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VISUALIZATION OF LUMINOSITY VARIATION IN THE COMBUSTION CHAMBER OF A DIESEL CYCLE ENGINE USING HIGH SPEED VIDEO CAMERA

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Abstract. *The investigation of using biodiesel and diesel blends in internal combustion engines is crucial, as it can help reduce dependence on fossil fuels and mitigate negative environmental impacts by reducing emissions of polluting gases. In this work, experimental evaluations of the use of biodiesel and diesel blends in a Diesel cycle engine were presented. During the experiment, combustion was monitored using a high-speed camera and an endoscope, which was inserted into a viewing window. The cycles were recorded as photographs taken at intervals of 2.5° of the crankshaft angles, with numerical values assigned to each pixel based on an RGB scale. Inside the combustion chamber, only the luminosity resulting from combustion process was present. Therefore, all observed luminosity was attributed to the combustion flame. The images were processed using Davis® software, and the weighted average of the pixel values was calculated, representing the luminosity inside the combustion chamber at a specific moment of the cycle. Comparisons were made between images obtained with 100% biodiesel (B100) and a mixture containing 10% biodiesel in diesel (B10) under varying loads. The collected data formed luminosity graphs in relation to the crank angles, which were parameterized based on the highest image value generated in the tests. The results showed that, for both fuels, the luminosity inside the combustion chamber increased with increasing load and flame duration under the same pressure, indicating a longer duration of luminosity inside the combustion chamber.*

Keywords: *High Speed Video, Camera, Combustion Engine, Combustion Analysis, Biodiesel, Diesel*

1. INTRODUCTION

Internal combustion engines are used in various applications, such as industrial, power generation, and transportation. Due to their complexity, it is crucial to understand their characteristics and behavior for optimal operation. Internal measurements are used to determine important parameters such as pressure, temperature variation, injection time, and heat release rate. One possible method to observe phenomena inside the combustion chamber during fuel burning is through visualization using endoscopy. Initially developed for medical purposes in 1806, the endoscopy technique involved visualizing the interior of the human body using a light conductor. During World War II, a new type of endoscope was developed and utilized for industrial applications to inspect the insides of large machines. Over time, this technique has been adapted for use in internal combustion engines to provide real-time diagnostics of combustion, mixture formation, and spray characteristics. The applicability of endoscopy is feasible by making appropriate modifications to the cylinder head of compression combustion engines, which allows access to the combustion chamber with minimal disturbance. Endoscopy is currently employed for observing and controlling emissions, particularly for analyzing the spatial distribution of soot inside the combustion chamber and measuring flame temperature, among other applications (AGARWAL; AGARWAL; SINGH, 2015; AGARWAL; JIOTODE; SHARMA, 2019).

However, the endoscopic viewing method presents challenges related to line of sight, which can vary depending on how the equipment is installed on the engine. Consequently, optical access is often limited and not necessarily orthogonal to the spray axis. Furthermore, the visualization window needs frequent cleaning due to the accumulation of soot, which can potentially interfere with the accuracy of results. Additionally, certain applications of endoscopy rely on external light sources. (YUAN et al., 2022).

This work seeks to contribute to the advancement of combustion visualization techniques and analysis of phenomena that occur during the burning of different types of fuels, with analysis of combustion characteristics in the captured images, although it is still a preliminary investigation of the usability of this method for measurements, and it would require further

investigation in future works to verify variable could be measured. In the case of this current work, the fuels used are pure biodiesel and a mixture of diesel and biodiesel, the latter at a rate of 10% of the mixture. And the method chosen for this is visualization by endoscopy in an engine-generator group under different workloads. According to Sirohi (2009), optical measurement methods are non-invasive and do not require physical contact. From the tests implemented and with the post-treatment of the images, it is possible to identify the quantitative relationship between the temperature distributions inside the combustion chamber (FERREIRA, 2021).

2. COMBUSTION AND ITS VISUALIZATION

The combustion is an exothermic chemical reaction that occurs in a short period, resulting from the oxidation of fuel by an oxidant. This reaction releases energy through heat and often light (MUKHOPADHYAY; SEN, 2019).

In internal combustion engines, combustion may involve premixed or non-premixed flames (diffusion flames). The flame represents a thin zone where the chemical oxidation reactions occur with high intensity. In the case of a spark-ignition engine, a premixed flame occurs. In this type of flame, the fuel and the oxidizer are mixed at a molecular level before the chemical reaction starts, and the flame propagates through the mixture, separating the already burned part from the unburned part. On the other hand, in a compression ignition engine, a non-premixed flame occurs. In this type of flame, the fuel and oxidizer enter the combustion chamber separately, and the chemical reactions take place at the interface of the respective regions where they come into contact. (TURNS, 2013).

According to Heywood (2018), the fuel flow into the combustion chamber is turbulent, therefore, its combustion essentially occurs as an unstable diffusion flame. That said, the analysis of the physical description of the flame is usually done in laminar flames, due to the difficulties of the physical study of a turbulent flow.

Turns (2013) presents the characteristics of a non-premixed jet flame. According to the author, as the jet is injected into the chamber, the fuel flows along the axis of the flame and is then diffused radially outwards, while the oxidizer is diffused radially inwards. The flame surface occurs at the point where the fuel and oxidant are in stoichiometric proportion, that is, at the point where the equivalence ratio, Φ , is equal to 1. Figure 1 shows the structure of the flame, as well as its length L_f .

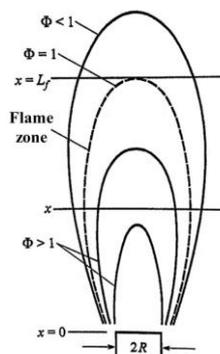


Figure 1 - Structure of a non-premixed laminar flame. TURNS (2013)

2.1 Biodiesel

Biodiesel is a renewable alternative to diesel fuel from biomass. The use of this type of fuel has grown due to its environmental benefits. It is obtained through the transesterification of the chemical structure of animal or vegetable fat molecules, or through the esterification of the fatty acids of these molecules. For a more suitable fuel, vegetable oil fat molecules are used (BRUNETTI, 2018).

Some of the advantages of using biodiesel are the following: it is not necessary to modify the engine to use this fuel and it has a greater specific mass than diesel oil, therefore, the same volume injected into the chamber corresponds to a greater mass of fuel. In addition, its cetane number is higher than that of the diesel oil and, as it is an oxygenated compound, the formation of CO and particulate matter is reduced (BRUNETTI, 2018).

2.2 Visualization by endoscopy

According to Agarwal, Agarwal and Singh (2015), for a real understanding of certain combustion characteristics that vary in time and space, such as flame temperature or soot distribution, a direct visualization of the combustion inside the combustion chamber is necessary. This visualization can be achieved by using an endoscope.

The endoscopy technique was initially developed for use in medicine, but its use has been extended to visualization and diagnosis of combustion in extreme conditions, such as in internal combustion engines (AGARWAL; JIOTODE; SHARMA, 2019). During World War II, Karl Storz developed a new model of endoscope to be used in industrial

applications, performing diagnostics inside large machines. The technique then began to be used in engines (AGARWAL; AGARWAL; SINGH, 2015).

Endoscopy visualization can be used in engines for the following applications: investigation of particle formation inside the combustion chamber (AGARWAL; JIOTODE; SHARMA, 2019); investigation of spray formation and mixtures, evaluation of piston temperature, gas flow pattern, flame propagation (AGARWAL; AGARWAL; SINGH, 2015); investigation of fuel injection and airflow parameters during admission (JIOTODE; AGARWAL, 2016).

3. EXPERIMENTAL METHOD

The company LaVision provides image capture systems for applications in the fields of fluid mechanics, combustion and diagnostics of sprays and particles (LAVISION GMBH, 2022). This work uses the DaVis 8 software, from LaVision, to carry out the necessary analyzes of the images obtained from the combustion inside the cylinder.

The software measures the color intensity value in the pixel and applies it within a chosen scale. A spreadsheet view option, as shown in Figure 2, displays the intensity values for each pixel in the image. As observed, the darker pixels have lower values than the lighter ones. When the analyzed image is in color, each of the red, green and blue color components of the RGB scale are classified within the scale (LAVISION GMBH, 2015).

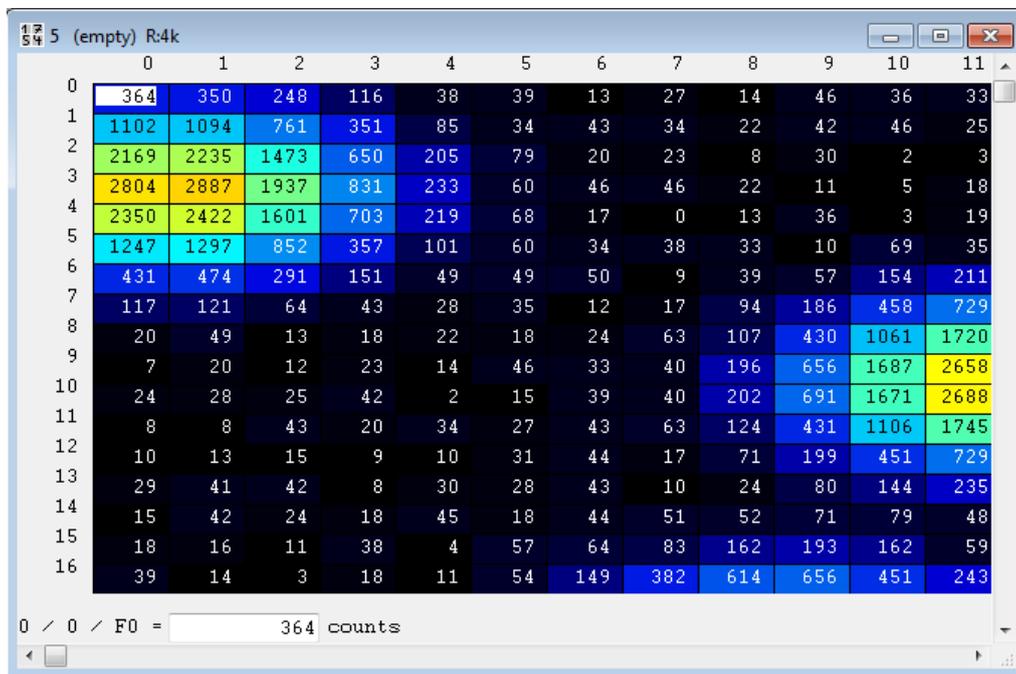


Figure 2 - Visualization of the spreadsheet of pixels and their intensities

The software is also able to calculate the average of the luminosity intensity of the image, through the intensity values of each pixel. With the average intensity value, the standard deviation of the intensities in the complete image is calculated, and the result is a scalar value. This value will represent the intensity of the entire image (LAVISION GMBH, 2015).

Figure 3 presents the block diagram of the experimental apparatus, showing all the stages used for conducting the tests.

For the experiments, an engine-generator was used, which is an instrumented system, and it is integrated with the LabVIEW software. This integration allows the user to observe in real time the measurements made on the engine. The high-speed camera, the PTU-X module and the DaVis software make up the visualization system, responsible for collecting the images. This system is synchronized with the engine-generator through a microcontrolled central (FERREIRA, 2021).

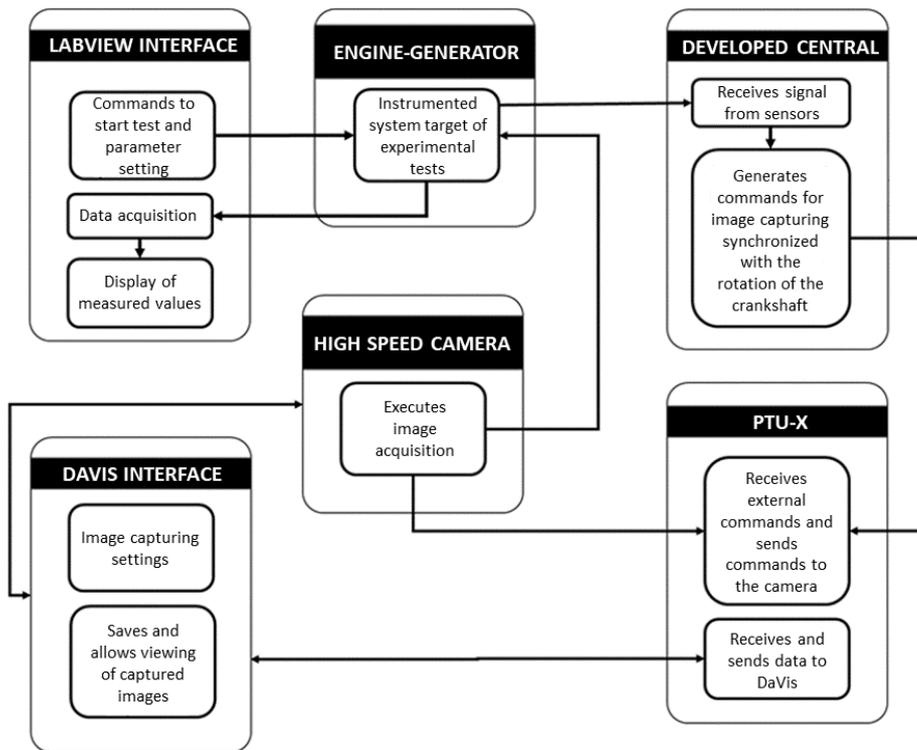


Figure 3 - Block diagram of the experimental apparatus. FERREIRA (2021)

Figure 4 illustrates the general layout of the visualization system integrated into the engine-generator configuration.

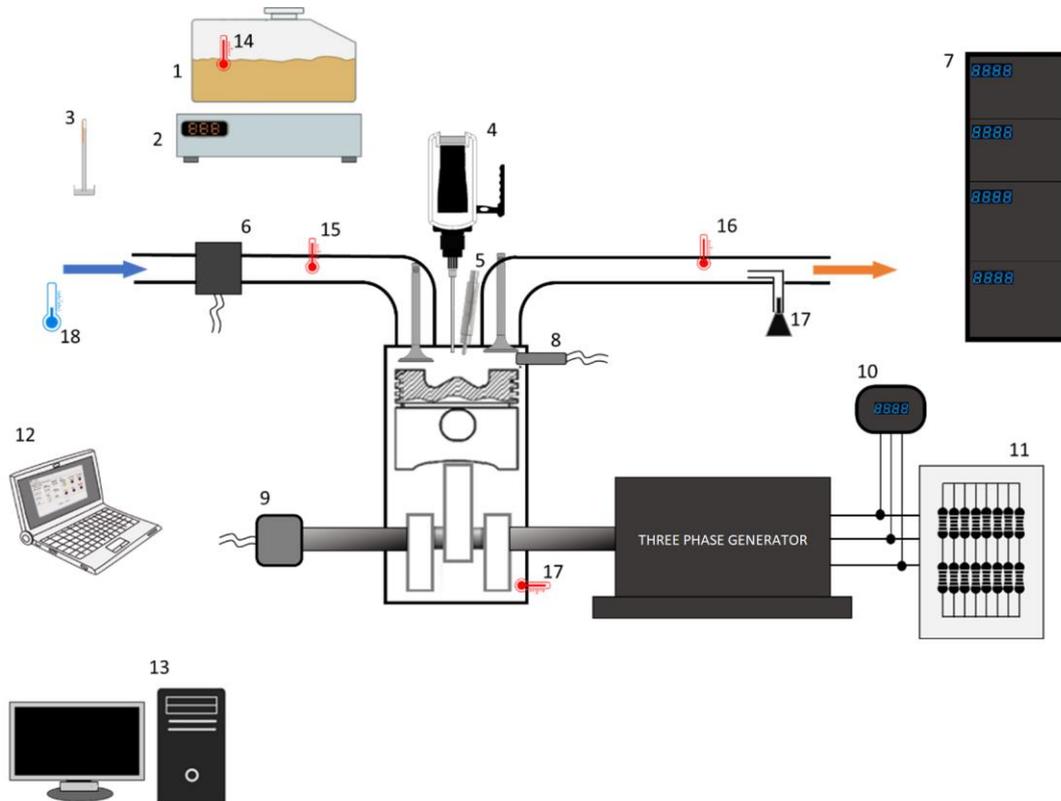


Figure 4 - General diagram of the visualization system and engine-generator. FERREIRA (2021)

Table 1 presents all the equipment used for conducting the tests, as shown in Figure 4.

Table 1 - Identification of the installed components

1	Fuel tank	11	Resistors bank
2	Scale	12	Computer and data acquisition system for the camera
3	Mercury barometer	13	Computer and data acquisition system for the motor-generator
4	High speed visualization system	14	Fuel temperature sensor
5	Fuel injector	15	Intake temperature sensor
6	Flow sensor	16	Exhaust temperature sensor
7	Gas analyzer	17	Crankcase temperature sensor
8	Pressure Sensor	18	Opacimeter
9	Encoder	19	Thermo hygrometer
10	Electric power measurer		

The high-speed camera used was a Phantom, model v611. Its capture rate can vary from 6,242 to 680,000 fps, depending on the image resolution. It communicates with the computer via Ethernet. A Nikon 50 mm lens was connected to it. To capture images inside the combustion chamber, the endoscope was attached to the camera. The endoscope used was a LaVision, with the code 1108770, equipped with an 8 mm diameter lens, while the tube length ranged from 214 to 220 mm. Figure 5 illustrates the positioning of the camera with the adaptation made by FERREIRA (2021). This adaptation included a support structure with a quartz lens inserted inside the head cylinder. The quartz lens enabled the visualization of the combustion chamber's interior without direct contact between the gases inside the cylinder and the endoscope. Additionally, a compressed air system was connected to the support structure, with an outlet to the atmosphere, which provided cooling for the endoscope.

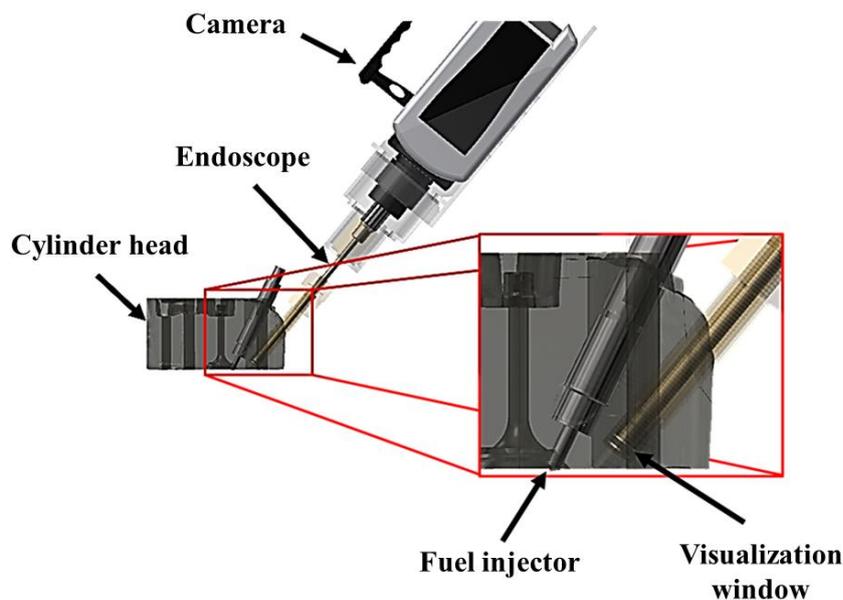


Figure 5 - Camera and endoscope placement. FERREIRA (2021)

Data collection on the engine was carried out following the ABNT NBR 6396 standard, which standardizes the procedures for testing non-vehicular internal combustion engines. Standard atmospheric conditions are defined by ISO 15550.

The engine tests were conducted using B10 (a mixture of 90% diesel and 10% biodiesel, a commercial fuel in Brazil) and B100 fuel. For the tests using B100 fuel, Macaúba biodiesel, derived from a native palm tree in Brazil, was utilized (pure Macaúba biodiesel). The system was tested with these two fuels across power loads ranging from 0 to 32.5 kW, at a fuel injection pressure of 450 bar, and a crank angle of -23° .

4. RESULTS

After performing the tests, each captured image was quantified based on the intensity of colors in the photos. This allowed the establishment of a luminosity ratio using the method defined by the standard deviation, as described in the methodology. The luminosity was then parameterized in relation to the highest measured value. This step was taken to mitigate the effects of accumulated dirt on the observation lens during tests with different fuels. Therefore, the analysis of results presented in this work will be related to the results obtained when the same fuel is used, as well as the combustion behavior observed during the tests. The layout of the Davis software, including an image capturing a moment of combustion, can be seen in Figure 6, along with the measured luminosity peaks observed throughout the cycles, as well as the luminosity peaks measured throughout the cycles. Ten cycles were measured per test under each power load, and their average was calculated. The average cycle for each power load was used to obtain the curve of luminosity variation.

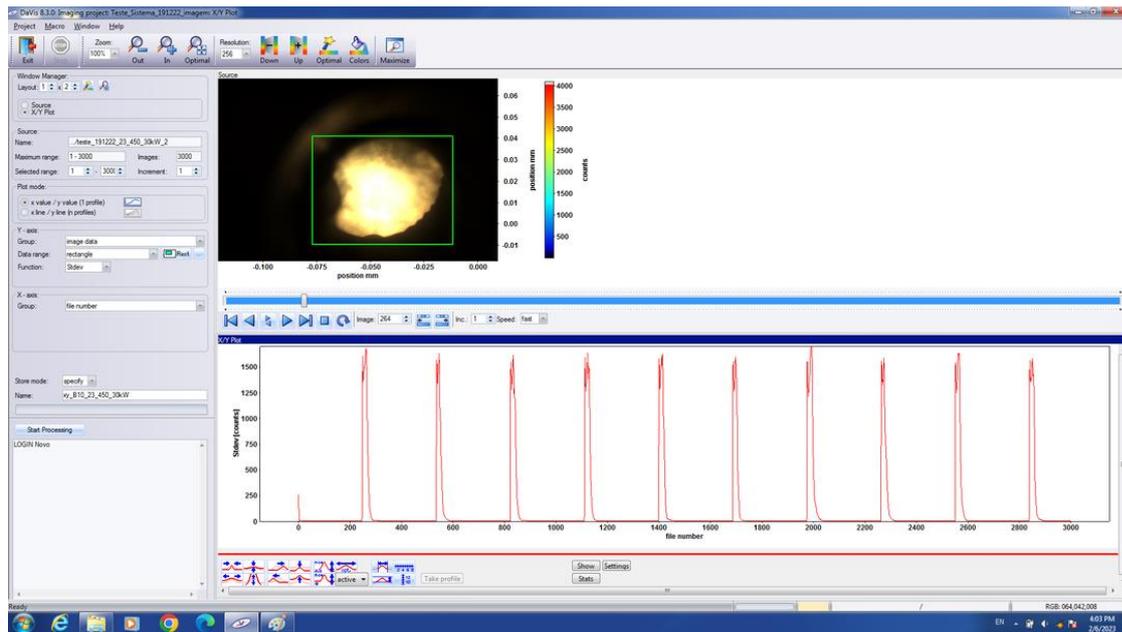


Figure 6 – Combustion visualization screen and graphical numerical results

The luminosity curves were then obtained based on the combustion behavior observed when the engine used each of the tested fuels. The comparison presented in this work is focused on the variation of power loads during engine operation. Figure 7 shows the luminosity curves using a B10 fuel. It is observed how the luminosity increases as the loads are raised. This happens because under higher loads the engine needs to do more work to keep functioning. It is evident how, at low loads, almost no luminosity is obtained, as the operation takes place well out of the working range of the engine. According to other tests performed previously on that same engine, the highest efficiency is obtained using loads above 25kW.

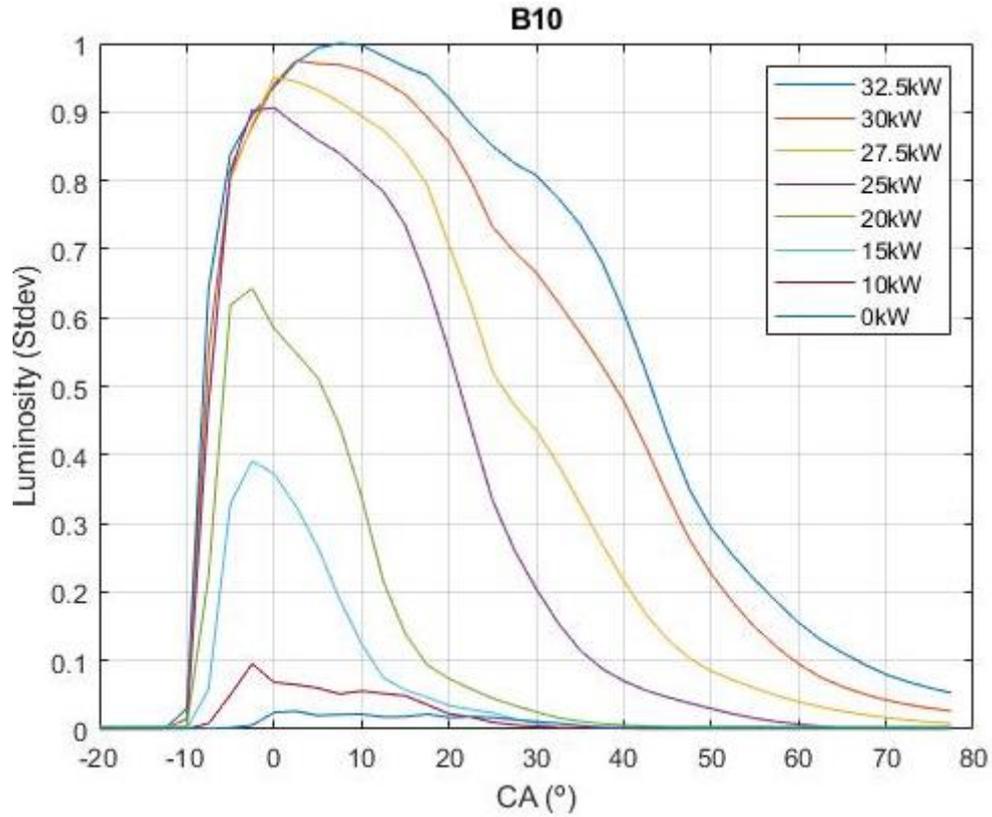


Figure 7 – Luminosity obtained from tests with B10 fuel

Figure 8, which presents the luminosity obtained during the tests using pure biodiesel (B100), shows a similar behavior to that obtained with B10. This indicates that, under higher power loads, the combustion duration is longer. Furthermore, comparing the combustion times, it is observed that pure biodiesel combustion exhibits prolonged intensity compared to B10.

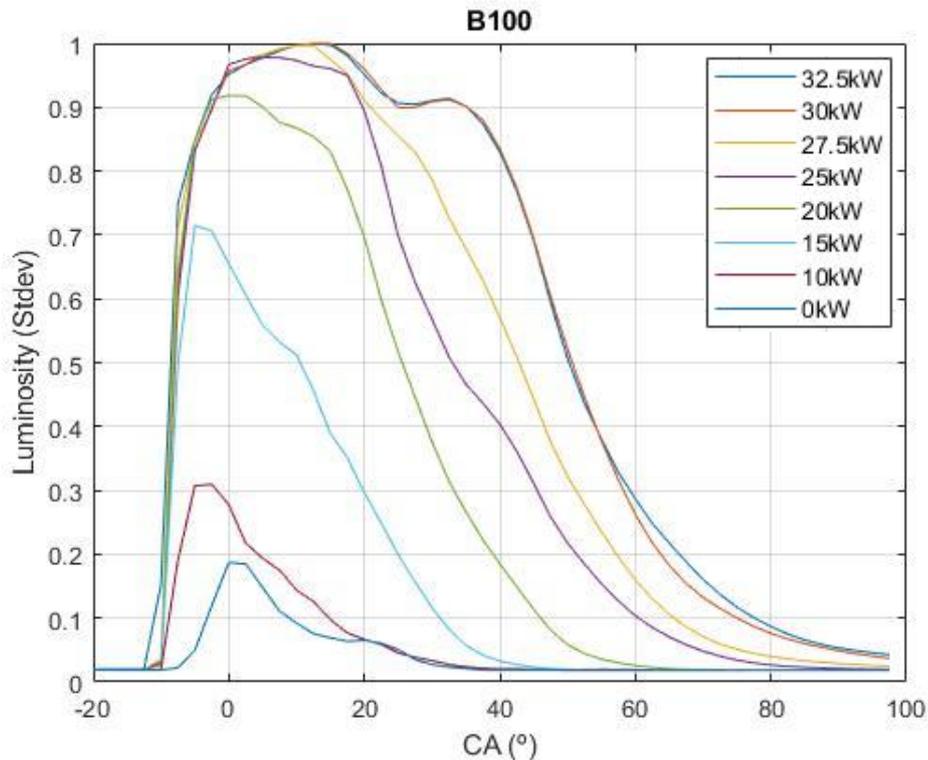


Figure 8 – Luminosity obtained from tests with B100 fuel

Another observation from Figure 8 is that it can be observed that biodiesel demonstrates better performance at lower loads, as there is a higher intensity in combustion, albeit small, up to a load of 20 kW. This observation is depicted in Figure 9, where the graphs were plotted at higher loads, indicating improved engine performance. Upon further analysis of this figure, it can be observed that, when keeping the same injection moment for both tests, the moment when combustion initiates can be considered the same for both power load conditions.

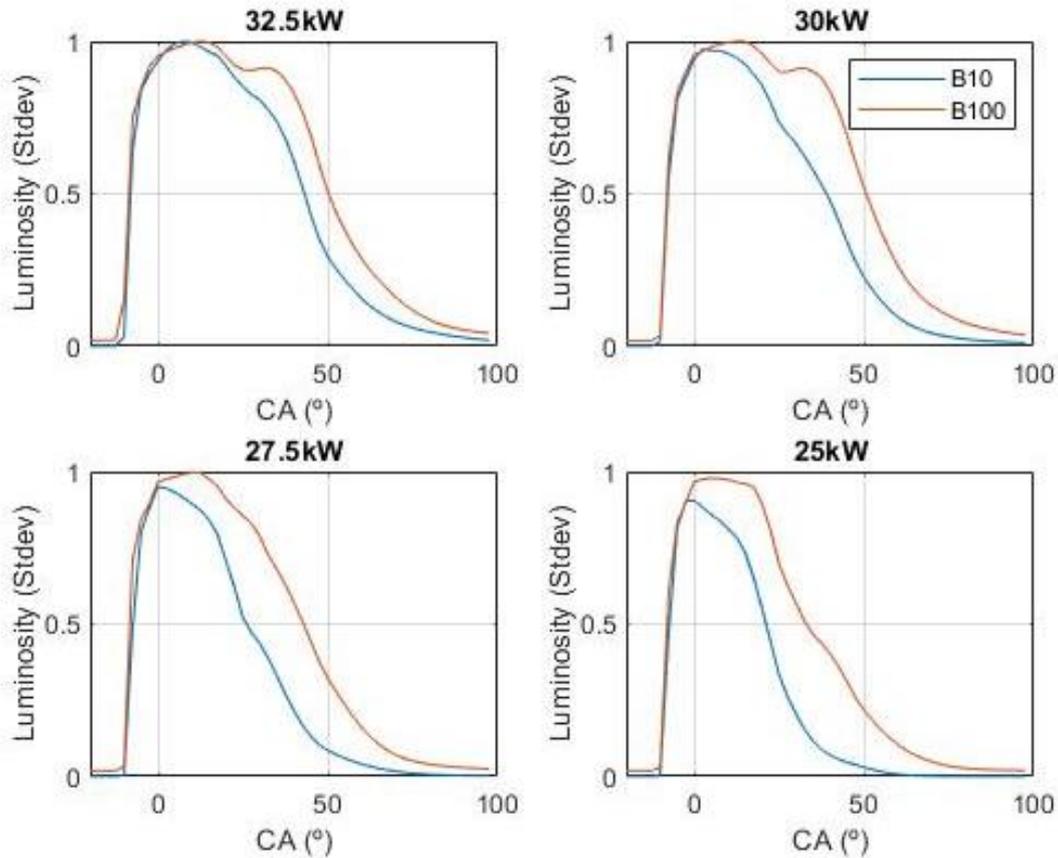


Figure 9 – Comparison of tests between B10 and B100 at the highest power loads

5. CONCLUSIONS

The results indicated that, for both fuels, at the same pressure, the luminosity inside the combustion chamber increased with higher power loads and longer flame duration. This means that the duration of visible combustion inside the chamber was also longer. The greater intensity of combustion observed with pure biodiesel compared to the diesel-biodiesel mixture may be attributed to the size of the carbon chain in pure biodiesel. This work contributes to the analysis of images in a graphical and numerical way, along with the observation of combustion inside an internal combustion engine, through the development of a visualization window. This is the first part of an investigation involving flame visualization through endoscopy, and how it could be used to measure variables during combustion. The feasibility of the method was verified, since it is possible to observe the variation of luminosity in different combustion conditions. In future works, it will be attempted to correlate the variation of luminosity to the variation of other variables.

The data were parameterized to ensure a valid comparison between the tested systems. This was necessary because dirt on the filming lens during the tests could interfere with the amount of light reaching the camera sensor. This is a factor that can be addressed and improved in future works.

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8. RESPONSIBILITY NOTICE

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