OPTIMIZATION OF THE FUEL INJECTOR TO AN INTERNAL COMBUSTION ENGINE BY MEANS OF LASER EQUIPMENT

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Abstract

The conducted tests were aimed at determination of the drop diameters and shaping of the velocity field at different configurations of the test injector. The test results allowed defining the relationship between the injector configuration and the distribution of velocities and dimensions of drops in the fuel stream. The effect of the fuel viscosity and injection pressure on the dimensions of fuel drop diameters and the distribution of the velocity field of drops in the stream were tested. The tests were carried out on a special test rig with a fixed volume chamber. The measurements were carried out with the use of laser Doppler measurement systems (PDPA, LDV). The tests were conducted for seven different fuel types varying in viscosity and surface tension. In addition, the injection pressure from 50 MPa to 130 MPa was applied. The test results allowed determining the relationship between the injector structure configuration, fuel types and fuel additives, and the distribution of velocity and an atomisation spectrum of drops in the fuel stream, and the air impact on the fuel stream.

1. Introduction

The current creation of a fuel-air mixture and its impact on ignition, combustion, etc. did not include the parameters related to the fuel stream and the combustion chamber aerodyne-mics. The preliminary tests carried out in the fixed volume combustion chamber and with the use of conventional methods for the creation of a liquid fuel mixture showed that it is not possible to obtain the charge ignition without the prior heating of the combustion chamber to the temperature of 80-90^{0}C. The liquid fuel ignition without the prior heating of the chamber is possible with the use of a new system for the mixture creation. It relates to the size of drops, their distribution in the stream and deposition of drops on the wall of the combustion chamber [2, 3, 4].

Thus, two main factors related to the process of creating the mixture will determine the ignition, combustion and emission of exhaust toxic components in the internal combustion engine [5]:

- dimensions of drops and their distribution in the stream,
- deposition of drops on the combustion chamber wall.

The first of these factors has a major impact on ignition, combustion and emission of nitrogen oxides and the second one has a fundamental impact on ignition, combustion and emission of hydrocarbons.

Relatively small fuel drops, with a hydraulic diameter smaller than the critical one, due to the short time of staying in the combustion zone, counteract the excessive emission of nitrogen oxides. In this case, a mechanism of the time of staying in the combustion zone predominates over the Zel'dovich thermal effect in relation to NO_x emission. It does not apply to the drops with a very small diameter close to or less than 1 μm, which are undesirable, both in relation to positive and compression ignition engines. The harmfulness of very small fuel drops mainly involves the promotion of the knocking combustion occurrence in positive ignition engines, and it contributes to the emission of solid particles in relation to compression ignition engines. It is also believed that the presence of very

small drops in the fuel stream (less than 1 μm) contributes to the increased emission of nitrogen oxides [1]. Such drops should be removed from the fuel stream. Currently, the work aimed at the removal of very small drops by using the fuels with appropriate properties obtained with the use of various additives is carried out. It is proposed to remove very small drops with the use of an original system for the mixture creation in an aerodynamic manner, which uses the phenomenon that small drops reduce their velocity much faster than the large ones after leaving the injector.
With regard to the relatively large fuel drops with a hydraulic diameter larger than the critical one, the Zel'dovich thermal mechanism is applicable. It is then assumed that the fuel drops depositing on the combustion chamber wall contribute to the emission of hydrocarbons. The drops deposit on the walls, if their velocity near the wall is low. This feature will be used in order to develop a new system for the mixture creation that involves an increase in the fuel stream homogenisation and a decrease in the proportion of small drops. The increased emission of hydrocarbons mainly concerns the drops with the low velocity and large diameters (drops with small kinetic energy per mass unit).
Hence, the problem of effective (optimal) fuel atomisation is vital and of great importance, among others, from the ecological perspective – it affects the natural environment pollution processes. Therefore, the extensive tests on the fuel atomisation spectrum, generated by a high-pressure electronically controlled fuel system, were carried out on the dynamic laser analysers, Laser Doppler Velocimeter (LDV) and Phase Doppler Particle Analyser (PDPA).

2. Test methodology

By taking into account the possibility of generating the fuel stream and the fact that the stream cannot come into contact with the fuel equipment elements, the selection of 2D measurement system in relation to the velocity and autocorrelation parameters and the time analysis were made in order to obtain additional information referred to velocity, assuming that the stream is turbulent and variable in time.

On the basis of the analysis of various methods for fuel atomisation testing – mechanical, electrical and optical ones – the laser Doppler method was selected because it allows for measuring the fuel streams with high density and short duration time, at the same time, providing high accuracy of the measurement results.
The Phase Doppler Method is based on the principles of light scattering interferometry. Measurements are made at a point referred to as the probe volume, which is determined by the intersection of two laser beams. As a particle passes through the probe volume, it scatters light from the interference fringe created by the intersecting laser beams. A receiving lens projects a portion of this refracted light onto several detectors. Each detector produces a Doppler burst signal. System uses a unique method to directly measure the sample volume simultaneously by means of particle size (PDPA) and velocity (LDV) equipment, and it enables an accurate determination of the particle number density and volume flux. The Phase Doppler method requires no calibration because the particle size and velocity are depended only on the laser wavelength and optical configuration. PDPA measurements are not based on the scattered light intensity, and, consequently, are not subject to errors from beam attenuation or deflection which occur in dense particle and combustion environments. View of 3-Beam Spectra Physics Laser and Bragg Cell, which splits one beam on two, is shown in the Fig. 1.

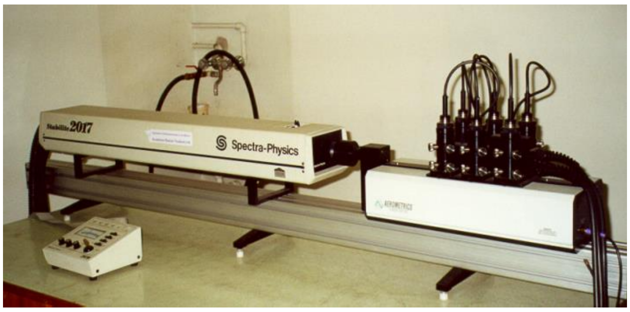

Fig. 1. View of 3-Beam Spectra Physics Laser and Bragg Cell
Source: own work

View of measurement space with injector tested, LDV, PDPA Transducers is shown in the Fig. 2. 3-LDV Analysers, PDPA Analyser, Traverse Programmer, Computer with Printer, Oscilloscope are shown in Fig. 3. Raw Doppler Burst

Signal in Tektronix Oscilloscope Screen during measurement is shown in the Fig. 4.

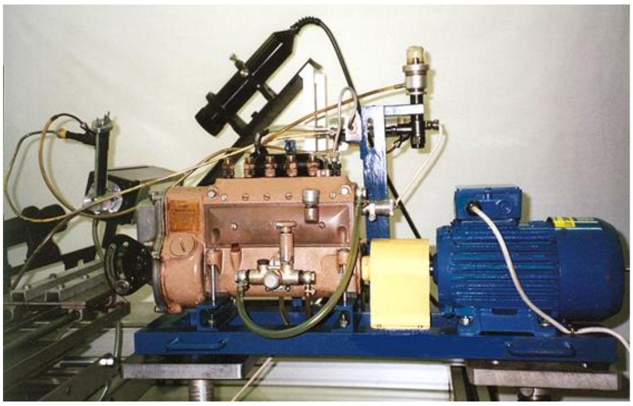

Fig. 2. View of measurement space with injector tested, LDV, PDPA Transducers
Source: own work

Fig. 3. 3-LDV Analysers, PDPA Analyser, Traverse Programmer, Computer with Printer, Oscilloscope
Source: own work

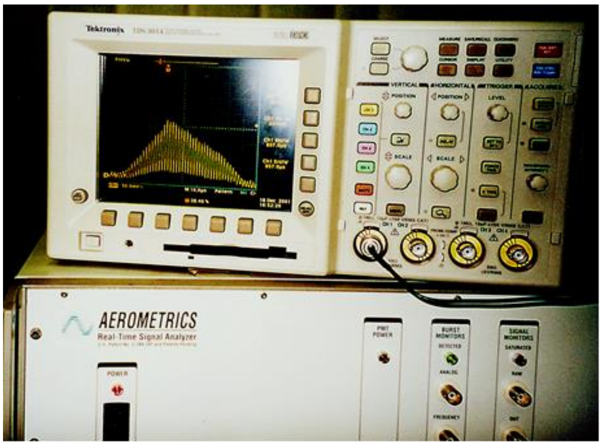

Fig. 4. Raw Doppler Burst Signal in Tektronix Oscilloscope Screen
Source: own work

The idea of the velocity measurements with the use of LDV system involves forcing the motion within the measurement space. The measurement space is determined by the intersection of two laser beams, zero and Doppler ones, in the centre of the transmitter of laser beams [1].

The measurement principle of velocity component consists in registration of change in laser beam frequency, which is proportional to fuel droplet velocity. Velocity component can be determined by using the following formula.

Research system PIV (Particle Image Velocimetry), Fig. 5, permits on the designation of the distribution of speeds of the fuel droplets. System PIV permits on simultaneous measurements of 12000 points, has very high resolution, guarantees high accuracy of measurements, allows for visualization of flow, including also the structure of turbulent flow, the terming of the turbulence and Reynolds stresses. Exemplary droplet speed field at the injection pressure of 50 MPa after 0.52 milliseconds presents Fig. 6. Moreover, the example of speed field with the injection pressure of 100 MPa after time of 44 milliseconds.

Fig. 5. View of PIV optical system
Source: own work

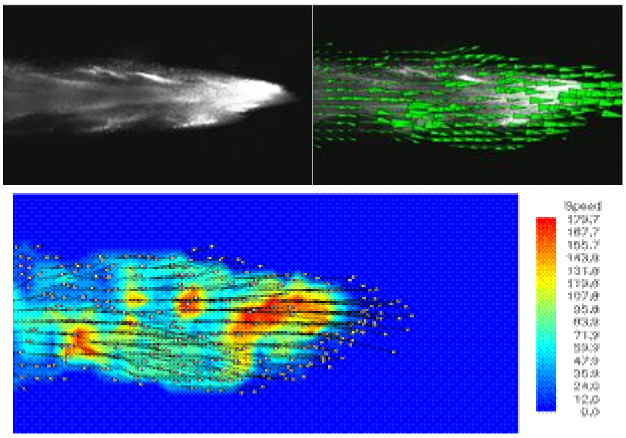

Fig. 6. PIV Flow Pattern with Velocity Vectors for No. 1 Fuel at 100 MPa Pressure
Source: own work

The measurement space is determined by the intersection of laser beams with a diameter of 1.4 mm, and it is a solid, the cross section of which has a diamond shape. The equipment records only these drops, which move within the measurement space. The measurement space volume can be changed only by changing the focal length or a change in the diameter of laser beams, which require a change in the system of lens. At the high focal length value, it is possible to measure larger diameters of particles; however, it also requires the use of higher laser power. In principle, the measurements should be carried out with the lowest possible laser power, but the one that is capable of providing the appropriate quality of measurements. Therefore, taking into account the type of measurements and possible range of drop diameters, the focal length value of 250 mm and the zero-radius distance from Doppler 39.74 mm for the axial direction and 39.68 mm for the direction perpendicular to the axis were selected. The velocities of drops are determined by measuring the time needed for the drop transition through the known distance between light bands. The laser equipment lenses gather the light scattered by the drops, and they direct it to the detectors, which generate an electric signal proportional to the intensity of the light scattered by drops. The distances of two detectors were determined with reference to AB 10.79 mm, and in relation to AC 32.16 mm. The velocity of drops is determined in accordance with the following formula:

$$V = \frac{f_{Doppler}}{f_0 \cdot 2sin\phi} \tag{1}$$

where: $f_{Doppler}$ –is a modulated frequency of the Doppler radius,

f_0 –is a frequency of the zero radius,

ϕ –is an intersection angle of laser beams.

In order to measure the diameter of drops, in the laser Doppler equipment, a phenomenon of the phase shift of monochromatic light waves (of a precisely defined wavelength) is used, and the shift is proportional to the diameter of drops. This principle of operation is used in the PDPA system of a laser device for measuring the diameters of drops. With the use of a Bragg cell and a real-time signal analyser (RSA), the Doppler radius for every laser beam was obtained.

The work implementation required the completion and adjustment of the test equipment and determination of operation parameters of the measurement and test equipment. On the basis of the analysis of the common rail system operation, the preliminary parameters of the measurement equipment operation that would make it possible to obtain the most favourable results were proposed. After the selection of the equipment operation parameters, while using the standard stream of drops, it was started to carry out the tests on the actual test stream, in the test chamber.

After the determination of the proper equipment operation parameters, it was necessary to specify the measurement points within the stream. Too small distance of the measurement points from the nozzle results in the situation that the stream is too compact, and the measurement results are incorrect. Therefore, it is necessary to choose such a measurement point, the closest to the nozzle, in which the stream decomposition into drops occurred. Such a measurement point was found at a distance of 65 mm from the injector.

In relation to PDPA system, five diameters that allow determining the stream parameters, such as D_{10}, D_{20}, D_{30}, D_{32}, D_{43}, were selected. Their meaning is as follows:

- D_{10} is an arithmetic diameter and it has a comparative meaning. It is calculated on the basis of the following relationship:

$$D_{10} = \frac{\sum_{i=1}^{n} d_i^2}{n} \tag{2}$$

where: d_i –diameter of particle,

n –number of particles.

- D_{20} diameter is a function of the area of drops and it allows for comparison of the average area of the measured drops. It is calculated on the basis of the following relationship:

$$D_{20} = \sqrt[3]{\frac{\sum_{i=1}^{n} d_i^2}{n}} \quad (3)$$

- D_{30} diameter is a function of the volume of drops and it allows for comparison of the measured drops. It is calculated on the basis of the following relationship:

$$D_{30} = \sqrt[3]{\frac{\sum_{i=1}^{n} d_i^3}{n}} \quad (4)$$

- D_{32} diameter is determined as the Sauter Diameter (SMD), it is a function of the ratio of volume to the area of drops, and it is used for analysing the heat and mass exchange processes. It is calculated on the basis of the following relationship:

$$D_{32} = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \quad (5)$$

- D_{43} diameter is determined as the Herdan Diameter, it is a function of the fourth power of the diameter of drops to the third power of the diameter of drops, and it is used for analysing the combustion processes. It is calculated on the basis of the following relationship:

$$D_{43} = \frac{\sum_{i=1}^{n} d_i^4}{\sum_{i=1}^{n} d_i^3} \quad (6)$$

The differences in the dimensions of the average diameters of drops are a measure of uniformity in the diameter dimensions of drops in the stream. The smaller the differences between the average diameters, the higher the spray uniformity. If all the drops in the stream had the same diameters, then all the average diameters of drops would be the same. The Sauter Diameter is of vital importance in the heat and mass exchange processes, however, the Herdan Diameter reflects the combustion processes. Therefore, these two diameters – D_{32} and D_{43} – are the most crucial in the issues of atomisation related to the operation of combustion engines.

The selected measurement points, in which the measurements were made, were presented in Fig. 7. In order to select the measurement points, the preliminary tests within the range from 50 mm to 350 mm from the outlet of the injector nozzle were carried out.

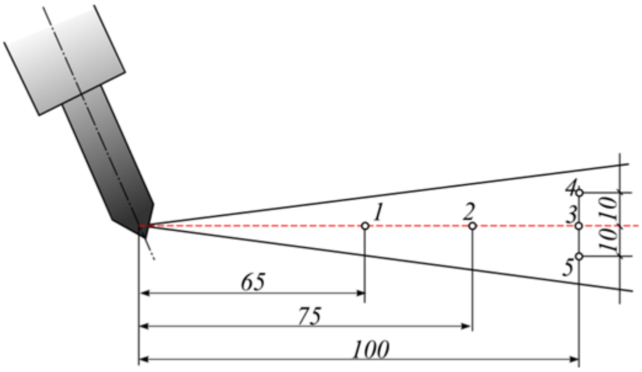

Fig. 7. Distribution of measurement points in the atomised fuel stream.
Source: own work

At larger distances from the nozzle opening, the more even distribution of drops was obtained. As the distance decreased, a larger dispersion of the test results occurred. Due to the approximation of the injection system operation to the operation in the engine conditions, a distance of measurement points of 65, 75, 100, in the stream axis, was selected, but at a distance of 100 mm, the measurements were also carried out within the points symmetrical to the stream axis at a distance of 10 mm.

3 Test rig

The tests of the diameters and velocities of drops were carried out on the test rig equipped with the laser Doppler dynamic analyser of the dimension and velocity of particles, that is Laser Doppler Velocimeter (LDV) and Phase Doppler Particle Analyser (PDPA). Fig. 8 shows the test chamber with glass panels, which allows for optical access to the inside of the chamber, and on the right side, there is the test injector, and in the inside of the chamber, there is a beam of intersecting green lasers, which determine the measurement space.
Furthermore, the test rig included a device supplying and controlling the injector operation, a high-pressure pump driven by an electric motor

with adjustable rotational speed, a common rail system (Fig. 9), a device for measuring the injected fuel temperature, a fuel injection control system, and a test injector.

The additional elements of the test rig are: an optical system of the drop velocity and dimension analyser, a laser beam transmitter, Spectra Physics type laser, a Bragg cell and a laser controller, a unit of detectors, a real-time signal analyser, an acquisition and presentation system of the test results, a coordinate table motion controller, and an oscilloscope presenting the Doppler signal.

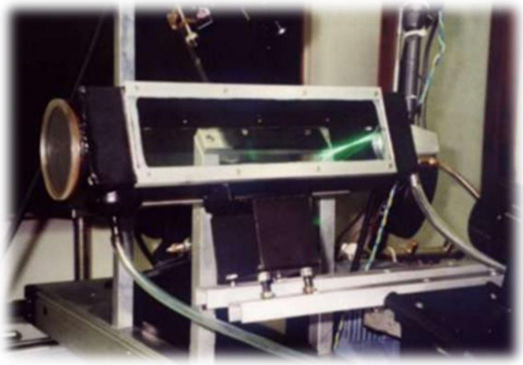

Fig. 8. View of the test chamber
Source: own work

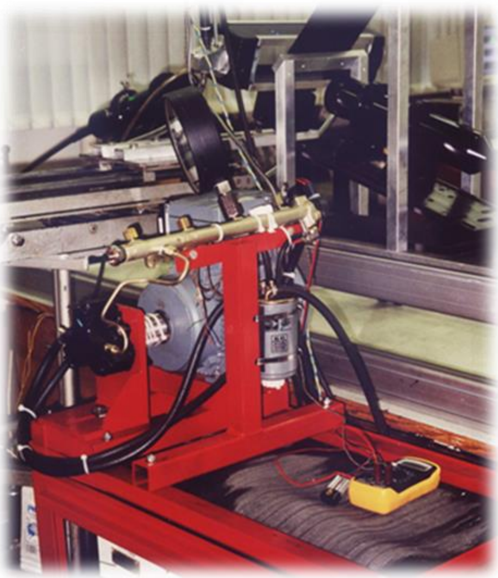

Fig. 9. Common rail injection system
Source: own work

4 Test results

In total, 520 tests were carried out, but the principle that in case of each measurement point at given settings (injection pressure, a type of the tested fuel), three single injections and one repetitive injection – fivefold, are made.

The measurements relate to one stream flowing from the injector, however, the other streams were directed to the overflow. The test results indicate the presence of a small number of large drops (l, to 5), which, however, significantly affect the value of the Sauter Diameter D_{32} and D_{43}, hence, in this case, the stream is better characterised by D_{10} average arithmetic diameters.

Table 1. The measurement results of the drop diameters of the test fuel No. 1 for various injection pressure values

	Fuel 1		
	Injection pressure [MPa]		
	130	100	70
D_{10}	4.187	6.575	8.705
D_{20}	4.718	7.802	10.142
D_{30}	5.285	8.862	12.076
D_{32}	6.837	12.04	16.387
D_{43}	7.951	15.56	19.549
V_1	0.585	1.118	2.593
V_2	0.51	0.394	0.513
V_3	0.585	1.118	2.594
RMS	1.819	3.159	3.656

The presence of large drops results from leaks of the common rail system injector. If the large drops are rejected during the processing of diagrams, the drop diameters adopt the dimensions which are characteristic of the common rail injection systems. A relatively small range of the measurement results within the measured pressure from 70 MPa to 130 MPa is characteristic. The differences in the drop diameters between fuel No. 1 and fuel No. 2 are within 20% (in case of the rejection of large drops, which should not be generated by the fully operational common rail system), however, the presence of large drops primarily affects the values of D_{32} and D_{43} diameters. However, the differences in the values of those diameters most commonly result from an unequal number of large drops in the stream.

The example results of the obtained values of the drop diameters during testing for only two selected (important in terms of the obtained measurement data) fuel types in the injection pressure function are presented in Table 1 and Table 2, and in Figures 10 and 11. 7 various fuel types were used in the tests.

Table 2. The measurement results of the drop diameters of the test fuel No. 7 for various injection pressure values

	Fuel 7		
	Injection pressure [MPa]		
	130	100	70
D_{10}	4.426	8.491	10.63
D_{20}	5.117	10.125	12.227
D_{30}	5.918	11.377	13.933
D_{32}	7.915	15.724	19.201
D_{43}	10.07	19.589	24.218
V_1	0.663	1.421	0.266
V_2	0.363	0.145	0.36
V_3	0.663	1.421	0.2665
RMS	1.628	3.087	1.127

Source: own development based on data obtained during the tests

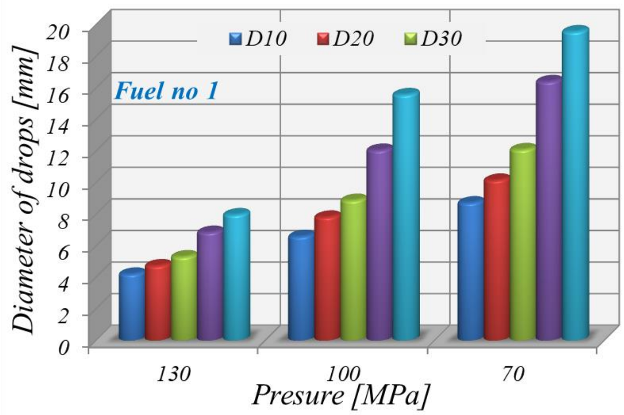

Fig. 10. Values of the drop diameters of the test fuel No. 1 for various injection pressures
Source: own work

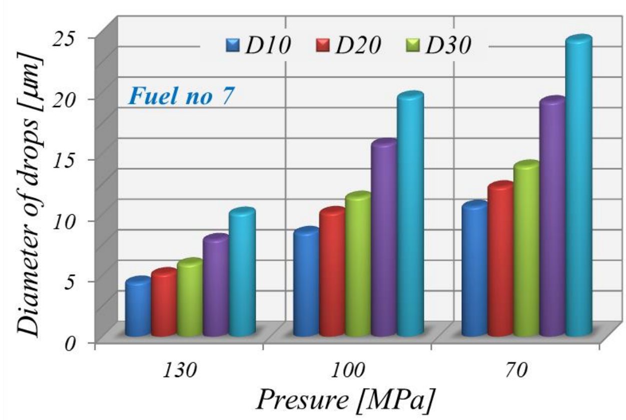

Fig. 11. Values of the drop diameters of the test fuel No.7 for various injection pressures
Source: own work

5. Conclusions

As a result of the carried out work, the following conclusions can be formulated:

- the test rig, which allows to carry out the atomisation tests by the high-pressure common rail injection system on the laser Doppler analyser of the dimensions and velocities of particles, was developed;
- the test methodology of the fuel atomisation with the use of the laser Doppler analyser was developed;
- the computer programmes that allow to conduct the tests, acquisition and processing of the test results were devised;
- the tests aimed at the determination of the measurement system optical parameters were carried out for conducting the common rail system tests, on the basis of which the impact of a fuel type and injection pressure on atomisation parameters was found;
- the injection system supplied with lower viscosity fuel generated the drops with a smaller diameter than the system supplied with higher viscosity fuel. If we compare lower viscosity fuel No. 1 with higher viscosity fuel No. 7, in case of fuel 7, the Sauter Diameter at the pressure of 70 MPa was higher by 28%, and at the pressure of 100 MPa, it was higher by 8%, and at the pressure of 130 MPa by 15%;
- it was found that along with an increase in the injection pressure, the diameter of drops

decreased, the Sauter Diameter (SMD) of drops at the pressure increase from 70 MPa to 130 MPa was reduced by 47% in relation to fuel No. 1 and by 41% in relation to fuel No. 7;

- on the basis of the obtained test results, the Rosin-Rammler distribution of a spectrum of drops approximating the actual atomisation spectra in the following form were determined:

$$1 - Q = exp\left[-\left(\frac{D}{X} \right)^q \right] \qquad (7)$$

where: D – droplets diameter;
Q – volumetric share of droplets with a diameter smaller than D;
X – parameter defining the contractual diameter of droplets;
q – parameter determining the degree of drops dispersion.

The X parameter specifies the diameter arbitrary, for which the volume fraction Q is 0.6321, which means that it is the diameter below which the volume of all droplets in the stream is less than 63.21%.
In turn, the q parameter is a measure of dispersion, i.e. the smaller is the value of this parameter, the more homogeneous the stream is and vice versa.
The measurements allow to determine the distribution of droplets in the fuel stream based on the Rosin-Rammler relationship, as well as several other dependencies, such as normal distribution, normal logarithm, modified Nakiyama-Tanasawa normal logarithm distribution and Matsumoto-Takashima distribution.
The results of laser spraying of the fuel stream allow the determination of many different parameters of the spray of atomized fuel.

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