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High pressure thermophysical characterization of fuel used for testing and calibrating diesel injection systems

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ABSTRACT

This paper reports experimental thermophysical measurements of a fuel (Shell Normafluid) used for testing and calibrating diesel injection systems and which meets the ISO 4113 specifications. Viscosity was measured from 0.1 to 200 MPa and from 293 to 353 K, using a falling-body viscometer. Speed of sound measurements were carried out from atmospheric up to 200 MPa in the temperature range from 283 to 423 K using a pulse technique operating at 3 MHz. Densities were determined from 283 to 423 K and up to 200 MPa. From these measurements, the volumetric derivatives properties such as isentropic and isothermal compressibilities were evaluated.

1. Introduction

The policy for the reduction of fossil energy consumption as well as for the reduction of automobile exhaust emissions, enforces to improve the performances of existing engines by using alternative fuels or by doing engine modifications. In case of diesel engine, one of the most important operating parameter that influences engine efficiency and emissions is the fuel injection system. Its purpose is to introduce the appropriate amount of fuel into the engine cylinder and to mix properly fuel to air in order to achieve a complete combustion. A possible way to improve combustion performance and reduce harmful emissions consists in injecting fuel under very high pressure [1,2]. Rising the injection pressure, in combination with a reduction of nozzle improves the dispersion of diesel spray and the atomization process. However, the variations in fuel properties caused by pressure change strongly impact on the injection mass flow rate, the spray structure and combustion efficiency and consequently have an influence on engine performances [3]. Thus, the conception of new injection systems and the optimization of injection processes under very high pressure require an accurate knowledge of the thermophysical properties of fuel over wide range of pressure. Among all the thermophysical properties of fuels, density, isentropic compressibility and viscosity have a strong influence on injection process. Actually, these properties directly affect the pressure wave amplitude and consequently the mass flow rate and the total amount of fuel injected in the cylinder. Density is the main property that influences the conversion of volume flow rate into mass flow rate [4]. The compressibility or bulk modulus acts on the wave amplitude but also on its velocity and thus on the fuel injection timing [5] whereas the viscosity has an influence on the pressure wave damping and the pressure loss in the injector feed pipe [4].

While for most of the pure substances involved in the composition of petrodiesels and in particular paraffins measurements of density, compressibility as well as viscosity have been conducted under pressure, such data remain scarce [6–8] for in diesel fuel. Moreover, when studies of this kind have been carried out, they generally concern only one physical property. In this context, we have initiated a programme of measurement of several thermophysical properties of petrodiesels and biodiesels under high pressure in the framework of the project New Advanced Diesel Injection Analysis for bio fuels (NADIA BIO) supported by the French automobile cluster "Mov'eo". This present work concerns the thermophysical characterization of a reference fluid which meets the ISO 4113 specifications. This fuel called "Normafluid" is usually used for testing and calibrating diesel fuel injection systems in laboratory. Several properties including density, speed of sound and viscosity have been measured from atmospheric pressure to 200 MPa at various temperatures (from 283.15 K to 403.15 K). Based on these sets of experimental data, the derivatives properties such as isentropic and isothermal compressibilities have been determined in the same P, T ranges.

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2. Experimental

2.1. Speed of sound measurement

The method deployed to carry out measurements of speed of sound in the Normafluid under high pressure is based on a pulse echo technique working at 3 MHz with a fixed path length. This frequency constitutes an acceptable compromise between lower frequencies which give clear signals but reduce precision and higher frequencies which allow a better precision of measurements but with a greater damping of wave in fuels. Moreover, this frequency is sufficiently low to avoid any dispersive phenomena as regards speed and it coincides with the speed of sound within the low frequency boundary. The apparatus, which has been described previously in detail [9], is essentially made up of two piezoelectric (PZT) elements placed on the opposite sides of an acoustic probe fixed into an high pressure vessel, and connected to an ultrasonic pulse generator (PANAMETRICS 5055 PRM). The speed of sound was determined from the measurement, by direct chronometry [10] of the travelling time of the wave through the sample by means of a numerical oscilloscope with memory storage. The length of the sample path was chosen around 60 mm. This length represents an acceptable trade-off between shorter distances which would reduce the damping but would also reduce measuring accuracy and longer trajectories which would have the advantage of increasing the accuracy of the measurements but would at the same time increase the damping of the wave. Its accurate value was determined at different temperatures and pressures by calibration with water using the data of Del Grosso and Mader [11], Wilson [12]. To ensure satisfactory thermal uniformity within the fluid, the vessel was immersed in a bath of heat-carrying fluid agitated and thermo-regulated by a Bioblock thermostat with a stability of 0.02 K. The temperature was recorded by means of a platinum probe (Pt100) placed inside the experimental vessel.

Two pressure gauges (HBM P3M) were used to measure the pressure. One is calibrated in the full scale (0.1–200 MPa) with an uncertainty of 0.2 MPa) whereas the other is only calibrated between (0.1 and 100 MPa with an uncertainty of 0.02 MPa) in order to achieve a better precision in this lower pressure range. The technique used for evaluating the time delay as well as the path length leads to an experimental uncertainty in the speed of sound about 0.06%. However, the ultimate precision depends also on the temperature measurement which leads an additional uncertainty of 0.04% and in the pressure measurement which involve an error less than 0.1% up to 100 MPa and 0.2% between 100 and 200 MPa. This accuracy has been confirmed by several tests performed with hexane [13] and heptane [9].

2.2. Density measurement

Density was measured between 0.1 and 140 MPa by means of an ANTON-PAAR densimeter equipped with a high pressure cell (DMA HPM) having an operating pressure range of 0.1–140 MPa in the temperature interval 283.15–403.15 K. The experimental setup was similar to the one described in a paper by Watson et al. [14]. The principle of this apparatus is to measure the period of oscillation of a U-shaped tube and to deduce the density which is related to the square of the period by a linear law whose the parameters are calibrated by the method proposed by Comuñas et al. [15] using vacuum and a reference liquid:water [16] or decane [17] depending on the PT investigated domain. The temperature of the high-pressure vibrating-tube cell of the densimeter was controlled by an external circulating temperature-controlled fluid and was measured with an Anton-Paar MKT 50 thermometer with an uncertainty of ±0.01 K between 283.15 and 403.15 K. The pressure was measured in the full pressure range with a Presens manometer (Precise Gold Plus) with an uncertainty of 0.015 MPa. Taking into account the uncertainties of the temperature, the pressure, the density of the reference fluid as well as the errors in the measurements of the period of oscillation for the vacuum and for both the reference and the studied liquid, the overall experimental uncertainty in the reported density values is estimated to be ±0.5 kg m^{-3} for all experimental conditions apart from measurements performed at atmospheric pressure in the temperature interval 373.15–403.15 K. For these particular conditions which require decane instead of water as reference fluid, the uncertainty is ±0.8 kg m^{-3}.

2.3. Viscosity measurement

At atmospheric pressure the viscosity was measured by using a classical capillary viscometer. For this purpose a Ubbelohde tube connected to an automatic AVS350 Schott Geräte Analyzer was used. The tube is fully immersed in a thermostatic bath in order to control the temperature of the fluid within 0.1 K. The capillary tube is provided with a calibration certificate however its accuracy was checked at different temperature using "Cannon Certified Viscosity Standard" reference fluids before performing measurements. Using this technique, the viscosity measurements are achieved with an uncertainty less than 1%. At higher pressures than atmosphere, the viscosity was measured using a falling-body viscometer. This viscometer, which has been described previously in detail [18,19], consists of a high-pressure cylinder in which a sinker moves through a liquid. Two coils were wrapped around the external face of the cylinder at a distance of 150 mm apart in order to detect the presence of the sinker by a change of their inductance and to measure the time taken for the sinker to travel between them. Knowing the difference between the density of the sinker ρ_S and of the liquid ρ_L, the viscosity η of the liquid is determined directly by measuring this transit time according to working relationship:

$$\eta(T,P) = K_a(T,P)[(\rho_S - \rho_L)\Delta\tau] \quad (1)$$

where K is a parameter depending on the falling body. Its value is evaluated at each working P, T condition by calibration with n-decane using the viscosity data reported by Huber et al. [20]. In order to improve the accuracy, the experiments are repeated several times for each P, T condition and the falling time $\Delta\tau$ considered in the working relationship corresponds to the average value of six measurements with a reproducibility of 0.5%.

The pressure of the sample within the viscometer is measured by a HBM-P3M with an uncertainty of 0.2 MPa. The temperature of the sample in the measuring cell and the piston cell is controlled by a circulating fluid supplied by an external thermostatic bath. The viscometer is placed in an automated air-pulsed thermal regulator oven in order to ensure a homogeneous temperature surrounding the system. The temperature is measured inside the measuring cell by a Pt100 probe connected to a classical AOIP thermometer with an uncertainty of 0.05 K. The overall uncertainty for the reported viscosity data is of the order of 2% up to 100 MPa and 4% between 100 MPa and 200 MPa. This accuracy was checked by several tests (see for instance the case of methanol [19] compared with the correlation proposed by [21]).

The Normafluid BR is a fuel marketed by Shell Company. It is a calibration fluid designed for testing the systems of diesel fuel injection and its properties like viscosity, density and compressibilities are akin to those of real diesel fuels, but with a weak risk of flammability. Its composition follows the specification of the standard ISO 4113. It was analyzed [22] by using a 2D GC technique that leads to advanced separation between components belonging to different chemical species. The composition in