Combustion Time of the oxygenated and non-oxygenated fuels in an Otto Cycle Engine

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Abstract

The flame propagation velocity in Otto cycle engines is one of the principal characteristics of fuel, and is fundamental in defining the ignition advance. The greater the propagation velocity the less the negative work required to compress the mixture before the upper dead point and the higher the cycle's efficiency. This paper presents experimental results of measurements of time between the fuel's ignition and the maximum rate pressure in the combustion chamber in a CFR (Cooperative Fuel Research) engine. The combustion time measurements were taken using oxygenated and non-oxygenated fuels as a function of the compression rate and stoichiometric ratio. The results indicate that the ramified chain oxygenates present low flame propagation velocities that ethanol of the linear chain oxygenate. The combustion velocity is directly proportional to the compression rate and decreases as the air/fuel ratio increases, becoming unstable at rates above the stoichiometric ratio.

Keywords: fuels; combustion velocity; Otto cycle engine

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1. Introduction

In a conventional spark-ignition engine, the fuel and air pass through the cylinder's intake valve into the intake manifold, where they are mixed with the residual gas and then compressed. Under normal operating circumstances, combustion is triggered by an electric discharge during compression. The flame front propagates through the air fuel-air mixture until it reaches the walls of the combustion chamber, where it is extinguished. At the onset of combustion caused by the spark from the spark-plug, the flame propagation is small and is accompanied by a slight increase in pressure (delay time) due to the combustion. The flame front increases progressively and propagates through the combustion chamber until the pressure inside the cylinder reaches its maximum after the upper dead point (UDP).

The combustion process is divided into four distinct phases: ignition, development, propagation and end of flame. Complete combustion must occur at a point (90º after UDP) that provides the maximum power or maximum torque. Combustion stars immediately after spark ignition, but, as the first stages are quite slow, the ignition delay is used to describe the first stage. Combustion end is quite difficult to be precisely determined, due to late burning phenomenon [1-2]. For these reasons, ignition delay and combustion end are usually arbitrarily defined; ignition delay can be, for example, considered as the time the gas burned ratio reaches the value of 5 [3] or 10% [4-5], combustion end as the time of this ratio reaches the value of 85 [5-6] or 90% [3]. If the onset of combustion advances progressively to before the upper dead point, the negative work of compression increases. If ignition is retarded, the pressure peak occurs later or its value is reduced. These alterations reduce the production of work during the course of expansion. The appropriate time for the onset of the combustion process depends on the flame propagation velocity and on the geometrical configurations of the combustion chamber. These depend on the engine design, the operating conditions, and the properties of the fuel-air mixture [4; 7-9].

Complete combustion is described at that in which the flame front moves through the combustion chamber until the air-fuel mixture is completely consumed and transformed into carbon dioxide and water. Due to the kinetics effects, during the combustion process carbon monoxide, unburned hydrocarbons and nitrogen oxide are present. Factors such as the fuel's composition, air-fuel ratio, geometrical details, temperature, pressure, compression rate and deposits in the chamber, determined the physical and chemical characteristics of the combustion process [10-13]. The reactions that occur during the combustion process are determined by mechanisms in series and parallels with initiating stages resulting from the formation of radicals and reactions due to the equilibria displacement. In many cases, due to the high release of energy and the resulting increase in temperature, the velocity of the reaction increases exponentially, leading to possible detonation or knocking.[4] Knocking depends on the temperature, the system's pressure, and the fuel's physicochemical characteristics.[7] At very low pressures, the system is outside the detonation region and the mixture reacts mildly. As the system's pressure and temperature increase, the intermediary products react with each other before the flame is extinguished near the cylinder wall, favoring the occurrence of knocking [4; 14-16].

In engines with god design, the turbulence inside the combustion chamber is proportional to the engine's rotation and increases the flame propagation velocity.[4] High rotations require a great advance in the ignition, because the spark timming for a given mass of fuel and air inside in the cylinder is set to give the maximum breake torque for an operating condition [4]. The geometrical parameters affect the turbulence and the surface area of the flame front. Aerodynamic details of the intake system contribute to the creation of an oriented gas flow, changing the flame's surface area and path. The shape of the combustion chamber also affects other criteria such as volumetric efficiency, knocking tendency and pollutant emissions. Combustion velocity measurements in a laminar system using pure hydrocarbons indicated that, for the same air/fuel ratio, the combustion velocity varies as a function of the fuel's chemical structure.[7; 17]

Due to the constant increase in crude oil-derived liquid fuel prices and the growing restrictions with respect to environmental contamination, growing interest has focused on alternative fuels [18-25]. These fuels can be classified as synthetic gasolines, gasolines with additives of oxygenated compounds such as methyl *tert*-butyl ether (MTBE), *tert*-amyl-ethyl-ether (TAEE), ethyl *tert*-butyl ether (ETBE), alcohols and gas fuels. The investigation of the flame propagation velocities of new oxygenated fuels like TAEE it is important to define the better ignition advance in order to take the maximum torque. This paper analyzes the variation in burn velocity of a Brazilian commercial gasoline (gasohol), isooctane, MTBE, TAEE, ethanol and vehicular natural gas (VNG) at different compression rates and air/fuel. The compression rates used in this study were 8:1, 10:1, and 12:1 for the liquid fuels and 14:1 for the LNG. The air/fuel used for each compression rate were 0.8 and 0.9 (rich mixture), and 1.0, 1.1 and 1.2 (lean conditions). The compression rates and stoichiometric ratios covered the typical operating range of commercial engines.

2. Materials and Methods

In this study, were used six different fuels: a commercial Brazilian gasoline (gasohol), isooctane 99%, MTBE 99%, TAEE 99%, ethanol 99.3% and VNG. The volumetric composition of the gasoline was 13% normal paraffins, 23% isoparaffins, 13% naphthenes, 11% olefins, 9% aromatics and 25% ethanol The VNG contained 89% methane, 7% ethane and 2% ethane. Table 1 lists the physicochemical characteristics of the liquid fuels used here. Figure 1 shows the distillation profile of Brazilian gasohol.

Include Table 1 and Figure 1

The tests to measure the burn velocity were carried out on a CFR engine (a Cooperative Fuel Research engine (year-1951) produced by the Waukesha Engine Division) modified with an Otto cycle cylinder head. The VNG was stored in a high-pressure cylinder equipped with a pressure control valve and dosing was done with a mixer mounted on the intake manifold of the CFR engine. The engine's original system, which was used for the other fuels, consisted of a three-barrel carburetor and adjustable height to adjust the air-fuel ratio.

The burn velocity was estimated using a D-1 knock detection sensor (a standard component of the CFR engine). The D-1 sensor has a stainless steel diaphragm, which induces a voltage in the coil through the action of pressure. The induced voltage signal is proportional to the velocity of the rate pressure in the combustion chamber. In this work the flame propagation velocities was define as angle between the spark ignition and maximum rate pressure inside the combustion chamber divided by the spended time. The angle consider as the flame propagation include the ignition delay [1;4] and the maximum rate pressure. The ignition advance was fixed in 10º in order to compare the flame propagation velocities for used fuels. The moment of ignition was obtained from the voltage signal of the primary winding of the electronic ignition control system. The piston's position was determined by a 600 mm diameter toothed wheel with 304 straight teeth and one slanted in the position relative to the upper dead point with the aid of an inductive sensor. To adjust the air-fuel ratio, a Bosch model LSU4 broadband lambda probe with a Motec model PLM converter was used. The signals recorder from to the rate pressure, position and ignition sensor were digitized using a CIO EXP GP and CIO DAS 16/330 data acquisition system with a sampling rate of 55 kHz. Figure 2 shows a schematic diagram of the system with the instrumentation used in the tests.

Include Figure 2

The burn time in the combustion chamber was defined as the interval between ignition and the maximum rate pressure inside the combustion chamber. The dimension of combustion velocity was expressed as s^{-1}, and the tests ware done in fixed rotation of 600 rpm (10 Hz). The “burn time” value of each fuel under the different conditions analyzed is the mean value of 45 consecutive cycles after complete stabilization of the operational conditions. With the entire operational conditions stable in the tests, the results obtained were compared. Figure 3 depicts the characteristic profiles of the signals from the position, rate pressure and ignition sensors for the engine test, using gasohol as fuel and a compression rate of 8.

Include Figure 3

3. Results and discussion

The flame propagation velocities are important to adjust the best ignition advance. Also it is possible to fit the dimension of the cylinder and compression rate in order to take maximum torque as a function of rotation and air-fuel ratios.

From the results presented in Table 1, we can see that oxygenated compounds present the biggest densities and antiknock index. The oxygenate compound TAEE present the lowest vapor pressure. The abnormal distillation profile presented by gasohol is due to the azeotropic mixture formed by ethanol and hydrocarbons.

Figure 4 shows the results of the flame propagation velocity measurement tests obtained as described earlier, for isooctane fuel as a function of the stoichiometric ratio and compression rates of 8, 10 and 12. These results indicate that, at a compression rate of 8, the flame propagation velocity diminishes as the air-fuel mixture increases. However, at higher compression rates, the combustion velocity increases along with the air-fuel ratio, reaching a maximum before of the stoichiometric region and diminishing with poor fuels.

Include Figure 4

Figure 5 presents the results of the flame propagation velocity measurement tests for the VNG fuel. Unlike isooctane, at a compression rate of 8, as the air-fuel ratio increases, so does the flame propagation velocity. Analogously, the flame velocity also increases along with the increase in compression rate and also presents a maximum in the stoichiometric ratio. Another important factor to emphasize is that the flame propagation velocity of natural gas is approximately 15% lower than that of isooctane.

Include Figure 5

The results of the combustion velocity measurement tests for the oxygenated fuel MTBE are shown in Figure 6. This fuel exhibited a reasonably stable flame propagation velocity at air-fuel ratios below the stoichiometric ratio, i.e., rich mixtures, which diminished as the mixture became poorer.

Include Figure 6

The oxygenated fuel TAEE, whose molecular structure is similar to that of MTBE but with a higher molecular mass, the results of the combustion velocity shown in Figure 7 showed a similar tendency. The difference was that, at low compression rates, the flame velocity of TAEE was slightly lower than that of MTBE.

Include Figure 7

Figure 8 shows the results of the combustion velocity measurement tests for the oxygenated fuel Ethanol. Note that the flame propagation velocity remained approximately stable at air-fuel ratios below the stoichiometric ratio, i.e., for rich mixtures, decreasing as the mixture became poorer. It should be noted that the flame propagation velocity of ethanol was higher than the velocities obtained for the fuels analyzed with values closes to 300 s^{-1}.

Include Figure 8

The flame propagation velocity tests of the Brazilian commercial fuel depicted in Figure 9 showed a significant increase in burn velocity when compared with the results presented above. Gasoline is a complex mixture of hydrocarbons and it is impossible to attribute this increase to any specific compound, but it is known that linear chain compounds and olefins have a higher combustion velocity than ramified and saturated compounds. Another point to keep in mind is the presence of ethanol in Brazilian gasolines, for ethanol shows a tendency to increase the mixture's octane rating. However, oxygenated compounds such as MTBE and TAEE presented flame propagation velocities below those of the gasoline, although ethanol showed values close to that of Brazilian gasoline, whose composition contains about 25% v/v of ethanol. Generally speaking, we found that the fuels with a high degree of purity present high octane ratings but low burn velocities.

Include Figure 9

The faster the fuel's burn velocity, the lower the burn angle should be. For high flame propagation velocities, one should use an ignition advance in order to minimize the negative work before the UDP. The maximum torque is obtain wend the maximum pressure occur at 90° after the UDP. Fuels with low flame velocity needs higher ignition advance in order to maximize the torque. For VNG, isooctane and gasoline, the highest combustion velocity occurs in the stoichiometric mixture condition, while the burn velocity of oxygenated fuels is higher when the mixture is rich ($\lambda = 0.8$ to 0.9) and diminishes when the mixture is poor ($\lambda = 1.1$ to 1.2). For air-fuel ratios above the stoichiometric ratio (poor mixture), the combustion process becomes unstable, with failures in the combustion cycle.

It should be noted that, as the compression rate increases, so does the flame propagation velocity. This is because the higher migration of mass and energy when density is high.[28]

We suppose that the flux of diffusing particles is motion in response to a thermodynamic force arising from an energy gradient.[29]

Figure 10 compares the results of flame propagation velocity as a function of air-fuel ratio and compression rate. As we can see, for rich mixtures ($\lambda = 0.8$) fuels such as ethers (MTBE and TAEE), gasohol and isooctane presents similar values for the flame propagation velocity. For oxygenates compounds ethanol presents highest values of flame propagation velocity and for the hydrocarbons the GNV the lowest for rich mixtures and getting high for poor mixtures. Methane has high activation energy in the oxidation process; this can explain the lower flame propagation velocity observed in air-fuel ration below the stoichiometric condition when the temperature of the combustion process is low. The best ignition advance for GNV should be higher than the gasoline and oxygenated fuels in order to get maximum torque. Ethanol has higher flame propagation velocity and the high velocity of gasohol can be attributed of the presence of ethanol in it formulation. The highest flame propagation velocity of ethanol can be explained due to the formation of intermediate species like acetaldehyde and formaldehyde with high reactivity that promotes the oxidation process. [30-31]

For all fuels analyzed, the flame propagation velocity increase when the air-fuel ratio is rich and near stoichiometric ratio. This behavior can be explained due to the combustion temperature increase near to the stoichiometric ratio. With the air-fuel ratio above to the stoichiometric ratio (poor mixture) the flame propagation velocity diminishes due to the reduction of the combustion temperature because the air excess.

Include Figure 10

4. Conclusions

The proper determination of the compression rate and ignition advance for the optimal performance of engines is strictly related with the type of fuel employed. Fuels with ramified chain and ether compounds show low flame propagation velocities. The flame propagation velocity of ethanol is higher than that of ramified and ether compounds. The use of compression rates exceeding 10 increases the combustion velocity as the air-fuel ratio increases but remains below the stoichiometric ratio. The combustion velocity diminishes at air-fuel ratios above the stoichiometric ratio. Fuels with high octane ratings can be used in engines with high compression rates. The higher the compression rate the greater the flame propagation velocity. To achieve high thermodynamic and mechanical performance, internal combustion engines with spark ignition should operate with high compression rates and, in order to minimize the negative work of compression, the ignition advance should be reduced to obtain the maximum greake torque.

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