DETERMINING THE SPEED OF SOUND, DENSITY, AND BULK MODULUS OF RAPESEED OIL, BIODIESEL, AND DIESEL FUEL

by

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Modern tendencies in the development of diesel engines include the operation of the system for injecting diesel fuel at pressures higher than 100 MPa. Knowing the characteristics of liquid fuels such as speed of sound, bulk modulus and density depending on pressure, is important for predicting the behavior of fuel injection systems for diesel engines and optimization of the same. The paper presents an original method and apparatus (device) for determining the speed of sound and density of fluids depending on the pressures. With this method, values of these characteristics for rapeseed oil, biodiesel, and conventional diesel fuel at pressures up to 160 MPa are determined. The method is non-destructive, it can also be applied to higher pressures than 160 MPa, as well as other liquid fluids that are used at high pressure – hydraulic oil, for example.

Key words: *biodiesel, rapeseed oil, diesel, speed of sound, bulk modulus, density, high pressure*

Introduction

One of the main characteristics of internal combustion engines is that their energy, exploitation and environmental indicators depend on the method of preparation and ignition of the mixture. From the aspect of diesel engines, this refers to systems delivering air and dosage (injection) of fuel. As for the dosage of fuel, constructions of modern diesel engine include direct injection of fuel into the cylinder with the possibility of more precise control and regulation of the injection process. Also, the tendency is to increase fuel injection pressures and develop fuel injection systems that can respond to such requirements.

On the other hand, there are trends in research and application of alternative liquid fuels for conventional diesel engines. It is this research, and the practical implementation thereof, that has presented methyl esters of vegetable oils, mainly rapeseed oil (rape methyl ester – RME, MER, ROME, typical biodiesel used in Serbia) as the optimal alternative liquid fuel for use in conventional diesel engines. Fuel injection characteristics depend on both, the type of injection system and fuel properties [1-5].

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When diesel engines work with methyl ester of rapeseed oil, slightly higher fuel consumption is observed compared to engines with conventional diesel fuel. Increased fuel consumption compared to diesel engines with conventional diesel fuel is, by the way, characterized by the appearance of the diesel engine with clean oil as bio-fuels (or bio-oils methyl and ethyl esters), regardless of whether they are diesel engines with a single or divided combustion chamber [6-7].

In analyzing the operation of the conventional fuel injection system (CFIE) [2, 6, 8, 9], it has been observed that certain fuel properties, such as speed of sound, density and bulk modulus, have a significant impact on the operation of fuel injection systems.

Theoretical basis

To determine the values of fuel pressure and velocity in the desired cross-section and time, it is necessary to know the speed of pressure wave propagation (unsteady transport of liquids in small diameter pipes, transport fuel by pressure waves ...), which is equal to the speed of sound propagation through the fuel [6, 8, 10].

For mathematical problem solving (systems of differential equations that can occur [6, 8]), the following relations must be taken into account:

– bulk modulus, which is defined as:

$$B = \rho \frac{\partial p}{\partial \rho} \tag{1}$$

– relationship between the speed of sound a, bulk modulus B and density ρ as:

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

– the speed of sound a is given by:

$$a^2 = \left(\frac{\partial p}{\partial \rho} \right)_{s=\text{const.}} \tag{3}$$

It is obvious that the knowledge of at least two of addiction is needed:

$$a = a(p,T), \;\; \rho = \rho(p,T), \;\; B = B(p,T) \tag{4}$$

Various researchers have recognized the dependency of these fuel properties on pressure and temperature, and performed some papers in order to quantify their relation [6, 11-16]. Tat *et al*. [12, 13] reported the tendency of these properties against the pressure up to 35 MPa, at 293-313 K. Ott *et al*. [14] measured the density and speed of sound at 83 kPa and temperatures from 278 to 338 K. Dzida *et al*. [15] measured the speed of sound within the temperatures from 293 to 318 K and at pressure from 0.1 to 101 MPa, measured the density under atmospheric pressure, and calculated it for higher pressure values. Payri *et al*. [16] measured the speed of sound at pressure from 15 to 180 MPa and temperature from 298 K to 343 K. The density was measured at atmospheric pressure and calculated at high pressures.

The aim of this paper is to present one way of simultaneously measuring the speed of sound and density of tested fuels at pressures up to 160 MPa.

Basic approach in choosing the method of measurement based on the idea that the fluid which was being tested, compressed (with a reduction in volume but constant weight), while monitoring pressure, measured (determined) volume (or through a change of volume, stroke, *etc*.) and on the basis of equation (5) to determine the density.

$$m = \rho V = \text{const.} \tag{5}$$

Furthermore, there is a need to find a possibility to determine the speed of sound through the fluid depending on operating pressure. Knowing the speed of sound and density, it is easy to determine the bulk modulus (2). Schemes of some of the standard methods for the determination of density (variable volume method) are given in fig. 1 [17].

The volume of tested fluid (F) is changing by movement of piston (P) of solid material (fig. 1(a), or by pushing the medium fluid (LP), fig. 1(b), or by the effect dilatation vessel – bellows cell (B), fig. 1(c), all as a consequence of changes caused by the controlled auxiliary pressure fluid (CF – compressing fluid under known pressure). The disadvantages of this and similar methods are noticeable when operating with the so-called "high operating pressures", which in this case have the assumed upper limit pressure of 160 MPa. This primarily refers to problems in sealing (fig. 1), and a possible leakage (dripping or wetting), or the loss of the substance (fluid being tested F), in the area around the piston (sealing) rings (S), which is very unacceptable in terms of measurement accuracy. For examples of b and c, there is also the problem of ensuring reliable operation of the apparatus at higher pressures. Since it is necessary to measure the speed and volume of fluid to be tested at the same time, and to provide reliable position of measuring equipment and functionality, it was concluded that the aforementioned methods of measurement (fig. 1) and the similar, in terms of set measure requirements, are not reliable enough and that it is technically very difficult and complicated (or unreliable) to remove the noted deficiencies, thus they could not be accepted for the planned measurements.

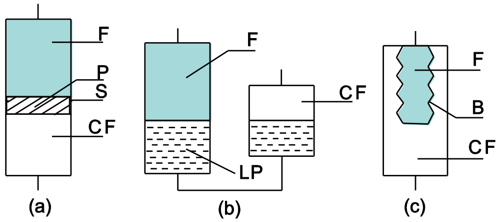

Figure 1. Methods of determining fluid density depending on pressure and temperature (examples) [17];
F – fluid being tested, P – piston, LP – medium fluid, B – bellows cell, CF – compressing fluid, S – piston (sealing) rings

Given the above analysis and conclusions, or perceived restrictions, on the use of standard methods of measurement to determine the fluid density investigated depending on the pressure, the approach that was based on the change in volume of the test fluid was abandoned, along with the interpretation of the equation $m = \rho V$.

Rather than using the approach $m = \rho V = \text{const}$, where we have constant fluid mass and variable fluid density and volume, consider the expression:

$$V = \frac{m}{\rho} = \text{const.} \tag{6}$$

In this interpretation, the required density values are determined on the basis of known and constant fluid volume and variable mass values, if these values are measurable. More precisely, if we have a closed vessel of constant (fixed) volume with known fluid mass, at the known pressure, we can calculate what the density of the fluid being tested is. If in the same vessel, we can add a known (measured or determined) mass of fluid, while fluid volume remains the same, we will raise the pressure in the vessel, making it possible to determine the value of the density of the fluid being tested at the new pressure. The speed of propagation of sound waves through the tested fluids (fuels) at varying operating pressures can be determined by comparative ultrasound measurement of suitable size.

Equipment and procedures

The condition of constant volume of fluid is reduced to the construction of the vessel that would allow "inaction" on the condition of raised pressure in the vessel (up to 160 MPa). More specifically, this high-pressure vessel (HPV) should not be dilating it in any way or should be dilating so that dilatations can be calculated and do not affect the accuracy of measurements.

In addition to this fundamental, the HPV must satisfy other technical requirements, especially in terms of tightness of joints, filling process and inserting measurement elements.

In accordance with the requirements set of test fuel at pressures up to 160 MPa, the original method was designed, and the original measurement apparatus built which allowed the appropriate measurements [6].

The basic elements of the apparatus (fig. 2) are:

– high pressure mechanical pump (HPP),
– high pressure vessel (HPV),
– installation that connects the high pressure pump and the high pressure vessel, with appropriate sealing elements, also with original technical solutions,
– ultrasonic device (UD) with ultrasonic probe (UP) and,
– measuring tube (MT).

There are two sections (fig. 2):

I – the installation at atmospheric pressure and
II – the installation at high pressure.

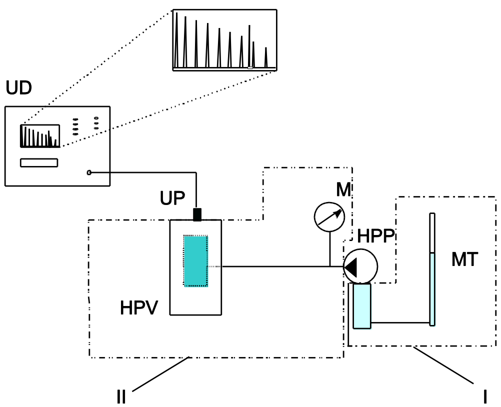

Figure 2. Scheme of the apparatus with measuring elements

The selection of HPP unit which pumps a certain amount of fluid is determined on the basis of the types of operating fluids, the approximate volume of fluid in the high pressure system, operating pressure and other criteria, such as, for example, pump operation without its own vibration, with a possibility of breaks while operating (due to the tightness of the testing system, testing the position of measuring elements), with a predicted air valve and so on.

The principle used in determining the density dependence of the tested fuel pressure at a known temperature is the starting point of an equivalent, constant mass, *i. e*. mass of intake fluid (at atmospheric pressure p_0, density ρ_0) is equal to the mass of fluid that is pumped into the HPV at pressure p_i and density ρ_i.

Simultaneously, ultrasonic measurement (direct pulse-echo method, single transmitting-receiving transducer 2.5 MHz) was carried out with the sound wave transmission time, through the "sandwich" structure, which was based on the determined speed of sound a_i at i-th fuel pressure p_i and tested fuels.

Calculation of stresses and 3-D dilatations (volume change from atmospheric pressure to 160 MPa) of HPV (fig. 3.) is also included in the results (Pro/Mechanica Structure analysis).

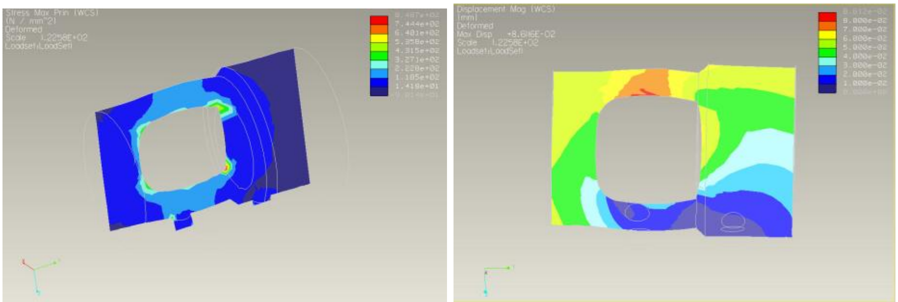

Figure 3. Stresses and dilatations of HPV at 160 MPa

Results and discussion

Measurements were conducted with three different fuels: pure rapeseed oil (PRO), rapeseed methylester (biodiesel – RME), and conventional diesel fuel. Measurements were carried out with the fuels temperature of 293 K, and operating pressures ranging from atmospheric pressure to 160 MPa.

The measurement results (average values for 10 measurements for each fluid) are shown in diagrams in figs. 4-7.

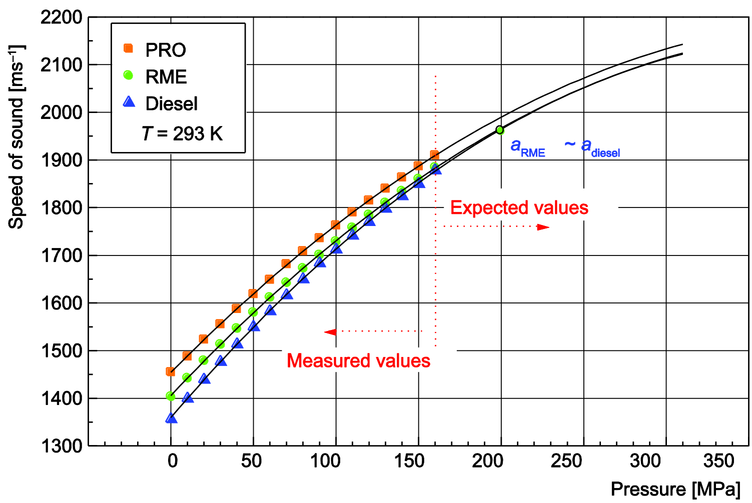

Figure 4. Speed of sound for tested fuels; experimental values from atmospheric to 160 MPa pressure and expected values for higher pressures

The value of the speed of sound (at atmospheric pressure and 293 K) for diesel fuel was 1356.82 m/s, 1403.57 m/s for RME, and 1454.70 m/s for PRO (average value for several measurements).

In order to make this information easier to use, the data obtained for isothermal curve T = 293 K were fitted to polynomial expressions, eqs. (7)-(9):

$$a = A_0 + A_1 p + A_2 p^2 \tag{7}$$

Table 1. Polynomial coefficients for eq. (7) for tested fuels

Fuel	A_0	A_1	A_2
PRO	1454.19209	3.508	$-4.0\cdot10^{-3}$
RME	1405.69827	3.691	$-4.0\cdot10^{-3}$
Diesel	1359.35185	4.053	$-5.0\cdot10^{-3}$

where a is the speed of sound, p – the fuel pressure, and A_0, A_1, and A_2 are polynomial coefficients (tab. 1).

The values of the speed of sound increase with the increase in pressure, while the differences in the speed of sound between the tested fuels reduce with increasing operating pressure (fig. 3). The analysis of these observations and certain assumptions in this regard show that there is a pressure on the border (≈ 200 MPa, at T = 293 K) which would equalize the value of the speed of sound for biodiesel with the value of the speed of sound for conventional diesel fuel [1].

The values of density also increase with the increase in operating pressure. The increase in density is approximately the same for all three tested fuels (fig. 5).

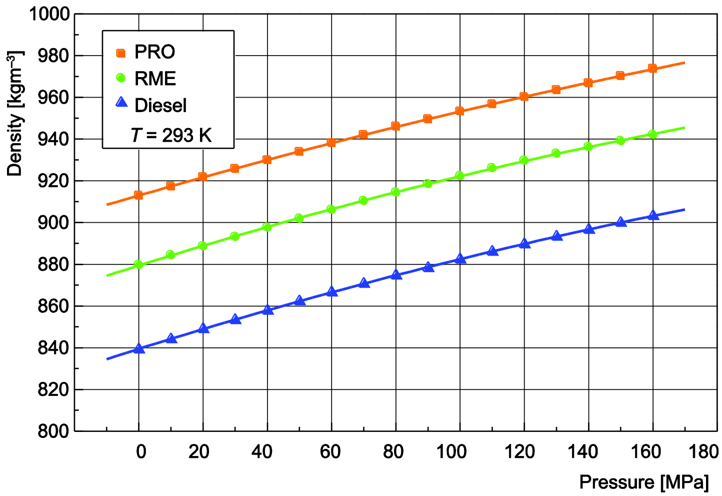

Figure 5. The density for tested fuels; experimental values

The values of density (at atmospheric pressure and 293 K, average values for several measurements) are:
- for diesel fuel, 839.3 kg/m^3 (EN 590: 820-845 kg/m^3),
- for RME, 879.7 kg/m^3 (EN 14214: 860-900 kg/m^3) and
- for PRO, 912.9 kg/m^3.

The polynomial expression is:

$$\rho = R_0 + R_1 p + R_2 p^2 \tag{8}$$

Table 2. Polynomial coefficients for eq. (8) for tested fuels

Fuel	A_0	A_1	A_2
PRO	912.93329	0.4420	$-3.9874\cdot10^{-4}$
RME	879.37945	0.4842	$-5.6303\cdot10^{-4}$
Diesel	839.43780	0.4833	$-5.3231\cdot10^{-4}$

where ρ is the fuel density, p – the fuel pressure, and R_0, R_1, and R_2 are polynomial coefficients (tab. 2).

When we know the speed of sound and density (for all three fuels) depending on the pressure, using Newton's form (2), for each i-th pressure we can easily determine the bulk modulus $B_i=B_i(a_i,\rho_i)$, *i. e.* define bulk modulus changes curve for the pressure range from atmospheric to 160 MPa (fig. 6).

The values of bulk modulus also increase with the increase in pressure for all three fuels, but as the diagram of changes of density shows, the rise of pressure does not significantly affect the differences in the bulk modulus values of the fuels.

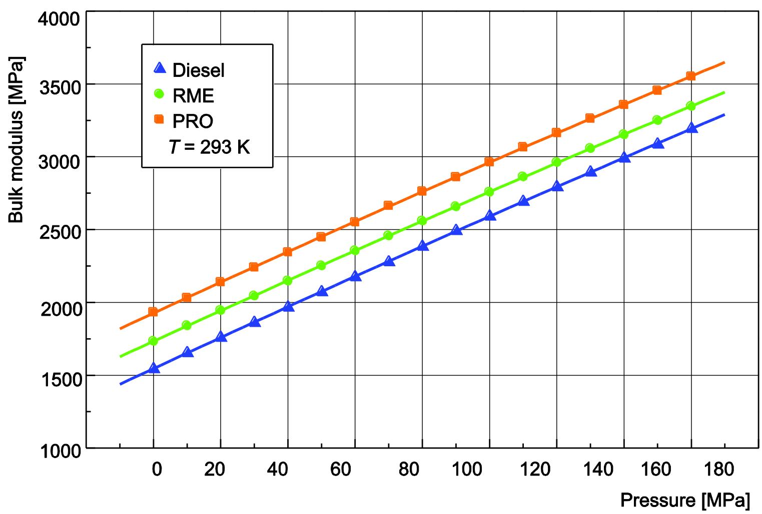

Figure 6. Bulk modulus for tested fuels calculated by experimental values of speed of sound and density

The polynomial expression is:

$$B = B_0 + B_1 p + B_2 p^2 \tag{9}$$

Table 3. Polynomial coefficients for eq. (9) for tested fuels

Fuel	D_0	D_1	D_2
PRO	1.9260 109	1.0668 107	$-3.11997\cdot10^{3}$
RME	1.7328 109	1.0545 107	$-2.83836\cdot10^{3}$
Diesel	1.5452 109	1.0720 107	$-2.69285\cdot10^{3}$

where B(MPa) is the bulk modulus, p(MPa) is the fuel pressure, and B_0, B_1 and, B_2 are polynomial coefficients (tab. 3).

In order to confirm the validity of measurements, we compared the measured values with the values of the speed of sound and bulk modulus, available in the literature [6, 8]. Comparative diagrams are shown in figs. 7 and 8.

The experimental values correspond well to the available literature values [6, 8] – up to 60 MPa. Since the same method of measurement was used for pressures of 60 to 160 MPa, we believe that the validity of results is confirmed.

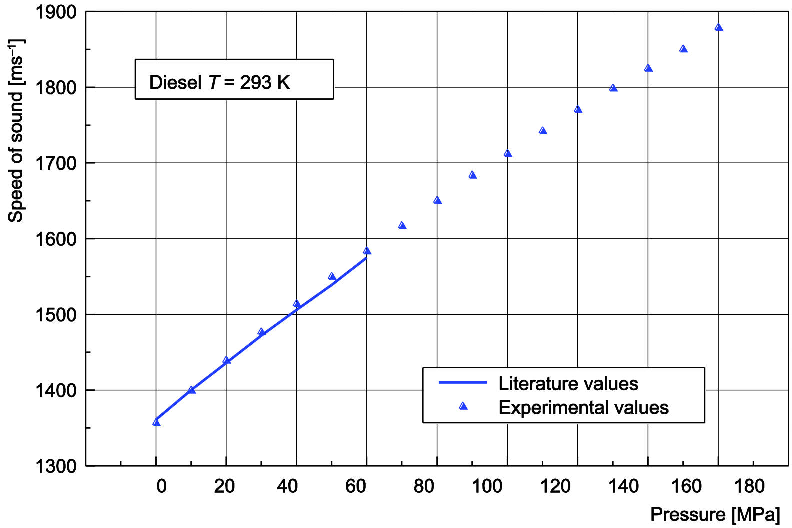

Figure 7. Comparative diagram of the speed of sound values for diesel fuel

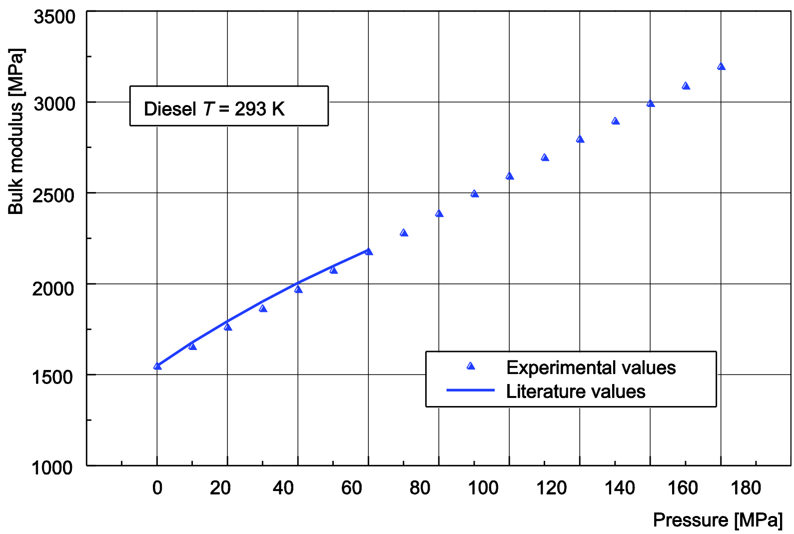

Figure 8. Comparative diagram of the bulk modulus values for diesel fuel

Conclusions

The paper presents specific ideas on how to measure the speed of sound and density, based on which the original measurement method was designed, and special original apparatus was built. The method is completely non-destructive. The process of preparation of measurement, calibration of measuring devices, measuring and the results of this experimental research is presented in detail in [6], while this paper provides some of the results with appropriate comments. The measurement results are presented in corresponding diagrams (fig. 4-6). Measurements were carried out for operating pressures up to 160 MPa. Conducted measurements show a significant increase in the speed of sound, density and bulk modulus of tested fuels with the increase in the operating pressure (tab. 4).

Table 4. The increase in values of speed of sound, density and bulk modulus at 160 MPa compared to the values at atmospheric pressure [%]

Speed of sound			Density			Bulk modulus		
PRO	RME	diesel	PRO	RME	diesel	PRO	RME	diesel
31	34	38	6.65	7.11	7.80	84	93	106

The impact of the speed of sound, density and bulk modulus on fuel hydrodynamic processes in the high-pressure part of the fuel supply system of diesel engines is gaining importance with the increasing operating pressures, which is today a tendency in modern fuel injection systems.

The knowledge of these physical quantities and relations, opens up the possibility to intervene on the existing fuel injection systems to optimize performance, or to model new fuel injection systems in the design phase. This knowledge is also necessary for the proper formation of the mixture and the combustion quality.

It should be noted that the presented method of measurement to determine the speed of sound, density and bulk modulus, has virtually no limits in terms of operating pressures. The constrcuted apparatus is dimensioned for operating pressures up to 160 MPa, but it is possible to build an apparatus for even higher operating pressures.

Furthermore, this method can be successfully applied to other liquid fluids – such as hydraulic oil. These facts provide a universal character to the used methods.

Notation

These research results were presented at the international conference, Alternative Fuels 2008, at the University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia.

Nomenclature

a – speed of sound, [ms^{-1}]
A_i, B_i, R_i – polynomial coefficients (i = 0,1,2), [–]
B – bulk modulus, [Pa]
m – mass, [kg]
p – pressure, [Pa]
T – temperature, [K]
V – volume, [m^3]

Greek symbol

ρ – density, [kgm^{-3}]

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