LASER RESEARCH OF FUEL ATOMIZATION AND COMBUSTION PROCESSES IN THE ASPECT OF EXHAUST GASES EMISSION

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Abstract

The fuel injection phenomena belongs to the most essential processes, which are object of many experimental and theoretical works, indispensable for development of contemporary internal-combustion engines, both the spark and compression ignition. The direct injection of fuel to the engine combustion chamber belongs to most advanced solutions and must realize at least two or even more different strategies of engine performance. Article presents the various research methods of the fuel atomization processes, being concentrated on laser methods, from which deserves on the emphasis the Particle Image Velocimetry (PIV) system, the Laser Doppler Velocimeter (LDV) system and Phase Doppler Particle Analyzer (PDPA) system. Article presents theoretical analysis relating the atomized fuel stream. The results of research based on the laser research equipment are also submitted in the article. Moreover presented are the results of research of the combustion process in the fixed volume chamber, where essentially two different strategies of the combustion process of homogenous and heterogeneous load were realized. The properly shaped fuel stream permits on obtainment of repeatable ignition and combustion in the wide range of the mixture variance. The essential meaning has the fuel stream disintegration, which influences advantageously on the level of the toxic exhaust elements emission, particularly on the hydrocarbon emission level because of the ignition dropout elimination and on the level of the nitrogen oxides emission because of short sojourn time of the fuel droplets in the combustion zone.

***Keywords**: combustion engine, fuel preparation, combustion processes, fuel spray, ecology*

1. Introduction

The fuel injection phenomena belongs to the most essential processes, which are object of many experimental and theoretical works, indispensable for development of contemporary internal-combustion engines, both the spark and compression ignition. The direct injection of fuel to the engine combustion chamber belongs to most advanced solutions and must realize at least two or even more different strategies of engine performance. The stream parameters encompass the average diameters of the fuel droplets of the main stream and surrounding streams, and also related statistic parameters, which result from the droplets dimensions dispersion, such as, among others, the Sauter D32 vicarious diameter.

Other essential stream parameters encompass, among others, the stream cone angles of both starting and final angle, stray of the stream, the end of stream penetration speed and maximum speeds, dribble on the injection end and distribution of the fuel mass within the stream. The additional parameters of stream are related with the variance between fuel separate injections. Performed investigations permit to estimate the dribble occurrence on the injection end and its influence on the characteristics of the fuel atomization process. Dribble is particularly unadvantageous with respect to the fuel streams characterizing it by small dimensions of droplets.

Injection systems to the spark ignition engines in the last period were developed fast. The new combustion systems are tending in the direction of a sole utilization of electronic control systems, including application of electronic control systems to common rail fuel systems, not only to the compression ignition engines, but also to the spark ignition engines. This type of the fuel injection system permits on the full computer control and monitoring of injection through the control of impulse timing and duration, as also through addition of additional fuels pulses or fuel repeated injections on one engine work cycle. The average injection pressures grow up systematically in the last time period, reaching the level of 10 MPa, but in some applications reaching even to 20 MPa. There is no yet sufficient data to estimate the influence of such pressure raise on the wear processes and the average durability of the fuel supply systems. However the newest solutions tend to the limitation of injection pressure and obtainment of high pressure injection related effects with other methods. The crevice and multihole injectors were developed, as also rotary injectors, which are finding even wider application and injectors with the variable output hole. One such injector being the object of the patent notification of Cracow University of Technology (M. Zabłocki) was the object of author laser research.

Last also the intensive works on injectors with the gas augmentation, but primordially with compressed air augmentation, which with the very small injection pressure (0.6-1.0 MPa) offer the comparable levels of the fuel atomization to the rotary multihole injectors, characterized by more then 10 times larger injection pressures.

The injector with the air augmentation was the object of diagnostic research both in original form in the Ford Fiesta automobile, and as the experimental modular version permitting on changes of atomization process parameters.

2. Research methods

To appreciate the fuel atomization processes, the different methods are applied which can be qualified to three basic groups: mechanical, electric and optical methods. Mechanical methods encompass the gathering of droplets on the glass surface with the appropriate coat for settled droplets holding, the gathering of droplets to vessels with the no diluting the fuel droplets liquid, application of melted wax, which has in the melted state the properties: density of 780 kg/m^3, kinematic viscosity $1.5*10^{-3}$ m^2/s and superficial tension 0.027 kg/s^2, nearing to naphtha properties with density 800 kg/m^3, kinematic viscosity $1.6*10^{-3}$ m^2/s, superficial tension 0.026 kg/s^2, the refrigeration of droplets method, the method of the cascade droplet catcher on the carbon and magnesium oxide surface with the segregation on different sizes. Mechanical methods require counting and measuring of droplets, they are labour-consuming and they can be utilized exclusively in the laboratorial conditions.

From electric methods possible to mention are: the wire loaded with the electric charge method, which removes charges dependant from the settling droplets dimensions and the method of the hot wire, which relies on fact that fuel droplets vaporize settling on the wire and cause cooling. This method was used in author research team. Optical methods can be fundamentally divided on the image and imageless methods. The image methods encircle the flash photography and the holography. Their application in practice is limited to research of the droplets with dimensions larger than 5 μm. Image methods permit, in order to droplet to be seen in the point and time, where the measurement is required. The errors which could originate from the union of droplets or their vaporization after injection are eliminated. The imageless methods can be divided on the two groups, the first, which counts and measures the separate droplets individually and the second, which measures the high figure of droplets simultaneously. Some imageless method equipment can deliver both information relating to the dimensions and speeds. Many optical diagnostic methods can be utilized to the analysis of the fuel atomization process. Recapitulating, it is possible to designate to optical methods: fast photography, the video analysis, the stream image scanning, holographic analysis, counting of individual particles, diffuse light interferometry, non axis diffuse light detection, the Doppler phase of particles analyzer (PDPA), the Doppler laser speed analyzer (LDA).

Research system PIV (Particle Image Velocimetry), Fig. 1, 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 with the injection pressure of 50 MPa, and after time of 0.52 ms presents Fig. 2. However the example of speed field with the injection pressure of 100 MPa after 44 ms time.

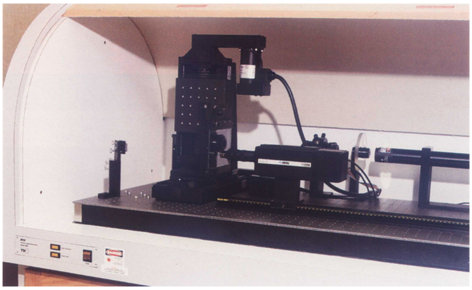


Fig. 1. View of PIV optical system

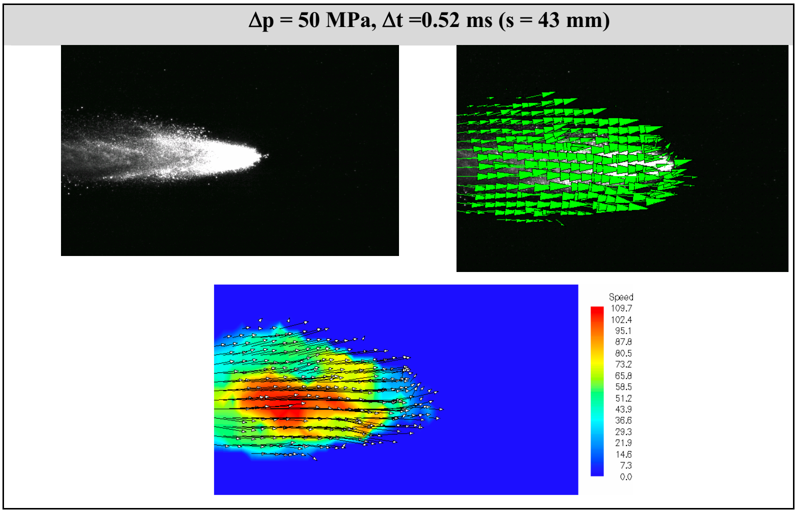


Fig. 2. Example of speed field with the injection pressure of 50 MPa

In the investigations of the atomized fuel stream, in the conditions mirroring the engine conditions, important is the knowledge of the droplets dimensions and their distribution in the fuel stream. For the needs of the process analysis for the stream creation, advantageous is to not make use of droplets set with the different diameters, but by droplet with the fixed diameter, characteristic for the data of atomization conditions. Research was performed with utilization of laser equipment LDV (Laser Doppler Velocimeter) and PDPA (Phase Doppler Particle Analyzer). Measurements were realized in measuring space, which is determined by two laser beams crossing itself, zero beam and Doppler beam from each transmitter. This space exists in the area of the optical focus of laser transmitter and has shape of rhomboidal solid, the maximum dimensions of which in the tuned optical system were: 1.76 x 1.4 x 1.4 mm. The diameter of laser beam was 1.4 mm; the distance of zero beam and Doppler beam was 39.74 mm, focal dimension was 250 mm. Optical system can be fitted to the range of occurring droplets dimensions and permits to widen measuring range both in the bottom direction, as in the top direction of the standard range.

The dimensions of measured droplets with given optical system will be contained in the range from 0.5 μm to 2.0 mm. The dimensions measuring range is dependant from the optical system and of the RSA processor type (Real Time Signal Analyzer), at the same time the shift of the laser beam phase from 30 to 3500 can be recorded. In any case optical system ought to be juxtaposed in such manner, in order to maximum of droplets dimension was smaller from smaller diagonal of the rhomboidal section, perpendicular to the component of the fuel stream speed, however the minimal dimension of droplets which can be recorded in the standard optical system are 0.5 μm and is such, which shifts the laser beam phase on value 30 or larger. System PDPA for the measurements of the droplets dimensions must be calibrated, however system LDV to the measurements of speeds does not require calibration and the reference is the measuring laser beam with the different wave length for each direction. Measuring system permits on the realizations of the measurements of speeds in 3 directions (3D), but the measurement rule for the droplet speed component relies on the recording of the frequency of laser beam change, which is proportional to the speed of the fuel droplet.

The component of speed can be defined from following dependence:

$$v_i = \frac{f_D}{f_0 2 \sin \Phi}, \tag{1}$$

where: vi - the component of the of droplet speed,
f_D - modulated frequency of the Doppler laser beam,
f_0 - the frequency of zero beam,
Φ - the angle between the zero beam and Doppler beam.

With respect to the PDPA system the choice of five diameters: D10, D20, D30, D32, D43 was made. Diameter D10 is arithmetical diameter and has comparative meaning. Diameter D20 is the function of droplets area and enables the comparison of a average area of measured droplets. Diameter D30 is the function of the droplets volumes and enables the comparison of the measured droplets volumes. Diameter D32, Sauter (SMD) diameter, is defined from the ratio of the sum of volumes to the sum of the surface of droplets and is applied to the analysis of the heat and mass transfer processes. The diameter D43, Herdan diameter, is defined from the ratio of the sum of the fourth exponent of the droplets diameters to the sum of the third exponent of the droplets diameters and is used in the combustion processes analysis and gives the better approximation of occurrences encircling the combustion processes.

Differences of sizes of droplet are a measure of homogeneity of a fuel spray. The essential part in estimation of injected fuel spray has the median referred to volume of droplets which is also determined in the measurement. Size of the droplet is determined on the ground the relative modulation of the laser-signal by drops flow by the measuring-area.

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \tag{2}$$

where: M - intensity parameter,
I_{max} - maximal intensity,
I_{min} - least intensity.

The dependence between the value determining intensity of the M laser beam measured with the measuring-system and size of the drop describes the equalization:

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

where: J_1 - the first order of the Bessel function,
D - size of droplet,
δ - distance between interferential stripes.

Emplacement of optical transmitters and receivers for the purpose of the measurement of velocity components in orthogonal pattern is not possible in combustion chamber. On that account, the slope pattern of coordinate is applied.

4. Results of the investigations

Fig. 3 presents the view of the measuring-space and the investigative chamber for research process atomization of the fuel, and Fig. 4 - presents the view of test chamber for research process of atomization and combustion.

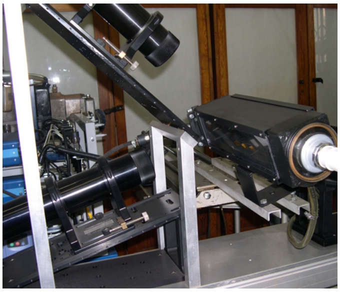


Fig. 3. View of the measuring-space and the investigative chamber for research the process of fuel atomization

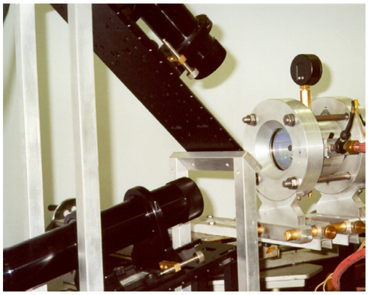


Fig. 4. Investigative chamber for research the process of atomization and combustion

If the fuel spray is homogeneous with reference to droplet's size, all diameters of fuel droplets are equal. Thus measures of the homogeneity of the spray of the fuel are differences between each kind diameters. It is evident that entirely homogeneous sprays are possibly only theoretically.
If the fuel spray is homogeneous with reference to droplet's size, all diameters of fuel droplets are equal. Thus measures of the homogeneity of the spray of the fuel are differences between each kind diameter. It is evident that entirely homogeneous sprays are possibly only theoretically. It is important that accomplishment of the combustion process at high engine loads and high rotational speeds with reference to engines with the direct-injection in the mode of homogeneous mixtures refer to the situation when essentially heterogeneous spray of fuel is regularly distributed in combustion chamber.

Next mode of engine operation - the stratified charge means that it is possible combustion and especially ignition, under conditions of very lean mixtures with reference to whole combustion chamber (so called total coefficient of air excess) and stoichiometric mixtures close to spark plug.
However basic question is obtainment of droplets of small dimensions for initiating of ignition and heating up whole mixture, where through the combustion very weak mixtures is obtained, what would not be possible under conditions of the homogeneous mode.
The homogenization with reference to diameters should go toward of the obtainment of small sizes of droplets of possible high homogeneity.
The obtainment such droplets can take place by increasing of injection pressure. However other methods for obtainment of small sizes of droplets are possible, in this so called the system of the gas (air) assist.
The modelling of the fuel spray is possible with several dependences. The most accepted method is the Rosin-Rammler method:

$$1 - Q = \exp \{- (D / X)q\}, \qquad (10)$$

where: Q - volumetric share drops of smaller diameter than D,
D - diameter of droplet,
X - mean size of droplets,
q - parameter of spread of droplet sizes.

The parameter X describes the diameter for which volumetric participation of Q equals 0.6321, what means that this diameter is, below which the volume all droplets in the spray is smaller than 63.21%. Then the q parameter is a measure spray dispersion, i.e. the value of this parameter is smaller the stream is more homogeneous and vice versa.

Performed measurement let on determination of distribution drops in the fuel spray on the ground Rosin-Rammler equation, as well as of several other equations such as normal distribution, logarithmic normal distribution, modified logarithmic normal distribution, Nakiyama -Tanasawa distribution and Matsumoto-Takashima distribution. Test results of laser researches of fuel spray atomization let on determination of many different parameters of fuel spray.

Along with laser-measurement for different configurations of injection systems were explored of the ignition and combustion processes were performed, whereat basically pressure registration in combustion chamber by means of piezoelectric sensors was performed, but also the photographic registration of the process of fuel atomization, ignitions and combustion in the constant of the volume chamber were performed.

Basically the ignition of liquid fuel in the constant volume chamber is not possible without initial heating up the combustion chamber. However in the performed research, combustion of liquid fuel without heating of the chamber was accomplished with special spray characteristics.

The ignition was realized at the use of a novel research injector and with means of modification the process of atomization for obtainment of small and homogeneous sizes of droplets in fuel spray. It reflects the strategy of the combustion of the homogeneous charge.

Whereat the homogeneous charge means not only as equable distributed drops of fuel in combustion chamber, but as equable distributed droplets in combustion chamber, homogeneous droplets with equal small sizes of drops. For these conditions, the repeatable ignition and the correct course the of the combustion process was reached.

Test results of the heterogeneous spray of fuel atomization concerning droplet diameters for two kind's basic droplet sizes of small in the area of about 10 μm and greater - in the area of approx. 50 μm are presented on Fig. 5. Test results of the heterogeneous spray of fuel atomization concerning droplet diameters for small sizes of droplets - D_{32}= 13.8 μm D_{43}=15.38 μm are presented on Fig. 6.

Fig. 7 presents test results of the heterogeneous spray of fuel atomization concerning droplet diameters for small sizes of droplets - D_{32}= 13.8 μm D_{43}=15.38 μm, and linear, volumetric and Rosin-Rammler distributions, D32=13.8 μm, D43=15.38 μm. Fig. 8 presents the distribution of the drop in the spray with the modified logarithmic normal Matsumoto-Takashim equation.

Fig. 9 presents the course the combustion process in the constant volume chamber for the fuel spray with proprieties presented on Fig. 5 (λ=2,5). Fig. 10 presents the course the combustion process in the constant volume chamber for the fuel spray with proprieties presented on Fig. 6 (λ=1).

5. Conclusions

Targets of the development of formation processes of the mixture pursue obtainment the spray with small sizes of the droplets. This is referred by not only to strategy of homogeneous combustion process but first of all to strategy of cold start where essential is use of the drop of small sizes.

Small sizes of the drop are received in the way of increasing of the injection pressure. However high increasing of the pressure unfavourably influences on durability of fuel equipment. Proposed novel mechanical method was put-upon in research of the ignition process of fuel preparation.

Applied fuels differ with the value viscosity and the surface tension what has an essential influence when the additives to fuels having different proprieties than petrol (ethanol) are applied.

Performed research of combustion process in the about the constant volume chamber shows that the ignition and right combustion are possible when the fuel spray is characterized with small sizes of the D43 diameter which exceeds the value of 30 μm.

If in the spray of the fuel drops of sizes exceeding 30 mms appear at the considerable number of small drops of the D43 diameter smaller than 30 mms, then the ignition and the combustion are also possible, though the combustion is characterized with different speeds in time whole process.

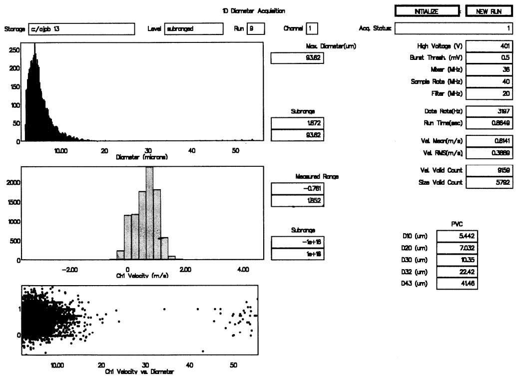


Fig. 5. Test results of the heterogeneous spray of fuel atomization concerning droplet diameters for two kinds basic droplet sizes of small in the area of about 10 μm and greater - in the area of approx. 50 μm a (8)

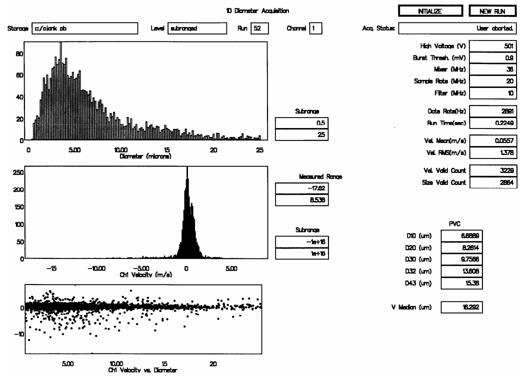
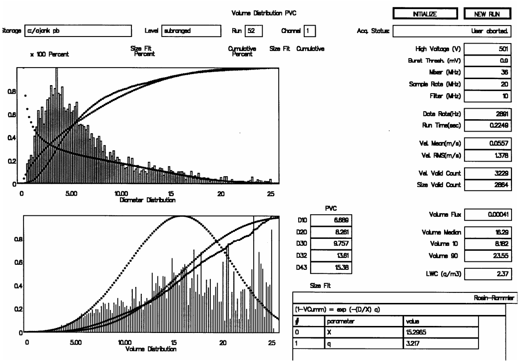


Fig. 6. Test results of the heterogeneous spray of fuel atomization concerning droplet diameters for small sizes of droplets - D_{32}= 13.8 μm D_{43}=15.38 μm



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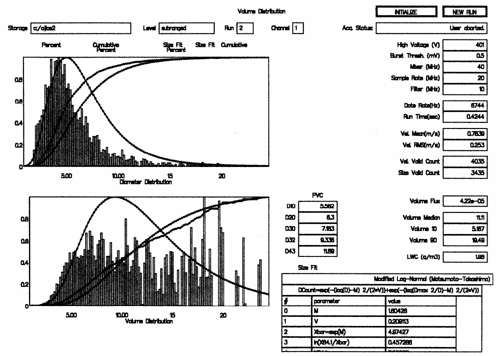

Fig. 8. Distribution of the drop in the spray with the modified logarithmic normal Matsumoto-Takashim equation

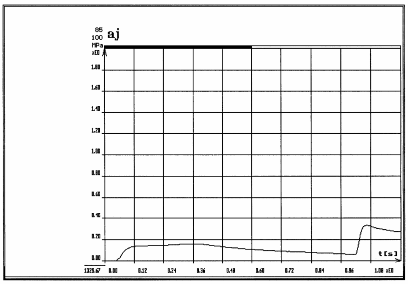

Fig. 9. The course the combustion process in the combustion the constant volume chamber for the spray of the fuel of proprieties presented on Fig. 5 (λ=2,5)

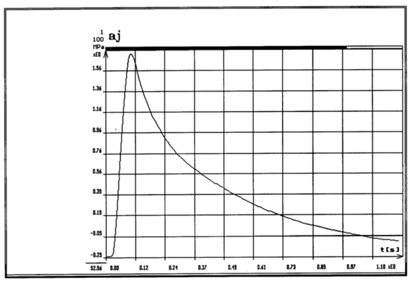

Fig. 10. Course the combustion process in the constant volume chamber for the fuel spray with proprieties presented on Fig. 6 (λ=1)

During research of the ignition and combustion process at elevated pressure in the constant volume chamber (to value of 1 MPa) with high sizes of the drop, when the D43 diameter is greater than 30 μμσ, the ignition is not possible, also at the additional essential increasing of the pressure in combustion chamber.

Determinant influence on the ignition under conditions of the cold combustion chamber has a fuel atomization.

The fuel atomization influences favourably on the emission level components of toxic exhaust gases, in this especially - on the level emission of hydrocarbons because of excluding of the apoptosis of ignitions and on the level of the issue of nitrogen oxides on account the short time of drop residing in combustion zone.

Fuel atomization from the point of view processes of combustion and ignition, as well as of the level of the emission characterizes the best substitutive D43diameter which the value is close to volumetric median.

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