Optical control method of fuel atomization in combustion chambers using high-speed video recording

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Abstract. The article gives the description of the optical method and the high-speed video registration test bed for determining the parameters of fuel atomization in atmospheric conditions. The diagram and operating principle of the test bed are described. The experimental results of the jet parameters when atomizing rapeseed oil and diesel fuel are presented.

1. Introduction

As it is known, in recent years, the requirements for internal combustion engines concerning the increase of power, the efficiency of engines and the emission control have been continuously raising. It should be noted that even a small improvement in the output characteristics of the engines leads to greater fuel savings across the country.

The main parameters describing the pulsed dispersed flow of the atomized liquid (including fuel) are the average particle (drop) size, their homogeneity and uniformity of the concentration distribution over the jet volume, the speed and direction of particles movement, as well as geometric parameters: the jet angle, the jet length, the width of the jet front edge. For practical purposes, the most important parameters are the fineness of the atomization, the concentration of fuel in the cross sections of the jet, the jet length [1-4].

In the development of methods and devices, strict requirements are imposed on the technological conditions of the atomization process: a short process time of 1 ÷ 6 ms with an average speed of 20 to 250 m/s and a dispersed composition of fuel drops from 5 to 120 µm. The equipment shall have sufficient speed and ensure the recording of processes with the necessary spatial and temporal resolution; it shall be vibration resistant. Photosensitive surfaces of diagnostic cameras and optical sensors shall be protected from the spattering of fuel gas suspension, which is continuously present during the execution of measurements.

To improve the mixing process, it is necessary to ensure that the atomized fuel enters the cylinder in accordance with a certain pattern, on which the process of supplying fuel to the oxidizer in the combustion chamber and the fineness of atomization largely depends. The completeness and dynamics of the combustion process are directly related to the characteristics of the fuel atomization into the cylinder, evaporation, mixture formation and the heat release pattern during fuel combustion [5-7].

Among the existing indirect methods for controlling the structure of fuel jets, the most preferred are optical methods based on the laws of radiation, propagation and interaction of light with matter when passing through a pulsed dispersed flow of particles of atomized fuel or other liquid [8-10].
In this study, the authors propose a method based on high-speed video recording of the fuel jet in its development with subsequent processing of frames, which belongs to the category of passive optical methods.

2. Materials and methods

The developed test bed of optical quality control of fuel atomization on the basis of high-speed video camera “VideoSprint/G6” is an add-on unit to the fuel test bed. The unit operates as follows: the fuel test bed supplies fuel through the pressure sensor to the atomizer. The jet is illuminated by the lighting device. Information on the speed and pressure is supplied to the computer. At a given time, the signal from the pressure sensor enters the synchronizer, which controls the start time of the chamber. Information from the synchronizer and the camera that captures the jet enters the computer.

At the end of the recording video process, information is transmitted to the computer, where specially designed programs determine the characteristics of atomizing fuel by the atomizer.

The absorption of radiation by a jet of an atomized liquid in its cross section is determined according to Bouguer law by the value of the optical thickness of the medium \( \varepsilon(x) \). (Figure 1). The attenuation \( K \) is determined, inter alia, by the concentration of particles \( n \). The concentration distribution in the cross section of the jet corresponds to the normal probability law.

\[
\varepsilon(r) = \frac{\varepsilon_0}{\sqrt{2\pi}} \exp\left\{\frac{-r^2}{2\sigma^2}\right\},
\]

where \( r \) are the coordinates of the small number of absorbing particles, \( \sigma \) is the standard deviation, \( \varepsilon_0 \) is a constant equal to the optical thickness in the absence of a dispersion medium.

![Figure 1. Diagram of light transmission through the fuel jet cross section](image)

Passing through the dispersed medium at a distance \( x \) from the center of the jet, the light beam goes through a layer of particles with a length \( \Delta H=2\Delta y \). Substituting the expression for the optical thickness of the medium in Bouguer law, after the transformation it is obtained

\[
P(x) = P_0 \exp\{-C(x) \int_0^{\Delta y} \exp\left[-\frac{y^2}{2\sigma^2}\right] dy\},
\]

where

\[
\Delta y = \sqrt{R^2 - \Delta x^2},
\]

\[C(x) = \frac{2\varepsilon_0}{\sigma^22\pi} \exp\left[-\frac{x^2}{2\sigma^2}\right]\] is a constant at a given coordinate \( x=\Delta x \).

The integral in exponent index \( \Phi(\tilde{U}(x)) \) is a tabulated function. From the relation (2), the authors obtain an expression for calculating the concentration by the brightness values in the image of the atomized fuel jet:

2
\[ \ln \frac{p(x)}{p_0} = -C(x) \tilde{\Phi}(U(x)) . \]  

The program for processing images of fuel jets, inter alia, allows eliminating noise in the images, increase contrast, calculate the brightness threshold above which the background for each frame is recorded, calculate the areas of brightness zones (optical inhomogeneities), build histograms and graphs, estimate experimental errors.

Noise is eliminated by a partial median filter with a 3x3 pixel window. Contrast enhancement is performed by a linear method. It is very difficult to determine the brightness threshold for images with fuel jets. To determine the brightness threshold, the “triangle” and “ISODATA” methods are incorporated in the program.

3. Study of the structure of the modified lead-tin-base bronze

Figure 2 illustrates the use of the “triangle” method to determine the brightness threshold, which shows a possible histogram of the jet image (on the x-axis – brightness b, on the y-axis – the number of pixels of the corresponding brightness h(b)). The jet has darker shades (closer to the y-axis), the background is light. From the analysis of h(b), there are two points: \((b_{\text{max}}, h(b_{\text{max}}))\) and \((b_{\text{min}}, h(b_{\text{min}}))\) – the first minimum value on the left of the histogram, distinct from zero. A straight line is drawn through these two points. Then, for each brightness value \(b_i \in \left[b_{\text{min}}, b_{\text{max}}\right]\), the distance x from the point \((b_i, h(b_i))\) to the line is calculated. The threshold value is the point \(b_i\), at which the distance x reaches the maximum. The result of the threshold method is shown in figure 3, b.

The essence of the “ISODATA” method (k-means clustering method) determining the brightness threshold is as follows. The initial value of the threshold \(T_0\) is 128 (according to the formula \(T_0 = 2^B - 1\), where \(B\) is the depth of the image in bits, in our case \(B=8\)). The average values of the brightness of the jet \(\bar{b}_c\) and the background \(\bar{b}_f\) are calculated as the ratio of the sum of the brightness of all pixels of the image belonging to the jet or the background, respectively, to the total number of pixels of the jet or the background, respectively. The next threshold value is calculated as the average: \(T_{i+1} = (\bar{b}_c + \bar{b}_f)/2\). The process is repeated until the threshold value is stabilized (until \(T_i \neq T_{i-1}\)).

However, there may be cases when the minimum brightness value in this image exceeds the value of 128, or vice versa, the maximum brightness value in the image does not exceed the value of 128, which means that, in this case, the “ISODATA” method will not find pixels of the jet or the background, respectively. Therefore, the method was modified as follows. First, the minimum and maximum brightness values are determined for this frame, next – the average between them. This will be the initial threshold value \(T_0\). Then, the algorithm is similar to the above. The result of the threshold method is shown in figure 3, c.

Figure 2. Thresholding by the “triangle” method
Figure 3. Visualization of the optical inhomogeneity of the jet at using different threshold methods: a – original image, b – image, the threshold for which is determined by the “triangle” method, c – image, the threshold for which is determined by the “ISODATA” method. The jet is divided into 6 brightness zones.

The disadvantage of high-speed video recording is the brightness flicker of frames. To solve the problem, the authors proposed an original linear method and a method using an artificial neural network, the use of which is justified by the complexity of the problem and the advantage of neural networks, which is their potential to develop their own solutions. A single layer neural network with nine inputs (the minimum brightness of the frame, the maximum brightness of the frame, the average jet brightness of the frame, the average brightness of the background frame and the average brightness of the background in all frames, the pixel belonging to the jet or the background, the frame width, the frame height, the brightness of the pixel) and one output with a sigmoid transfer function was used.

Firstly, the brightness threshold T is found for each frame, using one of the threshold methods. Each pixel with a brightness greater than T belongs to the background (otherwise to the jet). Knowing the threshold brightness T of the current frame, the average background brightness is calculated. The average background brightness of all frames shall be approximately the same with some acceptable error, but in reality, it can vary significantly. Then, the overall average background brightness of all frames is found, to which the brightness of all frames is aligned as follows. In the linear method, a difference between the total average background brightness and the average background brightness of that frame is found for each frame, and the brightness value of each pixel of the original frame is added or subtracted from that difference. In the method using a neural network, a gain factor having a value of from 0 to 2 is found, which is multiplied by the brightness value of each pixel of the original frame. As a result, the background is stabilized, and the jet is corrected, while the error in the background brightness is reduced and does not exceed 1%.

The approbation of the test bed was carried out using diesel fuel and rapeseed oil. Some characteristics of the fuels used are presented in table 1.

| Type of fuel            | Density, kg/m$^3$ | Kinematic viscosity, mm$^2$/s or 10$^{-6}$ m$^2$/s | Dynamic viscosity, 10$^{-3}$ Pa·s | Surface tension, 10$^{-3}$ N/m |
|------------------------|-------------------|-----------------------------------------------|-----------------------------------|-------------------------------|
| Diesel fuel, depending on the grade | $790 \div 875$ | $1.5 \div 6.0$ | $1.185 \div 5.250$ | $3.3 \div 40.3$ |
| Industrial rapeseed oil | $917$             | $75.1$                                      | $68.867$                         | $33.2$                        |
As a result of laboratory research of the process of atomization of diesel fuel and rapeseed oil using a high-speed registration of images of the jet in ascending order of delay time on the registration of the image relative to the start of injection, the following results are obtained.

Under equal conditions of fuel supply (equal portion of fuel at 825 HPFP shaft revolutions per minute) injection of rapeseed oil begins later than of diesel fuel in time for which the crankshaft is rotated by 3–3.5 degrees, despite the fact that for the same rapeseed oil an atomizer needle rises earlier in comparison with for diesel fuel. The structure of the rapeseed oil jet has a higher unevenness in the distribution of the fuel concentration in the cross sections of the jet, the jet opening angle of which is less than 25% compared to the jet of diesel fuel. The rapeseed oil jet spreads further (0.28 m) than the diesel fuel jet (0.23 m) at the same time, which is a consequence of the higher viscosity and surface tension of the rapeseed oil.

With the increase in injection pressure, the quality of atomization improves; heating of rapeseed oil improves the quality of atomization due to a decrease in the viscosity of the fuel; with an increase in the diameter of the nozzle, the structure of the jet deteriorates, and with an increase in the number of revolutions of the HPFP shaft per minute – improves. In addition, as a result of experiments it was determined that the dark brightness zones decrease over time development of the jet, and the light ones increase. With the increase of injection pressure, the area brightness of the dark zones expands, but the time of their decay reduces. Thus, when atomizing diesel fuel with increasing injection pressure from 60 MPa to 180 MPa, the brightness zone No. 2 (brightness range from 30 to 59 degrees of the ADC) increases in area from 0.18 to 0.31, the decay time decreases from 2.0 to 1.8 ms.

The developed control device also allows finding a correlation between the optical inhomogeneity of atomizing and the rate of heat release of the engine. With the use of the correlation analysis when dividing the brightness range of the jet into 6 zones, a stable direct relationship is established between the change in the areas of the brightness zones No. 2, 3 and the change in the engine heat release rate for all injection pressures and methods of diesel fuel supply. When the brightness range is divided into 4 brightness zones, a stable connection with the heat release rate is given by the brightness zone No. 2. In the case of atomization of rapeseed oil, the brightness zone No. 4 and No. 5 (when dividing the brightness range into 6 zones) or the brightness zone No. 3 (when dividing the brightness range into 4 zones) have a steady strong correlation with the heat release rate. Obviously, this is due to the fact that these brightness zones are present throughout the whole process of fuel atomization, while the brightest zone appears closer to the end of atomization, and the darkest zones, on the contrary, decay by the end of atomization. Knowledge of this connection allows solving an important scientific problem – to predict the rate of heat release based on the study of the jet structure atomized into the atmosphere, which will facilitate the study of the fuel equipment.

4. Conclusion

Based on the results of the studies, it is necessary to consider high values of viscosity and surface tension of rapeseed oil and carry out preparatory activities (heating) for the use of the latter as a fuel. The results obtained in this work allow proposing to increase the number of nozzle holes in the atomizer to cover a larger volume of the combustion chamber in order to improve the mixture formation.

The application of the developed measuring system and the proposed test bed allow obtaining images of the high-speed process of atomizing an arbitrary liquid, followed by the study of the jet structure in the dynamics, velocity and the jet geometric parameters.

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