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Determination of fuel atomization quality in compression ignition engines using acoustic emission signal

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The analysis of fuel injection processes in diesel engines showed the convergence of physical parameters affecting the mean diameter of the Sauter SMD (selected as a spray quality parameter) of the atomized fuel droplets and the parameters of the acoustic signal emission originating from the spring waves accompanying the atomization process. In experimental studies, the laser diffraction method was used to measure the atomization quality with the Malvern Spraytec device. For the acoustic signal recording and processing there was used the measurement set with a Fujicera 1045S sensor. The correlation between the values of the Sauter diameter and the energy of the acoustic signal has been obtained on the basis of which a method has been developed to assess the quality of fuel atomization in compression ignition engines by measuring the acoustic signal recorded during the fuel injection process.

Key words: *Diesel engines, fuel injection, atomization, Sauter mean diameter, acoustic emission*

1. Introduction

Basic requirements for the internal combustion engines primarily concern the limitation of toxic compound emissions in the exhaust gases and the reduction of fuel consumption. The achievement of these demands entails the application of various types of oxidizing and toxic compound reducing devices in the exhaust system and the organization of the work process in the combustion chamber. The areas of improvement of tested processes include: the preparation, injection and combustion of the fuel, which will enable a smaller amount of toxic compounds generated [11, 15] and can be reduced in the exhaust after-treatment system. In compression-ignition engines, such solutions concern inter alia using an injection equipment with the injected fuel of an increased pressure, which at present reach the value of 220–270 MPa e.g. Bosch injectors with the sensors: NCC and VCC EM (220 MPa) and piezo (250 MPa), heavy goods vehicles 270 MPa. There is also a research conducted on increasing that pressure to 300 MPa [11, 22, 33], regulating the course of fuel injection characteristic in storage systems of Common Rail type and optimizing the combustion chamber structure to the shape of injected fuel spouts [19, 21, 24, 36]. For each construction of diesel engine, there are specific optimal combinations of injection and atomization characteristics combined with the air charge and combustion chamber shape, which provide the best operation parameters of the diesel engine [31]. It should be emphasized that the occurring processes of fuel and air mixing make a decisive impact on physical phenomena (fragmentation and vaporization) and chemical phenomena (initial chemical reactions and oxidation), which have a decisive influence on self-ignition delay period, diffusive and kinetic combustion [12].

In this regard during examination of processes of creation, and combustion of flammable mixture in the diesel combustion chamber, what is essential are fuel drop diameters, which set among others evaluate the quality of the atomized fuel [15]. The laboratory tests of fuel atomization processes [5, 6] most frequently do not take into account the complex changes of flows and pressure inside the engine cylinder. Enhancing the computing capabilities made it possible to apply the numerical simulation methods in order to specify the shape of atomized fuel spout and the size of emerging drops. An example are the developed programs for the simulation of atomization process course [10, 18, 34] and liquid fuel drop evaporation [28, 30], where inter alia on the drop size depend the time of transition from the liquid to the gas phase, in which the fuel ignites and combusts.

Determining the size of atomized fuel drops entail the selection and application of the appropriate measurement method [1, 15, 16, 35] and specialized devices enabling the implementation of the selected method. Sometimes the complexity of the specialized equipment complicates the essential measurements. It needs to be emphasized that not every method of determining the quality of the atomized fuel is possible to be applied directly on a working diesel engine [10, 34].

On the other hand, processes occurring during the fuel flow and atomization are pulse in nature, during which the spring waves are formed emitting the acoustic signal at the same time [8, 9, 29]. Measurement of such a signal is simple enough, however the treatment and processing of that signal in order to gain diagnostics information concerning the work state of the specific engine element, is complex. First of all, it is related to recording all overlapping acoustic signals emitted by the elements of the working engine. Therefore, the energy level of the signal through the time-frequency decomposition of the signal enables the determination of the background noise which is characteristic in the designated frequency bands. The effective value of the signal is also the base value for determining the so-called "cut planes" in the result spectrum called the effect spectrum [25, 26]. The papers [4, 25, 26, 28] show the possibilities of using the acoustic emission (EA) to determine the technical condition of elements of injection equipment in compression-ignition engines, such as injection pump or injectors, but this information is usually of a nature comparative to the previously recorded model reference signal of injection equipment elements and does not have any features related to the quality of the processes taking place, including the quality of fuel atomization.

In the study source literature, there is lack of information on the topic of relation between fuel atomization quality and the emitted acoustic signal, which accompanies the atomization process. Therefore, the purpose of the conducted analytical and experimental studies is developing a method of determining the quality of fuel atomization in diesel engines in the form of droplet size and distribution in the injected fuel spout with the use of a non-invasive diagnostic method based on the analysis of the acoustic emission signal, emitted during fuel atomization.

2. Atomization quality and acoustic emission during fuel injection

2.1. Quality of the injected fuel atomization

For the fuel injection processes in compression ignition engines, it is important to know the mechanisms of the formation of an atomized spout. The issues and the history of the theory concerning the mechanism of the droplet formation are described, among others, in the works [2, 17, 20]. They concerned the disintegration of a cylindrical spout of non-viscous liquid in a vacuum, and the small disturbance method (Rayleigh mechanism) was used to analyse the instability and disintegration of the spout. In the next analyses, the viscosity of the liquid and its influence on the growth of disturbances, the influence of environmental forces on the spout, including those deflecting the axis of the spout and various parameters ranges of the phenomenon, and others were taken into account [17]. The complexity of the processes imposed the necessity to assume simplifications and limit ourselves to selected physical quantities influencing the atomizing phenomenon. The result of analytical tests based on differential equations and dimensional analysis are criterion equations and similarity numbers characterizing the course and effects of atomization. For compression ignition engines, due to the heat exchange processes, evaporation and droplet combustion, in the case of assessing the fuel spout in the combustion chamber, the criterion is the Sauter mean diameter (d_{32} or SMD – Sauter Mean Diameter), which expresses the equality of the volume ratio to the droplet surface (the amount of N_i drops of diameter D_i) in the spout real and theoretical: $D_{32} = \Sigma N_i \cdot D_i^3 / \Sigma N_i D_i^2$. Data on a representative droplet diameter, crucial for the analysis of the processes of heating, evaporation and combustion of fuel droplets in the diesel engine chamber, may come from various sources – literature, based on previously published results of experiments in atomizing and burning a spout of fuel [20], calculations according to formulas formulated thanks to the theory of similarity, semi-empirical or empirical formulas, confirmed in experience with available methods of determining the microstructure of the spout, e.g. [2, 13, 14, 28, 32]. These dependencies include:

- Hiroyasu and Kadota equation:

$$D_{32} = 2362 d_0^{0.262} \rho_A^{0.121} \rho_F^{-0.0665} \Delta p_F^{-0.0695} \quad (1)$$

- Tanasawa and Toyoda equation:

$$D_{32} = 3.98 \cdot 10^7 d_0 w_F^{-1} \sigma^{0.25} \rho_A^{-0.25} g^{0.5} \cdot$$
$$\cdot \left[1 + 3.34 \cdot 10^{-2} \eta g^{0.5} (\sigma \rho_F d_0)^{-0.5}\right] \quad (2)$$

and other [17]. Despite the differences in the dependencies obtained by the Authors, caused by individual methods and the measuring equipment used, it can be concluded that the droplet diameter in jet atomizers is influenced by the following physical quantities: nozzle hole diameter d_0, relative initial velocity of fuel in the gas (outflow from the atomizer) w_F, surface tension σ, dynamic fuel viscosity η_F, dynamic air viscosity η_A, fuel density ρ_F, air density ρ_A:

$$D_{32} = f(d_0, w_F, \eta_F, \eta_A, \rho_F, \rho_A, \Delta p, \sigma) \quad (3)$$

2.2. Acoustic emission

Acoustic emission as a method of diagnosing the phenomena occurring in internal combustion piston engines has not found wide application. However, among the few works on determining the technical condition of these engines, one can mention attempts to diagnose the condition of fuel injectors, which is important for such systems as storage (Common Rail type) or timing systems [4, 27, 28]. The main reason for this is the rather difficult processing of acoustic emission signals along with their further interpretation, which should indicate the location of the damage or provide information about the technical condition of this element, which imitates an acoustic signal. It is important for such elements or phenomena which cannot be investigated with other diagnostic methods, such as storage injection systems.

The processes taking place in the injector during fuel atomization, among others, are related to disturbances caused by the components of flow velocities [17, 23], which can be presented in the form of the Schnerr-Sauer model, in which the transfer equation has the form [16, 17]:

$$\frac{\partial \alpha}{\partial t}(\alpha \rho_A) + \nabla(\alpha \rho_A w_A) = \frac{\rho_A \rho_F}{\rho} \frac{d\alpha}{dt} \quad (4)$$

where: α – volume steam concentration, ρ_A i ρ_F – gas and liquid phase density, ρ – density of the mixture ($\rho = \alpha\rho_A + (1 - \alpha)\rho_F$), w_A – gas phase velocity.

Relationship between mixture density and gas phase density is presented by the equation:

$$\frac{d\rho}{dt} = -(\rho_F - \rho_A) \frac{d\alpha}{dt} \quad (5)$$

In turn, the difference in phases density; gas and liquid during turbulent flow, which occurs in the process of fuel atomization in compression ignition engines, is presented in a differential-integral form, linking turbulent motion with the acoustic field resulting from such a flow [3, 7]:

$$\rho_F - \rho_A = \frac{1}{w_0^2} A - \frac{1}{w_0^2} \frac{\partial}{\partial x_i} B + \frac{1}{w_0^2} \frac{\partial^2}{\partial x_i \partial x_j} C \quad (6)$$

where: w_0 – velocity of density fluctuation, x_i and x_j acoustic wave coordinates, A, B and C – respectively, integrals describing the acoustic field, the local speed of pressure impulse (pulsation) change and volume deformation.

For example the acoustic field (A) generated by the velocity disturbance source is presented by the integral [3]:

$$A = \int_S \frac{\partial}{\partial t}[\rho_i w_i \bar{n}] \frac{dS(i,j)}{4\pi r} \tag{7}$$

local velocity of momentum change (B) from the pulse character of pressure change:

$$B = \int_S \left[(\rho_i w_i + p_{ij})\bar{n}_i\right] \frac{dS(y)}{4\pi r} \tag{8}$$

volume deformation (*C*) under the influence of applied forces:

$$C = \int_V \frac{\bar{T}_{ij}}{4\pi r} dV(y) \tag{9}$$

where: S – surface of the disturbance source, $\bar{n}$ – surface normal S, r – volume distance from the surface S to the disturbance source, p_{ij}, T_{ij} – tensors of tensions and density of disturbance impulse stream.

It should be emphasized that the A, B and C integral equations mainly include the phase density parameters; gas and liquid (ρ_A and ρ_F) and their velocities w, surface tension σ and pressure difference Δp of the mixture and the medium into which this mixture is injected.

Developing the problem presented this way in paper [3] it was shown that frequency and the intensity of sound disturbances as well as the change in energy flux density are determined by velocities w and the change in density ρ, while the rate of change in acoustic resistance in the form of acoustic energy Z over time τ can be written in the form:

$$\left(\frac{\partial Z}{\partial \tau}\right)_{i,j,k} = \int_{w_1}^{w_n} \int_{\rho_1}^{\rho_n} (\partial w \, \partial \rho)_{i,j,k} \tag{10}$$

where: i, j, k – acoustic wave move coordinates.

Analysing the problem of acoustic phenomena presented in this way, it can be concluded that the energy of the acoustic signal:

$$Z = f\,(w_F, \rho_F, \rho_A, \Delta p, \sigma) \tag{11}$$

depends on the same physical parameters involved in determining the quality of the sprayed fuel (SMD) – velocity w, density ρ, pressure Δp and surface tension σ, present in equation (3), so it provides the basis for linking the fuel injection processes and the accompanying acoustic phenomena to evaluation of the quality of fuel atomization in compression ignition engines.

2.3. Analytical study

The above-mentioned mathematical relationships concerning fuel atomization and acoustic emission were used in analytical tests. At the same time, the essential construction parameters of the atomiser as well as the physical parameters of the selected fuels were selected for further experimental research. Figure 1 shows the cross-section of the tip of the D1LMK 148/1 type atomizer used in compression ignition engines of type 359, while Table 1 shows the geometric parameters of the atomizing slots.

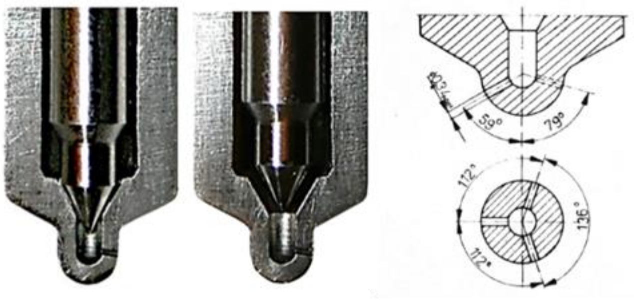

Fig. 1. Geometric parameters of D1LMK 148/1 atomizer used at the test stand

Table 1. Geometric parameters of slots of the atomizer D1LMK 148/1

No.	Parameter	Dimension
1.	Atomizer slot diameter do	0.34 mm
2.	Channel length Lo	1.2 mm
3.	Proportion Lo/do	3.5

The selection of this type of atomizer was not random and took into account the possibility of conducting further experimental tests on a laboratory stand. The same concerned the selected fuel – in the analytical tests there were used the physicochemical parameters of petroleum diesel fuel (DF) and its mixture with methyl esters of rapeseed oil (RME). Physical parameters of these fuels have been presented in Table 2.

Table 2. Physical parameters of the fuels selected for the analytical and experimental studies

Fuel	Kinematic viscosity	Density	Dynamic viscosity	Surface tension
	ν_F	ρ_F	η_F	σ
	10^6 m^2/s	10^{-3} kg/m^3	10^3 Pas	10^3 Nm
DF	4.49	0.8240	3.70	27.36
5%RME	4.57	0.8251	3.78	27.47
7%RME	4.63	0.8263	3.82	27.53
10%RME	4.65	0.8286	3.85	27.57
100%RME	5.39	0.8700	4.69	30.13

In the Figure 2 and 3 there are presented the results of analytical studies concerning determination of Sauter mean diameter of atomized fuels drops (SMD) on the basis of Hiroyasu and Kadota equations (equation 1) and acoustic resistance (Z) accompanying this atomization as a function of the pressure of selected fuels injection (equations 4–10).

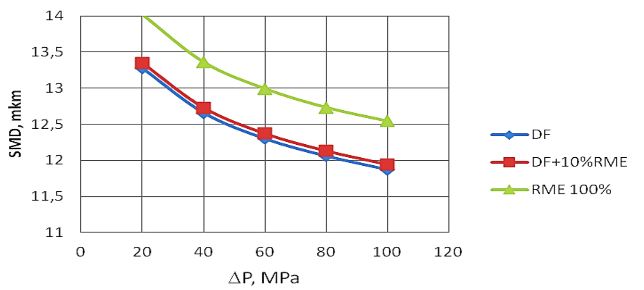

Fig. 2. Change of the average diameter of atomized fuel drop depending on the injected fuel pressure

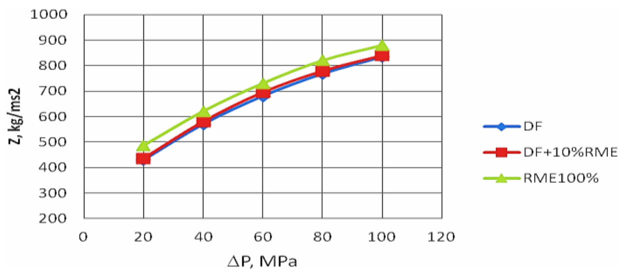

Fig. 3. Acoustic resistance change (*Z*) as a function of the pressure of selected fuels injection

The obtained results fully correspond to the physical phenomena of the fuel atomization process. Increasing the pressure of fuel injection causes the reduction of the droplet average diameter, and thereby the increase of acoustic emission of the atomization process. The same effect occurs also for the mixture of petroleum fuels with methyl esters of rapeseed oil (RME) – increase of density, viscosity and surface tension in the fuel mixture causes the SMD increase and the emitted acoustic signal increase.

3. Experimental studies

In addition to the previously discussed methods for determining the droplet diameter, coming from the source literature, based on previously published experimental results, calculations according to formulas based on the theory of similarity, semi-empirical or empirical formulas [26], the most reliable method for determining the representative value of the droplet diameter seems to be a direct analysis of the microstructure of the real atomized fuel spout using modern techniques of recording and processing signals [1, 19].

The Spraytec apparatus by Malvern (MAL 1057129), equipped with an optical system designed to measure the size of droplets in the range from 0.1 to 900 µm, was used to determine the structure of the fuel spout atomized in the atmospheric air. The instrument uses the laser diffraction technique, which measures the diffused light intensity distribution as it passes through the aerosol of a parallel laser beam. The beam with a wavelength of 632.8 nm emitted by the He-Ne laser is subject to collimation before entering the measuring zone of the instrument. The light diffused by the aerosol passes through an optical system that directs the radiation to a set of photodetectors. The results of the measurement of the diffused light intensity are subject to computer analysis in order to calculate the particle size distribution of the aerosol droplets which caused the specified distribution of the diffused light intensity.

The device uses software that allows to compare the effects of a laser beam diffusion while passing through a real set of droplets to the theoretical model of light diffusion proposed by L. Lorentz and G. Mie [18, 33]. The model results from solving Maxwell's equations for a beam of electromagnetic waves passing through a set of spherical particles using an infinite, convergent number series. The sampling frequency of the diffused light intensity distribution by the measuring module of the instrument can be up to 10 kHz. Thanks to the enclosed user software, it is possible to calculate and record the values of standard parameters (e.g., mean diameter D_{32}, volumetric concentration Cv), as well as other derivatives (e.g., arithmetic or geometric standard inflections of droplet distribution).

Laser light diffusion measurement signal, recorded by each device detector, consists of three components: an electronic background signal, an optical background signal and the actual laser light diffusion signal. The first two are distortions of the real image of the diffused light intensity. The software of the device automatically corrects the measurement signal by subtracting both noise components registered by individual detectors, just before starting the actual measurement. Both the corrected and uncorrected signals are recorded in the device memory, both for background control during the measurement and for further analyses.

During measurements, the correction option included in the application software was used for the results distorted by multiple light dispersions, caused by the high concentration of tested fuel aerosol. The algorithm for the multiple dispersion correction was a part of the measurement procedure, prepared and tested before the start of the measurement series [16]. It defined essential process parameters and device settings. They included, among others: injection character and optical properties of the liquid, the method of measurements triggering, alarm levels of the optical condition, the predicted shape and spatial position of the spout, the limit size of the droplets and the type of derivative parameters indicated in the analysis of the results. When designing the measurement procedure, the optimal distance of the spout from the optical system was established. It resulted from the assessment of the relative level of signals from different detectors. Too large a distance of the spout causes the loss of the measurement signal formed by the droplets with the smallest diameters (vignetting). Too short a distance causes accelerated contamination of the optics by the tested aerosol, despite the use of a pneumatic pollution reduction system. In addition, the measuring cross-section should be outside the zone of the compact fuel stream at the nozzle opening. At the same time, the considered measuring cross-section should be in the stabilized zone of the SMD. Since the measurement with the Spraytec device requires the prior determination of the spout flare angle α, the criterion for the distance of the measuring cross-section from the nozzle opening can be determined with the formula:

$$\frac{B}{D} = \frac{1}{2}\frac{\alpha}{2} \tag{12}$$

where: B – measuring cross-section distance to the atomizer slot, D – spout diameter in the measuring cross-section, α – spout flare angle, and the obtained parameters are entered into the Spraytec device dialog box (Fig. 4).

As mentioned earlier, the sources of acoustic emission are the moving parts of the engine, such as the piston-crank system, valves and others, as well as resonance effects that create background noise occurring in the low frequency range (< 1000 Hz) [25]. In the injection apparatus, the signal EA is created as a result of the propagation of the fuel pressure wave along the high-pressure lines as a result of slight changes in fuel pressure at the time of fuel injection and the emission resulting from the fuel phase change. The source of AE is also reflected waves due to the closing of the injectors, the closing and opening of the injection pump valves, not to mention the signals generated during the closing of the intake and exhaust valves. The determination of the fuel atomization EA signal is possible thanks to the use of the so-called event gate, which enables the analysis of the tested signal in the selected frequency band as opposed to the total acoustic emission band. It is not possible to record only the spectrum of the impulse emission emitted by the injectors, therefore it is necessary to use, in addition to the filter eliminating low frequencies, the highest possible sampling rates (separation of individual synchronous sources of acoustic emission in time) in the EA signal amplifier and the use of an event filter.

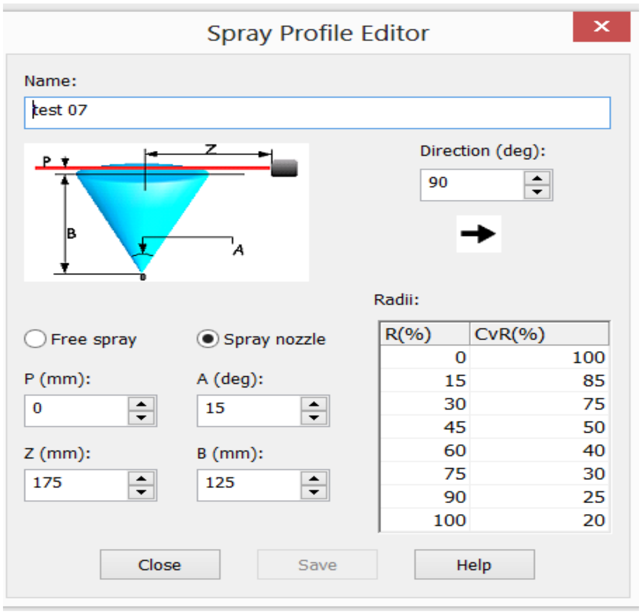

Fig. 4. Spout geometric parameters entry dialog box

The experimental tests were carried out on a special stand (Fig. 5), which included the above-mentioned Spraytec device (3), and the EPS 200 testing table by Bosch (4) for pumping fuel into the injector (1). One of the atomized fuel spouts is directed into the field of the laser beam, while after passing through this field, this spout, as well as the others, are directed to special traps (6) located in the fume cupboard (7). In turn, the acoustic signal is registered by the sensor (10) and is then amplified and processed in the tester (11). The stand is equipped with a set of thermocouples (8, 9), thus ensuring the uniformity of measurement conditions.

The module for acoustic signals registering made the measuring unit, consisting of acoustic emission sensor made by FUJICERA, type 1045S (Fig. 5, pos. 10) and tester-recorder of signal with the 24-bit analogue-to-digital converter and PC (Fig. 5, pos. 11 and 5). It needs to be emphasized that the sensor installation is not a technical problem and it can be located on the body parts of the injector at the laboratory stand as well as on a working diesel engine [4].

Atomization quality measurement method, basing on the SMD value criterion provides for entering to the Spraytec device menu certain structural parameters such as the atomizer distance to the laser beam, or the flare angle of the atomized fuel spout. Figure 6 shows an example of a screen shot of the measurement results for droplets distribution in the atomized fuel spout.

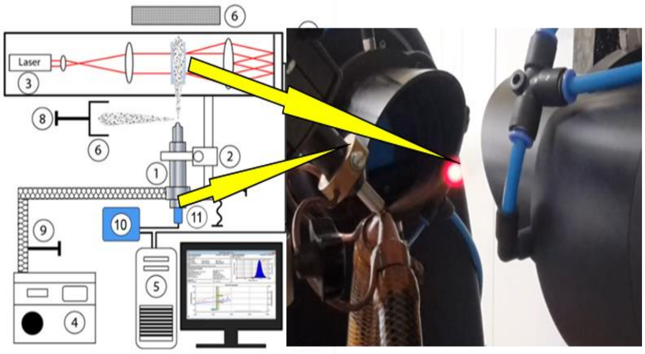

Fig. 5. Scheme of the experimental device for determining the quality of the atomized fuel and acoustic emission: 1 – nozzle, 2 – nozzle attachment point, 3 – Spraytec STP 5000 device, 4 – EPS 200 installation, 5 – personal computer, 6 – spray catchers, 7 – fume hood, 8, 9 – thermocouples, 10 – acoustic emission sensor, 11 – acoustic tester

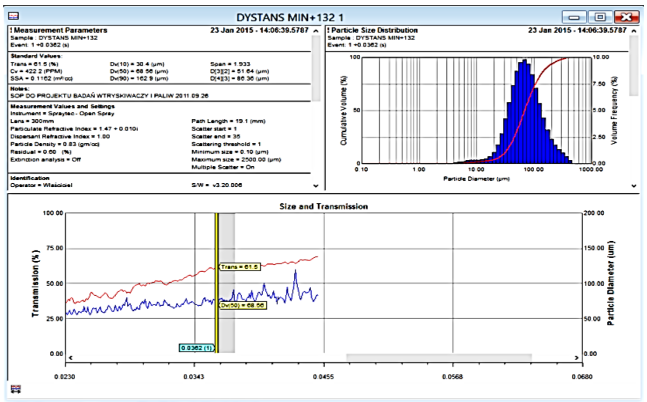

Fig. 6. Dialog box screen shot for differential and integral distribution of fuel atomization

In turn, the method of recording, processing and mathematical analysis of the acoustic signal [30] took into account the measurement of the source signal (Fig. 7a), determining the frequency band with the maximum signal (Fig. 7b) with the use of fast Fourier transform, and determining the maximum signal energy at a specific moment in time during the fuel injection process in the determined frequency band (Fig. 7c).

Such a presented algorithm of the procedure with the use of acoustic signal during the analysis process of fuel injection, is used, among others, for diagnosing the diesel engines injection device. For this purpose it is essential to determine the characteristic shape: signal energy – frequency band (Fig. 7c), which indicates the proper functioning of individual components of this device, such as high-pressure pump and the injector with its components. However, for the association of such phenomena as fuel atomization (and above all the quality of atomization) with the emitted acoustic signal of this process, the recording of the maximum value of signal energy in the determined frequency band is sufficient.

The method of EA measurement presented in this way was used in experimental tests with the use of a three-hole injector of the D1LMK 148 type (similarly to the analytical tests, Fig. 1), with only one spout being directed into the laser measurement field and the remaining ones directed to the spray catchers, which allows to eliminate disturbances caused by the superimposition of atomized fuel spouts. The value of the fuel injection start pressure changed in the range of 20.0–30.0 MPa. In these tests, as the reference fuel, there has been selected petroleum fuel (PN-EN 590 + A1: 2011 – analogous to analytical tests) used in compression ignition engines and its mixture with methyl ester of rapeseed oil (PN-EN 14214), the physical parameters of which are presented in Table 2.

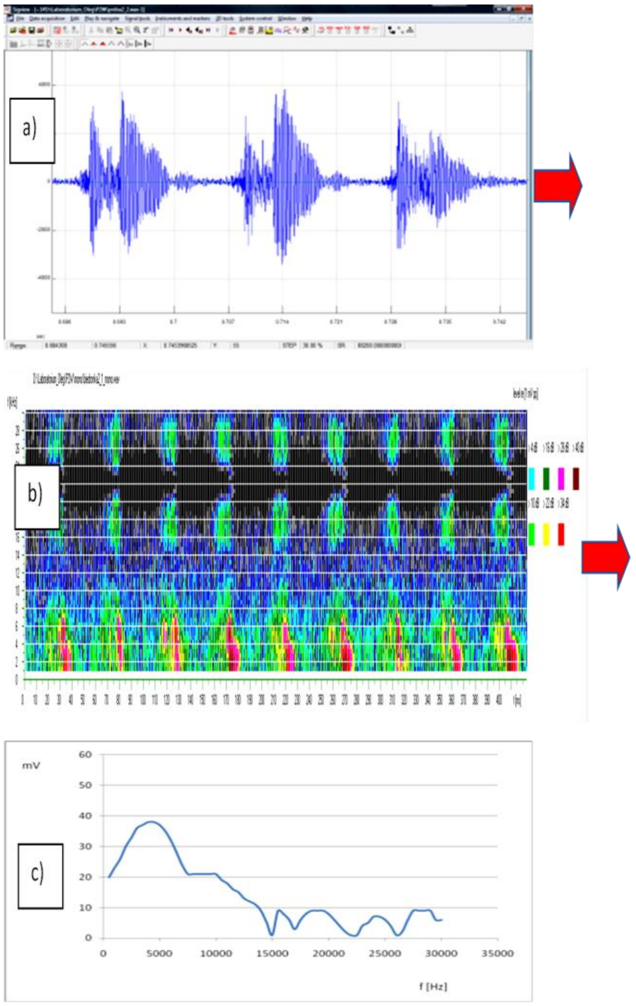

Fig. 7. Recorded source signal (a), transformation of source signal into time-frequency spectrogram and determination of the frequency band with the maximum signal (b), determination of acoustic emission signal energy in recorded frequency band at a specific moment in time (c)

Figure 8 and 9 show selected results of experimental tests concerning the registration of AE parameters and the distribution of droplets in the spout of the injected reference fuel at the change of the fuel injection start pressure.

The program for processing the recorded data of the Malvern device allows you to read the Sauter's average diameter for individual injections, which enables an unambiguous assessment of the atomization quality for selected measurement conditions – the selected fuel and the injection start pressure. In turn, the maximum signal energy in the 15 kHz frequency band was selected as a representative value of the EA signal.

Figure 10 shows the results of experimental tests on the determination of the atomization quality parameters of the reference fuel (SMD) and the acoustic emission signal level (EA) for the petroleum fuel (DF) and its mixture with the addition of 7% rapeseed oil methyl esters (RME) for the fuel injection start pressure 22.0 (Fig. 10a); 24.0 (Fig. 10b) and 26.0MPa (Fig. 10c).

The results of experimental tests presented in this way show a close relationship between the quality of fuel atomization, presented in the form of the average diameter of the atomized fuel drops (SMD), and the acoustic emission signal (EA) generated in the atomization process. The mathematical relationship of these results is described with high accuracy by polynomial equations (the coefficient of determination R^2 with a value above 0.98), while the direct relationship between the mean Sauter diameter and the energy value of the acoustic emission signal is fully described by the second-degree polynomial equation.

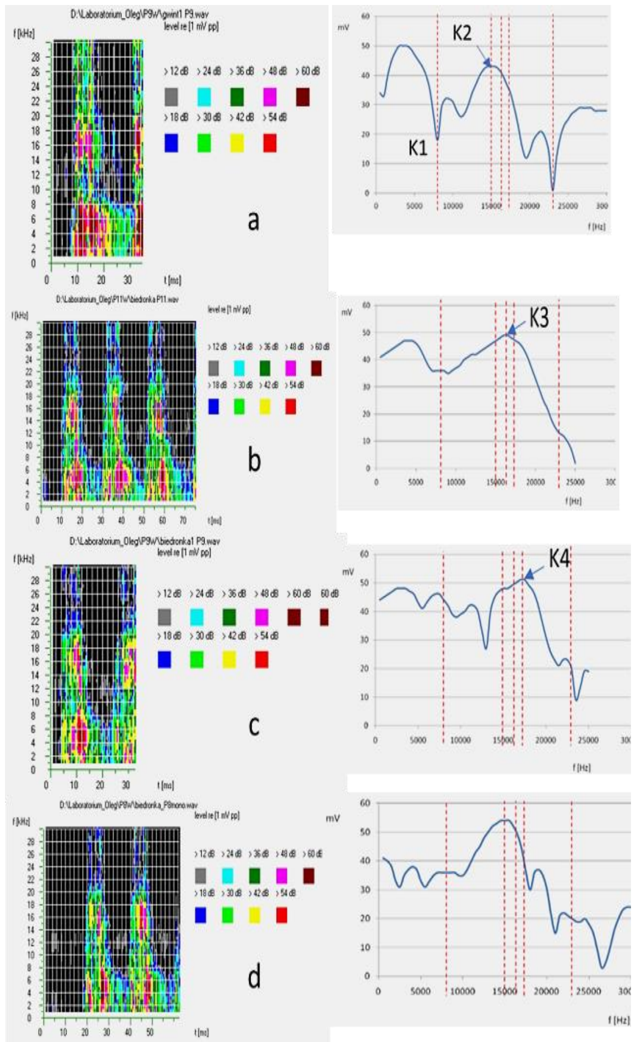

Fig. 8. Time-frequency spectrograms and energy of the EA signal in the recorded frequency band at a specific moment in time for the reference fuel: a, b, c and d – fuel injection start pressure, respectively 20.0; 22.0; 24.0 and 26.0 MPa; K1, K2, K3, K4 – reference points

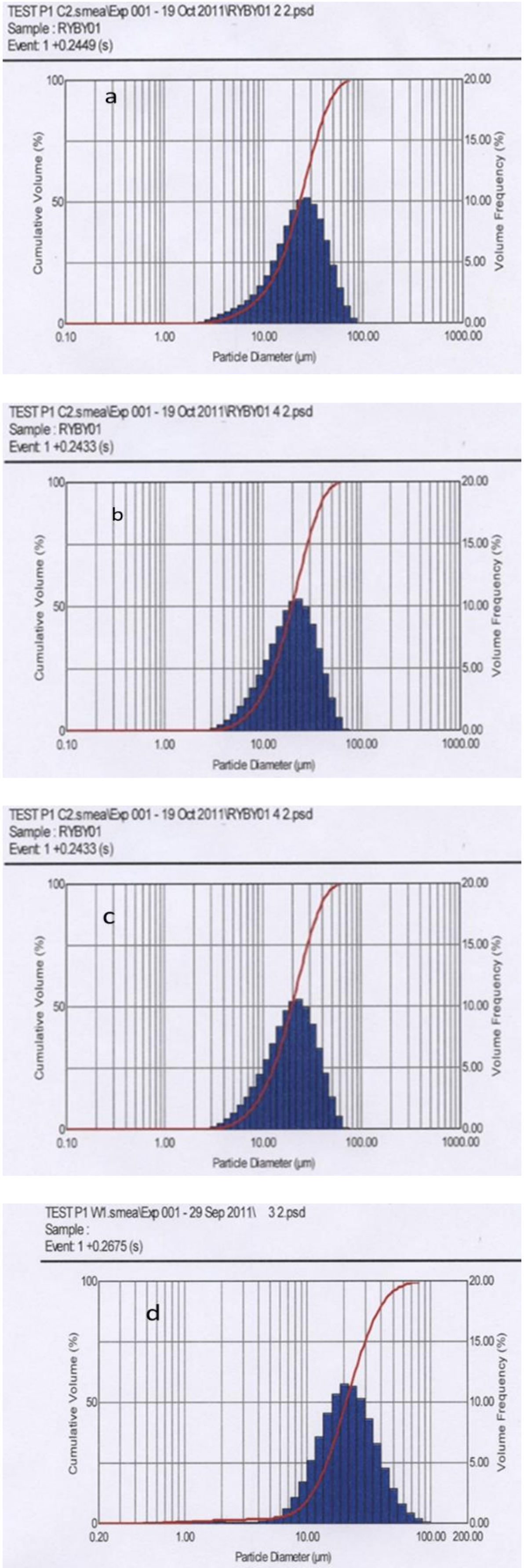

Fig. 9. Distribution of drops of the injected reference fuel: a, b, c and d – fuel injection start pressure, respectively 20.0; 22.0; 24.0 and 26.0 MPa

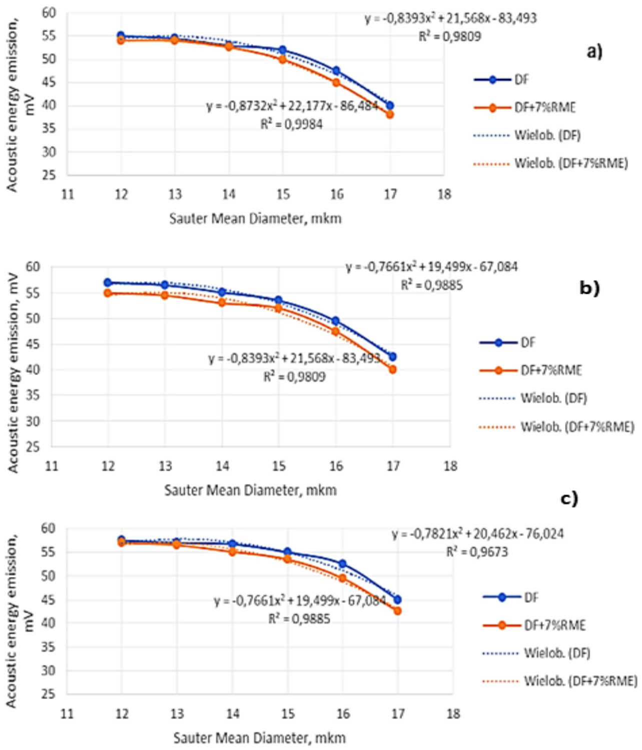

Fig. 10. Relationship between Sauter mean diameter of atomized fuel drop and level of the acoustic emission formed in the atomization process for the start fuel injection pressure: a – 22.0 MPa; b – 24.0 MPa; c – 26.0 MPa

According to the obtained results, the difference in the obtained relationships for petroleum diesel and its mixture with rapeseed oil methyl esters is 3%, which can be explained by the difference in the kinematic viscosity of these fuels (values of these parameters in Table 1 constitute 3%).

In turn, the method of determining the quality of fuel atomization used for diesel engines takes into account the measurement of the source signal emission level and determination of the signal energy in the registered frequency band. The obtained value of this energy is converted into the value of the mean Sauter diameter according to the second-degree polynomial equation. It is worth noting that this method enables the non-invasive assessment of the quality of fuel atomization directly on the running engine, thus enabling the diagnostics of the entire injection system of diesel engines.

4. Conclusions

The fuel atomization process is one of the main elements in the organization of the work process in compression-ignition engines. It has a decisive impact on obtaining the best economic and ecological parameters of their work. The qualitative determination of the fuel atomization process is directly related to the Sauter mean diameter parameter, the value of which is determined experimentally using complex test stands. The atomization itself takes place as a result of the hydrodynamic processes occurring in the fuel system elements, and one of the effects of this process is the formation of spring waves accompanied by the emission of an acoustic signal.

Based on the analysis of the state of knowledge and analytical tests, it was proved that in modelling the atomization and acoustic emission processes, the values of the same physical parameters of the fuel as density, viscosity and surface tension as well as the structure parameters of the atomizers, seem to be important, so it seems reasonable to combine these processes into a common model. For this purpose, experimental studies were carried out to determine the relationship of the quality parameters of the atomized fuel in the form of the Sauter's mean diameter, generated as a result of the acoustic signal atomization process. The measuring equipment used in the experimental tests – the measurement of the atomization quality using the laser diffraction method and the acoustic emission measuring set showed a high accuracy of the dependence of the discussed parameters. The second order polynomial equation can be successfully used to estimate the mean Sauter diameter of fuel drops using the value of the acoustic emission energy generated in the fuel atomization process. It should be emphasized that such tests can be carried out non-invasively on a working engine, which is a significant value in the field of research and operation of internal combustion engines.

On the basis of the presented method of determining the quality of fuel atomization using the acoustic emission signal, the direction of further research on the discussed issue is related to the development of universal mathematical relationships on the basis of second-degree polynomials during the statistical processing of the results of experimental tests when changing the physical parameters of fuels (density, viscosity, surface tension), structure of nozzles (diameter and length of spray slots) and fuel injection characteristics, including multiphase spraying occurring in Common Rail type injection equipment.

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