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THE INFLUENCE OF THE FUEL SPRAY STRUCTURE AND DYNAMICS OF ITS FORMATION ON SURFACE COMBUSTION OF BIOFUELS IN DIESEL ENGINES

Sergey P. Kulmankov[1], Sergejus Lebedevas[2], Vladimir Sinitsyn[3], Galina Lebedeva[4],
Sergey S. Kulmankov[5], Sergey Yakovlev[6]

[1, 3, 5, 6]*Dept of Internal Combustion Engines, Altai State Technical University,*
Barnaul, Russian Federation
[2]*Maritime Institute, Klaipėda University, Klaipėda, Lithuania*
[4]*Dept of Informatics, Klaipėda University, Klaipėda, Lithuania*

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Abstract. The paper presents the results of the experimental investigation of the structure of the fuel, rapeseed oil and diesel fuel sprays obtained by analysing their optical density. The results are obtained by investigating a conventionally designed fuel supply system and a high-pressure common rail system. The experimental data on the velocity and length of fuel sprays are given. The study has shown that when high pressure fuel supply systems are used, the fuel spray is increased by about three times, while its area is increased up to 50% and homogeneity is also higher. As a result, self-ignition delay time is reduced and the combustion process is intensified. The methods, taking into consideration the specific character of using the alternative types of fuel and high pressure systems, which have been tested in the experimental conditions, are suggested for calculating the time of self-ignition delay. The applied methods allow us to reduce the error of determining self-ignition delay time up to five percent. Based on the calculated data, the factors limiting the ignition of the sprayed fuel have been defined.

Keywords: fuel spray; velocity of a fuel spray; rapeseed oil; fuel supply systems; diesel engine.

Introduction

The investigation of the problems associated with the use of motor fuel obtained from animal fats and plant oils is the priority trend in transport sector development (EC 2003, 2011). This is of particular importance for the countries, whose economic development depends on the import of hydrocarbons and the products of their processing.

The arguments for reducing the dependence of economic development of countries on the import of gas and oil by increasing large-scale production of biofuels are very strong now. Therefore, the replacement of the oil products with biofuels is very important (EC 2003, 2011). The efforts made by the producers in this direction in the USA and the EU member-states were supported by their governments. This gave a great impetus for further increase in biofuels production (Braginskij 2008; PravRF 2013; PrezRF 2008). Now, biofuels for diesel engines are produced in 28 countries, including Germany, France and Japan, who are the leaders in this field.

Generally, in the EU member-states, biodiesels are used for diesel engines, while in the states of North and South America, bioethanol is used for spark-ignition engines. Fatty Acid Methyl Esters (FAME), obtained from the rapeseed, soybean, palm and other natural oils by their peresterification, are commonly used as biodiesels in the world (Chen *et al.* 2008; He *et al.* 2003; Chang *et al.* 1996; Van Gerpen 1996; Lebedvas *et al.* 2009, 2010; Makarevičienė *et al.* 2014; Labeckas, Slavinskas 2009).

For the producers of biodiesels in Russia, a decrease in the cost of their production is the priority issue. In general, the following groups of biodiesels are being developed and used in the world (Kulmanakov *et al.* 2009):

– Natural oils, mostly, rapeseed oil (in the pure form). The experimental investigations have shown that, due to different physical and chemical characteristics of rapeseed and petroleum oil, the former is not so effective for using in diesel engines, and, therefore, some elaboration in their design is needed;

Corresponding author: Sergejus Lebedevas
E-mail: *sergejus.lebedevas@ku.lt*

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- Biodiesel blends of rapeseed oil and diesel fuel in various proportions. These fuels are most effective from the economical point of view because, in this case, only some elaboration in diesel engine controls is needed. These types of biodiesels differently affect the ecological and power characteristics of diesel engines. In particular, fuel consumption and emission of toxic materials by these engines may be either increased or decreased, depending on their design features and operation modes (McDonnell 2000; Agarwal, Rajamanoharan 2009; Balat, M., Balat, H. 2008; Labeckas *et al.* 2003; Labecki *et al.* 2012; Rakopoulos *et al.* 2006).
- Pure FAME and blends based on diesel fuel and FAME. Their use allows a diesel engine to have satisfactory economic, performance and environmental characteristics, but the higher production cost of these types of fuels compared to other types of biodiesels described above is a disadvantage.

Each group of biodiesels has its advantages and disadvantages, which should be taken into account in choosing the energy strategy for a particular region. The choice of a particular type of fuel depends on the financial support of the state, as well as the possibility of upgrading the engine design, and the environmental requirements. In particular, in Russia, legislative and financial support of biofuels' production has not been widely practiced yet and, therefore, pure vegetable oil (mainly, rapeseed oil) or its blends with diesel oil, are used (Braginskij 2008; NREL 2009; Vysockij, Dmitrievskij 2008). However, it should be also taken into account that the best results can be obtained only by using a comprehensive and effective approach to solving energy problems.

The investigation described in this paper is aimed at the analysis of the processes taking place in the cylinders of a diesel engine for increasing the efficiency of using biofuels.

Using pure oils and their blends with mineral diesel oil in conventional mechanical injection systems considerably decreases the efficiency of fuel atomizing and mixing. As a result, incomplete combustion of biofuels, carbonization and lacquer deposits on the parts of a cylinder-piston system can be observed (Vysockij, Dmitrievskij 2008).

One of the most promising technologies of fuel supply for diesel engines used in vehicles is based on Common Rail (CR) systems and electronic control of fuel injection, which help to considerably increase their efficiency. CR systems ensure high injection pressure, as well as flexible control of a fuel spray and its structure, which can be determined by the methods of optical diagnostics (Es'kov *et al.* 2010; Greated *et al.* 2002).

Fuel combustion in diesel engine is usually a two-stage process, consisting of a rapid kinetic phase and a diffusion phase. The relationship between rapid and diffusion combustion directly depends on mixing processes, taking place in the diesel engine cylinder. In spite of the fact that the share of the self-ignition delay τ_i is small in the whole process of diesel fuel combustion, this phase is of considerable importance. In this context, the development of methods for determining τ_i values, allowing for accurate prediction in practice of the beginning of combustion (heat release) and defining the main laws of mixing is required. This would allow us to determine the interrelationship between the rate of fuel injection σ_f and the rate of heat release x. It could also help us to define the laws governing the main physical and chemical processes occurring in the combustion chamber of a diesel engine.

The parameters of the fuel spray and the characteristics of biofuel injection have been studied in a great number of works (Kavtaradze 2008; Broze 1969; Whitelaw *et al.* 2002; Kutovoj 1981; Sirignano 2014; Stiesch 2013; Valentino *et al.* 2011; Bang, Lee 2010; Desantes *et al.* 2009; Mancaruso *et al.* 2011; Labecki, Ganippa 2012). In determining these parameters, the methods of optical diagnostics are often used. They allow for non-contact control of the angle of the fuel spray opening, the length of the atomized fuel flow, the distribution of mass concentration and the spectrum of drops' dimensions with respect to the spray volume, as well as its geometrical parameters and the velocity of the spray front and its particular volumes.

Fuel distribution in the spray area is irregular, while the dynamics of movement of particular drops is rather complicated. These factors make it difficult to describe the internal structure of the fuel spray.

In the last decade, the Department of Internal Combustion Engines of the Altai State Technical University (Russian Federation) in cooperation with the Maritime Institute of Klaipėda University (Lithuania) performed a number of experimental investigations and calculations aimed at increasing the effectiveness of using various biodiesels in diesel engines from economic and environmental perspectives. In the present paper, the problem of enhancing the method of rapid video-recording and determining the quality of fuel supply based on the homogeneity of fuel spray zones, has been solved for the investigation of the process of fuel atomizing. The obtained experimental results were used for developing the methods of calculating the ignition delay time of fuel.

1. The Objects and Methods of Research

Optical indication of the fuel spray was performed using the test stand without an engine, while the processes of blending and combustion of blends in the diesel engine cylinder were performed using the setup of an engine (Greated *et al.* 2002; Šikalo *et al.* 2005). The processes of mixing and combustion were also studied.

Methods of measuring of the fuel spray parameters can be divided into contact and non-contact ones. Contact methods are associated with placing a probe in the investigated flow. A probe distorts the flow to some extent, thereby decreasing the accuracy and reliability of the obtained data. However, contact methods are widely used due to their simplicity. The use of a hot-wire anemometer or other types of probes is hardly promising for measuring the velocity of the atomized liquid. The main difficulty in using this method is associated with depositing the drops of a liquid on the probe surface and, consequently, covering it by the film of this liquid. Similarly, measuring a dispersed flow is not effective because the drops of a liquid coalesce to form a uniform mass in the sampler. To control the performance of the rapid pulsed flows of the atomized liquid, non-contact optical methods, referring to non-destructive control methods and capable of controlling flow characteristics based on a short recording period, are preferred.

Non-contact methods are based on measuring the characteristics of radiation, passing through the dispersed flow of moving particles, or radiation emitted by the moving particles.

Methods of optical diagnostics, allowing for non-contact control of the angle of the fuel spray opening, the length of the atomized fuel flow, the distribution of mass concentration and the spectrum of drops' dimensions with respect to the spray volume, as well as its geometrical parameters and the velocity of the spray front and its particular volumes, are used for determining the parameters of the fuel spray.

In this work, fuel sprays of diesel fuel and rapeseed oil (Greated *et al.* 2002; Šikalo *et al.* 2005) were investigated. A comparative analysis of the considered parameters of fuel sprays, was performed for a Conventionally Designed Fuel Supply System (CDS) or inline pump system (Mollenhauer, Tschöke 2010), with the pressure on the injector needle at the beginning of its upward movement reaching 27.5 MPa, and a system with a high-pressure accumulator, a CR fuel supply system, with the pressure in the accumulator ranging from 60 to 180 MPa.

A schematic view of the test stand for high-speed video recording is given in Fig. 1. The main principle of the operation of the stand was as follows: the electronic control unit of the engine UK-2 (1) sent an electric pulse to the control unit (4) at the specified moment of time (corresponding to a certain position of the crankshaft of the engine). Then, the electric valve of the high-pressure injector (6) was opened. The fuel found in the injector rail (5) under pressure ranging from 60 to 180 MPa was supplied to the atomizer (6) at the moment, when the electric valve was open. The pulse went from the electric valve (4) to the synchronizer (a timing unit) (2). It matched the voltage at the injector with that of a digital high-speed video camera, VideoSprint (9), and an Analog-to-Digital Converter (ADC), LA1.5 PCI (12), installed in a personal computer. The information signal was sent via the cable from the video camera (9) to the circuit board of the controller (11), also installed in the computer (10). In addition, a signal, indicating the moment of the exposure of the video camera (9) was applied to the LA1.5 PCI ADC (12). The signals of a synchronizing pulse sent by the timing unit (2) and the signal indicating the moment of the exposure of the video camera (9) were required for determining the record time of a specified frame, presented by the camera (9) and recorded by a personal computer (10). A fuel spray (8) atomized by the injector (6) moved along the screen surface (7), on the inner side of which a light source (3) connected to the power supply was found.

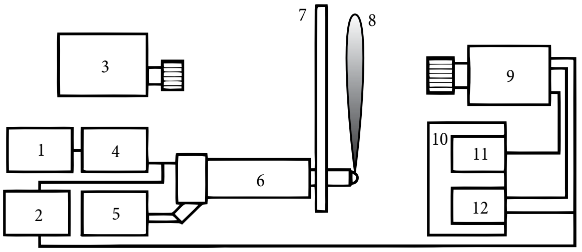

Fig. 1. A schematic view of the test stand for high-speed video recording for determining fuel spray parameters

For synchronizing the moment of starting a video recording with the beginning of fuel injection a signal from the piezoelectric transducer mounted in front of the injector was used (Es'kov *et al.* 2010).

The setup of an engine was a single-cylinder section of a diesel engine series with the diameter of the cylinder of 130 mm and the piston stroke of 140 mm. The engines of these dimensions are widely used. They are produced by the production associations of tractors and automobiles of YaMZ models. These are high-speed four-stroke diesel engines with direct fuel injection, volumetric and film mixing and water cooling. The main technical parameters of the tested diesel engine have been provided in Table 1. The experimental set-up had the required control and measuring instruments as well as special testing equipment (GOST R 51249-99; GOST 18509-88; GOST R 51250-99 standards). In testing, the control parameters of the engine performance were recorded, the pressure within the cylinder and the parameters of fuel supply (i.e. the pressure and the injector nozzle needle used) were indicated and harmful emissions (e.g. nitrogen oxide NO_x, carbon monoxide CO, and solid particles C, were measured. A detailed description of the test stand used is given in research by Markov *et al.* (2011).

Physical and chemical properties of the examined fuels complied with the presently valid standards. Thus, mineral diesel fuel complied with the GOST R 52368-2005 standard, while rapeseed oil conformed to GOST R 53457-2009. These properties are given in Table 2. The accuracy of recording the values of energy and environmental characteristics of diesel engine complied with the GOST R 51249-99, GOST 18509-88 and GOST R 51250-99 standards. These parameters are given in Table 3.

Table 1. Major parameters of the tested diesel engine UK-8

Parameter	Value
Cylinder diameter [mm]	130
Piston stroke [mm]	140
Compression ratio	16
Mean indicated pressure [MPa]	to 1.5
Rated speed, rpm	to 2000
Fuel injection	CR or CDS
Size of fuel injector nozzle	6×0.16 mm or 4×0.25 mm

Table 2. Properties of the examined fuels

Parameters	Rapeseed oil	Diesel fuel
Density [kg/m^3] at t = 20 °C	917	826
Boiling temperature of 10% fuel mass [°C]	311	180
Boiling temperature of 50% fuel mass [°C]	329	280
Temperatures at the end of boiling [°C]	341	360
Kinematic viscosity [mm^2/s] at t = 20 °C	76.0	3.8
Kinematic viscosity [mm^2/s] at t = 60 °C	19.7	–
Kinematic viscosity [mm^2/s] at t = 100 °C	8.04	–
Surface tension [N/m] at t = 20 °C	$33.2 \cdot 10^{-3}$	$27.1 \cdot 10^{-3}$
Cetane number, not lower than	40	45
Flash point [°C]	100	60
Ash content [%]	–	0.01
Fraction of total mass of water [%]	–	–
The lowest heat of combustion [MJ/kg]	37.3	42.5

Table 3. The measurement error of recording the parameters of diesel engine operation

Parameter	Measurement error
Torque [N·m]	±0.5%
Crankshaft rotation speed [rpm]	±0.5%
Average indicator pressure [MPa]	±1.0%
Liquid temperature in cooling and lubricating oil systems [°C]	±2 °C
Liquid pressure in cooling and lubricating oil systems [bar]	±1%
Fuel consumption [g/kW·h]	±0.5%
Fuel pressure in a high pressure fuel supply line [MPa]	±1%
Fuel supply angle at the beginning of the process, crank angle degrees [CA]	±0.5 °CA
Fuel supply angle at the end of the process, crank angle degrees [CA]	±0.5 °CA
Gas pressure in the cylinder [bar]	±1%
CO content in exhaust gases [ppm]	±5%
NO$_x$ content in exhaust gases [ppm]	±5%

2. Testing Results

2.1. Determining the Speed and Length of a Fuel Spray

The results obtained in investigating the variation of the speed and length of a fuel spray are given in Fig. 2. The dynamics of fuel spray development was calculated based on the data for the sequence of fourteen frames of a high-speed video camera. Each test performed in a particular mode was repeated five times with the consequent averaging of the obtained data.

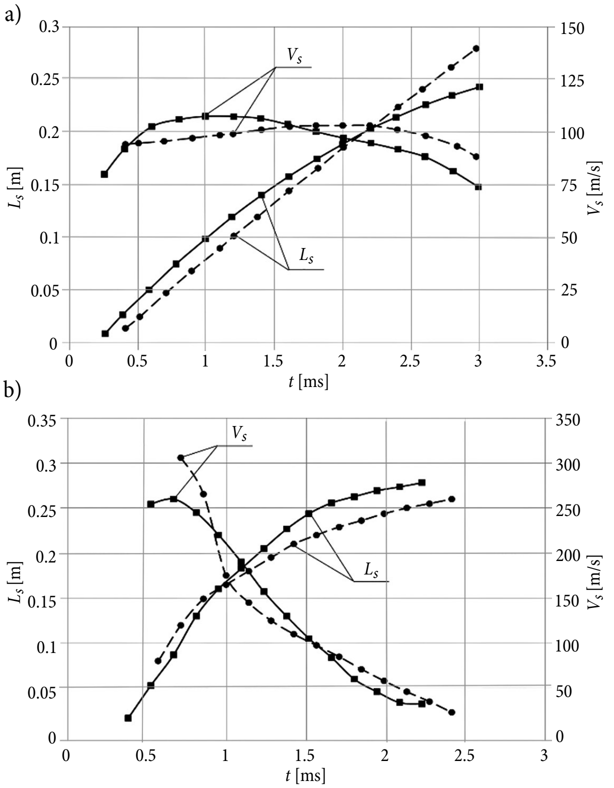

Fig. 2. The variation of the spray length L_S and the speed of the spray front V_S, in time for: a – CDS system; b – CR system (under the pressure of 180 MPa)

The analysis of speed variation of the fuel spray front showed that a higher initial and maximum speed was more characteristic of the CR system than of the conventional system. More intense slowdown of the fuel spray front could also be observed in the CR system. Higher speed and slowdown of the fuel spray in the CR system could be attributed to higher pressure as well as to smaller size and mass of the fuel drops.

The time of the fuel spray disintegration was shorter for the CR system. As a result, the lengths of the fuel sprays recorded by the measuring instruments of the test set-up were actually the same for both fuel systems. Different physical and chemical properties of diesel fuel and rapeseed oil suggested different speed of their outflow. The speed of the rapeseed spray in the CDS system was lower and did not actually change during the process. The speed of the diesel fuel spray at the beginning of discharge was higher, but, later, the intense slowdown took place. For the CR system, using rapeseed oil, a high initial fuel spray speed, decreasing in a short period of time, was typical. When fuel oil was used, a monotonous decrease in the fuel spray speed was characteristic of the whole range of observations. The temperature of the fuel was measured before it entered a high-pressure pump. For CR system, the temperature was maintained within the range of 26÷37 °C, while the pressure in the fuel accumulator ranged from 60 to 180 MPa.

In general, the use of the high-pressure systems ensures a higher speed of the fuel spray outflow. It intensifies heat exchange between the air flow and individual drops and results in a smaller drop size, which, in turn, promotes more rapid fuel spray breakup. All these factors help to decrease self-ignition delay time and intensify the combustion process (Vasil'ev 2007; Kulmanakov *et al.* 2011).

2.2. Investigating the Structure of a Fuel Spray

The experimental research into the variation of the fuel spray structure was based on the values characterizing the changes in the brightness zones of the fuel spray.

The process of fuel atomizing is shown in Fig. 3. The original view of the fuel spray and brightness zones marked out by the IT method of thresholding (segmentation) are also presented. For better understanding of the presented picture, the inverse view of the fuel spray is given.

In Fig. 4, the results of the investigation of the brightness zones of the diesel fuel and rapeseed oil sprays are given for the CDS system. The area S is shown in pixels for six particular brightness zones: 0÷27; 28÷55; 56÷83, 84÷111; 112÷139 and 140÷170 brightness values of ADC. A zone, corresponding to 0÷27 ADC brightness values, represents a section with high fuel concentration, which is usually found in the middle of the spray. This situation is characteristic of the beginning of injection, when a fuel spray has not yet started to disintegrate rapidly. A zone with the brightness of 140÷170 corresponds to the section with low fuel concentration.

The analysis of the data given in Fig. 5 allowed us to notice the variation of the relative areas of particular zones, depending on the injection time. In this case, a dynamic relative change in brightness zone areas S_{rel} is presented in fractions of unity. A comparison of graphs for diesel fuel and rapeseed oil showed that the total spray area had decreased by 25% for heavier and more viscous rapeseed oil. At the same time, a spray of this fuel was characterized by less uniform brightness zones. A fuel spray of diesel fuel was characterized by the proportional and uniform development of all zones, while a denser core was more typical of the rapeseed oil spray (Fig. 5).

In general, the use of the CR system, which is a fuel supply system of the accumulating type (Figs 6 and 7), increases the uniformity and the total area of the fuel spray. When the pressure in the CR system is 180 MPa, the increase in the total area of the fuel spray by 25% for diesel oil, and by 48% for rapeseed oil can be observed.

The analysis of the pressure influence on the fuel spray in the CR system showed that the spray length under high injection pressure was larger and it started disintegrating later than in the case of normal pressure. It was shown in the graphs by the increasing (in time) maximal areas of the zones of various brightness values (e.g. 80, 100, 120, 140, see Fig. 5). Thus, the maximum value of the brightest zone (160) was found in the breakup zone of the spray, whose brightness was getting more uniform, when it was getting smaller.

The results obtained in the research showed that the increase in the injection pressure at a particular moment of time led to the simultaneous growth of the area of a fuel spray due to the increase in its length and width. The changes in the fuel spray area were of non-linear nature similar to that characteristic of the dependence of the spray length variation on time.

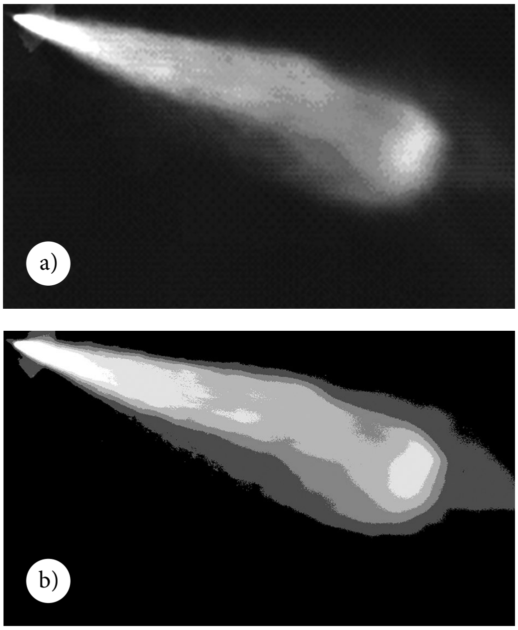

Fig. 3. The frames of video recording of fuel atomization (the images are inversed): a – a source image (the time of exposure is 35.5 µs, T_k = 0.3 ms); b – brightness zones selected by the computer program using the image thresholding method

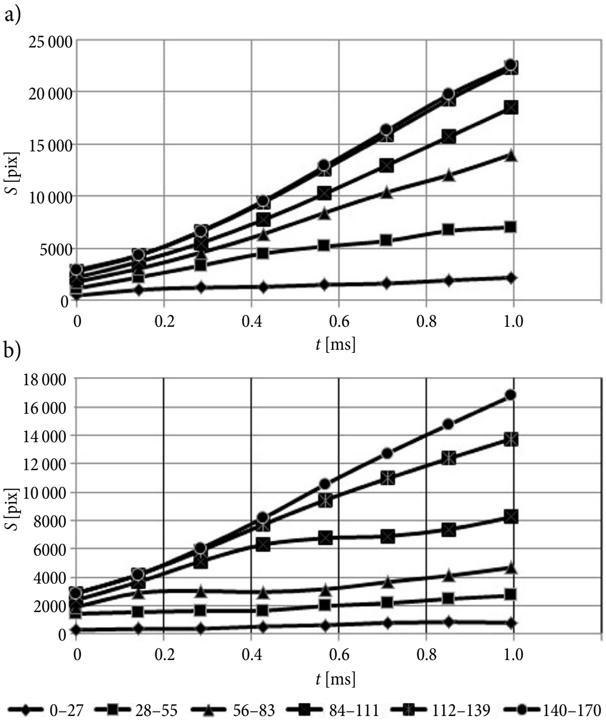

Fig. 4. The total area of the fuel spray and its distribution according to brightness zones for a CDS fuel supply system of direct injection when: a – diesel fuel was used; b – rapeseed oil was used

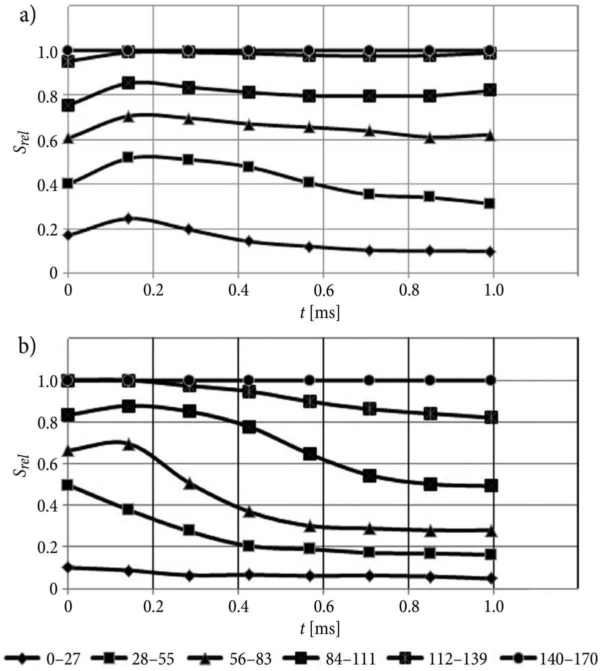

Fig. 5. The relation between the brightness zones for a CDS fuel supply system of direct injection when: a – diesel fuel was used; b – rapeseed oil was used

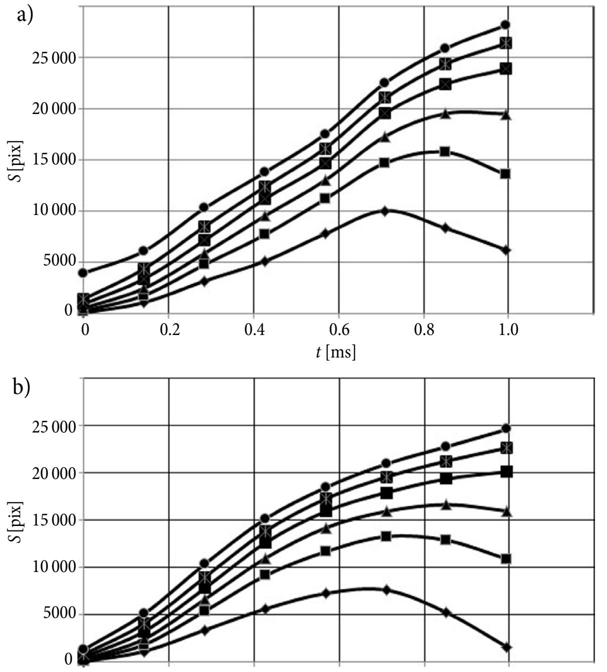

Fig. 6. The total area of the fuel spray and its distribution according to brightness zones for a CR fuel supply system under the pressure of 180 MPa when: a – diesel fuel was used; b – rapeseed oil was used

The CR system is also characterized by more rapid breakup of a fuel spray, leading to its higher uniformity. At the same time, the portion of the brightest and darkest zones decreases, while the portion of zones with medium specified brightness increases (Es'kov *et al.* 2010; GOST R 53457-2009).

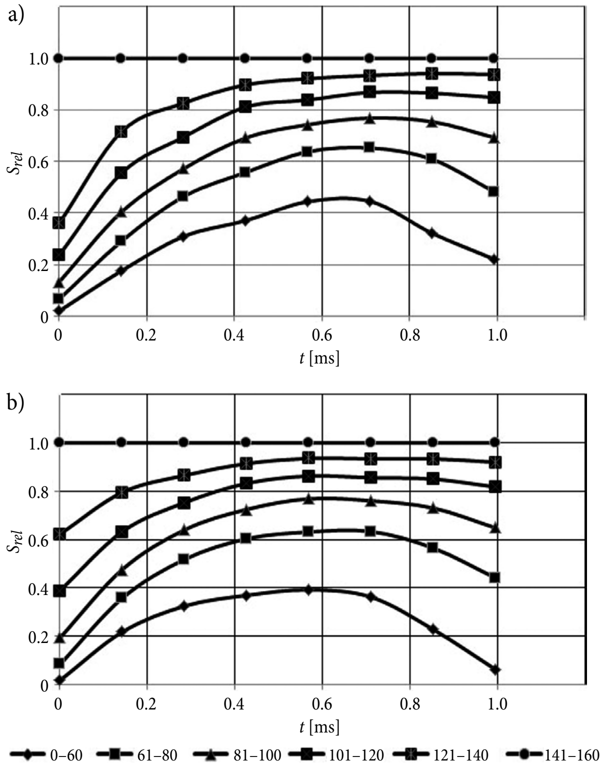

Fig. 7. The relation between the brightness zones of the fuel spray for CR fuel supply system under the pressure of 180 MPa when: a – diesel fuel was used; b – rapeseed oil was used

3. The Development of Methodology for Calculating Self-Ignition Delay and the Obtained Results

The aim of the authors was the development of the methods for determining the delay time of fuel self-ignition based on more thorough analysis of the physical and chemical processes taking place in the engine's cylinder.

The combustion rate of the atomized liquid fuel is usually determined by the rate of the physical process of mixing, i.e. the rates of fuel vaporization and mixing of the vapours with an oxidizer. The shorter the induction period, the smaller the amount of fuel supplied to the cylinder prior to its self-ignition (Arcoumanis, Kamimoto 2009; Zel'dovich *et al.* 1980; Warnatz *et al.* 2010; Keating 2007).

Usually, in the air-fuel mixture, prepared in the time of ignition delay, nucleation sites for ignition occur, which later spread over the combustion chamber. As a result, the parameters of the power stroke dynamics increase, including the pressure rate in the cylinder, as well as maximum power stroke pressure and the level of noise in diesel engine operation.

To reduce the 'toughness' of the working cycle and noisiness of the engine, either the induction period of self-ignition (at constant τ_i) or the amount of the supplied fuel should be decreased by changing the fuel supply law (Zel'dovich *et al.* 1980; Liberman 2008; Spolding 1985).

During a physical ignition delay, complicated physical processes, such as disintegration of the fuel spray into drops, their heating and vaporization as well as diffusion of fuel vapours and the air, occur in the engine. Only then, chemical cold flame processes take place. The ignition delay τ_i can be expressed as the total time of self-ignition delay due to physical τ_{phys} and chemical τ_{chem} processes (GOST R 52368-2005; Kulmanakov *et al.* 2011; Keating 2007):

$$\tau_i = \tau_{phys} + \tau_{chem}. \tag{1}$$

When analysing mixing and its effects, the 'elementary' physical processes associated with it, such as fuel injection, fuel spray formation and atomizing in the chamber space, as well as heating of the fuel and mixing its vapours with an oxidizer, should be considered individually.

In fact, a physical delay time of ignition consists of the time of fuel vaporization τ_{vap} and mixing of vaporized fuel τ_{dif} with an oxidizer:

$$\tau_{phys} = \tau_{vap} + \tau_{dif}. \tag{2}$$

In the diesel engine cylinder, the processes of vaporization and fuel mixing take place simultaneously. However, the vaporization rate of light fractions is higher than the rate of their diffusion in a drop towards its surface. As a result, even the heaviest fractions of the external layer of the drop evaporate and a deeper layer of the drop comes into contact with the air. Drops of a smaller size evaporate at an earlier stage.

In most cases, fuel is evaporated in the area of diffusion. The process involves the transfer of heat and mass from the surface of the vaporization area to the ambient air. In diesel engines, the essential fuel mass is supplied to and evaporated from the surface of the fuel spray. Fuel injection takes place at high initial speed and depends on the speed of the fuel spray formation in the air as well as the occupied space and range of drop sizes in the spray. Fuel vaporization is accompanied by the effective heat exchange between the fuel and the heated air, while the heat exchange rate is mainly determined by the rate of drops' vaporization. Since the period of vaporization is very short, its completion largely depends on the duration of the process, the amount of the supplied fuel and temperature gradients between the air charge and the drops of the fuel spray, as well as on the total area of the spray.

The time of vaporization was determined by Spalding dependence (Keating 2007):

$$\tau_{vap} = \frac{d_m^2 \cdot \rho_f}{\frac{8\lambda}{c_{vap}} \cdot \ln\left(1 + c_{vap} \cdot \frac{\left(T - T_0\right)}{L}\right)}, \tag{3}$$

where: d_m is median drop diameter; ρ_f is fuel density; λ is thermal conductivity; c_{vap} is heat capacity of vapour; T is air temperature at the time of injection; T_0 is the initial fuel temperature; L is latent heat generation.

The median diameter of a drop was calculated by the equation suggested by Kutovoj (1981):

$$d_m = d_0 \cdot \left(\left(1 + \frac{d_c}{d_2}\right) + 2 \cdot \left(1 - \frac{p_{av}}{2p_1}\right) \right. \times$$

$$\left. \frac{p_1}{p_{av} + \frac{p_1}{\pi} \cdot \frac{d_2}{d_c}} \cdot \left(\frac{l_c}{d_c}\right)^{0.125} \right) \cdot \left(\frac{\nu}{\nu_0}\right)^{0.15}, \tag{4}$$

where: d_0 = 16.5 μm is a constant coefficient; d_2 = 0.30 μm is a constant coefficient; p_1 = 15.0 μm is a constant coefficient; ν_0 = 5.23 mm^2/s μm is a constant coefficient; d_c is the diameter of the spray nozzle outlet; ν is kinematic viscosity; $p_{av} = 0.6 \cdot p_{max}$ is average injection pressure; p_{max} is maximum ignition pressure; l_c is the length of the spray nozzle outlet.

The relation between the concentration of fuel vapours and mass flow rate of vapours diffusing into the air flow were determined by the Fick's law, stating that the speed of transferring the mass of a substance per unit area is proportional to the concentration gradient (Stiesch 2013; Baumgarten 2006; Oppenheim 2008; Purmal' 2004):

$$m_D = -D_c \cdot \frac{dC_i}{dx} \cdot F, \tag{5}$$

where: m_D is the speed of transferring the mass of a substance per unit area; D_c is diffusion coefficient of gases and vapours of fuel; $\frac{dC_i}{dx}$ is the gradient of fuel vapours; F is area of transferring the mass of a substance.

The above given expression is valid for diffusion caused by the difference between the concentrations of the diffusing media. However, diffusion can also be caused by non-uniform distribution of temperature and pressure between the components of a medium. Thermal diffusion occurs in non-isothermal conditions. It is a second-order process, which is often neglected, even when combustion is considered. Barodiffusion in gaseous atmosphere is associated with pressure gradients, occurring, for example, under the action of centrifugal forces. The Fick's law for thermal diffusion and barodiffusion is described by the equation:

$$m_D = -D_T \cdot \frac{dT_i}{dx} \cdot F;$$

$$m_D = -D_P \cdot \frac{dP_i}{dx} \cdot F, \tag{6}$$

where: D_T is diffusion coefficient caused by the temperature gradient; D_p is diffusion coefficient caused by the pressure gradient; $\frac{dT_i}{dx}$ is gradient of temperature of gaseous atmosphere; $\frac{dP_i}{dx}$ is gradient of pressure of gaseous atmosphere.

3.1. Evaluating the Influence of a Non-Stationary Process of Fuel Drop Vaporization on the Mass of Fuel Vapours Diffusion into the Air Flow

At time $\tau_0 = 0$, a drop with the original radius $r_{ko} = a_0/2$ is in the medium of the indefinite extent, while at a distance from the drop centre, $x > r_{ko}$, the concentration of vapours is $C = C_\infty$. First, it was assumed that, in the process of vaporization, the original diameter of the drop did not vary and temperature did not get lower. Then, as a result of vaporization, taking place at the drop surface, $x = r_{ko}$, the concentration of vapour by the time moment $\tau > 0$ was $C = C_s$, where C_s was the concentration of saturated vapour. One-dimensional differential equation of diffusion was of the form:

$$\frac{\partial C}{\partial \hat{o}} = D_c \frac{\partial^2 C}{\partial x}, \tag{7}$$

with the initial and boundary conditions:

$\mathrm{C} = \mathrm{C}_\infty$; $\tau = 0$; $x > r_{ko}$;

$\mathrm{C} = \mathrm{C}_s$; $\tau > 0$; $x = r_{ko}$.

The solution was as follows:

$$C = C_S + \frac{\left(C_S - C_\infty\right)}{x} \cdot r_{ko} \operatorname{erf}\left(\frac{\left(x - r_{ko}\right)}{2} \cdot \sqrt{D_c \cdot T}\right), \tag{8}$$

where: $\operatorname{erf}(z)$ is the error function,

$$\operatorname{erf}\left(z\right) = \frac{2}{\pi} \cdot \int \exp\left(-z^2\right) dz.$$

According to the Fick's law, mass flow rate of fuel vapours, diffusing into the air flow per unit of time through the spherical surface concentric with the drop surface, is as follows (taking into account Eq. (8)):

$$m_D = -D_c \cdot \frac{dC}{dx} \cdot F = -4 \cdot \pi \cdot r_{ko}^2 \cdot D_c \left(\frac{dC}{dx}\right)_{x = r_{ko}} =$$

$$4 \cdot \pi \cdot r_{ko}^2 \cdot D_c \cdot \left(C_0 - C_\infty\right) \cdot \left(1 + \frac{r_{ko}}{\sqrt{\pi \cdot D_c \cdot T}}\right) =$$

$$m_{D_0}\left(1 + \frac{r_{ko}}{\sqrt{\pi \cdot D_c \cdot T}}\right), \tag{9}$$

where: $m_{D_0} = 4 \cdot \pi \cdot r^2{}_{ko} \cdot D_c \cdot \left(C_0 - C_\infty\right)$ is mass flow rate of vapours, corresponding to a quasi-stationary vaporization process.

The diffusion coefficient of gases and vapours of fuel is proportional to the air temperature T_b raised to the power of b and inversely proportional to pressure p_b of the medium (air), into which gases (fuel vapours) diffuse:

$$D_c = D_{c0} \left(\frac{T_b}{T_0}\right)^b \cdot \frac{p_0}{p_b}, \tag{10}$$

where: D_{c0} is the diffusion coefficient (the table value), $p_0 = 0$ is pressure [MPa], $T_0 = 273$ K is temperature under normal conditions and $b = 1.7$ is a constant coefficient.

Thus, taking into account the above considerations, the time of mixing the evaporated fuel with an oxidizer was determined by the equation:

$$\tau_{dif} = \frac{m_{D_0}^2 \cdot r_{ko}^2}{\left(m_D - m_{D_0}\right)^2 \cdot \pi \cdot D_c}. \tag{11}$$

According to the combustion theory supplemented with the concept of low- and high-temperature self-ignition mechanisms of hydrocarbon fuels, we could start the count of the chemical delay time of ignition, when the air and the fuel had been mixed and were in the gas phase, the initial pressure and temperature were constant, and there was no convective heat transfer to the wall. Consequently, the induction period was determined as the time, elapsing from the cold flame formation (the glow of excited formaldehyde) to the occurrence of the ignition sites (or the explosive reaction). According to the dependence of Frank-Kamenetskii (Zel'dovich *et al.* 1980), determining the variation of temperature, concentration and the reaction rate in time, we obtained:

$$\tau_{chem} = \frac{1}{\left(k_0 \cdot a_0^{n-1}\right)} \cdot \left(\frac{R \cdot T_0^2}{E \cdot \left(T_b - T_0\right)}\right) \cdot \exp\left(\frac{E}{R \cdot T_0}\right), \tag{12}$$

where: a_0 is the initial concentration of the reacting substances; n is the order of reaction; $R = 8.314$ kJ/(kmol·K) is a universal gas constant; T_0 is the temperature at which cold flame processes occur; E is the activation energy; T_b is the highest temperature of fuel burning out under adiabatic conditions; $k_0 = 2 \cdot \chi \cdot \sigma \cdot \sqrt{2 \cdot \pi \cdot R \cdot T \frac{(m_1 + m_2)}{m_1}}$ is a pre-exponential multiplier in the dependence, where σ is the square sum of the radii of the colliding molecules; m_1 and m_2 are their masses; χ is a steric factor (a possibility of the colliding molecules to have spatial orientation required for the reaction, which is calculated based on the theory of absolute reaction velocity).

A steric factor is calculated based on the theory of a transitional state as follows:

$$\chi = Z_{rot}(f^* - \sum f - 2),$$

where: Z_{rot} is the mean value of the statistical sum per one rotational degree of freedom; f^* is the number of the rotational degrees of freedom for a transitional state; $\sum f$ is the total number of the rotational degrees of freedom of reagents.

In Table 4 and Fig. 8 some experimental and calculated τ_i values for diesel fuel, determined by the suggested methods, are given.

The comparative analysis of the obtained data confirmed the validity of the suggested methodology for calculating self-ignition period. The difference between the values calculated by the suggested methods and the experimental data did not exceed 8%.

Table 4. The calculated and experimental ignition delay time for diesel fuel

Time of fuel injection	φ_{inj} = var [degrees]	325	330	335
Experiment	T [K]	690	727	767
	τ_i [ms]	5.83	4.38	3.13
Calculation of τ_i [ms]	by Wolfer's formula	14.16	7.95	4.56
	by Hiroyasu's formula	36.06	16.5	7.8
	by Tolstov's formula	3.12	2.18	1.98
	by the suggested method	6.01	4.71	3.24

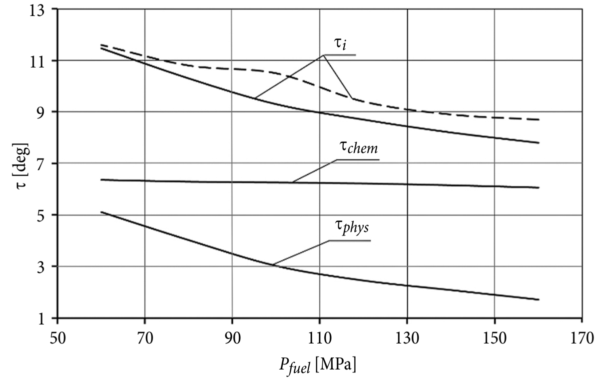

Fig. 8. The graphs of diesel fuel ignition delay variation depending on injection pressure: τ_i is the total ignition delay time (—— obtained by the calculation methods; - - - - based on the experimental data), τ_{chem} is a chemical component of ignition delay, τ_{phys} is a physical component of ignition delay

Conclusions

1. The investigation of the fuel spray parameters has shown that a Common Rail (CR) fuel supply system has a number of advantages over the traditional fuel supply system with direct injection because its application helps:
   - to decrease the size of the fuel drops;
   - to triple the maximal speed of the fuel spray and increase the fuel spray area by about 50%;
   - to limit the range of the specified highest and lowest brightness values of the fuel spray area, which means that, in this case, a fuel spray is of more uniform structure for both diesel fuel and more viscous rapeseed oil.
2. As a result, self-ignition delay time is decreased and the process of combustion is intensified.
3. The methods for calculating the delay time of self-ignition based on the main equations of the theory of vaporization and combustion of the fuel spray in the diesel engine cylinder are offered. The validity of these methods adapted to the analysis of modern CR fuel systems, using mineral diesel fuel and rapeseed oil, is also demonstrated.
4. The performed theoretical analysis of the physical nature of the atomized fuel ignition mechanism in the cylinder of a diesel engine allows the authors to analytically relate the characteristics of heat release x to the heat supply law σ_f and to determine the induction period for self-ignition τ_i.

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