THE INVESTIGATION OF IGNITION DELAY TIMES OF T-FUEL AND U-FUEL MIXTURES USING SHOCK TUBE WITH FLAME DETECTION

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ABSTRACT

The ignition delay in a diesel engine is defined as the time interval between the start of injection and the start of combustion. One of the techniques used to study the delay times in combustion ignition engines is the simulation of the phenomena in shock tubes. The dependence of the ignition delay time of fuels, and especially between mixtures of different fuels can be systematically studied as a function of fuel composition, temperature, and pressure. In this work a series of shock-tube experiments were undertaken to determine the ignition delay times for different mixtures of fuels. The effects of blending T-fuel and U-fuel on the ignition delay time using shock tube with flame detection were studied. Different mixtures of T-fuel and U-fuel in concentrations of 25%, 45%, and 75%, in addition to pure T-fuel and U-fuel were used. The results showed that mixtures with higher concentrations of T-fuel have lower ignition delays. Additionally, it was observed that the time interval between the beginning of the shock wave and the detection of the flame time is higher in mixtures with a higher proportion of U-Fuel, since the ignition delay time is greater in fuels with lower cetane number.

INTRODUCTION

The shock tube is a tool for the study of compressible flows, widely used in the fields of engineering, such as aeronautics, and combustion. Early studies using a shock tube dating from the late nineteenth century. Generally constructed of metal, the shock tube is defined by the union of two chambers separated by a diaphragm, which separates the high pressure section, called conductive, and a low pressure section, called driven section. The main objective for using shock tube is to produce shock wave that is originated when the diaphragm is broken by the pressure difference between the two sections. In this case, the shock wave travels from the conductive section to the driven section [1-5,10,12].

In combustion studies, the fuel to be studied is injected into the end of the driven section, which ignites due to the pressure resulting from the shock wave formed in the tube, since the temperature and the air equivalence ratio have suitable values [6-8].

It is observed in the literature that there is great interest in the combustion tests of the air-fuel mixture, since its characteristics directly influence the efficiency, power and volume of the engine pollutant emissions [6,7]. Moreover, about 80% of world energy comes from burning fuels of fossil origin [7].

A parameter that establishes the quality of a fuel is the cetane number, that provides a measure of the ignition characteristics of diesel fuel oil in compression ignition engines. A fuel having a cetane number accepted as the reference value, typically in the range of 73-75, said T Fuel, and a fuel with reference value between 20 and 22, said U-Fuel, can be used as secondary reference of cetane number.

According to [17], a standard method is used to determine the rating of diesel fuel oil in terms of an arbitrary scale of cetane numbers using a standard single cylinder, four-stroke cycle, variable compression ratio, and an indirect injected diesel engine.

The cetane number is inversely related to ignition delay of the fuel within a diesel engine, i.e., the higher the cetane number, the shorter the ignition delay. Usually the tests to obtain the cetane number for different fuels are conducted in CFR engines - Cooperative Fuel Research [6-9]. Fuel T-fuel standards and U-fuel are used as parameters in CFR engines, since both have known cetane numbers. Thus, the determination of cetane number of a test fuel is made in comparison to the values obtained with the standard fuel. The T-combustible fuel has higher cetane number of the U-fuel, and as consequence, the ignition delay T is less fuel-between. [10,11].

This ignition delay is an important parameter for determining the quality of fuel combustion, and for this reason the use of shock tube is important to quantify this phenomenon [1-5,6, 8].

The overall objective of this paper is to describe the operation of a shock tube for the measurement of delays ignition of different fuels using pressure sensors and sensor flame detector.

An experimental study of ignition delay mixtures of methane and hydrogen were conducted by [10]. The authors concluded that the ignition delay of the mixture CH4 / H2 decreased with the increase of the fraction of hydrogen. The ignition delay using 20% of H2 and 80% of CH4 was equal to one third of the delay found for the pure methane. Subsequently the same authors used the shock tube to determine if the ignition delay depends on the ratio of temperature, pressure, equivalence ratio within the tube [11].

Herzler et al. [12] did experiments to study the ignition delay of the mixture "n-heptane-air" with equivalence ratios between 0.1 and 0.4 at temperatures between 720K and 1100K using photoluminescence, at pressures of about 50 bar. It was observed that ignition occurs at the center of the shock tube from the image taken into the tube. At high temperatures the ignition occurs in two stages because there is pre-ignition. For smaller equivalences, the ignition delay increases because the activation energy decreases with decreasing temperature.

Saleh [13] used mixtures of diesel and biodiesel in their studies of ignition delay, and concluded that the air-fuel ratio influences the ignition delay, and this delay depends on the temperature in the tube.

In a recent study, a shock tube was used for the study of chemical kinetics in the ignition of oxygenated fuel TPGME (tri-propylene glycol monomethyl ether) [13]. This compound is an important fuel additive used to reduce soot in diesel engines, however, heretofore not had experimental data to validate the compound. The authors also implemented a mathematical model, which was compared with the experimental data.

The ignition delay experiment was defined as the time difference between the arrival of the reflected shock wave on the wall and the peak pressure of the shock wave. The results indicated that the sensitivity of the additive at different equivalence ratios and pressures produces significantly less soot that n-heptane. This comparison was made because both have almost the same cetane number, and similar properties of ignition.

Zhukov et al. [14] measured the ignition delay of kerosene and air mixtures in the shock tube. The temperature in the tube was controlled at 150° C to ensure homogeneity of the fuel mixture. A radiation laser system was used to measure the ignition delay from the emission of OH and the absorption of He-Ne.

NOMENCLATURE

P	[Pa]	Pressure
c	[m/s]	Velocity of sound
k	[-]	Specific heat ratio
R	[kJ/kg.K]	Gas constant
T	[K]	Temperature
Ma	[-]	Mach number of the shock wave
Special characters		
ρ	[kg/m^3]	Specific mass of the gas
Subscripts		
1		Properties of the conducted section
4		Properties of the flow before the shock wave
s		Shock tube
High		High pressure
Low		Low pressure

FUNDAMENTAL CONCEPTS

Generally the shock tube is composed of two sections separated by a diaphragm. In one section there is a high pressure caused by an inert gas (called driver section) and the other section, called driven section, usually has atmospheric pressure and ambient temperature. In this section the fuel is injected.

A shock tube has usually cylindrical cross-section in which a transverse diaphragm separates two masses of gas initially at rest [5]. One mass is at high pressure and is considered the driver section of the tube. The other mass, called the driven section, is at low pressure and forms the ignitable mixture of interest.

The diaphragm usually is burst by exceeding its structural strength through over-pressurization of the driver section. Also according to [5], this action sends a strong shock wave into the low pressure section increasing the static pressure and temperature of the mixture.

The diaphragm is generally metallic, and its thickness and composition are determinant and directly correlated with the maximum pressure that can be obtained before its breaking. A diagram of the shock tube is presented in Figure 1.

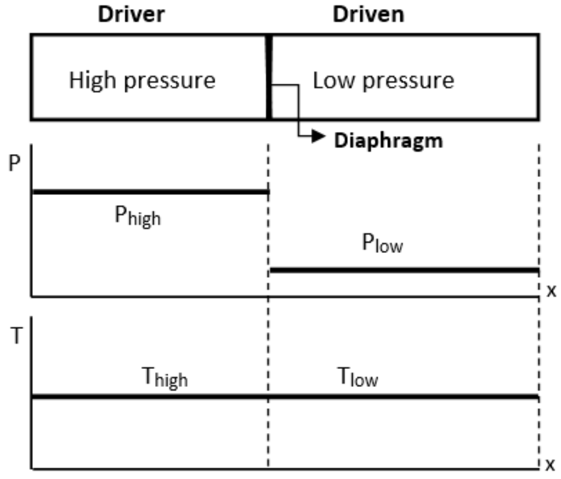

Figure 1 – Diagram of the shock tube [15]

In general the equations used to determine the parameters in shock tube consider an ideal gas, a constant specific heat, compressible flow in one direction, and steady state conditions. The ideal gas is represented by Equation 1:

$$P = \rho.R.T \tag{1}$$

The velocity of the sound inside the sock tube is given by Equation 2.

$$c = \sqrt{kRT} \tag{2}$$

After the diaphragm breaking, the shock wave travels toward the driven section.

Once the diaphragm is broken, the shock wave travels through the tube toward the driven section. In this case, four different regions with different temperature and pressures can be considered. These regions can be observed in Figure 2.

However, it can be considered that there are two gas states in the tube: one before and another after the diaphragm rupture. After the rupture, the state of the gas can be divided into at least four regions of different temperatures, pressures, densities and specific heats. This division can be observed in Figure (2).

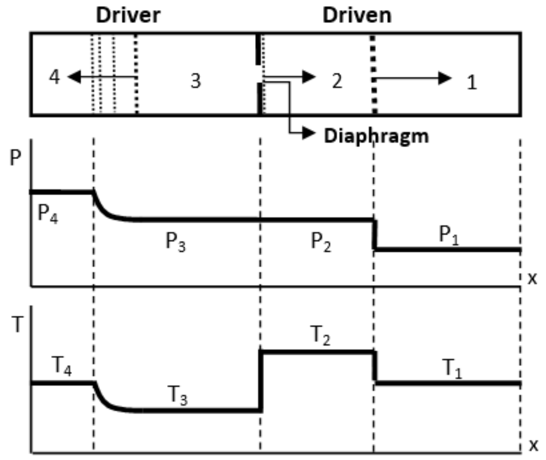

Figure 2 – Conditions after diaphragm breaking [8]

The shock wave travels through the driven section changing the pressure, the temperature and the air density. Consequently, an expansion wave is created and travels toward the driver section.

According to [8], the Mach number in the shock tube is determined by the Equation (3) and Figure 2.

$$\frac{P_4}{P_1} = \frac{k_1-1}{k_1+1}\left[\frac{2k_1}{k_1-1}Ma_s^2 - 1\right]\left[1 - \frac{\frac{k_4-1}{k_4+1}\left(\frac{c_1}{c_4}\right)(Ma_s^2-1)}{Ma_s}\right]^{\frac{2k_4}{k_4-1}} \tag{3}$$

The Flame

Flame is the result of the combustion of a gas. It can be visible or not, or may or not be luminous. The bright light occurs due to the presence of carbon particles during the combustion process.

The flame itself has four distinct areas: the inner zone that is dark, formed by a mixture of air and unburned gas, which has not reached the temperature of combustion. Following there is the region called blue zone, where there is a complete combustion of fuel, producing carbon dioxide and water. The third region is called the “reducing zone”, the brightest part where there is the decomposition of the fuel due to the amount of heat. The last region is called the oxidant zone area outside the flame, which comes into contact with atmospheric air, where the products obtained in the reduction zone burn easily, forming carbon dioxide and water [15,16].

Ignition delay

In diesel engines the temperature of the intake into the cylinder is greater than 500 ° C after being compressed. The fuel is injected into the combustion chamber to ignite. The time between the fuel injection and the start of combustion is called ignition delay. This delay gives information on the ignition quality of the fuel, that is, the shorter the delay, the better the quality of the combustion [6, 16].

This delay is because of the phenomena that must happen before combustion and is due to physical causes - time required for the spray fuel occurrence, the type of atomization of the jet, the vapor mixing time of fuel and air. Also should be considered, the heating, the evaporation of the fuel, and finally the chemical reactions that occur between the fuel and the air before combustion [6-9].

If the delay is too long, there is an accumulation of unburned fuel in the chamber. By this time, there is already a quantity of fuel in the combustion chamber, which will ignite first in areas of greater oxygen density before to the combustion of the complete charge. In this case, some auto-ignition can happen and the formation of pollutants can happen.

The cetane number (CN) indicates the ignition quality of the fuel. This number is obtained in standardized tests, and correlates the ignition delay with it. The higher the cetane number, the shorter the ignition delay and the higher the quality of the fuel. The lower the cetane number, the greater the ignition delay and the worse the quality of the fuel [8].

EXPERIMENTAL METHODOLOGY

The tests were conducted in a shock tube made with stainless steel, 6m long, 97.1 mm of inner diameter and 17.2 mm of thickness. The diaphragm was located exactly at the middle of the pipe. Figure 3 shows a schematic of the shock tube with the locations of the pressure and temperature sensors.

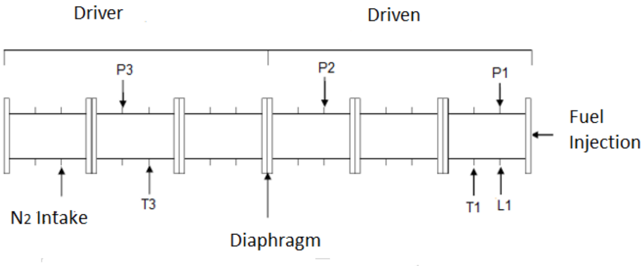

Figure 3 – Schematic of the shock tube

The temperature at the driver section was measured with an analogic sensor with the following characteristics:

- Calibrated directly in Celsius;
- Linear with scale factor of + 10mV / °C;
- Accuracy of 0.5 °C;
- Measuring range: -55 ° C to 150 °C;
- Operation: 4V to 30V;
- Linearity of ± 0,25ºC.

For the driven section, a PT-100 thermocouple with the following characteristics was used to measure the temperature:

- Measuring range: -270 to 1200 ° C;

- Sensitivity: 41μV / ° C.

Capacitive pressure transducers manufactured by AVL were used in the shock tube. Their characteristics are:

- Measuring range: 0 ... 250 bar; 3625 psi; 25 MPa.
- Nominal sensitivity: 35/2 pC / bar; 2.41 pC / psi; 350 pc / MPa.
- Cyclical temperature deviation: <± 004 / 0.2 bar.
- Load change rate: 1.5 mbar / ms.
- Sensitivity: <2%.

The light sensor consists of a photodiode sensitive to light, which has the following main characteristics:

- Flame detector with wavelength between 760nm-1100nm
- Sensing distance: 20cm (4.8V) ~ 100cm (1V)
- Detection angles up to 60 degrees.
- Operating voltage: 3.3V-5V.
- Analog voltage output inversely proportional to the light.

The T-Fuel and U-Fuel fuel are standard fuels with known cetane numbers. The T-Fuel have high cetane number of approximately 75, and the cetane number for the U-Fuel is about 20. As mentioned before, these fuels are used for calibrating CRF engines of pure or mixed fuels [7, 9].

The following fuel blends were tested in the shock tube:

- T100: T-100% and 0% U-Fuel;
- T75: 75% T and 25% U-Fuel;
- T45: 45% T and 45% U-Fuel;
- T25: 25% T and 75% of U-Fuel;
- T0: 0% T-fuel ratio is 100% U-Fuel.

The following parameters were established for the operation of the system:

- Copper thickness 0.4 mm membranes were used. The breaking pressure of the diaphragm occurred between 35 and 45 bar;
- The temperature in the driven section was controlled between 110 and 115 ° C;
- The amount of fuel injected was determined by the operator, according to the nozzle calibration and a stoichiometric value for the air-fuel ratio. It was established that would be used 500mg of fuel per test;
- The fuel injection trigger was controlled by the operator.
- The tube was completely closed in all tests, providing a volume of control isolated from the external environment.

Two data acquisition system were used in the shock tube for pressure and temperature measurements. Additionally, the pressure pump, and the injector control signal were controlled by another system.

RESULTS AND DISCUSSION

To analyse the operation of the shock tube with the objective to determine the ignition delay of fuel mixtures, the first test was conducted with pure solution of T-Fuel, ie, the standard fuel with higher cetane number. In this case, it is expected the lowest ignition delay time among the tests. Later, tests with blends with T-Fuel and U-Fuel were performed. As previously mentioned, the delay time within the shock tube is considered to be the time of the first increase of the pressure and moment that the flame occurs. The delay time is considered as the interval time Δt represented as the dashed line in the figures.

Figures 4 to 8 show the pressure and flame detection versus time and also the delay time results obtained with the T-fuel mixtures studied.

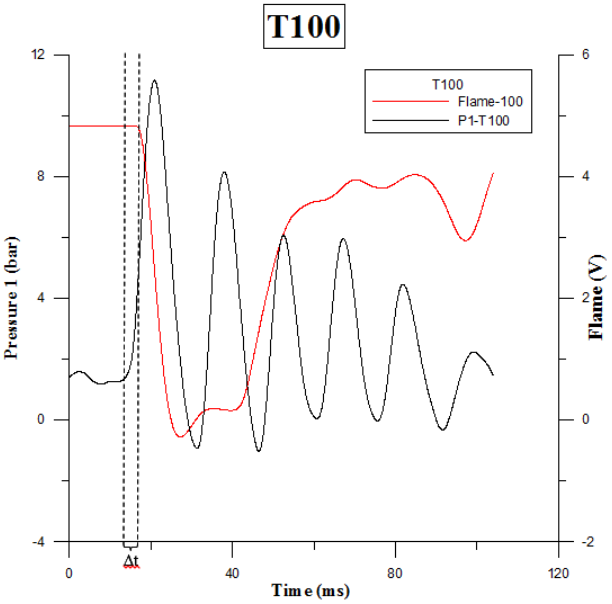

Figure 4 – Pressure and Flame detection versus time (T100)

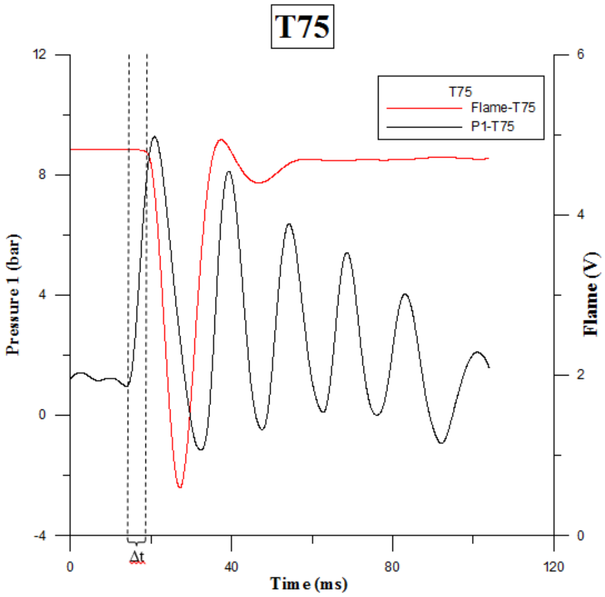

Figure 5 – Pressure and Flame detection versus time (T75)

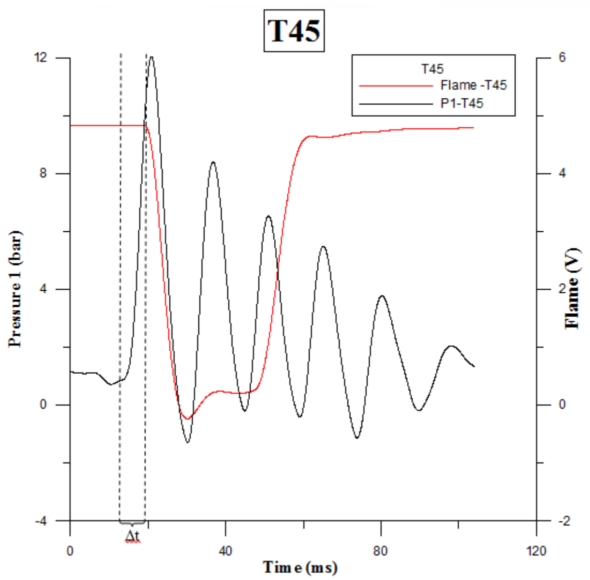

Figure 6 – Pressure and Flame detection versus time (T45)

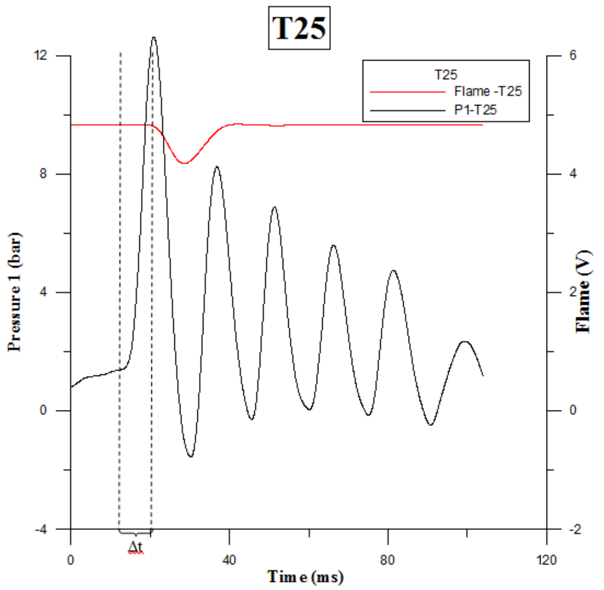

Figure 7 – Pressure and Flame detection versus time (T25)

From the graphics of the Figures 4 to 8 it is clearly observed that with the decrease of T-fuel concentration, the delay time is bigger. This is because that the standard fuel with a higher cetane number, should provide the lowest ignition delay time from the tests. It can be seen from the figures that the shorter time interval is that for T100 fuel. The literature [16] shows that the T-Fuel has high cetane number of approximately 75, and the cetane number for the U-Fuel is about 20.

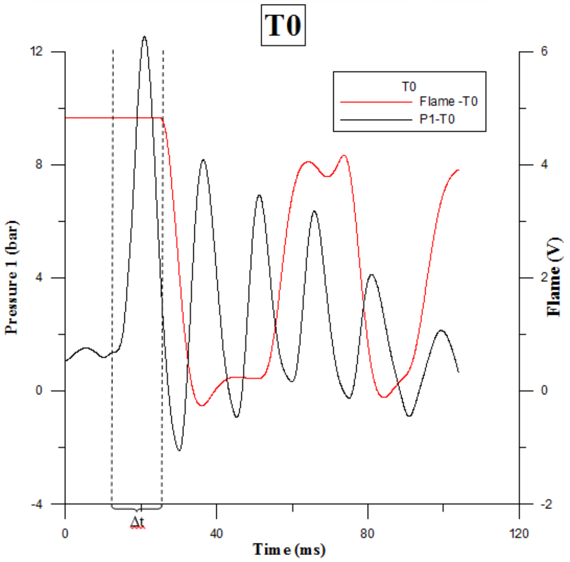

Figure 8 – Pressure and Flame detection versus time (T0)

Flame lifetime represents the time interval from the start of fuel ignition to the instant when flame extinction takes place. It is also noticed that there is an increase of the flame line for all tests, except for the T25. For the other fuel concentrations, it can be inferred that there is a subsequent combustions after the first one.

Table 1 presents the delay time measurements obtained from the tests. As mentioned before, the T100 fuel presents the shorter delay time.

Table 1 – Delay time measurements

Mixtures	Delay time (ms) (± 0.5)
T100	**4,7**
T75	**7,0**
T45	**8,2**
T25	**12,8**
T0	**15,9**

CONCLUSIONS

In the present work an experimental investigation in a shock-tube were undertaken to determine the ignition delay times for different mixtures of fuels. T-fuel and U-fuel in concentrations of 25%, 45%, and 75%, in addition to pure T-fuel and U-fuel were used. From these experiments, the following points have been concluded:

- Mixtures with higher concentrations of T-fuel have lower ignition delays. Additionally, it was observed that the time interval between the beginning of the shock wave and the detection of the flame time is higher in mixtures with a higher proportion of U-

Fuel, since the ignition delay time is greater in fuels with lower cetane number.

- There is a correlation between the cetane number and the measurement of the delay time in the shock tube. The T100 fuel presented the lowest ignition delay time and, according to the literature, has the largest cetane number among the blends of fuels studied.
- The breaking pressure of the diaphragm in the shock tube occurred between 35 and 45 bar;

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REFERENCES

[1] K. Fieweger, R. Blumenthal, and G. Adomeit, Self-ignition of S.I. engine model fuels: a shock tube investigation at high pressure, *Combustion and Flame, 109:599-619 (1997).*

[2] Alexander Burcat, Karl Scheller, Assa Lifshitz, Shock-tube investigation of comparative ignition delay times for C1-C5 alkanes, *Combustion and Flame, 16, 29-33 (1971).*

[3] Ivo Stranic, Deanna P. Chase, Joseph T. Harmon, Sheng Yang, David F. Davidson, Ronald K. Hanson, Shock-tube measurements of ignition delay times for the butanol isomers, *Combustion and Flame, 159 (2012) 516-527.*

[4] B.M. Gauthier, D.F. Davidson, R.K. Hanson, Shock tube determination of ignition delay times in full-blend and surrogate fuel mixtures, *Combustion and Flame, 139 (2004) 300-311.*

[5] L.J. Spadaccini, M.B. Colket III, Ignition delay characteristics of methane fuels, *Prog. Energy Combust. Sci. Vol 20, pp.431-460, 1994.*

[6] Bittle J.A.; Knigth, B. M., and Jacobs, T.J. Interesting behavior of biodiesel ignition delay and combustion duration. *Energy & Fuels*, Vol. 24, 2010, pp. 4166-4177

[7] Bermann, C. Crise ambiental e as energias renováveis. *Ciência e Cultura*, [In portuguese].Vol. 60, n.3, 2008, pp. 20-29.

[8] Totten, G.E. Fuels and lubricants handbook: technology, properties, performance, and testing. *ASTM International*, 2003, pp. 118-119

[9] Liu, J., Li, G., and Liu, S. Influence of ethanol and cetane number (CN) improver on the ignition delay of direct-injection diesel engine. *Energy & Fuels*, Vol. 25, 2011, pp. 103-107

[10] Zhang, Yingjia; Huang, Zuo Hua; Wei, Liang Jie; Niu, Shao Dong. Experimental and kinetic study on ignition delay times of methane/hydrogen/oxygen/nitrogen mixtures by shock tube. *Chinese Science Bulletin*, Vol. 56, 2011, pp. 2853-2861

[11] Zhang, C., Li, P., Li, Y.,He, J., Li, X. Shock-tube study of dimenthoxymethane ignition at high temperatures. *Energy & Fuels*, Vol. 28, 2014, pp. 4603-4610

[12] Herzler, J., Jerig, L., and Roth, P. Shock tubes study of the ignition of lean n-heptane/ar mixtures at intermediate temperatures and high pressures. *Proceedings of the Combustion Institute 30*, 2005, pp. 1147-1153

[13] Saleh, H.E. The Preparation and shock tube investigation of comparative ignition delays using blends of diesel fuel with bio-diesel of cottonseed oil. *Fuel 90*, 2011, pp. 421–429

[14] Zhukov, V. P.; Sechenov, V. A.; Starikovskiy, A. Yu. Ignition delay times of kerosene (Jet-A)/Air mixtures. *Moscow Institute of Physics and Tecnology, Cornell University Library*. 2014.

[15] Çengel,Y.A., and Boles, M.A. Termodinâmica. 7. ed. *AMGH*. Porto Alegre. 2013.

[16] Patro, T. N. Combustion study of hydrogen fueled di diesel engine simplified heat release analysis. *Int. J. Hydrogen Energy*, Vol. 18, N. 3, 1993, pp. 231-241.

[17] ASTM D613 – Standard Test Method for Cetane Number of Diesel Fuel Oil, An American National Standard, May 2003.