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Laser Research of the Fuel Atomization Process of Internal Combustion Engines

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Abstract. The paper presents test methods (mechanical, electrical and optical) for the fuel spray research in combustion engines. Optical methods, imaging and non-imaging can be used in laboratory and engine tests. Imaging methods include flash photography and holography. Their use is limited to testing droplet dimensions larger than 5 µm. Imaging methods have an advantage over non-imaging ones because they allow the droplet to be seen at the point and time where its measurement is required. Non-imaging methods can be divided into two groups: the first, which counts and measures, individual droplets one at a time, and the second, which measures a large number of droplets simultaneously. Exemplary results of research of droplet size distribution in fuel sprays are shown. In tests of atomized fuel spray, in conditions reflecting the conditions of the internal combustion engine, the size of droplets, their distribution in the spray and the velocity of individual droplets are presented. To determine the quality of the fuel spray, two substitute diameters Sauter (D_{32}) and Herdan (D_{43}) were selected, the first of which refers to heat transfer and the second to combustion processes. Laser research equipment including Particle Image Velocimetry laser equipment (PIV), Laser Doppler Velocimeter (LDV) and Phase Doppler Particle Analyzer (PDPA) were applied for testing fuel spray distribution for two kind of fuel. The atomization process from the point of view of combustion and ignition processes, as well as emission levels, is characterized by the best substitute diameter D_{43}, which value is close to the median volume. The most harmful droplets of fuel in the spray are large droplets. Even a few such droplets significantly change the combustion process and emission of toxic exhaust components, mainly NO_x.

Keywords: combustion engine, fuel injection equipment, fuel atomization, laser method, engine emission

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Лазерное исследование процесса распыления топлива двигателей внутреннего сгорания

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Реферат. В статье представлены методы испытаний (механические, электрические и оптические) для исследования распыления топлива в двигателях внутреннего сгорания. Оптические методы, техническая визуализация, системы без отображения цели могут быть использованы в лабораторных работах и испытаниях двигателя. Методы визуализации включают в себя съемку со вспышкой и голографию. Их применение ограничено размерами капель для тестирования, которые должны быть более 5 мкм. Методы визуализации имеют преимущество перед методами без отображения цели,

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потому что они позволяют видеть каплю в той точке и в то время, когда требуется произвести ее измерение. Методы без отображения цели можно разделить на две группы: первая, которая за один раз подсчитывает и измеряет отдельные капли, и вторая, когда одновременно производится измерение большого количества капель. В статье показаны типовые результаты исследований распределения капель по размерам в распылителях топлива. При проведении испытаний по распылению топлива в условиях работы двигателя внутреннего сгорания учитывались размеры капель, их распределение в распылителе, а также принималась во внимание скорость отдельных капель. Для определения качества распыления топлива были выбраны два подсменных диаметра Suter (D_{32}) и Herdan (D_{43}), первый из которых относится к процессу теплообмена, а второй – к процессу сгорания. Лазерный научно-исследовательский комплекс, включающий в себя лазерное оборудование для измерения скорости частиц (PIV), лазерный доплеровский измеритель скорости (LDV) и фазовый доплеровский анализатор частиц (PDPA), использовался для проведения испытаний по распределению распыления двух типов топлива. Распыление, с точки зрения процессов горения и воспламенения, а также уровней выбросов, характеризуется лучшим сменным диаметром D_{43}, значение которого очень близко к средней величине. Наиболее вредными каплями топлива в аэрозоле являются капли крупного размера. Даже несколько таких капель значительно влияют на процесс горения и выброс токсичных компонентов, главным образом NO_x.

Ключевые слова: двигатель внутреннего сгорания, устройство для вдувания топлива, распыление топлива, лазерный метод, выбросы двигателя

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Introduction

The fuel injection system is one of the key elements that are the subject of numerous experimental and theoretical works necessary for the development of modern combustion systems in both spark-ignition and Diesel engines. The direct fuel injection system into the engine's combustion chamber is one of the most advanced solutions and has to implement at least two or even more different engine modes. Parameters not related to the atomization process itself with regard to fuel supply systems include, among others, opening time, closing time, needle stroke, durability, stream range, noise level, power consumption, leaks and operating pressure range.

Fuel injection systems are dominant in spark-ignition and Diesel engines [1, 2]. These systems allow for accurate metering of fuel and feeding it to the combustion chamber [3]. They also allow for the appropriate shaping of the injection process for the shape of the spray, the dimensions of droplets, and the dosing of the amount of fuel. The use of optical methods using lasers to measure droplets' diameters and speed allow for significant progress in this field of research. In tests of atomized fuel spray, in conditions reflecting the conditions of the internal combustion engine, the size of droplets, their distribution in the spray and the velocity of individual droplets are possible to determine [3]. Droplets in the spray have different diameters, depending on the discharge conditions and fuel properties. From the point of view of the economics of the combustion engine operation and the emission of toxic exhaust components, differences in the size of droplets should be within a narrow range [4, 5]. To determine the quality of the fuel spray, two substitute diameters Sauter (D_{32}) and Herdan (D_{43}) were selected, the first of which refers to heat transfer and the second − to combustion processes. The stream parameters include the average diameters of the fuel droplets of the main stream and the surrounding spray, as well as the associated statistical parameters that result from the droplet size distribution. Important stream parameters include stream cone angles, both start and end angles, stream skew, penetration speed of the stream end and maximum speed, dripping after injection and fuel distribution within the stream. Additional stream parameters are related to the variability between individual fuel injections. The conducted research tests allow assessing the occurrence of dripping after the injection and its influence on the characteristics of the fuel atomization process. Dripping is particularly disadvantageous for fuel jets with small droplet sizes.

The common rail injection system allows full monitoring and computer injection control by the time and pulse length, as well as by adding additional fuel pulses or multiple injections for one engine cycle [6]. The average injection pressure increases steadily up to 10 MPa, and in some applications up to 12 and even 20 MPa. There is insufficient data yet to assess the impact of such pressure increases on wear processes and average durability of supply systems. Such data could ultimately reduce the tendency to increase fuel injection pressure for spark-ignition engines.

Work on back-up injectors, which at very low injection pressure (0.6–1.0 MPa) offer comparable levels of fuel atomization with multi-hole vortex injectors, which are characterized by over 10 times higher injection pressures. This type of injectors, however, requires the use of two separate injection control systems; moreover, it requires individual two controllers for one injector with different characteristics regarding pulse duration. It also requires the supply of compressed gas and air, which somewhat complicates the solution of the power supply system, e. g. a compressor is required. This system uses one system to control the fuel supply to the combustion chamber and another system synchronously to introduce the appropriate amount of compressed air [7].

Test methods for the fuel spray process in combustion engines

Various methods are used to test fuel atomization processes, which can be classified into three basic groups: mechanical, electrical and optical methods.

Mechanical methods for example include collecting droplets on a glass surface with a suitable coating to stop settling droplets, collecting fuel droplets for dishes with a liquid that does not dissolve fuel droplets, using molten wax.

The electric methods include the method of electrically charged wire, which removes the charges depending on the droplet dimensions, and the hot wire method, which consists in the fact that fuel droplets settling on the pipe evaporate and cool it. When there are no droplets on the wire, its electrical resistance is large and uniform along the length. When the droplets settle on the duct, its resistance decreases locally, in proportion to the droplet dimensions. The latter method is however an invasive method.

Optical methods can be used in both laboratory and motor tests. These imaging methods include flash photography and holography. Their use is limited in practice to testing droplet dimensions larger than 5 μm. Imaging methods have an advantage over non-imaging ones because they allow the droplet to be seen at the point and time where its measurement is required.

Non-imaging methods can then be divided into two groups, the first, which counts and measures individual droplets one at a time, and the second, which measures a large number of droplets simultaneously. It is important to know both the drop size and the speed for an accurate result. Some devices for the non-imaging methods can provide both information regarding dimensions and velocity.

Many optical research methods can be used to analyze the process of fuel atomization. However, they all have an important attribute, because they allow measurements without disturbing the stream of sprayed fuel. Optical research methods include: high speed photography, video stream analyzer, holographic analyzer, single particle counters, scattered light interferometry, non-axial scattered light detection, Particle Image Velocimetry (PIV) [8], Phase Doppler Particle Analyzer (PDPA), Laser Doppler Analyzer Speed (LDA).

Laser research equipment.
Particle image velocimetry laser equipment

Laser PIV equipment allows determining the distribution of the velocity of fuel droplets. PIV equipment allows simultaneous measurements of 12000 points, has a very high resolution, and guarantees high accuracy of measurements, enables visualization of flows, including turbulent flow structures. An important advantage is the ability to determine turbulence and Reynolds stresses. In addition, it ensures fast operation in an automatic cycle. Fig. 1 shows a diagram of PIV equipment, and Fig. 2 shows a view of PIV equipment.

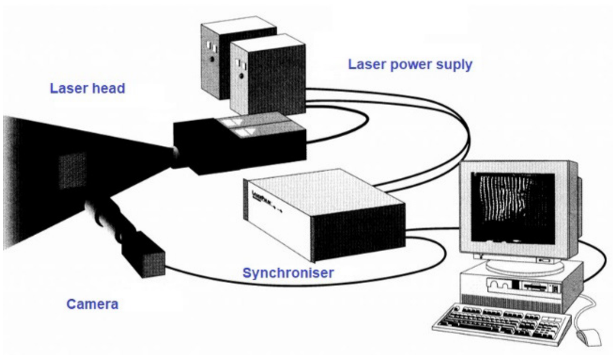

Fig. 1. Scheme of the PIV optical system

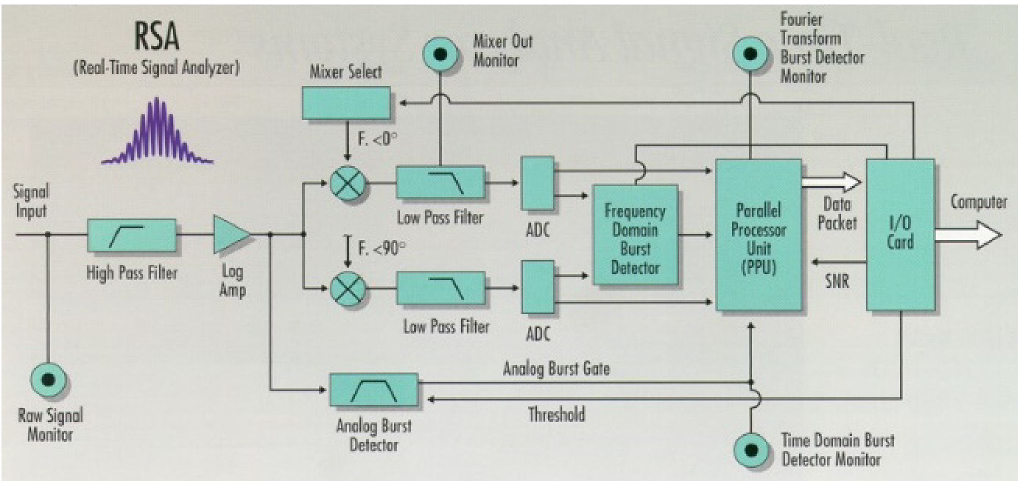

Fig. 2. Block scheme of the laser measuring system

PDPA and LDV laser research equipment

In tests of the atomized fuel stream, in conditions reflecting engine conditions, it is also important to know the size and distribution of droplets in the fuel stream. In engine conditions, the droplets have different diameters, depending on the discharge conditions and fuel properties. For the purposes of analyzing the stream creation process, it is better to use not a set of droplets of different diameters, but a droplet with a constant diameter, characteristic of given flow conditions. Several such conventional diameter droplets are specified in the literature. These include, among others, the average diameter of Sauter (D_{32}), arithmetic (D_{10}), surface (D_{20}), volumetric (D_{30}) and Herdan (D_{34}).

The tests were carried out using the LDV (Laser Doppler Velocimeter) and PDPA laser equipment, with a 5 W laser cooled with water. The block diagram of the laser measuring system is shown in Fig. 2. The measurements are carried out in the measuring space, which is determined by the intersecting two laser rays, zero and Doppler from each transmitter. This space occurs in the optical focus area of the laser transmitter and has the shape of a rhomboidal body whose maximum dimensions in the tuned optical system were 1.76×1.4×1.4 mm. The diameter of the laser beam was 1.4 mm; the distance between zero and Doppler rays was 39.74 mm, the focal length was 250 mm. The dimensions of the measuring space can be changed by means of the optical system of the transmitter (focal length), which should be selected for the expected range of droplet diameters occurring in the sprayed fuel stream. Droplet dimensions that can be measured are in the range from 0.5 to 2.0 mm, and when changing the parameters of the optical system, even up to 3.822 mm, except that the best results are obtained when choosing the optical system adapted to the sprayed fuel, in whose maximum droplet size is about 300 times larger than the minimum. The measuring range depends on the optical system and the type of the RSA (Real Time Signal Analyzer) processor, whereby laser phase shifts from 30 to 3500 can be recorded. In any case, the optical system should be arranged in such a way that the maximum droplet size is smaller from the smaller diagonal of the diamond section perpendicular to the fuel jet velocity component, while the minimum droplet size that can be recorded is 0.5 μm or is the one whose phase shift of the laser beam is 30 or greater. The PDPA system for measuring droplet dimensions is calibrated, while the LDV system for measuring speed does not require calibration. The measuring system of the apparatus allows the measurement of velocity in three directions (3*D*), and the principle of measuring the velocity component is to register a change in the frequency of the laser beam, which is proportional to the velocity of the fuel droplet. The velocity component may be determined from the following relationship

$$v_i = \frac{f_D}{f_0 2 \sin \Phi}, \qquad (1)$$

where v_i − droplet velocity component; f_D − modulated frequency of the laser Doppler beam; f_0 − zero beam frequency; Φ − intersection angle of zero and Doppler beams.

The measuring system allows the use of three different laser rays: green with a wavelength of 514.5 nm, blue with a wavelength of 488 nm and purple with a wavelength of 476.5 nm. Measurement of droplets consists in registering the deviation of the laser beam when passing through the droplet, which is proportional to its size. A droplet of fuel is observed from 2 detectors with two different distances AB 10.79 mm and AC 32.15 mm. In relation to the PDPA system, five diameters were selected to determine the stream parameters: D_{10}, D_{20}, D_{30}, D_{32}, D_{43}. The differences in the dimensions of individual droplet diameters are a measure of the uniformity of dimensions of the fuel stream. The droplet size is determined based on the relative modulation of the laser signal by the droplets flowing through the measurement area. The droplet size is determined from the following relationship:

$$M = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \qquad (2)$$

where M – intensity parameter; $I_{\max}$, $I_{\min}$ – maximum and minimum intensities.

The relationship between the value determining the intensity of the M laser beam measured by the measuring system and the droplet size is determined by equation

$$M = \frac{2J_1(\pi D/\delta)}{\pi D/\delta}, \qquad (3)$$

where J_1 – first type first order Bessel function; D – droplet size; δ – distance between interference fringes.

Placing optical systems to measure velocity components in the combustion chamber is not possible in an orthogonal system. An oblique coordinate system is used, which requires the use of transformation to transition to the orthogonal system. The best results are obtained when the laser scattered light receiver is placed at an angle of 30° to the direction of the beam of the transmitter.

Fig. 3 shows the 3D-measuring laser and the Bragg cell. Fig. 4 shows the system of signal analysis, acquisition and presentation of results. Fig. 5 shows a constant volume test chamber for research the atomization and combustion process.

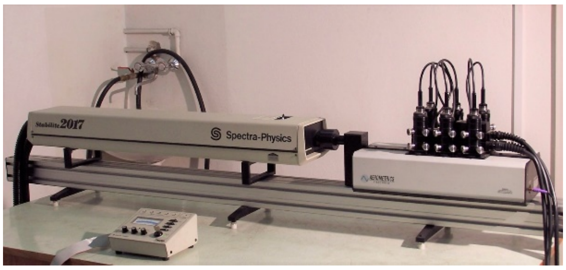

Fig. 3. 3D-measuring laser and Bragg cell

Fig. 4. View of the signal analysis system, acquisition and presentation of results

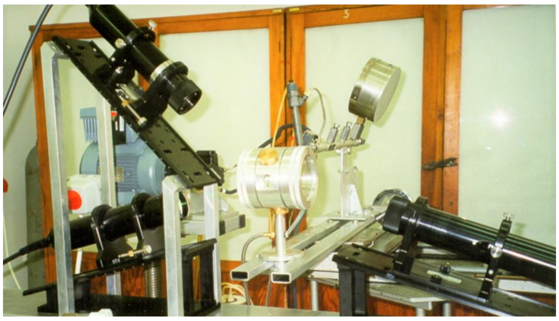

Fig. 5. Test chamber for testing the atomization and combustion process

Test results

Tests with the use of PIV apparatus [9] were carried out on the stand enabling the implementation of a single injection for different injection pressure values for two fuels (Fig. 6–8) with the properties presented in Tab. 1.

Table 1

Values of tested fuels

	Dynamic viscosity, mm^2/s	Density, kg/m^3	Surface tension, J/m^2
Fuel No 1	4.7	803.53	$35.9 \cdot 10^{-3}$
Fuel No 2	1.7	826.04	$36.8 \cdot 10^{-3}$

Tests using PIV apparatus allow determining the structure and distribution of velocity in the stream. The tests revealed velocity discontinuities and change of directions in individual areas of the stream, with the stream image significantly different for fuels with different viscosities. It should be noted that PIV velocity field measurements provide excellent illustrative material illustrating the velocity field. In most cases, the test results are rather qualitative.

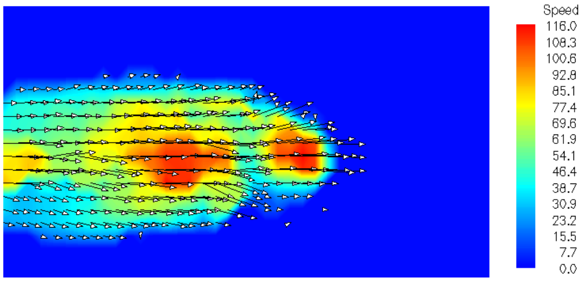

Fig. 6. Vector distribution and velocity fields for fuel No 1 for an injection pressure of 50 MPa

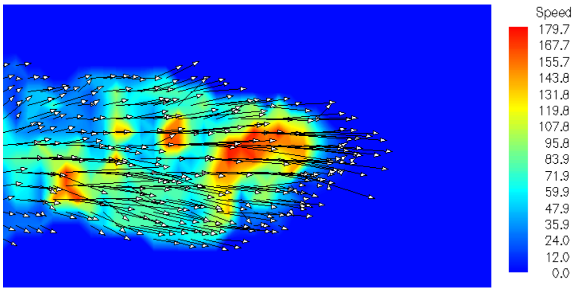

Fig. 7. Vector distribution and velocity fields for fuel No 1 for 100 MPa injection pressure

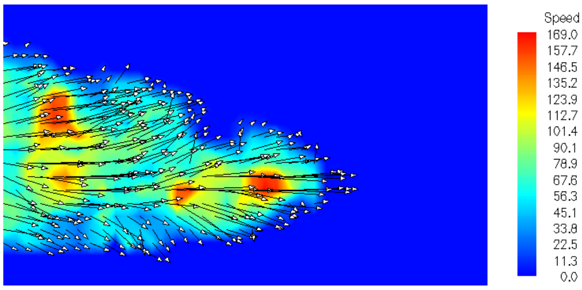

Fig. 8. Vector distribution and velocity fields for fuel No 2 for 100 MPa injection pressure

The laser equipment (PIV–PDPA) allows measurements of droplets in the range from 0.5 µm to 2.0 mm, and for the change of optical system (500 mm focal length) parameters even up to 3.822 mm.

Tests were carried out on the special stand shown in Fig. 5. The results of the droplet velocity tests that were made using the LDV laser apparatus are shown in Tab. 2. Examples of measurements were made in the injector axis at a distance of 65 mm from its hole in the fuel injection into the atmosphere. The results of testing the dimensions of fuel droplets using PDPA laser equipment are presented in Tab. 3.

Table 2

Results of velocity tests at measuring point 1 (LDV)

Injection pressure, MPa	v_1, m/s	v_2, m/s	v_{av}, m/s	v_{RMS}, m/s	Fuel
100	0.66	0.36	0.663	1.628	No 1
70	1.23	0.73	1.235	3.681	
100	0.50	0.39	0.501	1.266	No 2
70	1.31	0.39	1.312	2.847	

Table 3

Test results for the diameter of the droplets at measuring point 1 (PDPA)

Injection pressure, MPa	D_{10}, µm	D_{20}, µm	D_{30}, µm	D_{32}, µm	D_{43}, µm	Fuel
100	4.426	5.117	5.918	7.915	10.07	No 1
70	5.109	6.086	7.183	9.990	12.97	
100	4.451	5.241	6.171	8.554	11.04	No 2
70	6.388	7.441	8.807	11.52	14.72	

Test results of the sprayed fuel stream regarding the droplet diameters for small droplet sizes – D_{32} = 13.8 µm, D_{43} = 15.38 µm are shown in Fig. 9, 10. Fig. 11 shows the combustion process in a constant volume chamber for a fuel stream with the properties presented in Fig. 9, 10 ($\lambda = 1$).

Exemplary results of studies of droplet size distribution in a homogeneous spray are shown in Fig. 12, and in a spray with a dispersion of droplets – in Fig. 13. Fig. 12, 13 indicate that the Sauter diameter is 18.41 µm/20.99 µm, respectively and the Herdan diameter – 20.4 µm/25.94 µm.

The differences between the Herdan and Sauter diameters are respectively 1.99 µm/4.95 µm, which are 9.7 %/19.1 %. The smaller the average diameters between diameters, the greater the homogeneity of the fuel stream. An important role in assessing the fuel injection stream has a volume median of droplets, which is 20.14 µm/24.94 µm respectively, which is 99 %/94 % of the Herdan diameter, respectively.

The most harmful droplets of fuel in the spray are large droplets. Even a few such droplets significantly change the combustion process and emission of toxic exhaust components, mainly (NO_x) [9–11]. The atomization process from the point of view of combustion and ignition processes, as well as emission levels, is characterized by the best substitute diameter D_{43}, which value is close to the median volume.

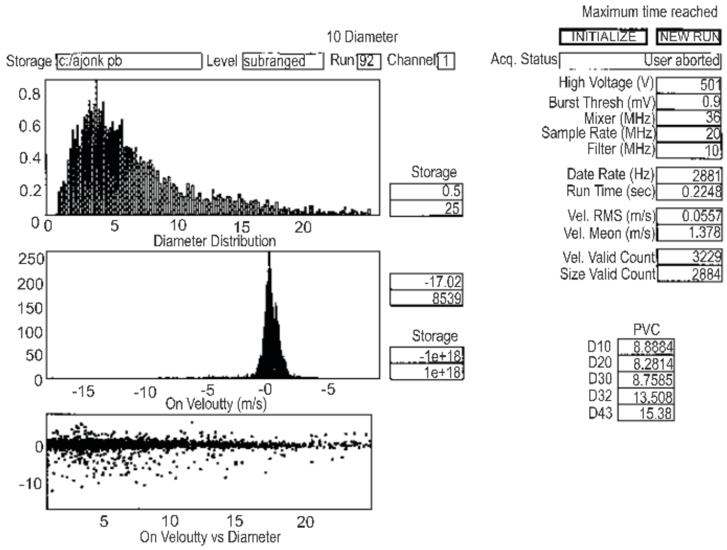

Fig. 9. Test results of the sprayed fuel stream regarding droplet diameters for small droplet sizes − D_{32} = 13.8 µm, D_{43} = 15.38 µm

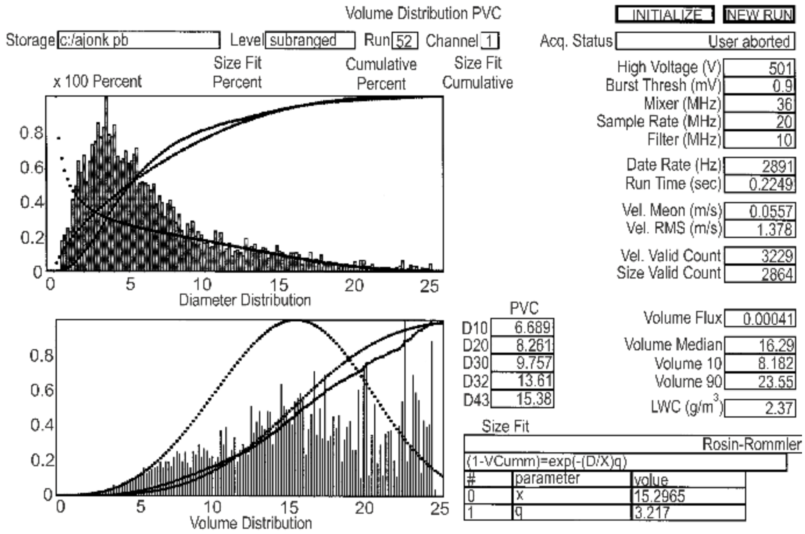

Fig. 10. Test results of the sprayed fuel stream regarding droplet diameters for small droplet sizes − D_{32} = 13.8 µm, D_{43} = 15.38 µm

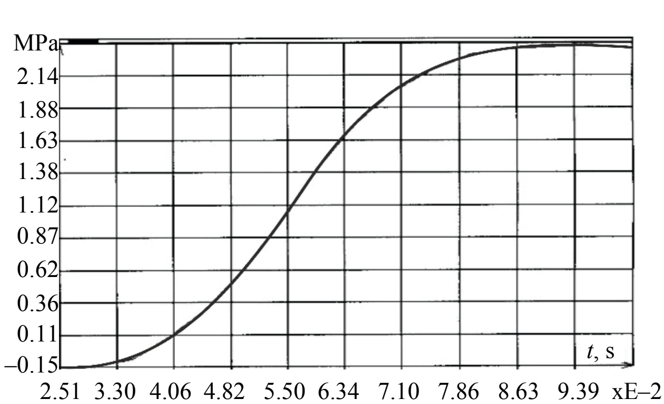

Fig. 11. The course of the combustion process in a constant volume chamber for the fuel stream with the properties presented in Fig. 9, 10 (λ = 1)

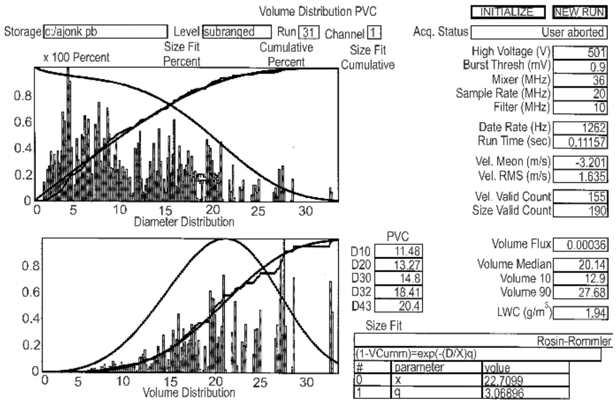

Fig. 12. Diameter distribution in fuel homogeneous spray

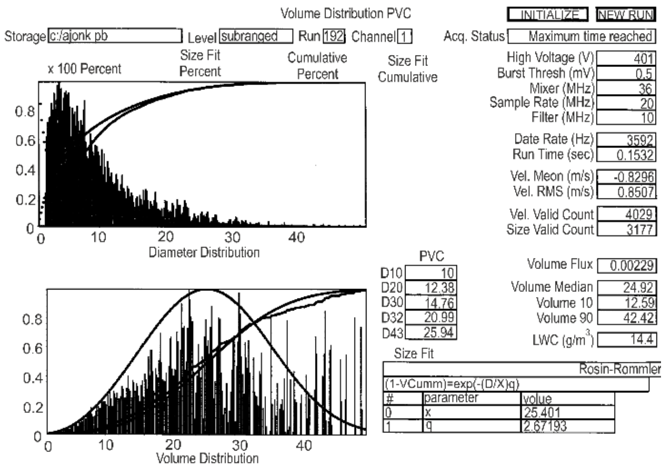

Fig. 13. Diameter distribution in fuel spray with dispersion

The main reasons for excessive fuel consumption and the emission of toxic exhaust components are inaccurate metering of fuel and improper preparation of the mixture. For proper fuel, metering as well as fuel preparation the fuel atomization process has the main influence. For the evaluation of the fuel apparatus, measurement of the Herdan diameter (D_{43}) should take place along the length of the stream at a distance of 2/3 of the spray range from the injector and 2/3 of the stream radius value from the spray axis.

CONCLUSIONS

1. The PIV test method allows the structure and distribution of velocity to be determined in a stream. It allows for qualitative rather than quantitative assessment.

2. PDPA and LDV laser methods allow determining droplet diameters, their velocity and dispersion.

3. The atomization process from the point of view of combustion and ignition processes, as well as the level of emissions is best characterized by a substitute diameter D_{43}, whose value is close to the median volume.

4. Directions of development of mix formation processes are aimed at obtaining streams with small droplet sizes. This applies not only to the homogeneous combustion process strategy, but above all to the cold start strategy, where it is necessary to use small-sized droplets.

5. Fuel viscosity, density and surface tension, depending on fractional composition, crude oil processing and additives, have the greatest impact on the physical stream formation processes.

6. Droplets in the large stream of fuel are the most harmful. Even a few such droplets definitely change the combustion process and the emission of toxic exhaust components, mainly (NO_x).

7. With increasing injection pressure, the diameter of the droplets decreased; the Sauter diameter of the droplets with pressure increase from 70

to 130 MPa decreased by 47 % for fuel No 1 and by 41 % for fuel No 2.

8. During tests of the ignition and combustion process for elevated pressures in a constant volume chamber (up to 1 MPa) at large droplet sizes, when D_{43} is greater than 30 µm, ignition is not possible, even with a significant increase in pressure in the combustion chamber. Fuel dispersion has a significant impact on ignition in cold combustion chamber conditions.

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