# Experimental Combustion and Emissions Evaluation of Ternary Mixtures of Diesel-Biodiesel-Ethanol in a CFR-ASTM Engine

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**Abstract**

The present work presents and discusses experimental performance and gaseous emission results of the use of ternary mixtures of diesel oil, biodiesel and ethanol in an ASTM-CFR engine. Eight different mixtures with biodiesel content equal to 8%, 20% and 60%, and ethanol content equal to 0%, 5% and 8% were analyzed. After the selection and preparation of the mixtures, the determination of the cetane number for each one was performed following the ASTM D613 standard. After cetane number evaluation, two off-standard operating conditions were selected, and performance and emissions were obtained. A thermodynamic analysis and a Bayesian inverse approach were applied and physical quantities of interest, such as indicated work, maximum pressure, rate of heat released by the fuel, ignition delay, and combustion duration, were obtained. In-cylinder pressure data were obtained through an AVL Indicating system installed in the ASTM-CFR engine. The heating values of each mixture were determined using a bomb calorimeter and thermal and indicated efficiencies were evaluated based on the total heat released by the fuel and the indicated work. Finally, a gaseous emissions analysis was conducted to evaluate the influence of the blend compositions, as well as of their cetane numbers, on the formation of NOx, CO and $CO_2$.

***Keywords:*** *Ternary Mixtures, CFT-ASTM, Bayesian techniques*

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## 1. Introduction

The recent interest in ternary blends of diesel, biodiesel and ethanol is motivated by environmental questions regarding the use of renewable power sources. However, the use of biofuels also imposes some questions related to the food-fuel duality. Therefore, biofuels obtained from non-food sources have a greater potential to be used in large scale. Some countries already have a large experience in producing ethanol with well-established distribution network. In the Brazilian case, ethanol is produced from sugarcane and is largely available for automobiles use all over the country. Although not suitable for direct use in compression ignition engines, the inclusion of biodiesel may compensate the ethanol low cetane number and generate a blend with properties like those found in diesel fuels. Also, in some cases where high viscosity and density vegetable natural oils or even pure biodiesel are used in engines, the addition of ethanol may alleviate problems related to clogging and fouling in the engine's pump and injectors.

Hansen *et al*. (2005) presented a brief review of studies related to blends of ethanol and diesel up to 2005. The authors briefly mentioned global parameters such as stability, cetane number, energy content, and emissions. They also reported some previous studies where blends with 10% and 15% of ethanol were used in a diesel base fuel. More recent reviews can also be found in the works of Shahir *et al*. (2014, 2015) and Mofifur *et al*. (2016).

Some studies related to gaseous emissions and engine performance of quaternary blends (including water) can also be found in the literature, such as the one by Lee *et al.* (2011).

Atmanli *et al*. (2013) studied phase stability, fuel consumption, thermal efficiency, and brake power of blends composed by diesel, n-butanol and cotton oil. Different contents of each component in the blend were analyzed, but no emissions or combustion analyses were performed. In a following study, Atmanli *et al*. (2015b) extended their previous work to include emissions analysis of NO, HC, CO and $CO_2$. Concerns related to the particulate emissions of engines burning ternary blends of ethanol, diesel and biodiesel were also addressed by Armas *et al*. (2012, 2013) who focused their study on city buses. A similar work, where specific consumption, thermal

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efficiency and gaseous (CO, $CO_2$, HC, and NOx) and particulate emissions were presented, was also published by Barabás *et al*. (2010), who analyzed ternary blends with 10% and 25% of biodiesel and 5% and 10% of ethanol.

Guarieiro *et al*. (2014) analyzed gaseous and particulate emissions from a diesel engine burning ternary blends of diesel, biodiesel and ethanol. In their study, they analyzed three compositions: (i) 5% of biodiesel and 95% of diesel; (ii) 5% of biodiesel, 89% of diesel and 6% of ethanol; and (iii) 100% of biodiesel. The focus of their paper was on the gaseous emissions of HC, NOx, CO and $CO_2$, as well as particulate emissions, although they also investigated power and fuel consumption.

Yilmaz *et al*. (2014) also investigated gaseous emissions (CO, NO and HC) of blends of diesel and biodiesel containing 3%, 5%, 15% and 25% of ethanol. No engine performance data was analyzed in this case.

Tse *et al*. (2015) presented an in-cylinder analysis of blends of diesel, biodiesel and ethanol. In their work, in-cylinder pressure curves as well as gross heat release rates were presented for blends with 0%, 5%, 10% and 20% of ethanol under five engine loads. From the in-cylinder data they also evaluated the combustion duration and particulate emissions.

An interesting optimization study of ternary blends of diesel, n-butanol, and cotton oil was performed by Atmanli *et al*. (2015a) in order to investigate the best concentration ratios that could minimize the gaseous emissions (NOx, CO, HC) and maximize performance (brake power and thermal efficiency) of a compression ignition engine.

Yilmaz *et al*. (2018) performed an investigation on quaternary blends composed of diesel, biodiesel, alcohol and vegetable oils. As the previous authors, they also investigated fuel consumption, brake power, and gaseous

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emissions of CO, HC, and NOx. However, a detailed analysis of the combustion was not performed. This work was derived from their previous paper (Yilmaz *et al.*, 2017), where ternary mixtures were analyzed.

An optimization study was also performed by Hussan *et al*. (2013), where the components of a ternary blends were adjusted to reduce engine fouling. Similar results were presented by Khoobbakht *et al*. (2016) where the blended levels of ternary mixtures were optimized to minimize the exhaust emissions of a compression ignition engine.

Emiroglu *et al*. (2018) analyzed ternary blends of alcohol, diesel and biodiesel. They analyzed the maximum in-cylinder pressure, the maximum heat release rate, ignition delay and combustion duration of blends with 20% of biodiesel and 10% of ethanol, methanol or butanol. The specific fuel consumption, smoke opacity and gaseous emissions (NOx, CO, HC) were also analyzed for the fuels considered. The works of Emiroglu *et al*. (2018) and Tse *et al*. (2015) provide a very good and detailed analysis of the combustion of ternary mixtures. Another work where the in-cylinder pressure data was analyzed for ternary mixtures was presented by Venu *et al*. (2017), where the specific fuel consumption, maximum pressure, heat release rate and combustion duration, together with gaseous (HC, CO, $CO_2$, NOx) and particulate emissions were analyzed. Prakash *et al*. (2018) also presented a paper with similar results, using ternary blends of bioethanol, diesel and castor oil.

From the above discussion, most of the recent works are mostly focused on the general behavior of the engine (brake power, fuel consumption, gaseous and particulate emissions) when running with different ternary fuels, rather than looking at the combustion inside the cylinder. The interest in analyzing in-cylinder data of ternary blends appeared in the literature in 2015 and more frequently in 2017.

This work follows some of the objectives of Tse *et al*. (2015) and Emiroglu *et al.* (2018) works but considering also an analysis of gaseous emissions and a more detailed analysis of the combustion characteristics. More specifically, we analyzed blends varying from 8% to 60% of biodiesel and from 0% to 8% of ethanol in a base-fuel containing diesel with 50 ppm of sulfur. The cetane number of these blends were evaluated in an ASTM/CFR engine. An AVL pressure sensor was installed in this engine, giving the indicated work for each blend, as well as their ignition delays and maximum pressure. In the present paper an inverse problem approach (Pasqualette *et al*., 2017; Hamilton *et al*., 2014) is also used to evaluate the rate of heat released by the fuel. Such approach is based on a Bayesian framework, where model and experiment uncertainties can be considered. It also does not depend on some empirical models for the combustion, such as the Wiebe's model. Therefore, it can be seen as an online estimating of the heat released by the fuel, as the combustion progress. As a result of this inverse problem analyses, the rate of heat released by each blend was estimated, together with the combustion duration, effective heat released by the fuel and peak values of the rate of heat release. These results were evaluated together with the ignition delay in order to discuss the pre-mixed and diffusive combustion phases. A bomb calorimeter was used to determine the higher heating value of each fuel, which was compared with the Bayesian results to obtain an estimate of the combustion efficiency. Finally, exhaust emissions are presented for NOx, CO, and CO2 and possible correlations with the cetane number and maximum pressure are discussed.

In section 2 the experimental apparatus is briefly presented, and section 3 discusses the experimental analysis, where two operational conditions were imposed to an ASTM-CFR engine. The cetane number, indicated work, ignition delay, and maximum pressure were analyzed for eight different blends of diesel, ethanol and biodiesel. Section 4 presents a Bayesian approach to estimate the rate of heat released by the fuel. The duration of combustion, maximum heat released by the fuel, total energy released, combustion and thermal efficiencies are presented. Section 5 presents the results for the gaseous emissions (NOx, CO, and $CO_2$), where the influence of cetane number, components of the blends and maximum pressures are analyzed. Finally, section 6 presents the final conclusions.

**2. Experimental apparatus**

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The apparatus used in this research consists of a variable compression ratio ASTM/CFR engine, used to determine fuel ignition quality in compression ignition engines. Such engine was modified with new temperature and pressure sensors, which enabled a precise adjustment and control of its operating conditions. The engine also received an AVL Indicating system to measure the real-time in-cylinder pressure. These data were used in this paper for the combustion analysis of different blends of ternary fuels. A bomb calorimeter (IKA works C-200) was used to measure the high heating values of the blends and a Testo XL-350 device was employed to measure gaseous emissions.

## 3. Experimental analysis

The diesel oil used in preparing the mixtures of the present work, containing 10 ppm of sulfur, consists of a binary blend comprised of 92% diesel oil and 8% biodiesel and was obtained from a local gas station. The mixtures analyzed are named, however, ternary blends since they consist of three components, namely: diesel oil, biodiesel and anhydrous ethanol. In this research a set of eight blends containing different proportions of diesel oil, biodiesel and ethanol in their composition were considered.

The tested ternary blends are designated as Bα Eβ where B and E stands for biodiesel and ethanol, respectively. The volumetric fractions of biodiesel and ethanol are respectively represented by α and β. The diesel oil volumetric content of each tested mixtures is readily available as $100 - \alpha - \beta$. The following blends were analyzed in this work: B8E0, B8E5, B20E0, B20E5, B20E8, B60E0, B60E5, and B60E8. Therefore, the contents of biodiesel varied from 0% to 60%, while the contents of ethanol varied from 0% to 8%.

The higher heating values (HHV) of the tested mixtures obtained from bomb calorimeter are shown in Table 1. As expected, the addition of ethanol to the blend reduces the mixture heating value and as shall be further presented, have a similar effect on the indicated work.

Table 1 - Higher heating values of the mixtures used.

| Mixture | Higher heating value (HHV) [MJ/kg] |
|---|---|
| B8E0 | 46.301 |
| B8E5 | 45.410 |
| B20E0 | 46.998 |
| B20E5 | 44.518 |
| B20E8 | 44.244 |
| B60E0 | 45.124 |
| B60E5 | 43.223 |
| B60E8 | 40.551 |

### 3.1. Cetane number

The determination of the cetane number (CN) for the tested mixtures follows the ASTM D-613 standard. Therefore, the engine operating parameters, such as speed, fuel consumption, ignition delay, injection advance (timing), and intake air temperature, have been adjusted to the standardized values and held constant during the experiment. Figure 1 shows the results for the CN obtained for the set of eight blends tested, where it is possible to notice the influence of the ethanol addition in the CN for the different mixtures. Cetane Number reductions are observed for all the biodiesel amounts considered as the concentration of ethanol is increased. The CN decrease for higher blend ethanol concentrations is more significant for the B20 fuel group. The CN for the B20E0 blend of 59.5 is reduced by 14.8% to 50.7 after inserting 5% of ethanol. With the addition of 8% ethanol, a further CN drop to 48.4 is observed, a relative decrease of 10.7% from the corresponding ethanol-free value. Results in Fig. 1 also show that the CN reduction for the B8 and B20 blends is less pronounced than the values observed for the B20 blends. A relative CN reduction of 4.3% and 4.6% is observed between the ethanol-free mixtures and the B8E5 and B60E5 blends, respectively. For the B60E8 mixture, the CN values are, respectively, 5.5% and 1.3% smaller than the B60E0 and B60E5. Thus, the insertion of ethanol impairs with a non-monothomic intensity the quality of the fuel. This decrease in the cetane number generates a large amount of energy released in the premixed combustion phase, creating high pressure peaks in the engine cylinder, as will be latter shown.

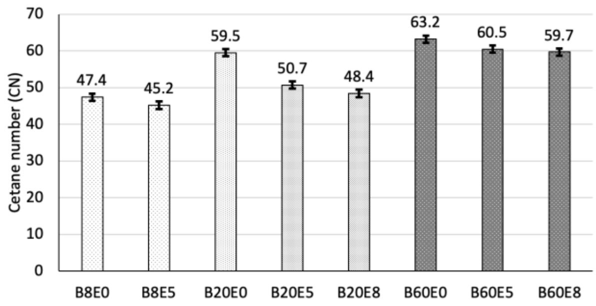


Figure 1 – Cetane number of the ternary mixtures separated by biodiesel groups.

On the other hand, it is observed that an increase of biodiesel concentration in the blends significantly improves the cetane number. Thus, for a fixed ethanol concentration one can verify that an increase in the biodiesel concentration leads to an elevation of the cetane number, which can be used to compensate the reduction of this property in blends where high ethanol concentrations are present.

### 3.2. Indicated work

For results shown from this section on, the original pressure sensor of the ASTM-CFR engine was replaced by an AVL Indicating system, allowing a more detailed analysis regarding the pressure variation inside the CFR engine cylinder. Two engine conditions were then analyzed in the present work:

- **Case A**: The engine operating conditions were adjusted to the values defined by the ASTM D613 standard regarding the blend B8E0. Therefore, the engine speed, compression ratio, fuel consumption, injection advance, fuel, lubricant and air temperatures were adjusted to match the conditions defined in this standard for a fuel containing 8% of biodiesel and 92% of diesel. All other mixtures were tested under these conditions.
- **Case B**: The compression ratio was increased 15% with respect to Case A, keeping all other parameters constant, in order to compare the results for a more severe condition of pressure.

Figure 2 illustrates the indicated work calculated for all mixtures, obtained using piecewise trapezoidal numerical integration to evaluate the area encompassed by the experimentally obtained in-cylinder pressure indicating diagram. One can visually perceive through this figure that, for a specific biodiesel group, there is a decrease in indicated work with the increase of ethanol concentration in the mixture. It is also interesting to notice that, for this operating condition, blends with 20% of biodiesel, in general, present higher indicated works than their B8 and B60 counterparts. Such a trend should not be generalized, however, since other parameters, such as the compression ratio, should be considered in this analysis.

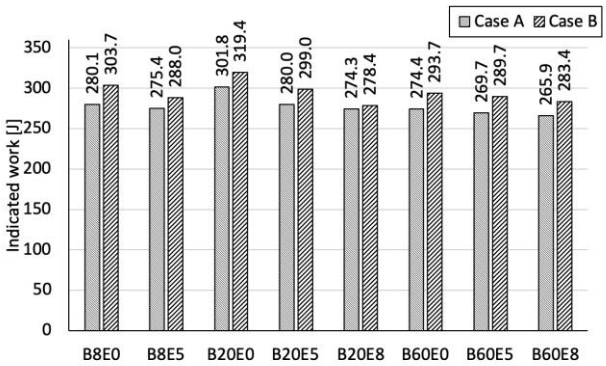


Figure 2 – Indicated work.

Increases of the indicated work with the compression ratio from 1.5%, for the B8E0 mixture, to 8.4%, for B20E8, can also be observed in Fig. 2, comparing Case A and B results. It is noteworthy that the indicated work increase with the compression rate is less pronounced for the B20 mixtures that for the mixtures with 8% and 60% of biodiesel. The indicated work values calculated in this section will be later used to verify the indicated efficiency of the engine operating with different blends in Sec. 4.

### 3.3. Ignition delay

Ignition delay results were obtained from measurements of the start of the fuel injection and the start of the combustion measured by the data acquisition system installed on the ASTM-CFR engine used. The start of the fuel injection was determined in terms of the crank angle position from a needle lift sensor signal coming from

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the injector nozzle, which was amplified and sent to the data acquisition system. The crank angle for which 5% of the initial amount of fuel is burned was associated to the start of combustion and determined through the AVL instrumentation system. Figure 3 shows the experimentally obtained data for ignition delay for the blends considered in the present work.

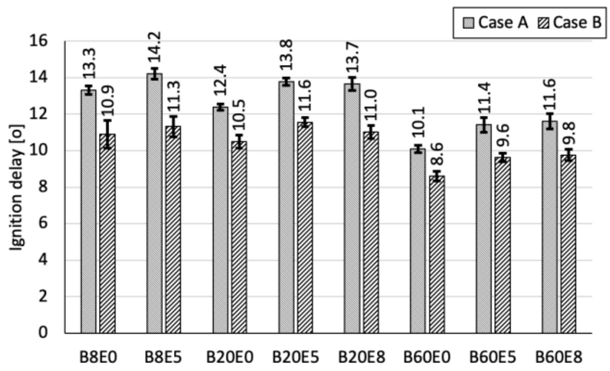


Figure 3 – Ignition delay.

Since ethanol withstands higher compression ratios than diesel without igniting, increases in ignition delays are expect as the ethanol content of the mixtures increases as shown in Fig. 3 for the Cases A and B and the B8 and B60 mixtures. This tendency is also in agreement with the results observed in Fig. 1, which presented the cetane number of the B8 and B60 blends, as the cetane number constitutes an indirect measurement of the ignition delay. For the B20 mixture, the ignition delay displays a non-mononothonic behavior, increasing (11.3% for Case A and 10.5% for Case B) as the ethanol content is increased from 0% to 5% and decreasing (0.72% for Case A and 5.17% for Case B) as the ethanol content is increased from 5% to 8%. Results depicted in Fig. 3 also indicate that biodiesel can perform as an additive, maintaining or decreasing the ignition delay, even for mixtures with high ethanol concentrations. For instance, results show that a mixture with 8% of ethanol and 60% of biodiesel (B60E8) presents an ignition delay (11.6$^{o}$) smaller than an ethanol-free mixture with 8% of biodiesel (13.3$^{o}$) considering Case A. Therefore, the addition of biodiesel in ternary mixtures may enable the use of a renewable fuel (ethanol) in addition to another of fossil origin, keeping the ignition delay at acceptable levels. Nevertheless, although blends with high ethanol concentrations still have adequate ignition delay and

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cetane number, the values of the associated indicated work, shown in Fig. 2 are lower than those found in blends with low concentrations of this component and further analyses of the combustion and overall efficiencies are still required.

For a given mixture, results depicted in Fig. 3 shown that the more severe test conditions associated with Case B led to smaller ignition delays when compared with experimental data obtained for Case A. An evaluation of the results in Fig.3 indicates that the ignition delay reduction between Cases A and B is more pronounced for mixtures holding higher ethanol contents. For the B8 mixtures, ignition delay reductions of 18.1% and 20.4% are observed between an ethanol free mixture (B8E0) and the B8E5 mixture, respectively. For the B20 mixtures, the ignition delays present a variation between Cases A and B for the mixtures B20E0 and B20E5 (15.3% for both) reaching 19.3% for the B20E8 mixture. For the B60 mixture family, the ignition delay reduction varies from 14.9% to 15.8% as the ethanol content is increased from zero to 5%. Further increase of the ethanol content for the B60 mixture leads to variation of the ignition delays between the considered cases. One possible explanation is that higher compression ratios increase the internal temperature of the combustion chamber, contributing to the burning of the fuel. Apparently, ethanol benefits more from this temperature increase than the other two components, although such claim still needs further investigation.

### 3.4. Maximum pressure

Figure 4 shows the measured in-cylinder maximum pressures for the eight different mixtures analyzed as obtained from the AVL Indicating system. From the engine durability point of view, very high-pressure peaks are not desirable. It is noticed, for Case A, higher maximum pressures are measured as the ethanol content of the mixtures increases. It is interesting to notice from the analysis of Figs. 3 and 4 that the ignition delay alone is not a parameter that measures well the quality of blends involving different fuels. In fact, Section 5.4 of the ASTM D-613 standard recommends certain precautions when using the standard to so-called unconventional fuels, such as ethanol and biodiesel. Results for Case A in Fig. 3 indicate that the B20E5 and B20E8 blends have similar ignition delays (13.8 and 13.7, respectively). Regarding the maximum pressure, results in Fig.4

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show a value of 45.2 bar for B20E8 and 43.7 bar for B20E5 (a difference of 3.43%). Results in Figs. 3 and 4 for the more severe Case B show that the use of blends with similar ignition delays lead to different maximum pressures. For instance, considering Case B results for the mixtures B20E0 and B20E8, Fig.3 show similar ignition delays (10.5 and 11.0, respectively) and a 7.1% lower maximum pressure for the ethanol free mixture. Therefore, in order to better explore the differences among the mixtures, other parameters, such as the heat release curves, will be analyzed later in this manuscript.

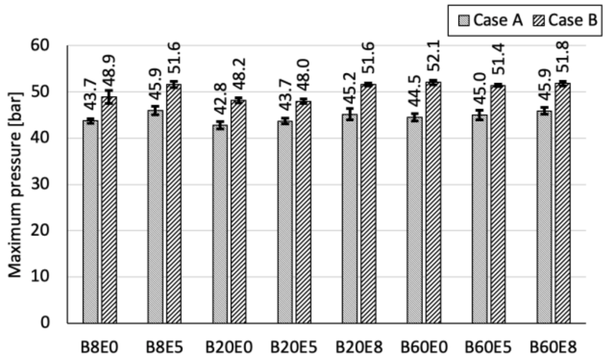


Figure 4 – Maximum pressure.

A large dispersion is observed in the maximum pressure for each blend analyzed, which is translated by the large error bars. However, one can notice that Case B, in general, presents a smaller variability (except for the B8E0 mixture) than Case A. One possible explanation for this, lays in the fact that high compression ratios lead to high overall pressure inside the cylinder and, consequently, elevated temperature values. These two factors contribute to the start of combustion and decrease its variability from cycle to cycle, resulting, therefore, in less dispersion of the data for each blend.

**4. Combustion quality analysis**

The pressure measurements, obtained through an AVL Indicating system was processed through a Bayesian inference analysis. Bayesian analysis, based on inverse problems techniques, allows unknown functions - in this case, the rate of heat release - to be estimated from experimental data (pressure inside the cylinder). In this work

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no correlation - such as that of Wiebe, for instance - was used to estimate the rate of heat release. Details on the technique employed can be found in Pasqualette *et al*. (2017). Bayesian techniques can also incorporate uncertainties in the model and in the measurements. In the following analysis, the pressure measurements used in the Bayesian analysis, at each crank angle, were taken as an average over 200 engine cycles. The standard deviations of those measurements were also considered in the Bayesian estimator. Therefore, instead of using deterministic data usual employed in some combustion correlations, the Bayesian results consider online measurements taken inside the engine as well as their uncertainties.

In the analyzes presented in this section, the *estimated* functions and variables were obtained with the Bayesian inference technique, while the *calculated* functions and variables have been determined through the direct calculation of the heat release rate, via a simplified model using the First Law of Thermodynamics (Pasqualette *et al*., 2017), where several assumptions are considered. Figure 5 shows the results obtained from the Bayesian analysis and the direct calculation using the simplified model. It is observed initially that both methodologies give similar values for the rate of heat release $dQ/d\theta$ in the initial crankshaft angles. After combustion starts, the *calculated* values of $dQ/d\theta$ are generally lower than those *estimated* by the Bayesian inference technique. It is also observed that there is a peak of heat release, just after the start of the combustion, which is accentuated as the percentage of ethanol added in the blend is increased (this fact will be better analyzed later), due to the increase in ignition delay and consequently the amount of heat released in the premixed combustion stage.

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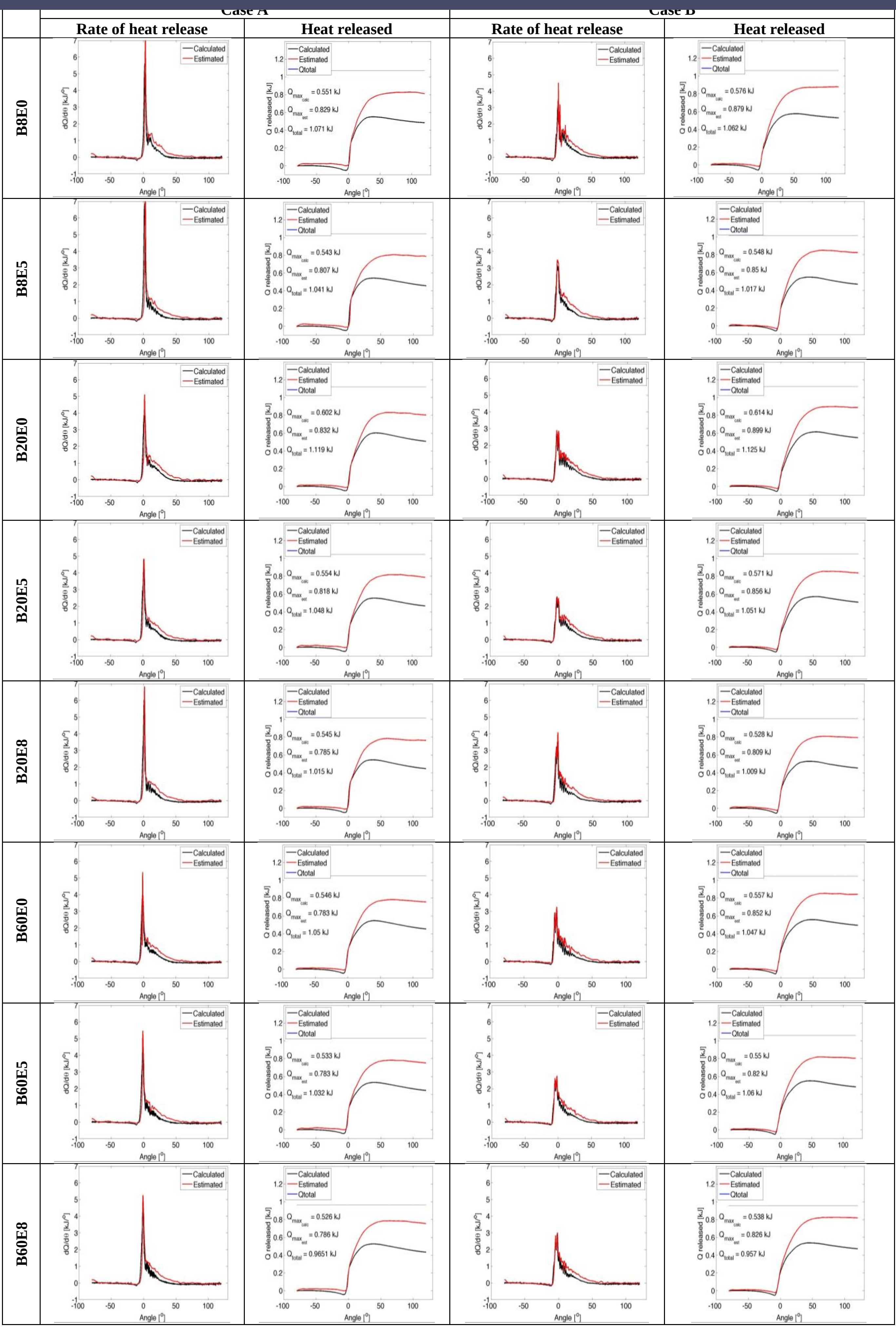


Figure 5 – Bayesian estimation results.

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It can be observed through the analysis of the heat-released curves (given by the incremental integral of $dQ/d\theta$ curve) that the $Q_{released}$ obtained by the Bayesian inference technique are closer to the total energy released by the fuel, $Q_{total}$, than the ones calculated via the simplified model. The $Q_{total}$ values were obtained by taken the mass of fuel injected into the engine per cycle (obtained through the acquisition and control system implemented in the ASTM-CFR engine), multiplied by the higher heating value of the fuel. Although the lower heating value is a better metric, such analysis serves as a basis for comparison between the two techniques for obtaining the heat released $Q_{released}$. Further analysis of these values will be addressed next.

Finally, comparing the $dQ/d\theta$ and $Q_{released}$ results for Case A and Case B, it is observed that the amount of heat released, $Q_{released}$, increases for Case B (possibly indicating a better combustion efficiency) and that the peaks of heat release rate, $dQ/d\theta$, decreases for Case B (increasing the compression ratio).

Such events were already expected, since, as mentioned earlier, the ignition delay for Case B is lower than for Case A, thus reducing the amount of fuel evaporated before combustion and, consequently, the rapid release of energy in the premixed phase. As the combustion turns out to be smoother and, in a certain way, more controlled, the heat released is better used with a more efficient combustion and therefore with a higher value of heat released, $Q_{released}$. Other analyzes of these results will follow.

### 4.1. Case A

The duration of combustion in terms of the crankshaft angle for the blends employed in this work are shown in Fig. 6. For Case A, where the engine operating condition is fixed for all mixtures, it is noticed that the duration of combustion appears to be affected by the concentration of ethanol in the blend. By fixing the biodiesel group, the duration of the combustion decreases with the increase of ethanol concentration in the blend. This fact can be better understood by analyzing the maximum rates of heat released, shown in Fig. 7, where there is a trend of peak elevation of the maximum rate of heat released with the increase of ethanol in the blends (for a fixed content of biodiesel). As can also be seen from the $dQ/d\theta$ curves shown in Fig. 5, the increase in ethanol

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concentration, associated with a longer ignition delay (see Fig. 3), causes a larger portion of the fuel to be evaporated before the start of its combustion, which increases the amount of heat released in the premixed combustion stage. This phase is characterized by a fast-burning fuel rate (as seen in the first column of Fig. 5), which increases with ethanol concentration. Because this happens very fast, the duration of the combustion decreases, since less fuel is left to be burned in the diffusive (slower) phase. It should be emphasized that the quality of fuels used in compression ignition engines is an inverse function of their combustion delay. Thus, increasing the ethanol content causes combustion to occur in shorter time intervals, which can generate high pressure peaks (as seen in Fig. 4), and in extreme cases might generates high stresses on the piston.

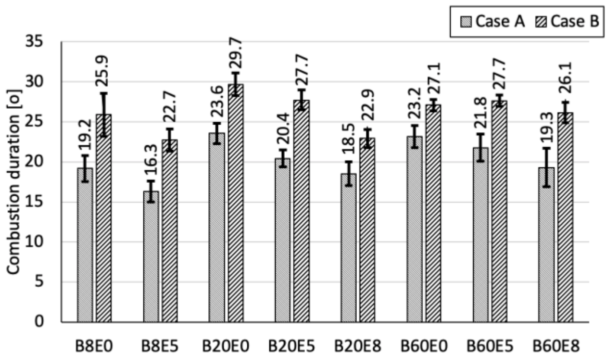


Figure 6 – Duration of the combustion.

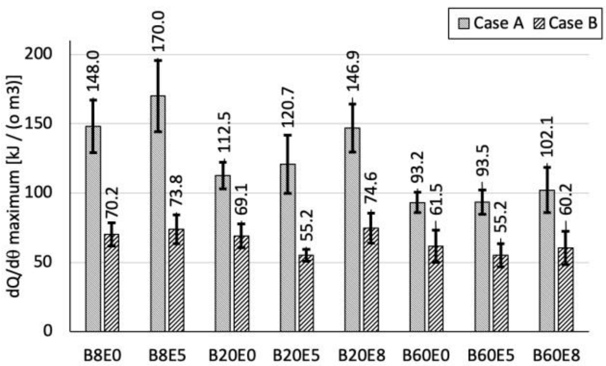


Figure 7 – Maximum heat release rate per unit volume.

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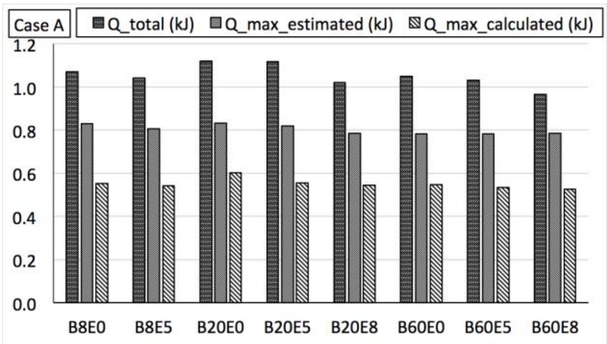
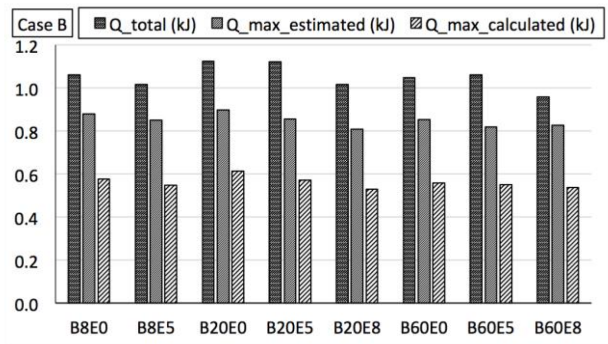
The $dQ/d\theta$ integral, shown in Fig. 5, gives the total amount of heat released during the cycle. These values are compared in Fig. 8(a) for Case A. As discussed above, the value estimated by the Bayesian inference technique approaches more closely $Q_{total}$ than the value calculated via the simplified approach. It is interesting to notice that there is small variation in the total energy released by the different blends. Thus, although blends with higher ethanol concentrations exhibit faster heat releases in the premixed phase, the total energy released varies little.




(a)




(b)

Figure 8 - Energy released during the combustion for (a) Case A and (b) Case B.

In order to obtain a more quantitative result on the combustion efficiency, Fig. 9 shows the ratio of heat released in relation to the total amount of heat contained in the fuel. Again, it is emphasized that the total amount of heat was taken to be the higher heating value (obtained through a calorimetric analysis) multiplied by the injected mass of fuel (obtained by the instrumentation installed in the engine). In fact, although the most appropriate parameter should be the lower heating value, this analysis serves only as a comparison between the efficiencies of the different blends. It is interesting to notice that, in cases where there is an increase in ethanol concentration, although a small drop in the value of heat released is observed (see Fig. 8a), the combustion efficiency increases (except for the B20E5 mixture). This fact can be better explained by observing Table 1, where it is noticed a decrease in the HHV when the ethanol concentration increases. Thus, although there is a drop in total heat released, the ratio between this value and HHV is still higher than in cases with less ethanol. Such outcome is interesting, though not intuitive.

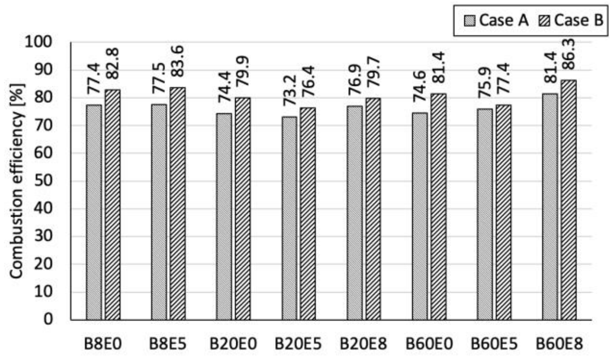



Figure 9 – Combustion efficiency (based on HHV).

Finally, an analysis of the indicated efficiency was performed based on the released heat ($Q_{released}$) and the indicated work performed by each mixture (see Fig. 2). Figure 10 shows the percentage ratio between $Q_{released}$ and the indicated work for each of the mixtures.

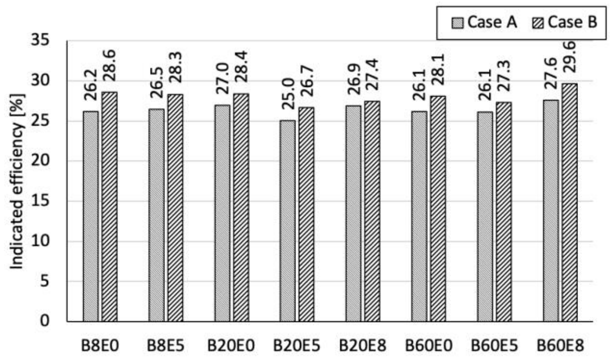



Figure 10 - Indicated efficiency of the ternary mixtures.

It is interesting to notice that, except again for the B20E5 mixture, an increase in the amount of ethanol for the same fuel family results in an increase in overall cycle efficiency. From the analyzed mixtures, the one with the higher efficiency was B60E8. However, it is also noticed that this was the one which obtained the lowest indicated work, as can be observed in Fig. 2. In this way, such fuel, for example, could be more efficient, but requiring a larger engine to generate the same amount of indicated work as a less efficient one (e.g., B8E0), but with a higher IMEP value.

### 4.2. Case B

Again, Fig. 6 illustrates that for a fixed amount of biodiesel the duration of combustion generally decreases with an increase in the ethanol contents in the blend. This is not the case for the B60E5 blend, which is statistically like the others in the same biodiesel group via comparison of error bars. However, it is interesting to notice that the duration of the combustion for the case with the highest compression ratio (Case B) is greater than the one observed for Case A. One possible explanation lays in the fact that the high compression ratio gives high values of pressure and temperature inside the combustion chamber, reducing the ignition delay and consequently the mass of fuel burned in the premixed phase. In this way, the diffusive phase of the combustion in this case will be longer than for Case A. Since the diffusive phase is characterized by slower combustion, the total duration of the combustion (in crankshaft angles) will be longer.

As for the previous section, one can try to relate the duration of the combustion with the rate of heat released by the fuel for the set of eight ternary blends for Case B. Figure 7 shows the maximum values of the heat released rates for this case. This figure shows an oscillating behavior with respect to the increase of the ethanol concentration for a fixed amount of biodiesel, and the increase in the rate of heat released per unit volume with the increase of the mass of ethanol in the mixture. However, in this operational condition (Case B) it is observed that the values present a large dispersion around the mean, making it difficult to trace a trend as previously done for Case A. It is suggested that in these cases more detailed analyzes shall be performed for other compression ratios in order to better understand such phenomenon. However, when comparing the maximum values of the heat-released rates for Case A and Case B, there is a drastic reduction of such values for Case B. This tendency of reduction with an increase in the compression ratio corroborates the previous claim related to the duration of the combustion. Lower values of heat released rates indicate that less fuel was burned in the premixed

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combustion stage, thus leaving more mass to be burned in the diffusive phase, which in turns increases the duration of combustion.

It is possible to combine the previous results in Fig. 8b, which shows the values for the energy released during the combustion. For Case B, as in the previous section for Case A, there is a small decrease in the total heat released with the increase of the ethanol concentration, for each biodiesel group. An analysis of the combustion efficiency and overall cycle efficiency can be seen in Figs. 9 and 10, respectively. For this operational condition (Case B), although there is an oscillation in the obtained values, a similar behavior is observed regarding the previous one (for Case A), where a higher concentration of ethanol seems to lead to higher values of efficiency. However, it is emphasized the need for further investigation to better elucidate the influence of the compression ratio on these results.

## 5. Gaseous Emissions

### 5.1. NOx emissions

The NOx formation is largely determined by the combustion temperature and the corresponding oxygen concentration. The influence of the formation of NOx with the maximum pressure is shown in Fig. 11, where a correlation is observed between the increase of the NOx concentration and the elevation of the maximum pressure. Results in Fig.11 also show an increase in the NOx concentration in the engine exhaust with the increase of ethanol mixture content. This NOx concentration increase may be explained by the cetane number decrease for mixtures holding higher ethanol contents as shown in Fig.1. As the cetane number decreases, the ignition delay increases, as observed in Fig. 2, allowing more fuel to evaporate. Once ignited, this larger mass of evaporated fuel leads the premixed combustion phase to release more energy than the diffusive phase, increasing the local temperature and pressure of the combustion products and enhancing the formation of NOx. Such behavior can be seen in Fig. 7, which demonstrates an elevation for the maximum rate of heat released with an increase in the percentage of ethanol, and in Fig 4, where one can observe a high value of maximum pressure for these blends.

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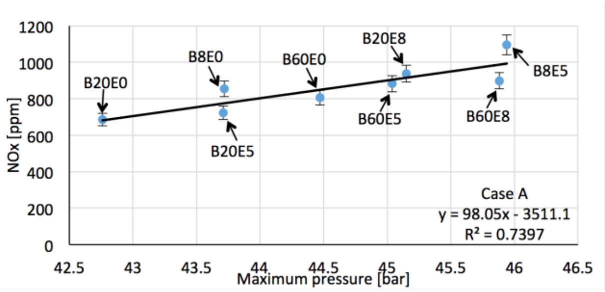
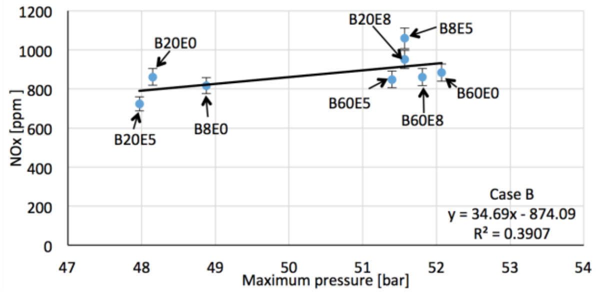


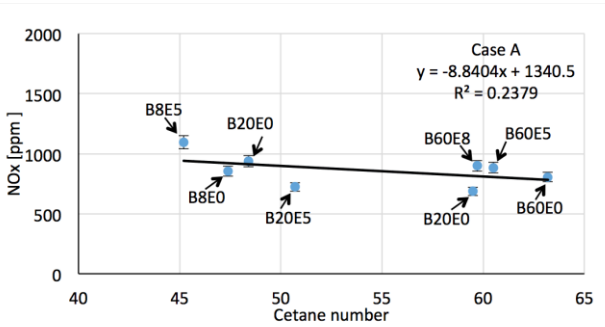

(a)



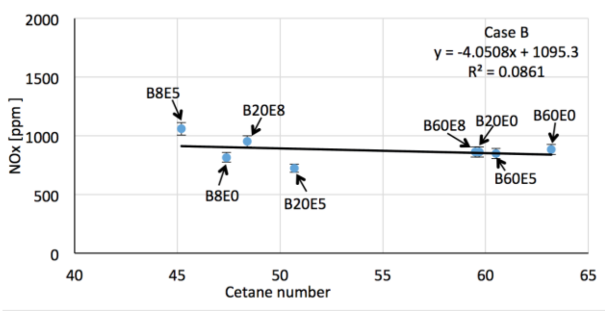

(b)

Figure 11 - Relation between NOx and maximum pressure for (a) Case A and (b) Case B.

Figure 12 shows a relation between NOx formation and cetane number. Fuels with low cetane number, i.e., with high ignition delays and high amounts of energy released in the premixed combustion phase, have higher levels of NOx in their gaseous emissions. This fact corroborates the aforementioned statement, in order to avoid mixtures that greatly diminish such a fuel quality parameter.




(a)

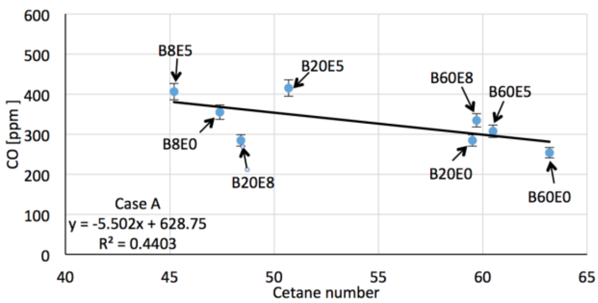



(b)

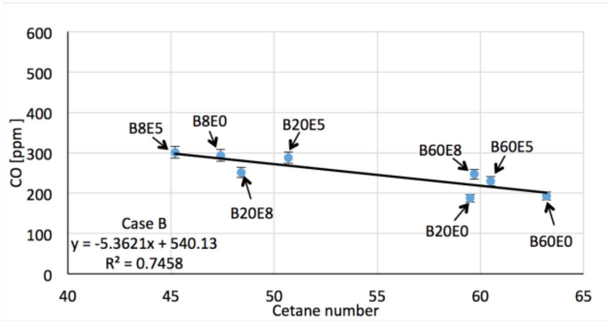
Figure 12 - Relation between NOx and cetane number for (a) Case A and (b) Case B.

### 5.2. CO emissions

The concentration of carbon monoxide (CO) in the CFR engine exhaust is shown in Fig.13 as a function of the mixture cetane number. Results show lower CO concentrations in the exhaust gas for fuel mixture with higher cetane numbers. This behavior is expected because an increase in the cetane number is associated with a better quality of the fuel combustion process.




(a)




(b)

Figure 13 - Relation between CO and cetane number for (a) Case A and (b) Case B.

### 5.3. $CO_2$ emission

Results depicted in Fig. 14 show that the cetane number has little influence on the formation of $CO_2$ for the analyzed mixtures. With respect to $CO_2$ emissions, these are associated to the quality of the combustion. As the concentration of ethanol increases, for a fixed amount of biodiesel, a decrease in the cetane number occurs, since ethanol has an extremely low value for this quantity.

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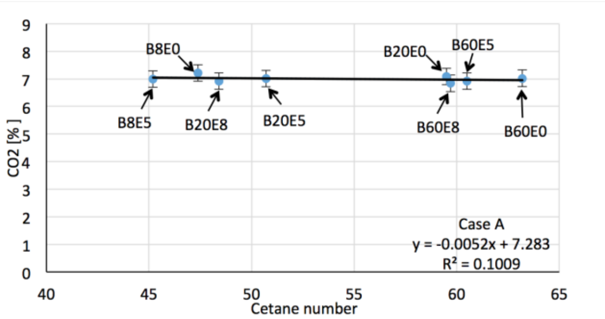
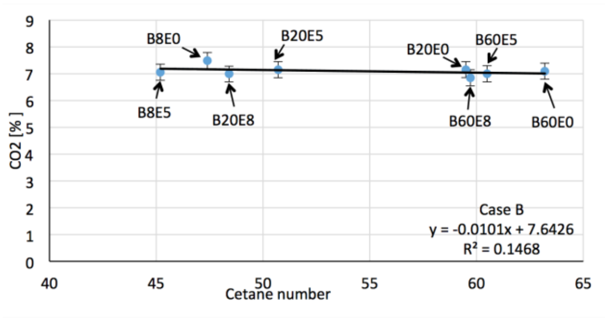



(a)




(b)

Figure 14 - Relation between CO2 and cetane number for (a) Case A and (b) Case B.

Thus, increasing the concentration of ethanol in the mixture could cause a less efficient combustion and a reduction of the $CO_2$ concentration is expected. On the other hand, the insertion of biodiesel contributes positively to the increase in the cetane number and, consequently, a higher percentage of $CO_2$ in the exhaust gases.

## 6. General conclusions

At the end of this paper, the following general conclusions can be drawn:

1. The introduction of ethanol in ternary blends results in a reduction of cetane number (Fig. 1), increasing the ignition delay (Fig. 3), the maximum rate of heat released (Fig. 7), the maximum pressure in the combustion chamber (Fig 4) and the NOx levels (Fig. 10).
2. The use of biodiesel in ternary mixtures tends to soften the adverse effects of ethanol addition in simple binary mixtures, due to the high value of biodiesel the cetane number.
3. An increase in the compression ratio causes a reduction in the ignition delay (Fig. 3), a decrease in the maximum rate of heat released (Fig. 7), an increase in the maximum pressure (Fig. 4), an increase in the combustion efficiency (Fig. 9) and an increase in the indicated efficiency (Fig. 10).

4. The decrease in the maximum rate of heat released (Fig. 7) causes an increase in the duration of combustion (Fig. 6) since more fuel is burned in the diffusive (slow) phase. This fact is also observed with the decrease of ethanol concentration in the blend.
5. Although fuels with a high concentration of ethanol generate less indicated work by the engine (due to its lower heating value, according to Table 1) for a same amount of biodiesel (Fig. 2), the ratio between the energy released by the fuel and the total energy increases, making its indicated efficiency slightly higher than fuels with less ethanol (Fig. 10). The same behavior is observed for the combustion efficiency (Fig. 9).
6. The value of the mean effective pressure for engines operating with fuels containing higher ethanol levels (for the same biodiesel concentration) is lower, indicating a lower amount of work generated by total displaced volume.
7. It was not possible to establish a clear relationship for the influence of ternary mixtures on CO and $CO_2$ emissions.
8. It was not possible to obtain definitive conclusions regarding the variation of the compression ratio in the emission levels of pollutants, requiring further studies to better understand the results.

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