work was to provide a general analysis of different blends of diesel and biodiesel, when the engine compression ratio and the injection timing were varied.

It was found that both the compression ratio and the injection timing directly influence the combustion emissions for all blends of fuels analyzed.

The ignition delay and the start of combustion both decreased when the volume fraction of biodiesel increase in the fuel blend. Such fact was expected, since the biodiesel has a higher cetane number then the Marine Diesel tested. The same trends were observed with an increase in the compression ratio.

CO emissions decreased as the volume fraction of biodiesel increased in the fuel blend. Same behavior was observed when the start of the injection was anticipated is most cases.

NOx emissions increased as the proportion of biodiesel increased in the blend and also when the injection started earlier.

Such behaviors are useful to show the influence of operating parameters such as fuel injection angle and engine compression ratio in the ignition delay and gaseous emissions in an engine running on biofuel blends.

In future work, in addition to measuring the ignition delay and gaseous emissions, it would be interesting also measure the power, in order to evaluate the specific emissions, and also the influence of the ignition delay on the engine power.

Other possibility would be to measure the pressure curve in the combustion chamber, in order to have a more precise evaluation of the combustion process.

6. ACKNOWLEDGEMENTS

The authors would like to thank the Brazilian agencies for the fostering of science, *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* (ANP), *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq), *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES) and *Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro* (FAPERJ), for the financial support for this work. Mr. Olivares is also greateful to the PRH37-ANP/MCT scholarship.

7. REFERENCES

ANP, 2011, http://www.anp.gov.br/pg=11850 (accessed in 10/19/2011).

ASTM, 1985, *Standard Test Method for Ignition Quality of Diesel Fuels By the Cetane Method*, ASTM D 613.

Biodieselbr, 2012a, http://www.biodieselbr.com/biodiesel/definicao/o-que-e-biodiesel.htm (accessed in 01/30/2012).

Biodieselbr, 2012b, http://www.biodieselbr.com/biodiesel/especificacoes/especificacao-biodiesel.htm (accessed in 01/30/2012)

Bittle, J.A., Knight, B.M., and Jacobs, T.J., 2010, "Interesting Behavior of Biodiesel Ignition Delay and Combustion Duration", *Energy Fuel*, Vol. 24, pp. 4166–4177.

Brazil, 2004, Grupo de Trabalho Interministerial, *Viabilidade do uso do biodiesel como fonte alternativa de energia,* Dezembro.

Bunce, M., Snyder, D., Adi, G., 2011, "Optimization of soy-biodiesel combustion in a modern diesel engine", *Fuel*, Vol. 90, pp. 2560-2570.

Buyukkaya, E., 2008, "Thermal analysis of functionally graded coating AlSi alloy and steel pistons", *Surface and Coating Technology*, Vol. 202, pp. 3856–3865.

Choi, C.Y., and Reitz, R.D., 1999, "An experimental study on the effects of oxygenated fuel blends and multiple injection strategies on DI diesel engine emissions", *Fuel*, Vol. 78, pp. 1303–1317.

Fang, T., Lin, Y.C., Foong, T.M., 2008, "Reducing NOx Emissions from a Biodiesel-Fueled Engine by Use of Low-Temperature Combustion", *Environ. Sci. Technol.*, Vol. 42, pp. 8865–8870.

Kojima, T., and Nishiwaki, K., 1994, "Numerical analysis of heat transfer in heat insulated diesel engines." *JSAE Rev* , Vol. 15, pp. 133–40.

Heywood, J.B., 1988, *Internal Combustion Engine Fundamentals*, McGraw-Hill.

McCormick, R.L., Tennant, R.J., Hayes, R.R., 2005, "Regulated emissions from biodiesel tested in heavy-duty engines meeting 2004 emission standards". *In: 2005 SAE Brazil fuels & lubricants meeting*, May.

Pimentel, V.S.B., 2002, *"Análise e diagnose de diesel-geradores operando com óleo de dendê 'in natura'*" Tese de D.Sc., Engenharia Mecânica, COPPE/UFRJ, Rio de Janeiro, RJ, Brasil.

Prasad, R., and Samria, N.K., 1990, "Transient heat transfer in an internal combustion engine piston." *Computers & Structures*, Vol. 34, pp. 787–793.

Scholl, K.W., and Sorensons, S.C., 1993, "Combustion of soybean oil methyl ester in a direct injection diesel engine", *SAE PAPER 930934*.

UNEP (United Nations Environment Programme), 2009, *Towards sustainable production and use of resources: Assessing Biofuels*.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.