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OPTICAL-GRAPHIC STUDIES OF HYDROGEN ADDITIVES' EFFECTS ON DIESEL FUEL ATOMIZATION PARAMETERS

Summary. This paper considers a promising method of enhancing the effectiveness of diesel engines. This method uses the addition of hydrogen in a small amount (up to 2% by mass). The hydrogen additive is added to the high-pressure fuel line before the injector. Based on the experimental findings, a reduction in the engine's specific fuel consumption of up to 3% was achieved in comparison to the baseline configuration. A research study was conducted at the Admiral Makarov National University of Shipbuilding using a newly established experimental setup to assess the impact of hydrogen additives on primary fuel delivery, spray characteristics, and overall engine performance. Among the experiments conducted, one investigated fuel atomization parameters, focusing on how the presence of hydrogen in the fuel influenced the fuel jet's characteristics. A high-speed camera with a high resolution was used to record the optical-graphic study to isolate and extract individual shots of the torch's expansion, thus obtaining images devoid of ignition and flickering. After conducting image processing and constructing jet models, along with subsequent analysis, it becomes apparent that the addition of hydrogen to the primary fuel results in an enhancement of spray quality. The torch volume expanded by approximately 10% to 15%, while the jet length diminished by approximately 8% to 10%. Consequently, the average diameter of the atomized fuel droplets decreases by up to 10%, with the extent of reduction contingent upon the initial parameters and configurations.

1. INTRODUCTION

The diesel engine is one of the most common types of internal combustion engines used in automobiles, locomotives, ships, and other modes of transportation. The primary advantage of diesel engines lies in their high efficiency, which is achieved through a high compression ratio of the fuel in the combustion chamber. It is crucial to ensure high-quality fuel atomization to attain the optimal operating conditions for a diesel engine. This involves creating fine fuel droplets evenly dispersed in the air. The quality of fuel atomization directly impacts the speed and completeness of combustion, as well as the emission of harmful substances into the atmosphere. In this article, we will explore the efficiency of fuel atomization in diesel engines and modern methods and technologies aimed at enhancing this process, particularly by using hydrogen additives.

Spraying fuel from a liquid state into small droplets with varying diameters and quantities is a crucial process in operating internal combustion engines and other industrial systems, such as boilers. This spraying process generates droplets, increasing the overall surface area of atomized fuel, which, in turn, accelerates evaporation and reduces the time required for it to occur.

For devices utilizing fuel atomization, such as liquid fuel nozzles in gas turbines, industrial boilers, diesel engines, and more, achieving a high-quality mixing of fuel and oxidizer is vital. This process enhances the rate of chemical reactions, leading to complete combustion [1].

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To meet the requirements for combustion quality, including higher combustion efficiency, reduced exhaust emissions, broader combustion uniformity limits, and consistent temperature distribution, the study of nozzle spraying parameters becomes of utmost importance [2].

The efficiency and environmental performance of compression-ignition engines are significantly influenced by the quality of fuel atomization and spray processes, which, in turn, are strongly dependent on the flow parameters within the injector nozzle. Modern diesel engines employ micro-holes with various configurations, making it imperative to assess the impacts of different designs on engine performance and emissions. Injector flow is governed by dynamic factors (such as injection pressure and needle lift) and geometric factors (including orifice taper and hydro-grinding).

The influences of dynamic factors on injector spraying, fuel combustion characteristics, and emissions have been examined by numerous researchers, as cited in [1-3]. Additionally, experimental studies have explored the impact of nozzle bore geometry on the overall behavior of injection and spraying, as documented in [4].

Benajes et al. [5] analyzed the impact of different nozzle hole shapes on the injection rate parameter within a common rail system at maximum needle lift on an experimental test bench designed for cavitation studies. Compared to a cylindrical bore, the conical bore was observed to reduce cavitation, enhance flow efficiency (head), and increase escape velocity. However, it should be noted that the fuel injection rate decreases with the conical bore due to the smaller cross-sectional area. Payri et al. observed “suppression” conditions with cylindrical nozzles, whereas, for conical nozzles, the mass flow rate consistently exhibited a proportional relationship to the square root of the pressure drop, indicating no cavitation at the nozzle outlet. They also noted an increase in the injection rate attributed to the appearance of vapors at the outlet of the nozzle with a cylindrical cross-section.

Khan et al. [6] compared cylindrical and conical nozzles and found that the geometry of the nozzle strongly influences the initial decay zone. They further studied the impact of hole geometry on the depth of penetration of the spray, its length, and the opening angle of the cone. In contrast, Payri et al. [5] and Blessing et al. [8] found that an increase in taper led to a longer spray length and a smaller cone angle in cases where no evaporation effect occurred. However, Bae et al. [7] discovered that the maximum spray departure length and cone angle decreased with an increase in hole taper, which contradicts the findings of Payri et al. and Blessing et al.

The combustion process within a diesel engine cylinder exhibits a dual combustion mode, encompassing a robust initial ignition flash and a diffuse afterburning flame for the remaining fuel. Most of the soot and unburned hydrocarbons are generated within the saturated premixed flame, while the emergence of NOx primarily occurs during the combustion of the residual fuel at maximum temperature.

In addition to the operational conditions of the sprayer, the design of the injector significantly influences spray performance. Numerous researchers have conducted experimental and numerical investigations to explore the impact of atomizer design on spray and combustion characteristics. Moreover, several studies have emphasized the substantial role of the internal flow within a diesel nozzle in influencing atomization and spray behavior [8].

A wealth of studies have addressed the hydrodynamics of injectors and the characteristics of fuel atomization. Som et al. [9] presented a numerical approach that combines the geometric features of fuel injectors with atomization parameters. In the initial step, this approach calculates essential quantities, including velocity, compression area, and turbulent kinetic energy. Subsequently, a Lagrange spray calculation employs these quantities to apply a novel primary sputtering model. Som et al. [10] also explored the impact of orifice shape on fuel atomization utilizing both numerical and experimental analyses. They observed that orifice taper significantly reduces cavitation and turbulence within the nozzle holes, decelerating the primary droplet breakup process. This effect increases the number of spray droplets, enhances penetration, and reduces the flare opening angle.

One of the methods that improves fuel atomization quality in a diesel engine, thereby enhancing the air-fuel mixture quality and combustion efficiency, is to utilize small hydrogen additives in the primary fuel. The objective of this study is to investigate the impact of hydrogen enrichment on the atomization process of a standard diesel engine injector.

2. MATERIALS AND METHODS

The present study employed a direct analogy method comparing the processes in an engine running on conventional fuels with those in a common injection (CI) engine when using hydrogen fuel additives in the primary diesel fuel. This approach enables the identification of solutions that ensure viable technical propositions, investigates the influence of hydrogen presence, and confirms the proposed assumptions. The positive effects of using hydrogen in diesel engines through various methods have been extensively examined [11-15]. However, this work proposes an innovative and relatively rarely explored approach.

An affordable and effective method for introducing an admixture into the primary fuel is based on the solution detailed in the author's previous works [16]. The core principle of this device involves introducing a gaseous additive, such as hydrogen, into the diesel fuel through a high-pressure pipeline located just ahead of the nozzle, using a specialized mixer (Fig. 1). This initial phase happens during the rarefaction wave (Fig. 2). Simultaneously, as the compression wave takes place, the main fuel gets impregnated with hydrogen and is subsequently dispensed through the nozzles into the cylinder. Following the injection of fuel and the decrease in pressure within the combustion, hydrogen quickly disperses from the diesel fuel. This dispersion assists in disintegrating fuel droplets and effectively occupies the cylinder's volume. The amount of gas additive that can be efficiently incorporated into the diesel fuel is initially controlled by the pressure at the installation's inlet, as elaborated in the author's prior publication [14].

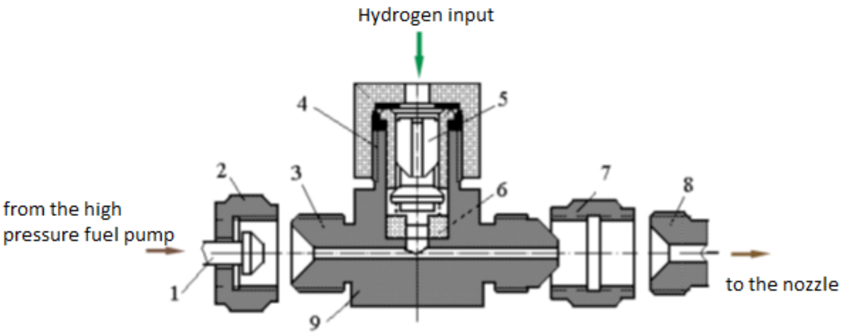


Fig. 1. Schematic draw of the feeder and small impurities of hydrogen in diesel combustion engines

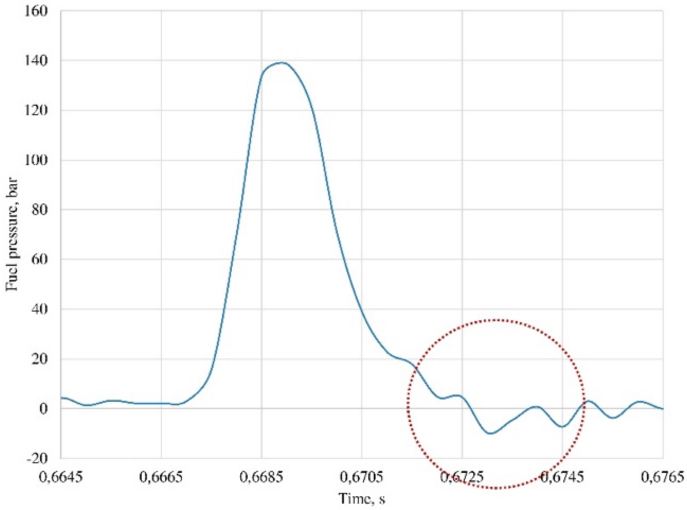


Fig. 2. Fuel pressure changes oscillograms at the injectors

The processes in the working cycle of compression ignition engines using small hydrogen additives, particularly the combustion process, are influenced by numerous factors, including chemical kinetics of fuel combustion, thermodynamics, gas dynamics, and heat and mass transfer. Utilizing mathematical modeling based on classical equations in differential form, along with appropriate initial and boundary conditions, can provide a challenging means to describe the processes taking place within the actual working cylinder and components of the exhaust gas tract.

The processes of fuel atomization and combustion, when combined with small hydrogen additives, are further complicated due to the presence of gaseous hydrogen, which significantly impacts the aforementioned processes. Consequently, mathematical models necessitate the incorporation of certain assumptions, empirical equations, and experimentally obtained constants to accurately represent these intricate interactions.

This experimental study's purpose is to check the adequacy of the working cycle refined mathematical model of an internal combustion engine operating with small hydrogen impurities. The aims are to obtain reliable data on the combustion process of fuel saturated with gaseous hydrogen and to determine the influence of the engine's main parameters of the working process on the efficient and ecological indicators.

The primary goal is to explore fuel atomization parameters and the impact of introducing hydrogen into this process. The inclusion of hydrogen in the atomized diesel fuel droplets substantially contributes to the improvement of fuel jet development and fuel droplet fragmentation. As a result, it affects the calculated parameters, notably the average atomized fuel droplet diameter and fuel jet length.

The method for investigating the fuel atomization process using photographs of the fuel spray involves specialized techniques and equipment to capture and analyze this high-speed process.

Experimental work

An experimental installation, MDV-1, was established using the 4Ch11/13 engine's diesel fuel system to investigate fuel atomization processes. The schematic representation of this setup is depicted in Fig. 3. The experimental setup comprises three subsystems:

- a subsystem for researching the fuel injection parameters with hydrogen addition
- subsystem of measurements
- automation and regulation subsystem

The fuel system of a 4CH11/13 diesel engine powered by a three-phase electric motor was developed as the basis of research into the injection process of a turbo-piston diesel engine operating with the addition of hydrogen on the wave of a pressure drop in the high-pressure fuel line.

In contemporary high-speed diesel engines, the fuel delivery process occurs within an incredibly brief window, typically lasting only one to three milliseconds, particularly at the peak rotational speed of the crankshaft and fuel delivery pump. Compression and fuel injection exhibit a non-continuous pulsating nature. Diesel fuel functions as an elastic medium in which pressure wave fluctuations propagate at speeds ranging from 1200 to 1600 meters per second. Even the slightest alteration in the volume of a fluid-filled hydraulic system results in an immediate pressure shift.

In a closed fuel system, disturbances originating from a source result in the propagation of fuel pressure pulses. These pulses encounter obstacles at the system's endpoints, leading to partial reflection from the surfaces. This reflection process gives rise to reverse and cumulative waves, which, in turn, significantly distort the injection characteristics. Near the conclusion of the injection and fuel delivery cycle, pressure waves that bounce off the closed injection valve can lead to recurring spikes in pressure values, persisting even beyond the primary injection interval. Consequently, so-called "sub-injections" occur. These sub-injections are undesirable because they are associated with low injection pressure and coarse, uneven fuel atomization. The consequences of such sub-injections are manifold. They lead to an increase in exhaust gas smoke, greater soot deposition on cylinder walls and piston surfaces, and higher specific fuel consumption. They also create favorable conditions for the coking of nozzle sprayer orifices.

Following the conclusion of the fuel supply, the propagation and rebound of waves in the high-pressure system (comprising the pump plunger, discharge nozzle, and nozzle) gradually diminish due to irreversible energy losses from friction. Residual pressure is then stabilized. Typically, the influence of wave phenomena on fuel supply parameters is more pronounced when the fuel line is longer and the injection pulse frequency is higher. However, pump-nozzle systems, which lack a discharge nozzle, are not significantly affected by wave oscillations and do not exhibit this behavior.

Hydrogen is transferred from a five-liter container (referred to as container 1) through reducer 2 and enters additive addition valve 4. This mixing device, denoted as 4, is positioned ahead of nozzle 12, which is securely mounted on a stand and oriented with the atomizer directed into measuring cup 11. The high-pressure fuel pump (HPFP) 7 is actuated by a three-phase alternating current electric motor 5, which is connected via a coupling. This electric motor operates with rotational frequency regulation achieved through a frequency converter.

A digital tachometer is affixed to the coupling of the HPFP to monitor its rotational speed. Fuel consumption through the HPFP is quantified using measuring cup 11. To record hydrogen pressure, a pressure sensor, specifically the "PD100-DI6.0" from "OVEN," has been installed (referred to as sensor 3).

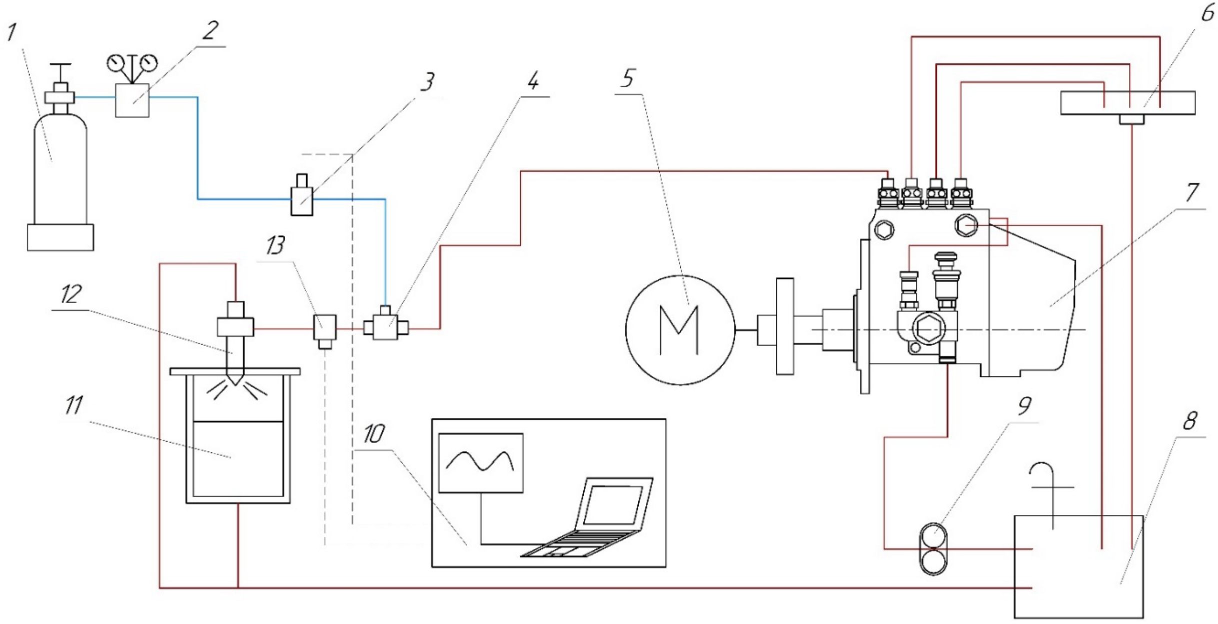


Fig. 3. Installation diagram: 1 - hydrogen cylinder; 2 - hydrogen reducer; 3 - pressure meter; 4 - mixing devices; 5 - motor; 6 - fuel drain capacity; 7 - HPFP; 8 - discharge tank; 9 - fuel pump; 10 - computer system of measurement and data processing; 11 - injection container; 12 - nozzle; 13 - pressure sensor

Fig. 4. Dynamic pressure sensor AutoPSI-S by "Optrand"

An "AutoPSI-S sensor" 13 repeater was employed for measuring pressure within the fuel system. This sensor is a fiber-optic device designed for operation in high-temperature environments. It features a maximum measuring range of up to 200 MPa and provides an output signal of 5 V. This sensor facilitates the determination of the initiation point of fuel injection, allows for a qualitative assessment of fuel pressure, and enables the examination of processes within the high-pressure tubing.

The initial signal from the primary sensors at the MDV-1 stand was electronically transmitted to an oscilloscope and subsequently to the “IRIS” 10 computer-based measurement and data recording system.

Experimental confirmation of the addition of hydrogen impurities into the main fuel influence on the performance indicators of the 1CH8.6/7.2 engine, the DVZ-2-MDV stand

The experiments were carried out at an ambient temperature of 298 K and an atmospheric pressure of 101 kPa on DP according to DSTU 3868-99 (which corresponds to the requirements of the European standard EN 590:2009). The values of environmental parameters during the study were constant.

Fig. 5 shows the results of experimental studies of engine operation depending on the load mode when operating on diesel fuel according to the load characteristic and using hydrogen additives. The results of experimental studies show when the engine runs on diesel fuel in the form of load characteristics and a graph of the fuel consumption dependence on the frequency of the crankshaft’s rotation. The dependences of the hydrogen impurity concentration (Fig. 6), the engine power values, and its fuel consumption were obtained and plotted at a constant hydrogen pressure of about 10 MPa.

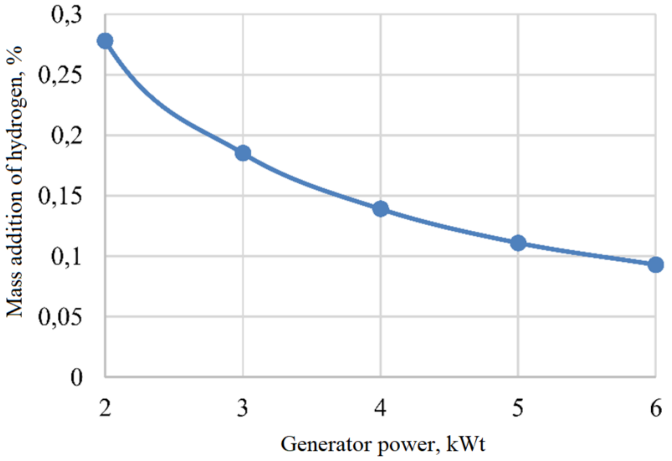


Fig. 5. Comparative operational characteristics of the 1Ch8.6/7.2 engine when working with small hydrogen impurities and on “clean” fuel

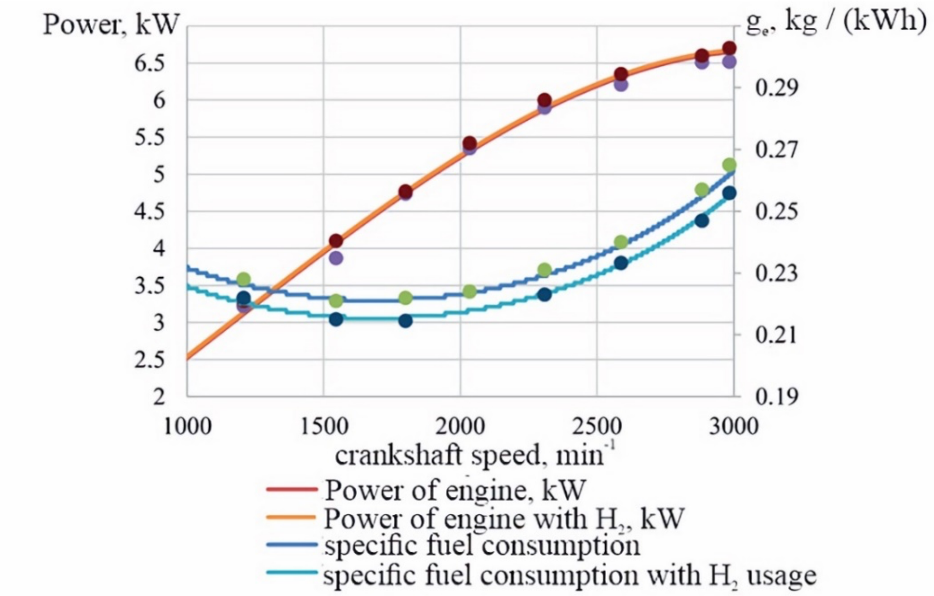


Fig. 6. Dependence of the hydrogen mass admixture on the engine load at a pressure of 10 MPa

3. RESULTS AND DISCUSSION

Optical studies of the parameters of the fuel atomization process with small hydrogen impurities

A specialized setup was developed for high-speed video recording of spray jets from a nozzle (illustrated in Fig. 7) in order to study the process of diesel fuel spraying with the incorporation of additives.

The control system (1) of the laboratory setup sent a pulse to synchronize the operation of the HPFP and the fuel delivery to the nozzle (3). Sensor (2) provided a signal to the synchronization unit (5). This synchronization ensured that the video camera started recording simultaneously with the initiation of fuel pumping and spray emission from the nozzle. Information from the video camera (4) was transmitted to the laptop (6) via a sensor cable. The fuel jet ejected from the nozzle (3) spread in a direction parallel to the surface of the recording screen. Hydrogen was supplied to the mixing device from a tank via a reducer at a pressure of 5 MPa.

Video recording was carried out by a protected Xiaomi action camera, specifically the Yi 4K Action Camera, at a frame rate of 120 fps in high resolution. The objective of this camera consists of seven lenses made of optical glass, has a 155° field of view, and is equipped with an F 2.8 aperture capable of allowing more light, resulting in clearer images that are less sensitive to changes in lighting conditions. This is why this camera was chosen for use.

In conventional studies cited in the literature, individual photo frames of the spray are typically processed. However, this work introduces a novel approach that analyzes the brightness variations throughout the entire range of fuel spray progression. This method involves the processing of multiple spray cycles, each containing 5 to 10 frames. The images in a series are processed sequentially, with each cycle of development highlighted separately. This processing technique allows for the examination of changes in the clarity and dynamics of various regions and zones within the fuel jet.

The use of high-speed video recording is preferred in this study, as it provides a more comprehensive understanding of the fuel atomization process compared to single-frame photographs. One drawback of high-speed video recording is the alternating brightness changes between frames. The approach of using image negatives with background illumination was adopted (depicted in Fig. 8) to mitigate flickering in brightness.

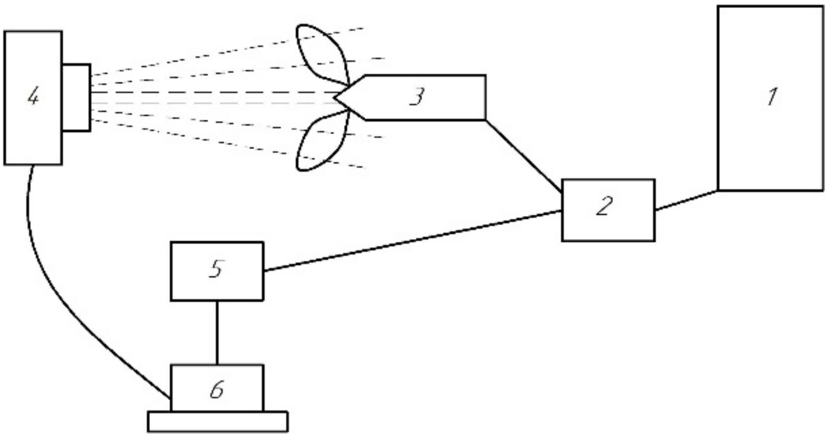


Fig. 7. Scheme of the video recording stand

Image processing of fuel jets

Image processing for the captured images was performed using "CorelDRAW Graphics Suite." In these scans, the fuel jet typically has indistinct boundaries, making it a challenging task to delineate these boundaries. The objective is to identify and highlight the areas of interest to analyze the quality of droplet atomization in the image.

To process these images of fuel jets, a segmentation method was employed. Segmentation involves dividing the image into two parts: the foreground and the background. This operation allows areas within the image that appear visually homogeneous to be isolated, effectively dividing the image into regions of similar characteristics. It is important to note that there is no one-size-fits-all segmentation mode suitable for assessing the quality of fuel spray across all images. Hence, image processing is carried out using an analytical frame distribution method. Traditionally, a depiction of the fuel jet shows a cone-shaped appearance with a denser central part compared to the outer region. When the fuel jet is evenly saturated with droplets, the image will generally exhibit a single shade or vice versa. This feature is critical for assessing the quality of fuel spray.

The image processing and assessment of fuel atomization parameters based on jet photographs are critical stages in scientific research and technical applications where investigating and measuring fuel jet characteristics is pivotal. The image processing methodology can be broken down into steps conducted in a prescribed sequence. A detailed description of this process is presented in the following paragraphs. The first stage involves capturing photographs of the fuel jet. A high-speed camera is used to record the fuel atomization process, ensuring optimal illumination to obtain clear and detailed jet images. After acquiring the images and selecting quality frames from the sequence, frame correction and processing are performed to enhance image quality and remove any noise that may occur during high-speed capture. Tools are utilized to convert the image into a bright negative with brightness and contrast adjustments to make the image more informative.

Following image processing, jet segmentation is carried out to determine the region of interest and isolate fuel jets within the image. The fuel jets are highlighted using segmentation tools like threshold filtering and contour detection algorithms.

Once segmented images of acceptable quality are obtained and scale considerations are accounted for, tools are employed to measure the size of individual jets and their geometric characteristics. The collected data are then organized in a tabular format, and appropriate statistical analysis is conducted, both with and without the fuel additive. Subsequently, calculations are applied by integrating the results of the statistical analysis into a mathematical model of the fuel atomization process. This yields data such as the average fuel droplet size, concentration, and other significant parameters characterizing the atomization process.

Fig. 8 depicts typical images of atomized fuel jets obtained through experimental methods and processed as described above. The images show that the fuel jets without hydrogen are longer and have a smaller spray angle than those with hydrogen. Indirect 3-D models of these jets (shown in Fig. 9) were constructed using the acquired data for integration into a physical modeling software environment for further in-depth investigation. A schematic representation comparing the two jets (with and without hydrogen additives) is illustrated in Fig. 10.

Mathematical model and mathematical description of changes in the characteristics of sawing and combustion

At the Department of Internal Combustion Engines at the National University of Shipbuilding, a mathematical model for the operational cycle of an engine running on conventional fuel was developed. This model draws from the research and works of esteemed authors, including Professors M.M. Glagolev, M.K. Shokotov, M.F. Razleytsev, R.M. Petrychenko, V.G. Semenov, A.P. Marchenko, and Associate Professor D.S. Minchev, among others. The heat dissipation process in engines is described using equations initially proposed by Professors O.S. Lyshevsky and M.F. Razleytsev.

Numerous authors have investigated aspects such as the delay period for spontaneous combustion, the average diameter of atomized fuel droplets, and the length of the flame in engines equipped with direct fuel injection. Significant correlations have been established from these collective research efforts. These findings are attributed to Heywood's work.

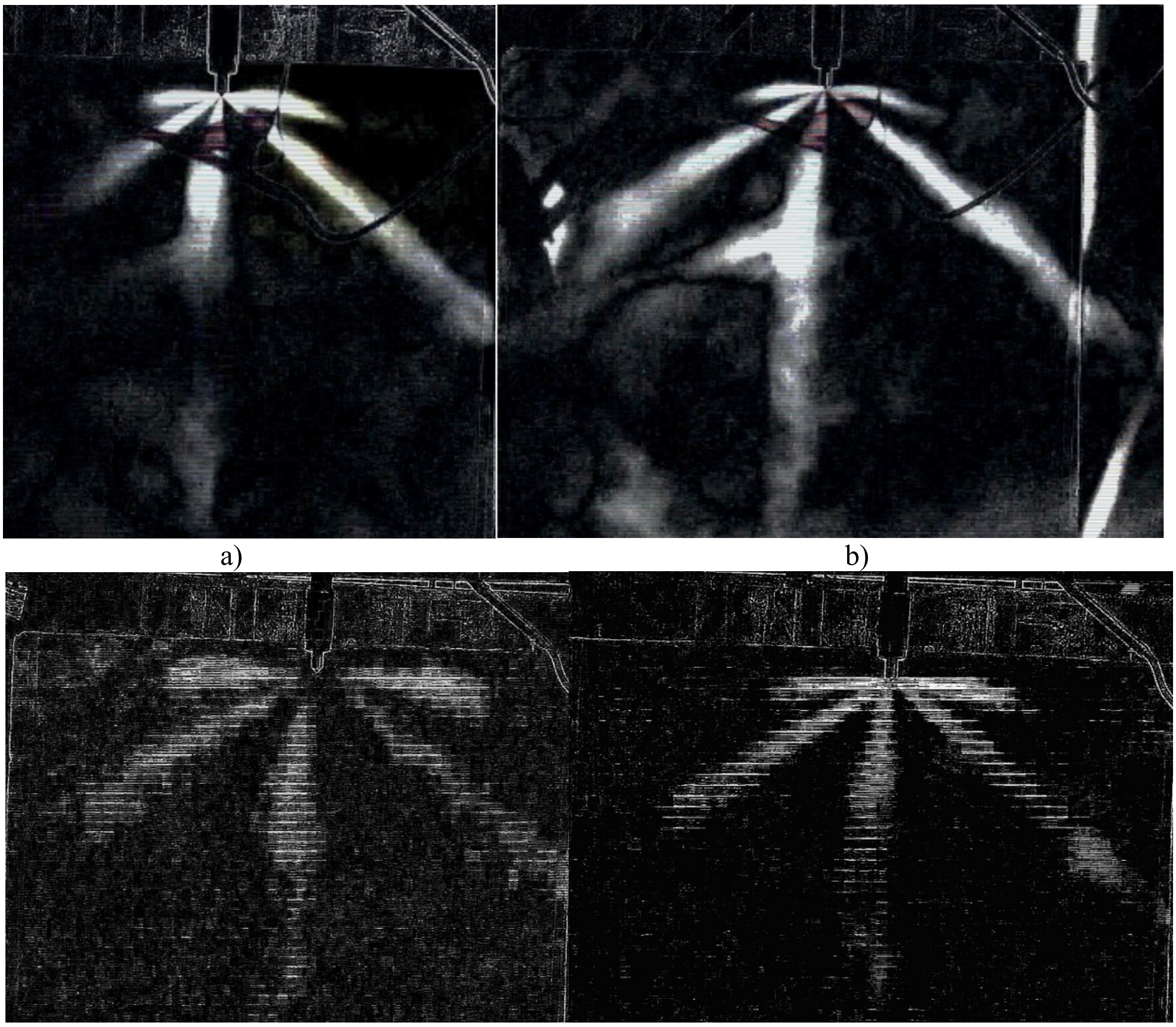
$$\tau_i = (0.36 + 0.22 \cdot C_m) \times \exp\left(E_A \left(\frac{1}{R \cdot T} - \frac{1}{17190} \right) + \left(\frac{21.2}{p - 12.4} \right)^{0.63} \right); \tag{1}$$

Kinetic equation of heat dissipation dynamics at the fuel supply section

$$\left(\frac{dx}{d\tau} \right)_1 = A_0 \frac{G_c}{V_в} \sigma_i \left\{ \exp\left(\phi_0 \tau \right) \right\} \left(\sigma_i - x_0 \right)_{till \ldots x_0 = 0}^{before \ldots x_0 = \sigma_i} + \psi \frac{d\sigma_i}{d\tau} + A_2 \frac{G_c}{V_c} \left(\sigma_i - x \right) \left(\alpha - x \right). \tag{2}$$

Equation of the rate of heat dissipation at the initial stage of fuel combustion

$$\frac{dx}{d\tau}=\left(P_0+\frac{d\sigma_i}{d\tau}\right)/\left(1+A_1\left(P_0+\frac{d\sigma_i}{d\tau}\right)\right). \tag{3}$$



a) b)

a) b)

Fig. 8. Photos of photofixation of fuel spraying with a nozzle a) with hydrogen additives and b) without additives

a) b)

Fig. 9. Models of atomized fuel torches: a) diesel fuel and b) fuel with hydrogen impurities

Relative evaporation constant, real

$$\tau_i=\frac{Az/\alpha^{0.6}}{K/d_{32}^2}. \tag{4}$$

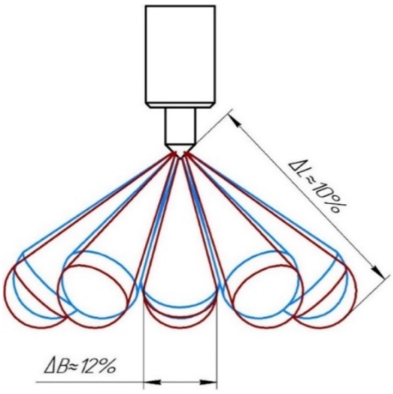


Fig. 10. Change in the structure of fuel jets from the use of a hydrogen additive up to 10% of the length of the free flight of the torch

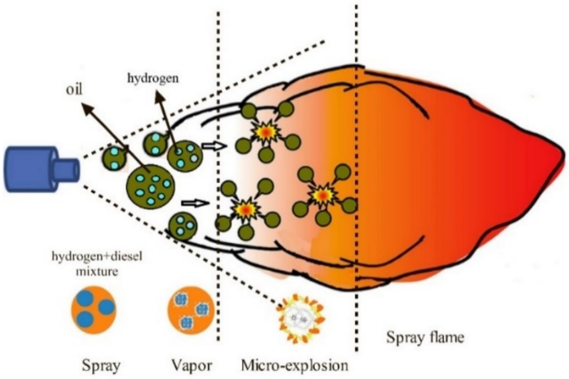


Fig. 11. Scheme of the hydrogen admixture's effect on the fuel spray atomization in the cylinder

Weber's criterion characterizes the ratio of surface tension and inertia forces.

$$We = \frac{U_0^2 d_c \rho_f}{\sigma_f} \; . \tag{5}$$

Average surface diameter of atomized fuel droplets

$$d_{32} = E_{\kappa} d_c \left(\rho \cdot We\right)^{-0.266} \cdot M^{0.0733} . \tag{6}$$

Determination of the length of the free departure of the torch

$$L = 3.07\left(\frac{\Delta p}{\rho_g}\right)^{0.25} \cdot \sqrt{\left(td_n\right)} \cdot \left(\frac{294}{T_g}\right)^{0.25} . \tag{7}$$

In a different view

$$L = \left(\frac{d_c U_0 W_e^{0.21} M^{0.16}}{\sqrt{2} D_c \rho}\right)^{0.5} \tau^{0.5} , \tag{8}$$

As can be seen, there is a direct relationship between the average droplet diameter and the length of the jet derived by Weber (1931) [28] and refined by Grant and Middleman [29]:

$$L_c \big/ d_{32} = 8.51 W_e^{0.32} , \tag{9}$$

Based on Equation 9, an increase in the average diameter of atomized fuel droplets is directly proportional to the length of the fuel jet, as larger droplets carry more kinetic energy. Consequently, as illustrated in Fig. 10, a decrease in the length of the flame spray can indicate a reduction in the average diameter of atomized fuel droplets, which is supported by the widening of the jet.

Notations in calculation formulas:

τ_i - Ignition delay period; E_A - Fuel activation energy;

A_z - Coefficient in the formula for calculating the average diameter of sprayed fuel droplets;

α - Excess air coefficient; P_0 - Initial pressure in the cylinder;

d_{32}^2 - Zauter's mean square diameter of sprayed fuel droplets;

We - Weber number; U_0 - Velocity of the sprayed fuel jet;

ρ_f - Fuel density; d_c - Nozzle diameter;

E_κ - Dimensionless coefficient in the formula for calculating the average diameter of fuel droplets;

L - Length of the spray jet; ρ_g - Density of sprayed fuel in the cylinder;

T_g - Temperature of gases inside the cylinder.

4. RESULTS AND CONCLUSION

The experimental setup enabled us to observe changes in the primary operational parameters of an engine running on a blend of hydrogen and conventional fuel with a high degree of accuracy. It provided valuable insights into the impact of hydrogen on atomization characteristics and the overall performance of the engine. This, in turn, allowed us to refine the mathematical model describing the atomization and evaporation process of fuel when hydrogen is introduced as an impurity. Consequently, the accuracy of the mathematical model for the engine's operational cycle was significantly enhanced.

Based on the analysis of our findings, several significant effects of hydrogen impurities in the fuel can be deduced:

- The average diameter of fuel droplets was reduced.
- For the first time, we observed that as the hydrogen concentration in the fuel increases, the flight distance of the jet (L) decreases, while the width of the jet's body (B) increases.
- The shape of the flame torch transitions into a teardrop configuration.
- There is no noticeable sharpening at the beginning of the torch, suggesting that the super-enriched core of the jet has experienced some degree of disruption.
- The opening angle of the torch shows a considerable increase.

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