

Application of Acoustic Emission in Diesel Engines Diagnostics

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Abstract— The analysis of the processes taking place in the cylinder of a compression-ignition engine shows a high dependence of the ecological and economic parameters of its operation on the fuel atomization process. The parameter of mean droplet diameter (SMD, Sauter) used for this purpose can be used to assess the quality of fuel atomization, but its determination is only possible during laboratory tests on special stands. The article proposes a combination of testing the spraying quality with measuring the size of the acoustic emission signal originating from the elastic waves accompanying the spraying process. The relationships between the Sauter diameter and the acoustic signal level obtained in this way can be used directly on the running engine. In the experimental tests, the laser diffraction method was used to measure the spray quality using the Spraytec device from Malvern, and a measurement set with a Kistler sensor was used to record and process the acoustic signal. A relationship between the values of the Sauter diameter and the energy of the acoustic signal was obtained, on the basis of which a method was developed for assessing the quality of the fuel atomization process in compression-ignition engines by measuring the acoustic signal recorded during the fuel injection process.

Keywords— Sauter mean diameter, acoustic emission, diesel engines, fuel injection, atomization

I. INTRODUCTION

The analysis of the state of knowledge [2, 7] regarding the simultaneous reduction of the emission of toxic compounds in exhaust gases along with the reduction of fuel consumption indicates that they largely depend on the first period of the combustion process - the period of auto-ignition delay. The initial phase of feeding the combustion chamber with fuel, consisting in atomizing the fuel, is crucial for further processes of preparing the fuel-air mixture and its ignition. The fuel stream delivered to the atomizer under high pressure breaks up into drops. The droplet size (and the resulting total surface area) at specific fuel condition parameters and atomizer geometry depend on the viscosity and surface tension of the fuel.

For fuel injection processes in compression-ignition engines, it is important to know the mechanisms of spray formation. The issues and history of the theory regarding the mechanism of drop formation are described, among others, in works [1, 11, 12]. They concerned the breakup of a cylindrical stream of inviscid liquid in a vacuum, and the small perturbation method (Rayleigh mechanism) was used to analyze the instability and breakup of the stream. Later analyzes took into account the viscosity of the liquid and its influence on the development of disturbances, the influence of

environmental forces on the stream, including those deflecting the axis of the stream and various ranges of phenomenon parameters, and others [11]. The complexity of the processes required simplifications and limitations to selected physical quantities influencing the spraying phenomenon. The result of analytical research based on differential equations and dimensional analysis are criterion equations and similarity numbers characterizing the course and effects of spraying. For compression ignition engines, due to the heat exchange processes, evaporation and combustion of drops, when assessing the fuel stream in the combustion chamber, the Sauter mean diameter (D_{32} or SMD - Sauter Mean Diameter) is used as a criterion, which expresses the equality of the volume ratio to the drop surface (number of N_i drops with a diameter D_i) in the real and theoretical stream: $D_{32} = \sum N_i D_i^3 / \sum N_i D_i^2$.

Data on the representative size of the drop diameter, necessary for use in the analysis of the processes of heating, evaporation and combustion of fuel drops in the chamber of a compression-ignition engine, may come from various sources - literature, based on previously published results of experiments in the atomization and combustion of fuel streams [20], calculations according to formulas formulated thanks to the similarity theory, semi-empirical or empirical formulas, confirmed in experience by available methods for determining the microstructure of the stream, e.g. [1, 8, 9, 18, 21]. These dependencies include:

- Hirojasu and Kadot equations

$$D_{32} = 2362 d_0^{0,262} \rho_A^{0,121} \rho_F^{-0,0665} \Delta p_F^{-0,0695} \quad (1)$$

- Tanasawa and Tojoda equations

$$D_{32} = 3,98 \cdot 10^7 d_0 w_F^{-1} \sigma^{0,25} \rho_A^{-0,25} g^{0,5} [1 + 3,34 \cdot 10^{-2} \eta g^{0,5} (\sigma \rho_F d_0)^{-0,5}] \quad (2)$$

and others [11]. Despite the differences in the relationships obtained by the authors, caused by individual methods and measuring equipment used, it can be concluded that the diameter of the drops in jet atomizers is influenced by the following physical quantities: the diameter of the atomizer opening d_0 , the relative initial velocity of the fuel in the gas (outflow from the atomizer) w_F , surface tension σ , dynamic viscosity of fuel η_F , dynamic viscosity of air η_A , fuel density ρ_F , air density ρ_A :

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

In turn, acoustic emissions as a method for diagnosing phenomena occurring in piston combustion engines have not been widely used. Among the few works on determining the technical condition of these engines, one can mention attempts to diagnose the condition of fuel injectors [5, 6], which is important for systems such as storage systems (Common Rail type) or timing systems [3]. The main reason for this is the rather difficult processing of acoustic emission signals and their further interpretation, which should indicate the location of the damage or provide information about the technical condition of the element that imitates the acoustic signal.

The processes occurring in the injector during fuel atomization are, among others, related to disruptions caused by the component flow velocities and the phenomenon of cavitation [13, 15].

In turn, the difference in the densities of the gas and liquid phases during turbulent flow, which occurs in the process of fuel spraying in compression-ignition engines, is presented in the differential-integral form, linking the turbulent movement with the acoustic field created as a result of such flow.

Developing the issue presented in this way, in [2, 4, 14, 19] it was shown that the frequency and intensity of sound disturbances as well as the change in the density of the energy stream are determined by the speeds w and the change in density ρ , while the speed of change of acoustic resistance Z in time τ can be written in characters:

$$\left(\frac{\partial Z}{\partial \tau}\right)_{i,j,k} = \int_{w_1}^{w_n} \int_{\rho_1}^{\rho_n} (\partial w \partial \rho)_{i,j,k} \quad (4)$$

where: i, j, k – coordinates of the moving acoustic wave.

Analyzing the presented issue regarding acoustic phenomena, it can be concluded that acoustic resistance:

$$Z = f(w_F, \rho_F, \rho_A, \Delta p, \sigma) \quad (5)$$

depend on the same physical parameters involved in determining the quality of the sprayed fuel (average Sauter diameter) - speed w , density ρ , pressure Δp and surface tension σ , appearing in equation (3), so this provides the basis for linking the processes of fuel injection and accompanying acoustic phenomena to assess the quality of fuel atomization in compression-ignition engines.

II. EXPERIMENTAL RESEARCH

Experimental tests were carried out on a special stand (Fig. 1), which includes the Spraytec device (3) presented above and the EPS 200 testing table from Bosch (4) for pumping fuel into the injector (1). One of the sprayed fuel streams is directed into the laser beam field, and after passing through this field, this stream and the others are directed to special catchers (6) located in the fume hood (7). In turn, the acoustic signal is recorded by the sensor (10) and is later amplified and processed in the tester (11). The station is equipped with a set of thermocouples (8, 9), thus ensuring uniform measurement conditions.

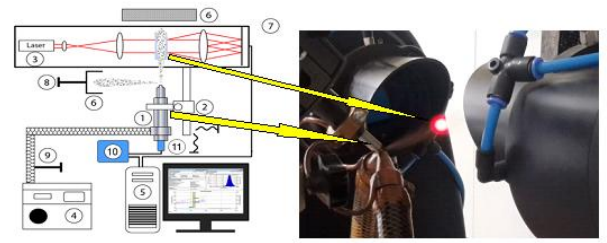


Fig. 1. Scheme of the experimental device for determining the quality of the atomized fuel and acoustic emission.

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.

The acoustic signal recording module was a measurement unit consisting of a 4371 V acoustic emission sensor from Bruel&Kjaer (Fig. 1, item 10) and a tester-signal recorder with a 24-bit analog-to-digital converter and a PC (Fig. 1, item 11 and 5). It should be emphasized that the installation of the sensor does not pose any technical problems and can be located on the injector body elements, both in the laboratory and on the running combustion engine [3, 10, 16, 17].

The spray quality measurement method, based on the SMD value criterion, provides for introducing some design parameters into the Spraytec device menu, such as the distance of the sprayer from the laser beam or the opening angle of the sprayed fuel stream. Fig. 2 shows an example screenshot of the results of measuring the distribution of drops in the spray of fuel spray.

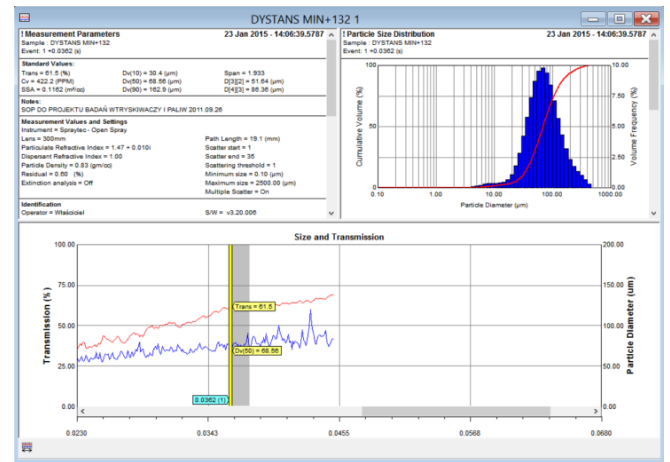


Fig. 2. Screenshot of the differential and integral fuel spray distribution dialog box

In turn, the method of recording, processing and mathematical analysis of the acoustic signal [22] included measuring the source signal (Fig. 3, a), selecting the frequency band with the highest signal (Fig. 3, b) using the fast Fourier transform and determining the highest signal energy in specific time moment during the fuel injection process in the selected frequency band (Fig. 3 c).

The presented algorithm for using an acoustic signal during the analysis of the fuel injection process is used, among others, to diagnose the injection equipment of compression-ignition engines. For this purpose, it is important to determine the shape of the characteristic: signal energy - frequency band (Fig. 3c), which indicates the correct operation of individual

components of this equipment, such as the high-pressure pump and the injector and its elements. However, to link phenomena such as fuel atomization (and, above all, the quality of atomization) with the emitted acoustic signal of this process, it is sufficient to register the maximum signal energy value in a designated frequency band.

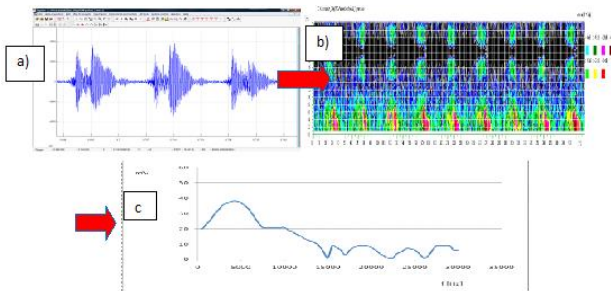


Fig. 3. Source signal (a), selection of the frequency band with the highest signal (b), determination of the energy of the acoustic emission signal in the recorded frequency band (c)

In the experimental tests, a three-hole injector type D1LMK 148 was used, with only one stream directed into the laser measurement field and the remaining streams were directed to the spray catchers, which allows to eliminate interference caused by the application of sprayed fuel streams. The value of the fuel injection start pressure changed in the range of 22.0 ÷ 30.0 MPa.

For experimental tests (analogous to analytical tests), petroleum fuel (PN-EN 590+A1:2011) used in compression-ignition engines and its mixture (up to 10% vv) with rapeseed oil methyl ester (PN-EN 14214) were selected as references. It should be noted that the choice of a mixture of DF and RME corresponds to the introduction on the market of such a mixture with an RME content of up to 7% (PN-EN14078).

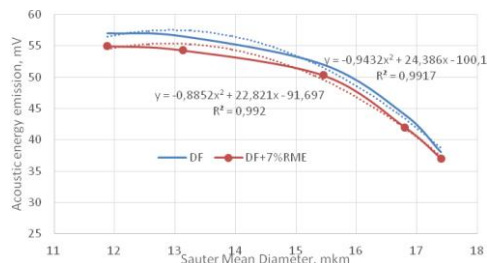


Fig. 4. Dependence of the average Sauter diameter of a sprayed fuel drop and the level of acoustic emission generated in the spraying process

The results of the experimental tests are shown in Fig. 8, which presents selected results of the analysis of the change of the SMD parameter (D32) with the change of the acoustic emission signal during spraying of the tested fuels. According to the obtained results, the difference in the obtained relationships for petroleum diesel oil and its mixture with rapeseed oil methyl esters is 3%, which can be explained by the difference in the dynamic or kinematic viscosity of these fuels (the values of these parameters included in Table 1 constitute 3%).

As a result of such research, it can be concluded that the relationship between the average Sauter diameter and the energy value of the acoustic emission signal is fully described by a second-degree polynomial equation:

$$y = -0,9432x^2 + 24,386x - 100,1 \quad (6)$$

whose coefficient of determination R^2 is 0.992.

The obtained results allow us to establish a strict relationship between the quality of the sprayed fuel in the form of the average Sauter diameter value and the acoustic emission emitted during fuel spraying. The method for determining the atomization quality of fuel used in compression-ignition engines involves measuring the emission level of the source signal and determining the signal energy in the recorded frequency band. The obtained value of this energy is converted into the value of the average Sauter diameter according to the proposed equation (6).

III. CONCLUSION

The fuel atomization process is one of the main elements in the organization of the working process in compression-ignition engines and has a decisive impact on obtaining the best technical, economic and ecological parameters of their operation. The qualitative determination of the fuel atomization process is directly related to the average Sauter diameter parameter, the value of which is determined experimentally using complex research stations. The spraying phenomenon itself takes place as a result of hydrodynamic processes taking place in the elements of the fuel system, and one of the effects of this process is the creation of elastic waves accompanied by the emission of an acoustic signal. Based on the analysis of the state of knowledge and analytical tests, it was proven that in modeling the spraying processes and acoustic emission, the values of the same physical parameters of the fuel, such as density, viscosity and surface tension, as well as the design parameters of the nozzles, play an important role, so it seems reasonable to combine these processes into a common model. For this purpose, experimental research was carried out to determine the relationship between the quality parameters of the sprayed fuel in the form of the average Sauter diameter and the acoustic signal generated as a result of the spraying process. The measuring equipment used in the experimental tests - measurement of the spray quality by laser diffraction and the acoustic emission measurement set - showed high accuracy of the dependence of the discussed parameters, and the obtained polynomial equation (6) can be successfully used in the assessment of the average Sauter diameter of fuel drops using the value of the acoustic emission energy generated in the process fuel spraying. It should be emphasized that such tests can be carried out on a running engine, which is an important value in the field of research and operation of combustion engines.

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