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COMPARATIVE STUDIES OF THE BIODIESEL FUEL JET DEVELOPMENT DYNAMICS IN COMMON RAIL AND CONVENTIONAL DESIGN FUEL SYSTEMS

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Abstract. The results of comparative diesel and biodiesel (Rapeseed oil Methyl Ester (RME) and Rapeseed Oil (RO)) fuel jet structure studies by optical scanning method are presented. There is an interrelation between the dynamics of fuel jet development by the Common Rail (CR) with single-phase injection and Conventional Design System (CDS) and the parameters of mixture formation, which are typical for transferring the operation of the Diesel Engine (DE) from mineral diesel to RME and RO. The structure of the Diesel Fuel (DF) jet is significantly more heterogeneous by the size and number of droplets in CDS in comparison with CR. From the moment of the injection the presence of zones less saturated with fuel contributes to a relatively short induction period – 5° ca. compared to 11…12° ca. in the CR system. Using RME in the CR system in comparison with DF, increases the heterogeneity of the fuel jet, thereby causing a shorter (by 1…2° ca.) induction period in the whole investigated range of injection pressures of 60…160 MPa. The injection of a non-heated RO is accompanied by the shape and structure fluctuations of the fuel jet. RO heating to 65 °C stabilizes the structure of the jet and increases the share of less saturated zones. Promising way of use for the optical scanning method in the mathematical modelling of the DE working process is proposed.

Keywords: diesel engine, common rail, conventional design system, fuel system, fuel jet structure, rapeseed oil methyl ester, rapeseed oil.

Abbreviations

AltSTU – Altai State Technical University (Russia);
CDS – Conventional Design System;
CN – Cetane Number;
CR – Common Rail;
DE – Diesel Engine;
DF – Diesel Fuel;
FAEE – Fatty Acids Ethyl Ester;
FAME – Fatty Acids Methyl Ester;
KU – Klaipėda University (Lithuania);
LIF – Laser-Induced Fluorescence;
RME – Rapeseed oil Methyl Ester;
RO – Rapeseed Oil;
SMD – Sauter Mean Diameter.

Introduction

The limited world reserves of petroleum fuels, increasing consumption and greenhouse gas emissions contribute to transfer of the DE to alternative renewable fuels – biodiesel. In the EU countries, the dynamics of this substitution is regulated by a number of European Parliament directives (EC 2005, 2009). In *Directive 2009/28/EC* it is planned to reach 10% share of renewable energy in the transport sector by 2020. The transport sector strategic development document for the EU countries, White Paper, also calls for use of biofuel in the transport sector instead of mineral fuel (EC 2011).

In the Western countries, certified methyl and ethyl esters of vegetable oil fatty acids (FAME, FAEE) are used as biodiesel. For example, in EU countries – RME certified in accordance with the EN 14214:2009.

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In countries of Eastern Europe (Belarus, Ukraine, Russia, etc.) (Markov *et al.* 2011; Zhosan *et al.* 2012), and also partially in the EU countries (Labeckas, Slavinskas 2009), pure vegetable oils, primarily RO and their mixtures with petroleum diesel, are often used as biodiesel. Their production technology is much less expensive, and the cost of pure vegetable oils is less than that of FAME.

One of the most important tasks is to optimize the parameters of engine working process operating on biodiesel (RME, RO). Part of this task is the study and optimization of fuel injection parameters and characteristics. The relevance of solving this task is due to the differences in the physical-chemical properties of RME and especially RO from diesel: density, viscosity, surface tension, evaporation, etc. (Kegl *et al.* 2008; Markov *et al.* 2013).

For the operated DE fleet, this task is solved by optimizing the adjustment parameters and design of the fuel system and combustion chamber: selecting the optimum injection pressure (CR system), nozzle atomizer design (diameter, number of spray holes) and preliminary heating of RO in the CDS (Marchenko *et al.* 2005).

The relevance of the research and optimization of biodiesel injection in DE causes not only a wide range of research aspects, but also development of new research methods. The main parameters of the liquid fuel atomization quality in the DE combustion chamber are: the dispersion composition and distribution of fuel concentrations, angle, velocity and length of fuel jet. The most informative for optimizing the fuel supply system parameters, but at the same time complicated, are the methods for studying the fineness and homogeneity of fuel atomization (Mollenhauer, Tschöke 2010; Ashgriz 2011; Lyshevskij 1981; Lewińska, Kapusta 2017).

At present, optical methods are successfully used for measuring the fineness of atomization and concentration of droplets in a fuel jet (Van de Hulst 1981; Kerker 1969). Lewińska and Kapusta (2017) studied the parameters of the microstructure of DF spray using the LIF method in combination with Mie scattering. Based on the obtained imaging diesel spray form and distribution of droplets in the gas phase were determined. Pastor *et al.* (2012) used this method to determine the SMD, but to enhance the fluorescence effect, indicator Rhodamine B was added to the fuel. The method is widely used by other researchers – Li *et al.* (2011) investigated the characteristics of the swirl spray. Linne (2013) and Linne *et al.* (2006) developed an optical technique called ballistic visualization when light passes through a cloudy environment, the photons that make up this light experience a different amount of scattering. Sedarsky *et al.* (2009) and others demonstrated that from ballistic images it is possible to obtain the speed data of the spray.

One of the most accurate methods for determining the droplet size is a method of laser diffractoscope. Its working principle is based on measuring the scattering of a laser beam. The angle at which the drop disperses light is inversely proportional to its diameter. This method was used by Klyus *et al.* (2013) and Krause, Klyus (2013) to determine the distribution of droplets in the jet of DF and DF mixtures with biocomponents. The same method proved itself very good with the establishment of SMD and distribution of droplets in the residual fuel jet, despite the opacity of the tested fuel (Klyus, Zamiatina 2017). However, the fineness and dispersion analysis of the atomized fuel is carried out in a fixed section of the jet. Therefore, to evaluate the structure of the entire jet, it is necessary to repeat the experiment many times.

To determine the speed, angle, and length of the fuel jet, the method of high-speed photography is most often used. Wang and others (Wang *et al.* 2017) used the method of high-speed photography to measure the injection angle and speed of four types of fuels.

The article presents comparative studies of the jet development characteristics of the DF, RME and RO in CR with single-phase injection and CDS fuel systems by optical sensing method, developed by scientists from the AltSTU (Es'kov *et al.* 2014).

This article presents the results of the next stage of joint research by scientists from AltSTU and KU into the use of biodiesel in DE (Lebedevas *et al.* 2006a, 2006b; Kulmanakov *et al.* 2009, 2016).

The objectives of the research were:

- determination of fuel jet structure and dynamics development features in the fuel supply systems under study in correlation with the self-ignition and combustion dynamics of diesel and alternative fuels;
- study of the influence of fuel supply system design and adjustment parameters on the structure and development dynamics of the fuel jet;
- evaluation of the viable optical sensing method uses in the research of fuel supply system characteristics in DEs.

1. Research methods and subjects

1.1. Optical sensing method

The scheme of the high-speed photography stand, used for the optical sensing method, is shown in Figure 1. Fuel is supplied into the injector at a given pressure: from 60 to 180 MPa in the CR system and ~65.0 MPa in the CDS system (1750 min^{-1}). During spraying, the fuel jet moves along the surface of the screen, illuminated from the inside by a light source. High-speed video camera (video shooting frequency – 7042 frames per second) records the temporal development of a fuel jet. Synchronizer coordinates the nozzle opening moments and start of video recording, the control unit coordinates the operation of the camera, computer and injector. More detailed scheme of the stand, as well as the scheme of optical measurement and screen (Figure 2) is described in the work of the authors (Kulmanakov *et al.* 2012).

Experimental studies of the fuel jet structure dynamics were carried out by the evaluation of brightness changes in the fuel jet zones. Brighter zones correspond to a greater density of fuel jet zones with smaller reference numbers.

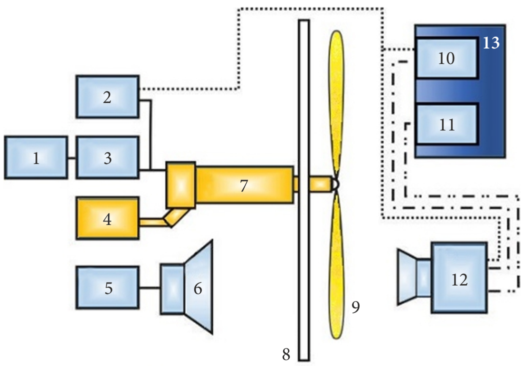

Figure 1. Schematic diagram of a high-speed video shooting stand for determining the parameters of a fuel jet: 1 – electronic engine control unit; 2 – synchronization devices; 3 – control block; 4 – fuel tank; 5 – power supply unit; 6 – light source; 7 – nozzle; 8 – screen; 9 – fuel jet; 10 – ADC LA 1.5 PCI; 11 – controller board; 12 – high-speed video camera "Videosprint"; 13 – PC

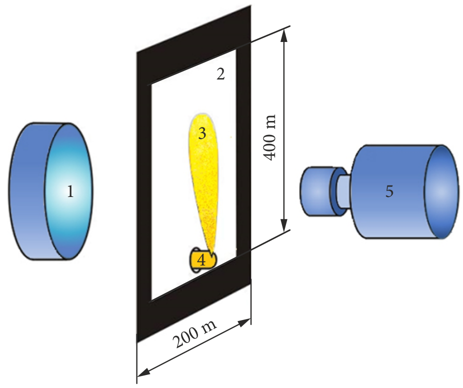

Figure 2. Optical measurement scheme and screen design: 1 – lamp; 2 – scattering screen; 3 – fuel jet; 4 – nozzle; 5 – high-speed video camera

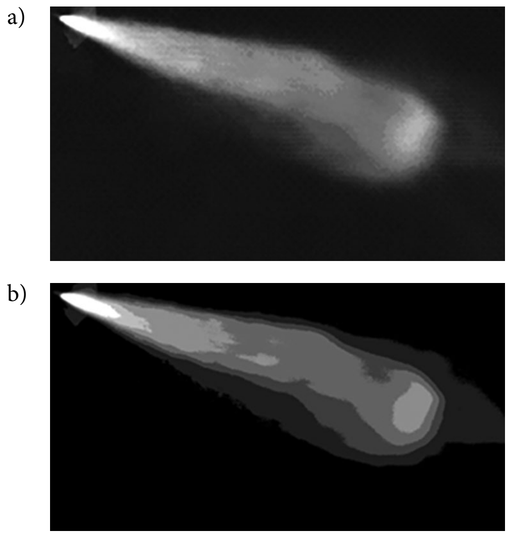

Figure 3. Fragments of recording the image of the fuel atomization process (image inverted): a – initial image (exposure time 35.5 µs; b – brightness zones, allocated by the computer program on the image using the threshold segmentation method

An example of image processing of the fuel atomization process using the original computer program (Es'kov, Gibel'gauz 2011) is shown in Figure 3. The figure shows the instantaneous initial image of the jet, recorded by high-speed filming, and the brightness zones allocated by software, using the threshold segmentation method.

1.2. Test fuels

Comparative measurements were performed using mineral diesel according to GOST R 52368-2005 and EN 590:2009, biodiesel RME according to EN 14214:2009 and RO according to GOST R 53457-2009. The main physical-chemical properties of the tested fuels are given in Table 1.

The brightness of the zones, which is the basis of the optical scanning method, evaluates both the size of the droplets and the density of the droplets in the air. Based on fundamental research of the fuel jet (Lyshevskij 1971; Mollenhauer, Tschöke 2010; Ashgriz 2011), these phenomena are in close interrelation. The fragmentation of droplets into smaller ones mainly occurs in the peripheral zones of the fuel jet's middle part, which interacts intensely with the air flow. In the inner region of the jet along the axis large-sized fuel droplets, without encountering air resistance, move at high velocities, eventually forming a dense, fuel-saturated core and jet front. The described character of the fuel jet development is clearly visible in Figure 3, obtained by the optical scanning and threshold segmentation method. Authors of publications have made the assumption to interpret differences in the brightness of fuel jet zones as the size and number of drops in the zone. The results of the performed studies confirmed the adequacy of the assumptions.

Table 1. Physical-chemical properties of fuels

Index \ Fuel	RME	RO	DF
Density [kg/m^3] (temperature) [°C]	887 (15)	917 (20)	831 (15)
Kinematic viscosity [cSt] (temperature) [°C]	4.48 (40)	19.7 (60)	1.91 (40)
Freezing point [°C]	−13	−23	−33
Flash point [°C]	90	>100	57.5
Ash [% m/m]	0.009	–	–
Water [% m/m]	0.17	–	0.0021
Surface tension [mN/m] at 50 °C	29.92	31.23	25.61
CN	54	40	51

1.3. Research plan

Fuel testing by the CDS system was performed at a high-pressure fuel pump rotation rate of 875 min^{-1} (corresponding to the 1750 min^{-1} rotational speed of the DE); CR system – also when the DE rotational speed corresponds to n = 1750 min^{-1}. In the CDS system, the influence of heating RO to 65 °C on the characteristics of the fuel jet is estimated. Fuel injection is carried out by a nozzle with an effective total of 4 nozzle holes with cross-section μf = 0.21 mm^2. The plan of the experiment is shown in Table 2.

To substantiate the estimates and conclusions made in the course of the research, the materials of the motor DE workflow tests of the authors with CR and CDS fuel supply systems were partially used.

Table 2. The plan of the experiment

Fuel	CDS		CR					
	26 °C	65 °C	Fuel injection pressure [MPa]					
			60	80	100	120	140	160
DF	+	–	+	+	+	+	+	+
RME	–	–	+	+	+	+	+	+
RO	+	+	–					

2. The results of the study and their discussion

2.1. Fuel jet structure dynamics in the CR and CDS system

The results are shown in Figure 4 (S_i/S – the relative share of the i-brightness zone relative to the total area of the fully formed fuel jet).

A characteristic difference in the dynamics of fuel jet structure change in the CR system is the successive transition of zones with large droplets into zones with smaller droplets. Thus, in Figure 4a, the maximum of each subsequent zone as its brightness increases (interpreted as a decrease in the diameter of the droplet) is observed at the time of the disappearance of the previous zone-with a larger droplet diameter (darker zones). Thus, the "transition" of zone 1 into zone 2 ends at 1200 μs, zone 2 into zone 3 at 1550 μs, zone 3 in zone 4 at around 2250 μs. The trend persists with increased fuel injection pressure (Figure 4b). In the CDS system, from the moment of the injection, formation and fuel jet development, zones in the entire range of the droplet diameter range occur approximately equally (Figure 4c).

It is obvious that the traced dynamics of the fuel jet development should significantly affect the difference in the induction period values, as is known, determined by its physical τ_f and chemical τ_{ch} nature. When the chemical τ_{ch} nature is equal, the physical τ_f for the CDS system is shorter, since the presence of zones with a small droplet diameter creates more favourable conditions for the evaporation of droplets, the formation of free radicals and the occurrence of autoignition from the injection moment (Lyshevskij 1971; Mollenhauer, Tschöke 2010). Indeed, motor test data showed a 2-fold difference of φ_t: 5.3° ca. by CDS system vs 11…12° ca. by CR system with single-phase injection for the test mode of loading and the magnitude of the cyclic fuel supply.

Increasing the injection pressure in the CR system causes a time shift in the zone transition - the decay of large droplets near the injection start, (Figure 4b), thereby reducing value of τ_i. As a result, τ_i is reduced, but significant differences in τ_i are maintained until a pressure increase in CR system to 180 MPa: 8.5° ca. vs above-mentioned 5.3° ca. in CDS fuel supply system.

Intensive single-phase fuel injection in the CR system with a relatively long value of τ_i, results in autoignition practically coinciding with the phase of the fuel injection end.

With the observed character of mixture formation and combustion, the controllability of the combustion process is lost, and the phase of kinetic combustion becomes predominant. With such combustion, the most toxic components - nitrogen oxides NO_x are intensively formed (Reitz, Duraisamy 2015; Baumgarten 2006; Zel'dovich *et al.* 1980). Obviously, this circumstance should be taken into account by optimizing DE work on various fuels, including when transferring their work into alternative types of fuel – RME and RO. In addition, in practice, in CR system a multi-phase, controlled injection is used, which, in comparison with the CDS system, allows to increase energy and improve ecological characteristics.

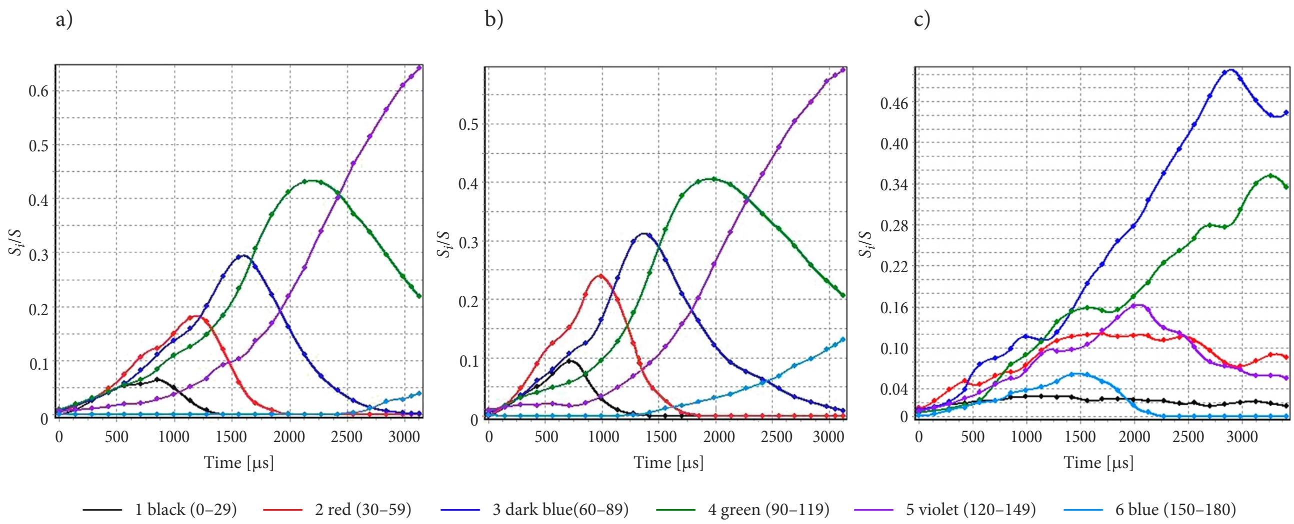

Figure 4. The structure of the fuel jet: a – CR system (60 MPa); b – CR system (100 MPa); c – CDS system (26°C, 1750 min^{-1})

2.2. Fuel jet structure dynamics when transferring DE work from mineral diesel to RME

Comparison of diesel and RME fuel jet in the CR system, performed in a wide range of injection pressures P_f = 60…160 MPa, allows to give the obtained results and their analysis a great generality. A fragment of the results obtained at P_f = 160 MPa is shown in Figure 5.

In contrast to the dynamics of DF jet structure development discussed above, the nature of RME injection has characteristic differences in the entire investigated range of P_f. Disintegration of the RME jet into smaller droplets comes ~15…30% faster from the moment of the injection (estimated by the position of the maximum brightness zones). It should be especially noted that structure of the RME jet is less homogeneous and, practically throughout the entire injection, its structure consists of brightness zones 2 through 5. At the same time, during DF injection, a gradual transition of zones occurs.

As a result, on the one hand, an earlier ignition of the RME should be expected, on the other hand – a smaller fraction of the combustible mixture is prepared for ignition compared to DF. Accordingly, we should expect a softer and more controlled combustion process. With this mixture formation, the maximum heat release rates are reached in the diffusion combustion phase, which forms the fuel economy indicators (Hansen *et al.* 1997; Ma *et al.* 2015).

The data of motor tests of the authors fully confirm the results of the performed analysis. In particular, in the whole investigated range P_f, the induction period τ_i for RME is by 1…2° ca. shorter. At this, smaller activation energy (higher CN) of RME compared to DF should also be taken into account, since it also causes a reduction in the chemical nature of the induction period τ_i. Similar data were obtained in other works (Barradas Filho *et al.* 2015; Lebedevas *et al.* 2013; Li *et al.* 2017).

2.3. Dynamics of RO jet injection in the CDS system

Figure 6. shows changes in RO fuel jet structure dynamics, when inlet temperatures of the CDS fuel system high-pressure pump are 26 and 65 °C.

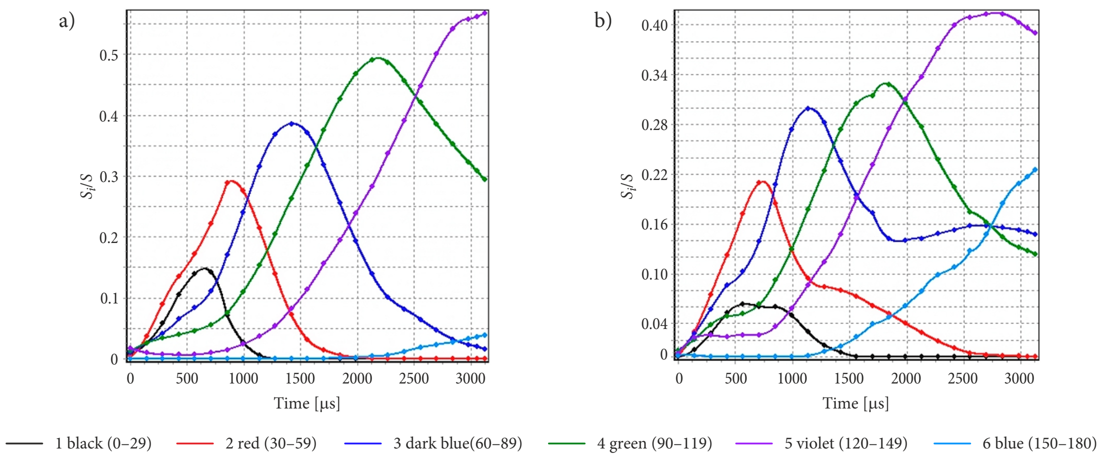

Figure 5. The structure of the fuel jet in CR system: a – DF; b – RME

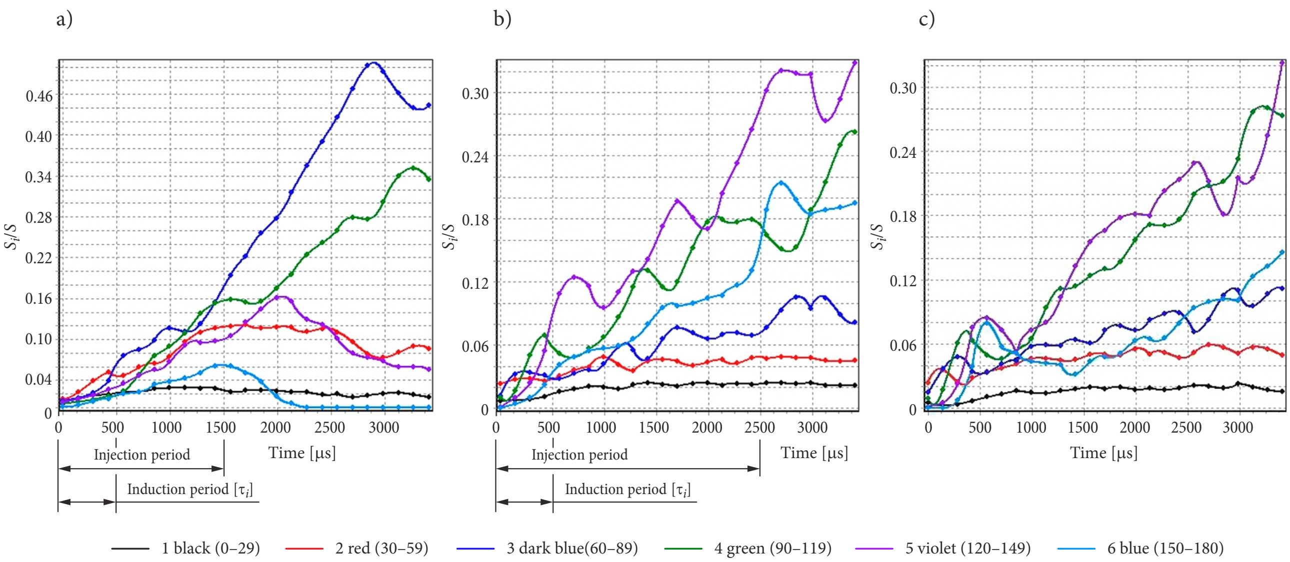

Figure 6. Fuel jet dynamics in the CDS system during injection: a – DF (26 °C); b – RO (26 °C); c – RO (65 °C)

In comparison with diesel (Figure 6a), the total volume of the RO fuel jet has a pulsating character, especially at a temperature of 26°C. The most unstable zones of the jet are zones with the smallest optical density – 4, 5 and 6 (Figure 6b). In case of preheated inlets to 65 °C stability of the oil jet structure dynamics significantly improves (Figure 6c). This may be due to a reduction in the viscosity of RO from 73 mm^2/s to ~18 mm^2/s when it is heated from 26 to 65 °C. For all research options, during the engine tests, almost identical duration of the induction period was obtained (~5° ca. or ~500 μs). However, due to the higher RO viscosity, the injection time is ~65% greater than with D.

Analysis of the RO fuel jets structure shows that by the end of τ_i the relative proportion of zones with a lower density of fuel droplets (4, 5 and 6 zones) increases when RO is heated: from ~55 to ~75% respectively for 26 and 65 °C. Thus, a more favorable combustion character of preheated RO should be expected. This is confirmed by data from experimental studies (Marchenko *et al.* 2005).

3. Promising directions of optical scanning method application

The research results indicate the adequacy of the method application when performing a qualitative comparative analysis of various design variants of injection systems for diesel and alternative fuels.

At the same time, certain additions to the method application make it possible to pass from qualitative to quantitative estimates of the fuel jet structure development dynamics. In addition, they can be useful for supplementing mathematical models of intra-cylinder processes in DEs.

So, with the assumption that the zones of different optical density of the fuel jet are interpreted as characteristics of fineness and uniformity of spraying, it becomes possible to estimate the expected spectrum of fuel droplet sizes and their development in the injection time.

For this purpose, using the known analytical dependencies grounded on integrated injection parameters, for example, for marine diesels (Lyshevskij 1971), or later studies (Lyshevskij 1981), the average diameter of the fuel droplets d_k for the fuel supply process is determined. Thus, on the basis of a generalization of the experimental material by criterial dependencies, the analytical dependence of d_k is obtained (Lyshevskij 1971):

$$\frac{d_k}{2 \cdot a} = 3.01 \cdot \left(\rho \cdot We\right)^{-0.266} \cdot M^{0.073}, \tag{1}$$

where: a – jet radius at the nozzle outlet; ρ – fuel density; $We = \frac{w^2 \cdot \rho \cdot 2 \cdot a}{\sigma}$ – Weber number; $M = \frac{\mu^2}{\rho \cdot d \cdot \sigma}$ – criterion M; w – jet velocity; σ – surface tension; μ – dynamic viscosity; d – nozzle diameter.

Determination of the Equation (1) parameters by optical scanning method and laboratory tests of the physicochemical properties of fuels do not present difficulties.

Similar definitions of d_k are proposed by other researchers (Hiroyasu 1985; Lefebvre, McDonell 2017; Dos Santos, Moyn 2011).

By the method of threshold segmentation, the fuel jet is divided into a finite number of brightness zones (in the performed studies – 6 zones). Therefore, the average brightness is determined using finite differences:

$$A_{avr} = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} A_i \cdot S_i}{\sum_{j=1}^{m}\sum_{i=1}^{n} S_i}, \tag{2}$$

where: A_i – the brightness of the i-th zone at the j-th time of the injection; S_i – the relative area of the i-th brightness zone at the j-th time of the injection.

Using d_k and A_{avr}, the conversion coefficient of the brightness zones during the fuel jet development in the appropriate range of fuel droplets diameters is calculated:

$$X = \frac{d_k}{A_{avr}}. \tag{3}$$

Using the X coefficient, the values of the fuel jet are calculated into the distribution of the corresponding d_i values.

4. Using the method in the computational studies of internal combustion engine

Modern mathematical models, including multi-zone models (Kuleshov 2004; Kolade *et al.* 2004), use the average fuel droplets diameter as input data for the fuel injection characteristics and injection process calculation.

At the same time, the spectrum of the fuel droplets diameter dynamically changes during the injection time. It would be advisable to take these changes into account when modelling the processes of mixture formation. Obviously, in order to achieve this it is necessary to have an analytic dependence of homogeneity and fineness parameters changes in the fuel jet, in other words – spectrum of fuels droplet size dynamic changes as a function of the fuel delivery time.

The analysis of the obtained data, as well as the data from other studies (Pimentel 2006), confirm the correspondence of the fuel droplets spectrum at any time to the normal distribution law of the probability density:

$$f\left(x\right) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{\frac{\left(x-m\right)^2}{2 \cdot \sigma^2}}, \tag{4}$$

where: σ – standard deviation; m – median.

The values of σ and m obtained during research are generalized by the analytical dependencies as a function for the fuel jet development time. They can also complement the mathematical modelling methods of the DE workflow.

Conclusions

Comparative studies of the fuel jet structure of mineral diesel and biodiesel (RME and RO) have been carried out using optical scanning method for the CDS and CR with single-phase injection fuel supply systems. The obtained data allow predicting the probabilistic changes in the characteristics of the mixture formation at the design stage when transferring the DE for operation on alternative fuels:

1. The structure of the diesel jet in the CDS compared with CR is much more heterogeneous in size and number of droplets. The presence of less fuel saturated zones from the beginning of injection contributes to a relatively short induction period 5° ca. and the subsequent favourable heat release characteristic. With single-phase fuel supply in the CR system, a consecutive occurrence and transition of zones with a higher fuel density into a zone with a lower fuel density is observed. As a result, a 2-fold longer induction period of fuel ignition 11…12° ca. is observed. Therefore, in practice, in CR system a multi-phase, controlled injection is used, which, in comparison with the CDS system, allows to increase energy and improve ecological characteristics.
2. Using RME in the CR system in comparison with DF increases the heterogeneity of the fuel jet, thereby substantiating the observed reduction of the induction period by 1…2° ca. in the entire investigated range of injection pressures 60…160 MPa. As a result, the parameters of the working process dynamics are reduced and a more favourable character of mixture formation and combustion should be expected, which contribute to an increase of the indicated efficiency during operation with RME in comparison with D, which is also confirmed in practice.
3. The structure of the fuel jet DF and RO in the initial phase of injection in the CDS system is practically the same, contributing to almost the same duration of the induction period ~5° ca. At the same time, the injection of a previously unheated RO is accompanied by fluctuations in the shape and structure of the jet. Heating to 65 °C stabilizes the structure of the fuel jet and increases the proportion of less fuel-saturated zones, which contributes to reducing the induction period and the injection duration.
4. Promising directions of using the optical scanning method in the mathematical modelling methods of the DE workflow are proposed.

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