

Experimental Characterization of the Thermodynamic Properties of Diesel Fuels Over a Wide Range of Pressures and Temperatures

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ABSTRACT

The influence of pressure and temperature on some of the important thermodynamic properties of diesel fuels has been assessed for a set of fuels. The study focuses on the experimental determination of the speed of sound, density and compressibility (via the bulk modulus) of these fuels by means of a method that is thoroughly described in this paper. The setup makes use of a common-rail injection system in order to transmit a pressure wave through a high-pressure line and measure the time it takes for the wave to travel a given distance. Measurements have been performed in a wide range of pressures (from atmospheric pressure up to 200 MPa) and temperatures (from 303 to 353 K), in order to generate a fuel properties database for modelers on the field of injection systems for diesel engines to incorporate to their simulations.

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INTRODUCTION

The performance of diesel engines is strongly influenced by the thermodynamic properties of fuels for several reasons. Differences from one fuel to another may affect the injector operation, thus affecting the spray evolution and influencing the quality of the air-fuel mixture, which in turn affects the combustion phenomenon. This will result in different levels of emissions, noise and performance of the engine [1].

More specifically, the properties that affect the performance of diesel injection systems include but are not limited to speed of sound, density, viscosity and bulk modulus [2, 3, 4, 5].

With regard to the density, several authors have concluded that fuels with lower density result in a smaller mass flow rate for the same injection conditions (namely injection pressure, backpressure and energizing time), leading to lower mass quantities being introduced in the cylinder [6, 7]. In addition, viscosity plays a key role on injector dynamics, affecting the opening and closing stages of the injector and thus leading to different injection rate shape, injection duration and total mass delivered to the cylinder [8, 9]. In typical common-rail injector systems, the bulk modulus also affects the injection due to its influence on speed of sound, leading to a different propagation of pressure waves along the injector (from the high pressure pump to the injector needle) thus advancing or delaying the needle opening and the start of injection [10]. Furthermore, the speed of sound and bulk modulus are necessary to perform experimental injection rate measurements with the Bosch method, since the technique is based on the transmission of a pressure wave through a tube [11, 12].

The fuel properties stated before present an important dependence on pressure and temperature, as several authors have reported [2, 5, 13, 14, 15]. However, most of the studies report data either for relatively low pressures, or for fluids different than diesel fuels. Due to the high pressures reached in diesel injection systems nowadays (up to 200 MPa) and different temperatures depending on the operating conditions (from cold start to hot conditions), an extension on the database is needed for research purposes. On one hand, this will help experimental researchers understand some consequences that the growing injection pressures will have on the engine performance. On the other hand, this database is especially valuable for modelers, since the inclusion of the variation of the fuel properties with temperature and pressure is becoming a standard in 1D and computational fluid dynamics calculations [16, 17, 18].

The objective of this paper is to present a methodology to experimentally determine some of the most influencing thermodynamic properties of diesel fuels (namely speed of sound, density and bulk modulus) at a wide range of temperatures (from 303 to 353 K) and pressures (up to 200 MPa), representative of common-rail systems. The methodology consists of transmitting a pressure wave along a high-pressure line and measuring the time it takes for the wave to travel a given distance, thus determining the speed of sound for different conditions. The density values will then be theoretically derived from the speed of sound measurements, also leading to the isothermal bulk modulus determination. The installation is calibrated with an alkane (n-dodecane) whose properties are known for a wide range of temperatures and pressures and the measurements are validated with another known alkane

(nheptane). Finally, the methodology is tested for a reference diesel fuel and its winter variation, and correlations are given for the dependence on their properties with pressure and temperature.

THEORETICAL FOUNDATION

The speed of sound (a) in a fluid imposes how fast a pressure wave will be propagated in the medium. A small pressure disturbance travelling through a high-pressure one-dimensional pipe of length L covers that distance in a time t , since:

$$a = \frac{L}{t} \quad (1)$$

With regard to compressibility, the isentropic and isothermal bulk modulus (B_S and B_T , respectively) are defined as:

$$B_S = \rho \left(\frac{\partial p}{\partial \rho} \right)_S \quad (2)$$

$$B_T = \rho \left(\frac{\partial p}{\partial \rho} \right)_T \quad (3)$$

where p is the pressure, T the temperature, S the entropy and ρ the density of the fluid. Both definitions of bulk modulus are related to each other as follows:

$$\frac{1}{B_T} = \frac{1}{B_S} + \frac{T\alpha^2}{\rho C_p} \quad (4)$$

where α is the isobaric coefficient of thermal expansion, whereas C_p designates the isobaric heat capacity.

As stated by [19], the isentropic bulk modulus and the speed of sound are related to each other through the density:

$$a^2 = \frac{B_S}{\rho} \quad (5)$$

Thus, combining Eqs. (2), (3), (4), (5):

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

This equation can be solved for an isothermal line, thus obtaining the relation between density and speed of sound:

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

The first term of the right side of Eq. (7) corresponds to the density at a reference pressure. For convenience, this will be taken as the atmospheric pressure, since it can then be directly measured with a hydrometer. The other terms are the deviation to take into account the effect of pressure on the density at a given pressure. The second term can be evaluated from the evolution of the speed of sound with pressure for a given isothermal line. Thus, this term can be evaluated from the speed of sound measurements, given that enough pressures are tested for a certain temperature. Finally, the last term is related to the difference between specific heat capacities (C_p and C_v) for the fluid. This difference is not significant for liquids [3, 13, 19], which leads to this last term being the smallest contribution to the density. In addition, it is not modified in a substantial way with the pressure, and thus it will be computed assuming that α and C_p are constant. With all, it is possible to calculate the density at any pressure and temperature condition, only by measuring the density at atmospheric pressure and performing the speed of sound measurements in the experimental facility described in the following section. The isentropic bulk modulus can then be evaluated by applying Eq. (5).

EXPERIMENTAL

It has been demonstrated that the measurement of the density at atmospheric pressure and speed of sound at different pressure and temperature conditions make it possible to determine the density and the isentropic bulk modulus at any condition. Thus, the present section deals with the experimental facilities that allow the measurements of speed of sound and density at atmospheric pressure.

Density Measurements

The first step in order to determine the density of a diesel fuel at any condition of temperature and pressure is to establish the variation of the density with respect to the temperature at the atmospheric pressure, as demonstrated by Eq. (7).

Density measurements were then performed with a standard hydrometer, taking into account the considerations stated by the ASTM D1298, including those corresponding to the calibration procedure. With all, the accuracy of the hydrometer was determined to be $\pm 5 \times 10^{-4} \text{ kg/m}^3$. Measurements were taken at different temperatures ranging from 300 to 350 K, in steps of 5 K. Temperature regulation was achieved by means of a thermostatic bath, shown in Figure 1 together with the used setup.

These tests were also validated by measuring the density by a second procedure, which is based on using a Pycnometer, also following the standard method established in the ASTM D1217. The device consists of a volume of 10 ml, with an accuracy of $\pm 1.16 \times 10^{-4} \text{ ml}$ estimated during its calibration.



Figure 1. Setup for the measurement of density at atmospheric pressure. The image shows the different equipment used in the facility: 1) temperature regulator; 2) diesel specimen inside a test tube; 3) hydrometer; 4) thermometer.

Speed of Sound Measurement Facility

In addition to the determination of the speed of sound itself as an interesting property affecting diesel injection systems, speed of sound measurements are valuable to establish the density of a fuel at high pressures and temperatures. Recall Eq. (7), whose second term at the right side showed the need of determining the speed of sound variation with the pressure for a given temperature.

As it has already been stated, the speed of sound is determined by measuring the time it takes for a pressure perturbation to travel along a certain distance. Several methods have been used in order to determine the speed of sound at pressures higher than the atmospheric, including the ultrasonic cell method [20]. However, in the present work, the authors opted for a setup that allows to couple the facility to the common-rail injection system, with the consequent simplicity to test diesel fuels.

Figure 2 shows an image of the facility and its setup, where it can be seen how the injection system was used. Fuel is extracted from the tank by a high-pressure pump that raises its pressure and delivers it to a rail, where the pressure is controlled. Before reaching the injector, the fuel travels through a long high-pressure pipe, which forms the basis for the measurement, since it is the line through which the measured pressure waves will travel. In order to measure those pressure waves, two piezo-resistive Kistler pressure sensors (able to work under pressures up to 300 MPa) are located in different points of the high-pressure line, defining the measurement section, as seen in Figure 3. The length of this section needs to be long enough to

allow for a clear acquisition, but short enough to minimize signal attenuation. In the end, the length between sensors was established as 4 m. The internal diameter of the pipe needs to be small in order to ensure a one-dimensional transmission of the wave, and was set to 2 mm. After the high-pressure line, the fuel reaches the injector and, in the case of an injection event, is discharged in an Injection Rate Discharge Curve Indicator (IRDCI), where the injected mass flow rate is determined using the Bosch long tube method [11] and registered to check a proper operation of the facility.

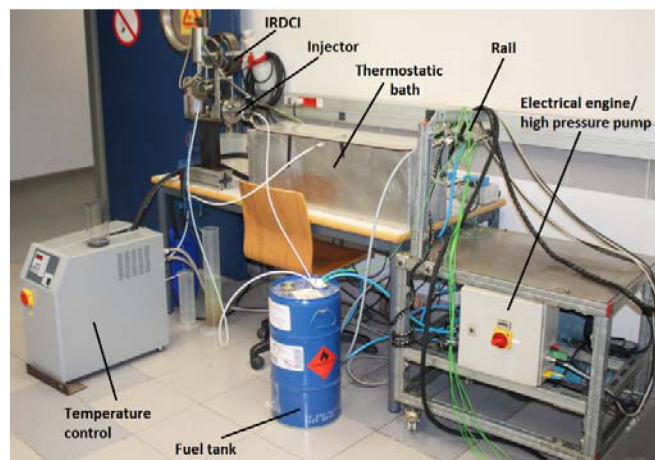


Figure 2. Speed of sound determination experimental setup.

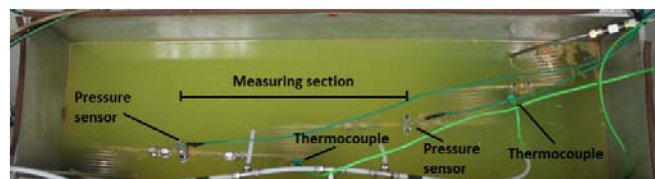


Figure 3. Glycol thermostatic bath of Figure 2, containing the high-pressure lines.

With this setup, a pressure disturbance is produced with an injection event due to the depression generated in the tube by the injector opening, resulting in the fuel being discharged in the IRDCI, as stated in [12]. This pressure disturbance is measured at the two positions of the high-pressure line where the pressure sensors are located. An example of the acquired signals is shown in Figure 4. The injections were carried out at a small frequency (0.1 Hz) in order to avoid interaction between the waves of successive injections. It is also important to note that a long segment of high-pressure line (about 8 m, which corresponds to twice the length of the measurement section) was left between the measuring section and the injector (recall Figure 4) so that, for a certain injection, the rebound of the pressure wave does not interact with the perturbation being measured, interfering with the signal acquisition. The signal acquisition was performed by means of a Yokogawa DL708 digital oscilloscope and recorded in a personal computer for processing purposes. For each operating point, 25 repetitions were taken. The pressure signals at the two locations were recorded for each of the repetitions and processed in order to obtain the travel time of the pressure wave (Δt) between sensors. Finally, an averaged value of Δt was accepted as the result, due to the small dispersion between repetitions (quantified as 0.5%).