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Alternative method for bulk modulus estimation of Diesel fuels

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HIGHLIGHTS

- An alternative method for the estimation of fuel bulk modulus has been developed.
- Time lags between energizing and injection rate of injectors do not depend on fuel type.
- Initial time lag between energizing and injection rate depends only on the injector type.
- Rear time lag depends on both injector type and injection pressure in piezoelectric injectors.

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ABSTRACT

The knowledge of Diesel fuel properties has great relevance for the analysis and comprehension of phenomena related to fuel injection, fuel–air mixture formation and diesel combustion processes. This work proposes an alternative method for estimating the bulk modulus of diesel fuels by means of an experimental installation commonly used for determining fuel injection rates from common rail injection systems. Three fuels were tested in the mentioned installation: commercial Diesel fuel (blended with 5.8% of biodiesel), hydro-treated vegetal oil (HVO) and gas to liquid (GTL) fuel from natural gas by means of low temperature Fischer Tropsch process. Results were obtained by testing two different injectors (solenoid operated and piezoelectric injectors) under different injection pressures and energizing times. Fuel temperature at inlet of the high pressure injection pump was controlled, keeping constant the pressure inside the fuel injection indicator. From the experimental work, data analysis and post-processing, bulk modulus of fuels tested has been estimated and compared to results obtained by diverse authors with different experimental installations and methods. Results obtained in this work show small differences compared to published data. Additionally, the initial time lag between the signal of the electric pulse when the injector is energized and the beginning of the injection rate profile depends only on the type of injector without influence of type of fuel and operating conditions. However, the rear time lag between both mentioned profiles depends only on injector type (when the solenoid operated injector was tested) while, with piezoelectric injector, it also depends on both energizing time of the injector and injection pressure.

1. Introduction

In this work, Diesel fuels with paraffinic composition have been tested and compared to a fossil Diesel fuel, using an experimental installation used for determining fuel injection rates from different common rail Diesel injectors and different fuels, under variation of injection pressure and time of energizing. This installation has been described in previous works [1,2] was presented.

The knowledge of fuel injection rates is essential for researchers and manufacturers of Diesel engines in several situations. One example is the calculation of heat release, for a better description of the evolution of the combustion process. Instantaneous fuel mass flow rate is not taken into account in several works addressing the thermodynamic diagnosis from the engine in-cylinder pressure [3–5]. In other works, although the information about the injector needle lift is known, the fuel mass flow rate by stroke is still unknown [6,7]. Currently, there are published works which have been conducted under steady state operation [8] and under transient engine operation [9], where the only experimental signal from injection process characterization is the electric pulse of the injector energizing.

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In most of published works which include instantaneous fuel mass flow rate by stroke in combustion diagnosis, authors have estimated this information by means of simple models of injection rates [10], or actual fuel injection rates determined experimentally (with fuel injection indicator) and, then, this information is coupled to the thermodynamic model of combustion diagnosis [11]. The latter procedure is possible because in both cases (when the injection rate is obtained with injection indicator and when the actual engine is tested), the electric pulse of the injector is registered in synchronization with both the in-cylinder pressure and injection rate.

Currently, most Diesel engines are equipped with injectors commanded electronically and from them it is easy to register the energizing electric pulse. However, for those researchers without possibility to use injection rate indicators, it is complex to synchronize a model for predicting fuel injection rate if the initial (d_1) and/or rear (d_2) lags between electric pulse and the calculated injection rate profile (see Fig. 1) are not known.

When the detailed knowledge of the injection system operation (or only the injector operation) is needed [12–14], or when the study of the Diesel fuel spray evolution is necessary [15], the knowledge of fuel properties, particularly the bulk modulus and the speed of sound [16–18], are essential. For example, Boehman and co-workers explained the slight advance of start of injection through the increase of bulk modulus of biodiesel fuels with respect to diesel fuels when mechanical injection systems are used in diesel engines [18]. These authors also supported their conclusions based on two of the works done by Tat et al. [19,20]. In the first of these works [19], the authors present correlations for determining bulk modulus, density and speed of sound for methyl and ethyl soyate esters (as biodiesel fuels), and compared it to correlations of these parameters for two diesel fuels (N°1 an N°2). These correlations were obtained at 21 °C and from atmospheric pressure to 35 MPa. In all cases correlations were linear depending on the pressure rise. In the second work [20], the authors extended the investigation by studying a wide range of temperatures (between 20 and 100 °C), using a similar range of pressure. In this case authors studied the effect biodiesel composition on bulk modulus, speed of sound and density. They found that there is a direct relationship between the bulk modulus increase when biodiesel is used, and its earlier start of injection, which might be the cause of NOx increase in engines with mechanical injection systems.

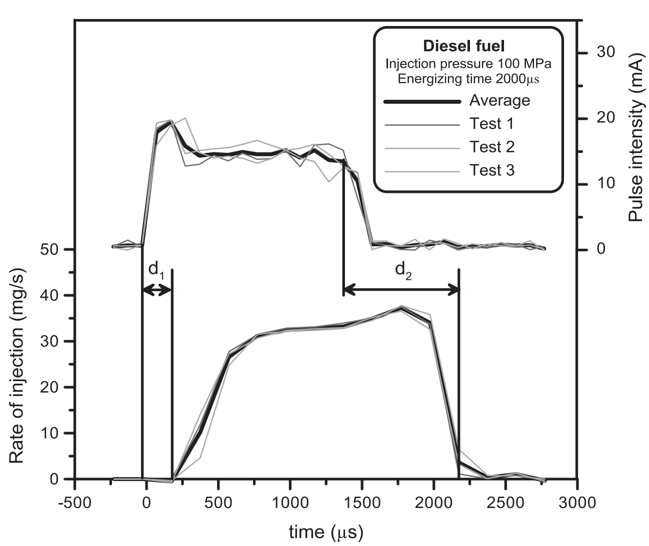

Fig. 1. Time lag, initial (d_1) and rear (d_2) between the injector energizing signals and their respective rates of injection profiles under three repetitions Rp1, Rp2 and Rp3 and its mean profile *M*. Test from solenoid operated injector.

The works previously cited [17–20] used the method and experimental techniques stablished in Ref. [21] for bulk modulus determination, which are different in comparison to the method and experimental techniques used in the present work.

This work has been focused, on one hand, on the experimental determination of the effect of injection parameters, type of injector and type of fuel on time lags between electric pulse of injector energizing and the injection rate profile. On the other hand, the bulk modulus of tested fuels was estimated. In both cases, a methodology was developed to combine experimental data analysis and post-processing with calculation of mean values of bulk modulus. Experimental data has been obtained by means of an indicator type IAV–EVI 2 [22], and through the equation that defines the rate of injection [23] (see Eq. 1).

$$\dot{m}_{f(t)} = \frac{A_T \Delta p_{(t)}}{a} \tag{1}$$

where $\dot{m}_{f(t)}$ – is the fuel mass flow rate (kg/s), A_T – is the section of the anechoic tube (m^2), $\Delta p_{(t)}$ – is the pressure increase over the pressure stablished at the internal volume of the hydraulic unit of the rate of injection indicator (Pa), and a is the speed of sound in the fuel contented in the volume of the hydraulic unit (m/s), which depends on pressure and temperature of fuel.

The speed of sound can be calculated through other fuel properties as Eq. (2) shows:

$$a^2 = \frac{B}{\rho} \tag{2}$$

where B – is the fuel bulk modulus and ρ – is fuel density.

Two common properties used in fluid engineering are the isentropic bulk modulus B_S (Eq. (3)) and the isothermal bulk modulus B_T (Eq. (4)).

$$B_S = \rho \left(\frac{\partial p}{\partial \rho}\right)_S \tag{3}$$

$$B_T = \rho \left(\frac{\partial p}{\partial \rho}\right)_T \tag{4}$$

where ∂p – pressure increase of fuel and $\partial \rho$ is the fuel density variation.

In general, the relationship between B_T y B_S can be expressed according to Eq. (5) [18]:

$$\frac{1}{B_T} = \frac{1}{B_S} + \frac{T\alpha^2}{\rho C_p} \tag{5}$$

where α represents the isobaric coefficient of thermal expansion, and c_p is the specific heat value at constant pressure, and T is the fuel temperature.

Combining Eqs. (2) and (5) it is found that:

$$\left(\frac{\partial \rho}{\partial p}\right)_T = \frac{1}{a^2} + \frac{T\alpha^2}{C_p} \tag{6}$$

Solving Eq. (6) for the isothermal case, the following relationship between fuel density and speed of sound can be obtained:

$$\rho(p,T) = \rho(p_0,\ T) + \int_{p_0}^{p} \frac{dp}{a^2} + T\int_{p_0}^{p} \left(\frac{\alpha^2}{C_p}\right) dp \tag{7}$$

The first term at right side of Eq. (7) represents the main contribution on the fuel density determination, which can be determined by measuring the density at atmospheric conditions. The second term can be evaluated using mean values of the speed of sound at each value of fuel temperature considered. The last term represents only a small percentage with respect to the first term and it is usually very small in the case of liquid fuels. This term is related to