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ANALYSIS OF MEASUREMENT METHODS FOR FUEL INJECTION SPRAY PARAMETERS FROM MARINE ENGINE INJECTOR

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Abstract

One of the main factors influencing on the optimal combustion process in a marine diesel engine's cylinder is the fuel injection spray and the fuel atomization. The complexity of mentioned phenomena in the marine diesel engine's cylinder may cause difficulties in their analysis. Measurement methods, allowing obtaining information about the process of fuel injection and evaporation in the diesel engine's cylinder are qualified as optical visualization methods. It provides non-invasive measurement of parameters of fuel injection spray. The article presents the analysis of various aspects of optical measurement methods application that allow specifying parameters of fuel injection spray in the diesel engine's cylinder. Initial studies were carried out using Mie scattering method. In addition, visualization obtained by shadowgraphy method was presented also. The constant volume chamber was used as a working area. The conventional light source was used in case of Mie scattering and a laser light source in shadowgraphy. For the lighting test was used a double-pulse Nd:YAG laser. The wavelength laser 532 nm was used. A course of the injection process was recorded by high-speed camera. The Mie scattering method allows analysing the fuel injection phenomena in macro scale. Specified geometric parameters. The shadowgraphy method allows to asses parameters of diesel fuel injection from marine diesel engine's injector in the micro scale.

Keywords: *marine diesel engine, spray characteristics, optical methods, Mie scattering, shadowgraphy*

1. Introduction

The marine diesel engines are the basic source of propulsion in vessels. There are strict rules that refer to energetic efficiency and reduce the emission of toxic compounds. This is the reason for research connected to the optimization of the fuel combustion process, taking place in the cylinder of the marine engine. The complexity of apparitions that take place during the fuel atomization process, the fuel spray evaporation, the mixing, and the fuel ignition generates the necessity to analyse parameters of fuel spray phenomena. The process of injection spray into the combustion chamber of diesel engine influences on both the emission of toxic compounds into the atmosphere and the fuel consumption. The combustion pressure analysis is the classical method of control, diagnosis and studying the influence of modification of the fuel injection system [11]. In the case of the combustion pressure, measurement there is no information about the process of the fuel injection spray. During the fuel injection spray into the combustion chamber of diesel engine, a cone-shaped spray with specific tip penetration is generated. One of the factors that influences on the process of fuel injection spray is the construction of the fuel delivery system. The analysis of fuel spray parameters may provide the information about energetic and ecological properties of fuel supply system in marine engine. In the work [12] contains the analysis of fuel spray parameters for different constructions of fuel injector in the marine diesel engines and in the spark ignition engines. Each parameter describes the quality and uniformity of the fuel spray into the combustion chamber of diesel engine. The analysis of fuel spray is described using the external parameters (macro parameters) and the internal parameters (micro parameters) [10]. These parameters are closely linked and dependent on construction and exploitation of the fuel injection system. Fig. 1. illustrates the macro and the micro parameters of the fuel spray. In terms of macro parameters, there are the tip penetration and the spray angle.

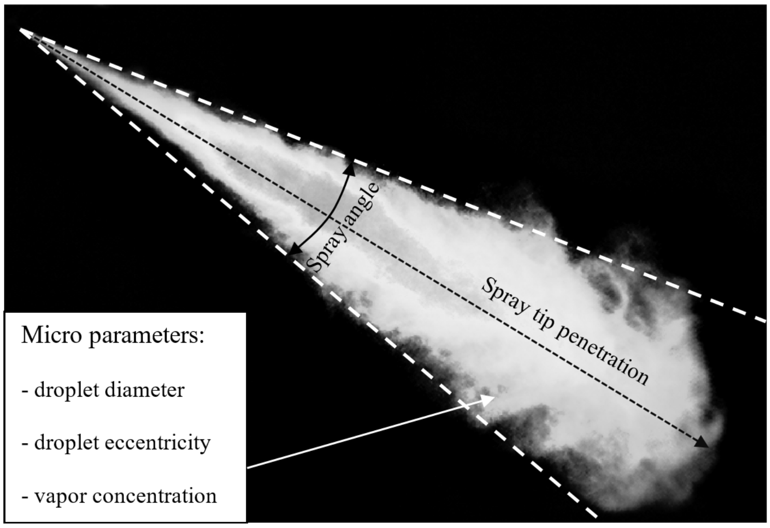


Fig. 1. The parameters used for the fuel spray characterization

The spray angle is the angle, which determines the geometrical shape of the fuel spray. The spray tip penetration determines the maximum axial distance reached by the fuel spray from the injector nozzle [10]. It is necessary to remember that the fuel spray tip penetration is changeable in time and space during the fuel spray injection process. The work [9] presents characteristics of fuel spray parameters in diesel engines. Two areas can be differentiated in the distribution of the fuel spray. One of them includes the steam of spray. It consists of drops with large diameters and speeds and the area that surrounds the core, which consists of drops with smaller diameters and speeds. The second one includes the area of small diameters where fuel and air mix. It is characterized by lower fuel concentration level, which is notable in Fig. 1. in the shape of fuel spray. The micro parameters that specify the microstructure of the fuel spray are presented in Fig. 1. also. The microstructure of the fuel spray injected into the combustion chamber is very important for the engine combustion process. It affects the quality of produced fuel-air mixture, the rate of evaporation, the mixing with air and the generation of toxic compounds. Therefore, minimization of the fuel droplet sizes is desirable. To define the micro parameters two features are being used: the degree of atomization and the uniformity of atomization [10]. There are some difficulties in examining the fuel injection process caused by the quickness of the droplets disintegration process along with air turbulences. Determination of parameters of fuel spray is impeded due to the character and conditions of the fuel spray injection process. The increased development of measurement technology and the introduction of stringent regulations that concern the efficiency of combustion process in marine engines are the reason for conducting tests. Measurement methods, allowing obtaining the information about parameters of the injected fuel spray, are qualified as optical visualization methods.

According to presented considerations, the main target of the paper is analysis of measurement methods of fuel injection spray parameters from marine engine injector. Considered optical visualization methods are Mie scattering and shadowgraphy. For chosen methods, the components of test rig are presented. Several exemplary visualizations are shown for applied measurement parameters. Tests were carried out on the diesel oil.

2. Optical visualization methods

The determination of parameters of the process of fuel injection spray in *on-the-job* conditions might be severely limited or impossible to prepare by means of construction aspects.

Consequently, the measurements are taken in laboratory conditions using optical visualization methods. One of the advantages of optical visualization methods is their non-invasiveness in tested process of fuel injection spray; however, they require the optical access. Because of it, it is necessary to provide the accurate test rig equipped with the tool that simulates the conditions similar to the ones that occur in combustion chamber of marine engine. The simplified constructions are being used, for example, constant volume chambers or laboratory engines with optical access [1]. The [4] shows the research that was conducted with optical method and that focused on the possibility of determining the quality of fuel spray created by fuel spray injector of car diesel engine. The quick-change process of fuel injection spray is recorded with high-speed cameras and in the presence of adequate source of lighting. Besides the recording devices that have high range of parameters, the optical visualization methods require the proper lighting of taped processes. In the optical measurement technique for fuel spray, the laser beam is used to light the recorded image. The work [5] illustrates analysis of the impact of the type of lighting on terms of tested parameters. It was stated that using the halogen lighting in optical visualization methods allows measuring only the macro parameters. On the other hand, using the laser lighting allows measuring only the micro parameters i.e. the speed and direction of each drop in the fuel spray. Laser lighting has the advantage over the alternative source in the way that it requires short time to generate more radiation energy. Additionally, the signal of laser lighting can convert generated beam of light into laser sheet [5]. The laser beam is characterized by low divergence [5]. In terms of tested parameters of fuel spray and the operating principle, it is possible to differentiate optical visualization methods like: shadowgraphy, Mie scattering, Particle Image Velocimetry (PIV), PLIF/PLIEF –Planar Laser Induced Fluorescence/Planar Laser Induced Exciplex Fluorescence. Using PIV to measure the parameters of fuel spray created by fuel injector in marine engine enables visualization of the structure and the vectors of drops speed field in different distance from exhaust nozzle. The PLIF method is the optical technique, which facilitates visualization of the concentration area for liquid-gas phases. This method uses the apparition of fluorescence caused by laser light wave. Alternative method for PLIF is PLIEF. PLIEF consists in adding the marker, for example, a combination of two hydrocarbons, to the fuel [5]. The [2] presents the analysis of laser optical technique PLIEF in diesel sprays. As stated in [2] PLIEF is a reliable technique to assess macro parameters.

The preliminary assessment was undertaken to measure the fuel spray created by injector of marine diesel engine. The assessment focused on measurement capabilities of optical method techniques to determine both macro and micro parameters of diesel fuel spray produced by the injector of the marine engine.

2.1. The measurement analysis of optical methods

The preliminary parameter tests of fuel spray produced by the injector of the marine engine were conducted in cooperation with Laboratory of Institute of Heat Engineering of Warsaw University of Technology [6]. The tested object was the injector of four-stroke laboratory marine diesel engine type 3 Al 25/30. The parameters of laboratory marine diesel engine are presented in [8]. For preliminary tests of both macro and micro parameters analysis of fuel injection spray process of marine engine injector, the measurement system was used and it is shown in [6] with Mie scattering and shadowgraphy. The fuel system of marine engine injector was supplied by common rail system.

2.1.1. Mie scattering

Mie Scattering method consists in recording the intensity of light that is dispersed in the spray of atomized diesel fuel. In preliminary tests, the researchers considered the measurement of macro parameters of fuel spray produced by one hole in injector nozzle. The diameter of the nozzle injector was 0.375 mm. The other holes of injector nozzle were plugged. The pressure of fuel injection was constant and equals 40 MPa. The opening pressure of injector was set to 35 MPa. The fuel injection spray pressure corresponds with the opening pressure of the solenoid valve. In the preliminary tests, the diesel fuel was injected into constant volume chamber and then the images of fuel spray were registered. The constant volume chamber was the measurement space. It had the optical access. The optical access was provided by one observation window, mounted on the wall of the chamber. The parameters of constant volume chamber are presented in Tab. 1. Two 250 W lamps were used as a source of light. The video camera and the light were directed into one point, which was the observation window of the chamber. The high-speed camera Photron FASTCAM SA1.1 was used as image recorder. The parameters of high-speed camera are as follows: the resolution 768x512 pixels and 15,000 frames per second. The data analysis and image processing were conducted by means of calculating module named Spray Master LaVision 8.3.0. Fig. 2. presents the example of the visualization of fuel spray for the 4 ms period after valve opening.

Tab. 1. The parameters of constant volume chamber

Dimensions	200 x 200	mm
Diameter of the observation window	140	mm
Translucency	100	mm
Underpressure	43	MPa
Measurement space	nitrogen	–
Distance from lamps	600	mm
Distance from camera	450	mm

Fig. 2. The example image obtained by Mie scattering method

Figure 2. shows the exemplary visualization of fuel injection spray obtained with Mie scattering method. Fig. 2. was processed in terms of removing the background and putting the mask. Then, the calculation module was applied to the processed image. Mie scattering method allows determining the most important macro parameters of fuel injection spray of diesel fuel. In given visualization (Fig. 2.) obtained with Mie scattering methods, it is possible to observe the turbulence of charge in the cylinder. It is necessary to remember that the Mie scattering method

uses the light dispersion phenomenon in tested medium. Accordingly, in the obtained image, the lighter the shade, the more dispersed the tested engine fuel is observed. Received data is the basis for further analysis of macro parameters of fuel injection spray.

2.1.2. Shadowgraphy

The optical measurement method named shadowgraphy involves axel lighting of studied object and records the shadow of the image by the camera. Emberson et all in [3] present the results of their research on the parameters of the tip penetration and the spray angle obtained by the shadowgraphy method by means of atomized hydro-fuel emulsion in the diesel engine. The constant volume chamber was used as the measurement space and the LED lighting was used also. The shadowgraphy was used in the preliminary tests to search for parameters of diesel fuel sprayed by the injector of the marine engine. The shadowgraphy method was used to measure the micro parameters i.e. the diameter and the distribution of fuel droplets. The diameter of the nozzle injector was 0.325 mm. The parameters of diesel fuel injection were the same as with Mie scattering. The shadowgraphy methods rely on illuminating the diesel fuel injection spray and registering the image of fuel injection spray shadow. A constant volume chamber of previously mentioned parameters was used (Tab. 1). Due to the measuring principle of shadowgraphy method, the second window was installed in the chamber. The components of test rig were placed in the one axis. The measurement were carried out using the test position presented in [6] – shadowgraphy. The chamber was placed between the source of light and the camera that registered the shadow image. For the lighting test, a double-pulse Nd:YAG laser with a wavelength of λ = 532 nm was used. The diffuser optics was used to obtain the exceeded illumination space. The power of the laser light was set to approximately 30%. In target to achieve a high depth of field a long distance microscope (Maksutov Cassegrain Catadioptric QM1) is connected to the camera. The camera and the long distance microscope are mounted on an optical bench [6]. The distance between the long distance microscope and tested medium is determined by the magnitude of observed space in dissonance function. Two magnifiers were used. The magnification was 1.5x and 2x. The total magnification was 3x. Setting the distance depends on total magnification and size of observed space. Accordingly, to Fig. 3 and magnitude of observed space included in Tab. 2, the distance between long distance microscope and a camera in a constant volume chamber was set. The parameters sCMOS camera is presented in Tab. 3.

Tab. 2. The parameters of long distance microscope

Type	QM1	
Working distance	560 to 1520	mm
Clear aperture	89	mm
Numerical aperture	0.06 – 0.02	-
Barlow lens	1.5x and 2x	
Field of view	2125 x 1792	µm
Distance	100	cm

Tab. 3. The parameters of sCMOS camera

Type	Imager sCmos	-
Rate	50	fps
Resolution	2560 x 2160	pixels
Pixel size	6.5 x 6.5	µm

Figure 4 presents the obtained visualization. The fuel injection spray was registered at the exit of a nozzle of injector (Fig. 4a.) and at the final part of fuel injection spray where the gas phase occurs (Fig. 4b.). Fig. 4a presents the outline of obtained fuel injection spray after exiting the nozzle. No drops were observed. For Fig. 4b applied calculation model facilitated determining the diameter of the biggest drops, however, this result is not dependable in terms of quality and uniformity analysis of the fuel spray.

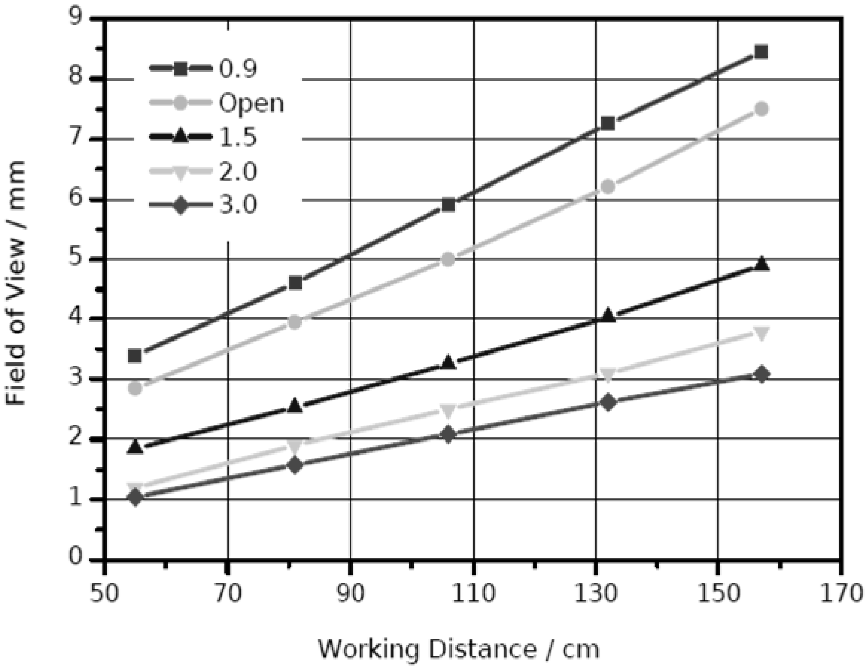
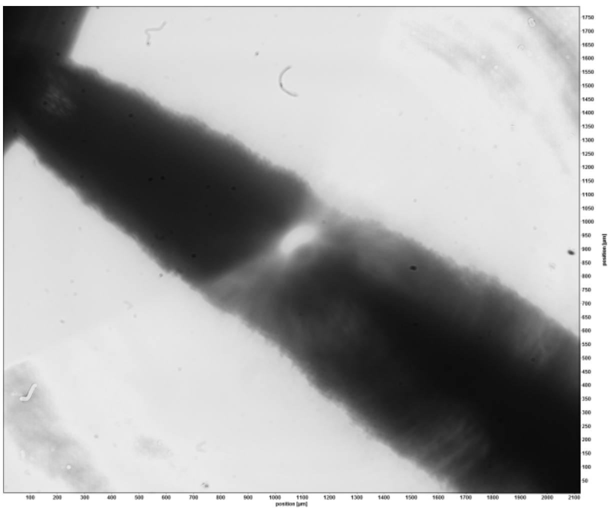


Fig. 3. The field of view as a function of distance [7]

a)



b)

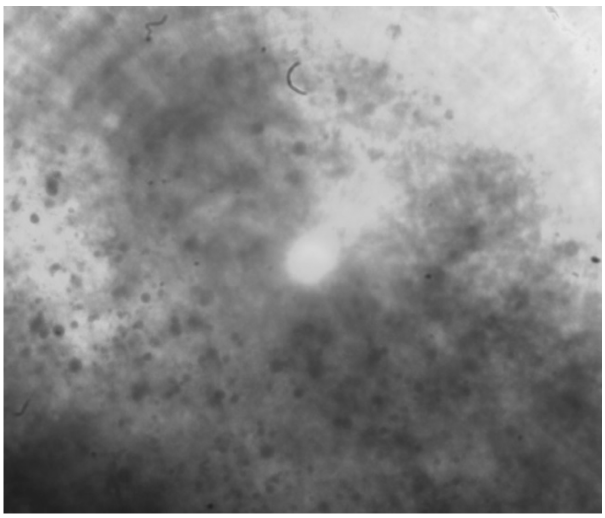


Fig. 4. The example image obtained by the shadowgraphy

3. Conclusions

The optical visualization methods create the wide range of measurement capabilities of the fuel spray produced by the injector of the marine engine. The optical visualization methods enable noninvasive and fast parameters measurement of atomized liquid spray. Because of this, the optical visualization methods are used in research that focuses on fast-changing processes like fuel spray injection or fuel atomization. The following conclusions were formed for the parameters of measurement equipment. The exemplary measurements that were presented in the article with the Mie scattering and shadowgraphy method. Accordingly, the following conclusions were presented:

- described Mie scattering method that uses the illumination of two lamps with 250 W and high speed camera allows measuring the macro parameters of the diesel fuel injection spray from the marine engine injector,
- for the parameters of the test rig presented in the article, the shadowgraphy technique that operates on laser lighting is not the proper method to test micro parameters of diesel fuel spray produced by injector of the marine engine Sulzer 3 Al 25/30. Despite the laser lighting and long distance microscope, the diesel fuel at presented injection parameters is too dense medium to determine the micro parameters of fuel spray,
- the advantage of high speed video recording of diesel fuel injection process is the opportunity to analyse the continuous process of fuel injection spray or, through playing particular frames back – the images,
- it was stated that the crucial aspect of obtaining the legitimate measurement results is the use of visualization and measurement devices that have wide range of parameters. The second factor that influences the quality of obtained results is the proper lighting of tested object,
- the disadvantage of applying the constant volume chamber is its inability to recreate the actual conditions of the combustion chamber i.e. the temperature variation and the pressure. Therefore, further research on macro and micro parameters of the fuel spray created by the injector of the marine engine Sulzer 3 Al 25/30 shall be conducted.

Acknowledgments

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