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Analysis of the structure of the atomized fuel spray with marine diesel engine injector in the early stage of injection

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This paper presents the results of the experimental research of the atomized fuel spray with the marine diesel engine injector in the constant volume chamber. The specificity of the phenomena occurring in the marine engine cylinder was the reason to use the optical visualisation method in the studies – the Mie scattering technique. This work presents an analysis of the influence of different geometry of outlet orifice and opening pressures of marine diesel injector on the macrostructure of the fuel spray. In the results, it was observed that the increased L/D ratio of the outlet orifice of the injector caused: an increase in the spray cone angle and a decrease in the spray tip penetration in the early stage of injection. Furthermore, it was defined that the characteristic of spray tip penetration over time was power, whereas the spray cone angle over time was a logarithmic function.

Key words: *marine diesel engine, marine diesel engine injector, early stage of injection, spray cone angle, spray tip penetration*

1. Introduction

Two- or four-stroke diesel internal combustion engines with direct in-cylinder fuel injection are used in marine ship engine rooms. A consequence of the fuel combustion process of marine engines is the emission of toxic compounds in the exhaust gases, such as nitrogen oxides (NO_x) or carbon oxides (CO_x). These marine diesel engines are usually fueled by marine diesel oil and heavy diesel oil. It should be mentioned that research is also conducted on the use of alternative fuels in marine diesel engines [28]. It is widely known that the amount of toxic compounds emitted in the exhaust of marine engines into the atmosphere is closely related to the fuel combustion process in the cylinder [8]. Consequently, the tightening requirements associated with meeting acceptable levels of toxic emissions in marine engine exhaust gases have become a major motivation for research work in this area.

The fuel injection system is responsible for the correct combustion of fuel in the cylinders of marine engines. The injectors are the main building block of the injection system, as they are responsible for the process of injecting and spraying the fuel at the correct time and dose**.**

The marine diesel engines use the closed injectors with a needle that opens under the force of compressed fuel [11]. The main difference in their design is using spray tips with different numbers and geometry of fuel outlet orifices. The geometry of the nozzle outlet orifice of the injector is one of the main factors determining the atomization process of the fuel spray [22]. Consequently, numerous research works are being carried out to determine the influence of various design features of the injector outlet orifice on the spray pattern of diesel engine cylinders [3–5, 27]. One such design feature considered in the research work is the ratio of outlet orifice length (L) to outlet orifice diameter (D) – (L/D). As previously mentioned, fuel injectors are used to atomize the fuel from liquid form into fine droplets. It should be noted that fuel in droplet form evaporates more quickly and mixes with air leading to an explosive mixture with the correct ratio of air and fuel masses. Therefore, the fuel atomization process is so important that it will affect the subsequent self-ignition process of the fuel-air mixture. The fuel injected under high pressure into the engine cylinder forms a cloud of droplets of varying diameter and spatial distribution.

The high injection pressure of the fuel in combination with the small outlet orifice of the injector results in the first atomization of the fuel stream into droplets, referred to as primary atomization, already during fuel flow through the orifices [21]. The fuel flowing from the spray nozzle outlet into the pressurized gas (in the cylinder) undergoes further rapid atomization into droplets. This decomposition is defined as the secondary atomization of the fuel spray into droplets [21]. The different forces govern the primary and secondary atomization process of the fuel spray. These forces are conditioned by the place of their occurrence and are classified into internal and external. The internal forces come from the fuel flow inside the injector. They include cavitation or fuel flow disturbances [2, 24, 26], and are influenced by the geometry of the injector's outlet orifices, inaccuracies resulting from the machining process of the orifice surface, or vibrations from the needle, and the injector itself [3, 5, 8]. On the other hand, the external forces result from high pressure and temperature in the cylinder.

In the fuel injection, atomization, and combustion process analysis, the information on the parameters determining the external shape and internal structure of the fuel cloud becomes crucial. This information constitutes the parameters referred to as macro and micro [16]. In the cylinder of a marine diesel engine, macro parameters provide information on the volume of the sprayed fuel. The knowledge of this geometry is required for the appropriate configuration of the injection system. The external shape of the spray cloud is characterised by macro parameters: spray tip penetration (STP) and spray cone angle (SCA).

The literature includes the mathematical models for calculating the STP and SCA, based on the results of the experimental research of the fuel injection and spray process [1, 6, 7, 14, 27]. These mathematical models are mainly determined by: the pressures of the fuel injection process, the geometry of the injector outlets, or the density of the gas in the chamber. A pioneering two-stage model for the STP was presented in the work of Hiroyasu and Arai [12]. The two stages of the model rely on the fact that the early stage of injection of the fuel spray is directly proportional to the passage of time, and after a certain time t_{break} is proportional to the square root of time. This model was often the basis for defining new models [10, 13, 20]. It should be noted that, most mathematical models for the SCA do not account for the passage of time [12, 14, 23, 25]. This macro parameter is calculated as a constant maximum value.

The different designs of marine diesel engines with direct in-cylinder fuel injection in relation to the design of engines used in the automotive sector make it necessary to familiarise ourselves with the fuel injection and spray process in the cylinders of these engines [17, 18].

Considering the importance of the injector design parameters conditioning the fuel injection process into the cylinders of marine engines, the main aim of this paper is to analyse the effect of changing the L/D ratio of the outlet orifice of a marine engine injector on the geometry of the fuel spray. The paper particularly focuses on the early stage of atomization because, due to the relatively low rotational speed of direct-injection marine diesel engines, the fuel injection usually occurs within a few degrees of the crankshaft angular position before the TDC. This is the time when the air compressed by the piston forms the smallest volume of the high-temperature working space, which exceeds the self-ignition temperature of the fuel. As a result, the first foci of fuel spontaneous combustion appear in the cylinder space already during the initial fuel injection due to rapid processes of atomization into droplets, evaporation, and mixing with air. It is important to note that fuel combustion begins when not all the fuel has yet been delivered to the cylinder, and the fuel-air mixture formation continues throughout the fuel injection period. It is, therefore, important to carry out an analysis of the characteristics of the injected fuel spray into the cylinder at the early stage of spraying and not when the fuel spray has already developed and reached its maximum size.

2. Experimental test and method

The experimental research of the spray geometry was carried out on a laboratory bench using the constant volume chamber (CVC) presented in Fig. 1 [9, 10].

The CVC, measuring 200 mm × 200 mm in length and width, was filled with the inert gas – nitrogen. The backpressure in the chamber amounted to (P_b) 3.2 MPa. The backpressure in the chamber, corresponded to the pressures in the combustion chamber of the Sulzer 3 Al 25/30 marine diesel engine at the start of fuel injection into the cylinder, i.e. 18° before the TDC, operating at a correspondingly lower load. The diameter of the CVC access window was 100 mm. The principle of the fuel injector system was based on a common-rail system. A high-pressure fuel system (UPS – Unit Pump System) kept the fuel pressure constant at around 50 MPa. The fuel injection time was 0.04 s. A Sulzer 3 Al 25/30 marine diesel engine injector was used for the fuel injection and spray process in the CVC. The mechanical type injector was adjusted for three injector opening pressures P_o: 15, 25 and 35 MPa, respectively, by means of a needle pressure spring. The fuel pressure downstream of the injector was measured with a Kistler piezoresistive pressure sensor type 4067E designed specifically for measurements in hydraulic injection systems of internal combustion engines [15].

Only one nozzle orifice was active in the spray tip of the injector, and the others had been plugged. The dimensions of the injector orifice design parameters considered are presented in Table 1.

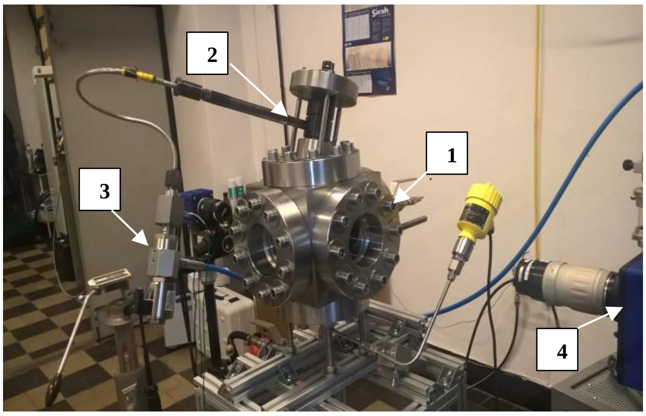


Fig. 1. Experimental laboratory set-up: 1 – constant volume chamber, 2 – marine diesel engine injector, 3 – Kistler 4067E pressure sensor, 4 – high-speed camera

The spray pattern was recorded using the Mie Scattering optical technique with a high-speed Photron SA1.1 camera with a recording frequency of 40 kHz [10, 19]. Two halogen lamps with a total output of 500 W were used to illuminate the chamber. The tests were conducted at 20–25°C. The used fuel was diesel, with a density of 816.1 kg/m^3 at 40°C.

Table 1. The nozzle dimensions

Nozzle	Diameter [mm]	Shape [-]	L/D [-]
1	0.285	cylindrical	10.9
2	0.325	cylindrical	9.5
3	0.375	cylindrical	8.3

Each measurement of the registration of the injected diesel spray into the constant volume chamber was repeated three times to eliminate coarse errors. A series of images of the injected diesel spray into the CVC were obtained from each trial. The example images for different times from the start of diesel injection are presented in Fig. 2.

The photographs of the diesel spray pattern obtained from the experimental research were subjected to image processing in the specialist software DaVis 8.4. On the basis of the graphically processed images, the geometric dimensions of the diesel spray pattern were calculated for the considered L/D ratio of the injector outlet orifices and injector opening pressures.

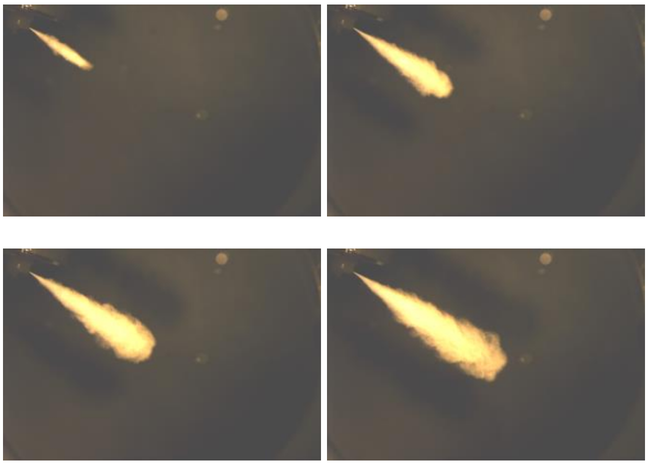
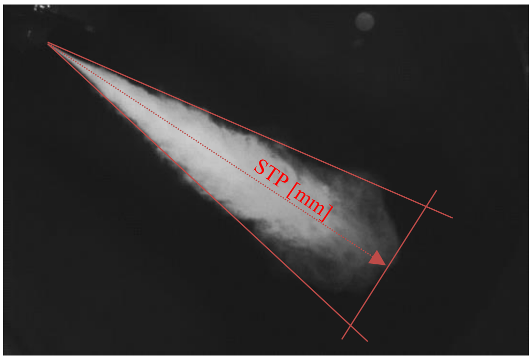
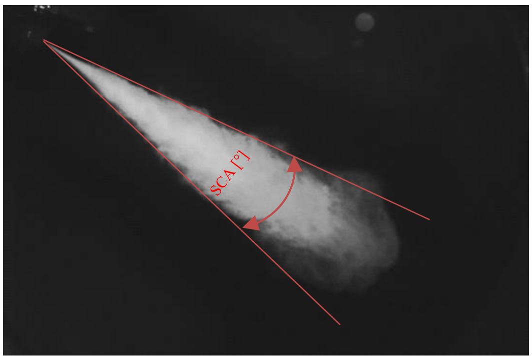


Fig. 2. The example results photos of diesel spray without outlet hole marine engine injector, L/D: 8.3; P_o: 15 MPa, P_b: 3.2 MPa

The STP is defined as the maximum reach of the fuel spray pattern in the cylinder. The SCA is the apex angle between two straight lines with a common origin at the injector outlet. The straight lines define the boundaries of the sprayed fuel in the radial direction from the spray symmetry. The definition of the STP is presented in Fig. 3a, and SCA in Fig. 3b.



a)



b)

Fig. 3. The definition of: a) TP, b) SCA

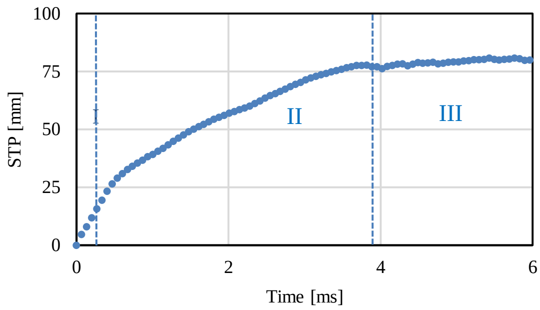
3. Results and discussion

As part of the experimental research carried out, the STP and SCA measurement results were obtained for the spray pattern of diesel fuel from a marine diesel engine injector.

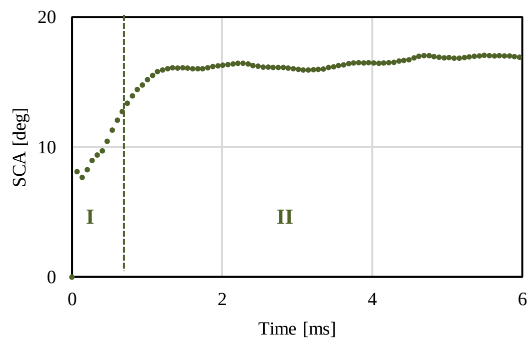
According to the example experimental results presented in Fig. 4, both the STP and SCA are time-dependent. As mentioned above, the macro parameters increase as the spray propagation time in the CVC increases. The STP characteristics of the chamber propagation were divided into three stages (Fig. 4a) and the SCA into two stages (Fig. 4b). According to Fig. 4, the stage one (I) was defined as rapid growth over a generally short period of time.

For stage (II) (Fig. 4a) for the STP, a more gentle and prolonged increase in the STP over time was observed until the stage (III), defined as "stabilisation – maximum STP", was reached. The rapid STP stage results from the initial velocity imparted to the jet by the occurring pressure difference between the injector opening pressure and the back-pressure in the CVC (P_o – P_b). During this time, the first break-ups of the spray into droplets also occur, mainly caused by the phenomena of primary atomization and secondary atomization. These phenomena include the occurrence of turbulence in the fuel jet flowing through the outlet orifice and the influence of forces from the gas medium with increased density in the CVC. In the stage (II), the diesel spray's atomization intensifies mainly due to the gas medium's aerodynamic forces in the CVC. Consequently, the stage II lasts longer than the stage I, and the STP growth during this time is more gentle. In the stabilisation stage (III), the range of the spray front reaches its maximum value. During this time, the maximum atomization of the spray into droplets occurs for the given experimental conditions.

The characteristics of the SCA over time were divided into two stages. The stage (I) similarly to the STP represents an initial rapid increase in the SCA.



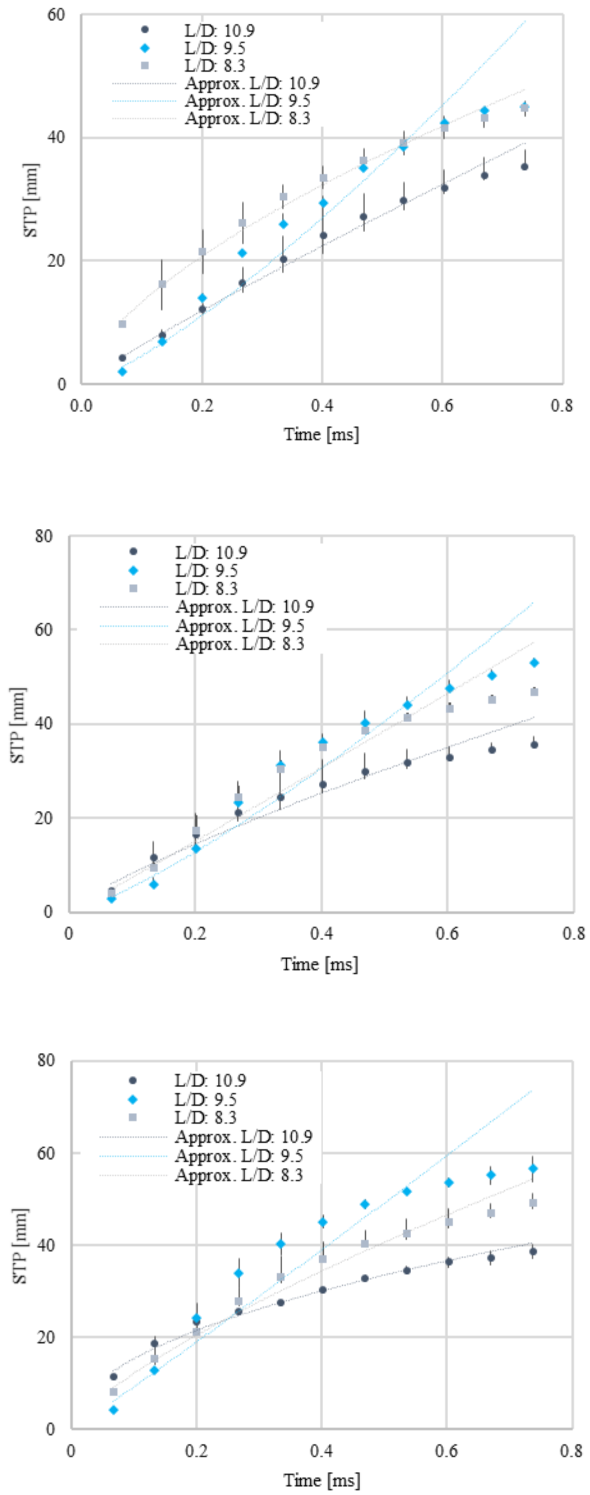
a)



b)

Fig. 4. The example of results: L/D: 10.9; P_b: 3.2 MPa, P_o: 15 MPa, a) STP, b) SCA

The initial rapid increase in the SCA is mainly due to the difference in P_o – P_b pressure. The increased gas density in the CVC causes the diesel droplets contained in the injected fuel cloud to be decelerated and deflected from the jet axis. The extremities of the spray's break-up into droplets, increasing the surface area occupied by the fuel. After approximately 1.2 ms, there is stabilisation and oscillation around a constant maximum SCA value, referred to as the stage (II) as shown in Fig. 4b.



a)

b)

c)

Fig. 5. The characteristics of the STP in the early stage of injection independent of different L/D ratios and opening pressures: a) 15 MPa, b) 25 MPa, c) 35 MPa

Figures 5 and 6 present the STP and SCA characteristics from injection start to 0.7 ms depending on the L/D ratio considered. The error bars present maximum and minimum values from each repeated measurement relative to the average.

In order to analyse the effect of the L/D ratio on the STP in the early stage of the spraying phase, an approximation method was applied using an appropriate mathematical function. The approximation lines are presented in Fig. 5 and 6. The best fit to the presented STP results was obtained using a power function. R^2 coefficients were calculated to assess the fit of the power function to the experimental data. The regression equations were determined for the specified functions according to the general form of the power function according to the general equation (1).

$$\mathrm{STP(t)} = \mathrm{a\,t^n} \tag{1}$$

where: STP – spray tip penetration; a, n – the regression coefficients; t – time [ms].

The calculated R^2 coefficients stand at 0.93–0.99, respectively, indicating a very good fit of the power function to the experimental results for time-dependent STP in the early stage of diesel spraying.

Table 3. The coefficients of regressions STP equations

P_o	L/D	a	n	R^2
15 MPa	10.9	51.67	0.91	0.99
	9.5	86.78	1.27	0.96
	8.3	58.04	0.64	0.99
25 MPa	10.9	52.88	0.80	0.95
	9.5	96.66	1.25	0.97
	8.3	78.501	1.02	0.96
35 MPa	10.9	46.90	0.49	0.98
	9.5	101.20	1.04	0.93
	8.3	68.32	0.75	0.98

Table 3 presents the calculated coefficients of the regression equations for the presented STP characteristics over time as a function of the L/D ratio and the injector opening pressures P_o considered. Based on the obtained directional coefficients "a" of the regression equations, it was observed that a change in the L/D ratio of the outlet orifice causes a change in the course of the STP characteristics during the early stage of diesel spraying.

Using Fig. 5 and Table 3, we have observed that as the L/D value of the injector fuel outlet increases, the STP decreases. For P_o: 15 MPa, the smallest STP was obtained for the L/D = 10.9 and the largest for the L/D value = 8.3. The STP for the L/D = 8.3 increased by an average of approx. 55% and for the L/D = 9.5 by 26% in relation to the STP for the L/D =10.9. However, it should be noted that for P_o: 25 and 35 MPa, the highest STP was observed for the L/D = 9.5, which increased by approximately. 35–36%, while for the L/D = 8.3, it increased by 21–24% with respect to the STP for the L/D = 10.9. An increase in L/D, i.e. a decrease in the diameter of the outlet orifice (for a constant orifice length L), results in a change in the fuel flow conditions in the orifice at certain injector opening pressure conditions. The diesel oil used in the tests is characterised by a significant viscosity and density, and therefore a change in the outlet geometry can lead to turbulence in the high-pressure fuel flow in the injector outlet.

For P_o: 25 and 35 MPa, the initial STP (from 0 to approx. 0.2 ms) is greater for the L/D = 10.9 of the outlet hole compared to the other L/D values considered. This is the result of an intensification of the diesel spray's atomization due to the increased gas density in the chamber. The higher pressure difference (P_o – P_b) leads, for the L/D value of 10.9 of the outlet hole, to conditions in which the fuel spray atomizes faster and more intensively, which is associated with a temporary increase in the STP.

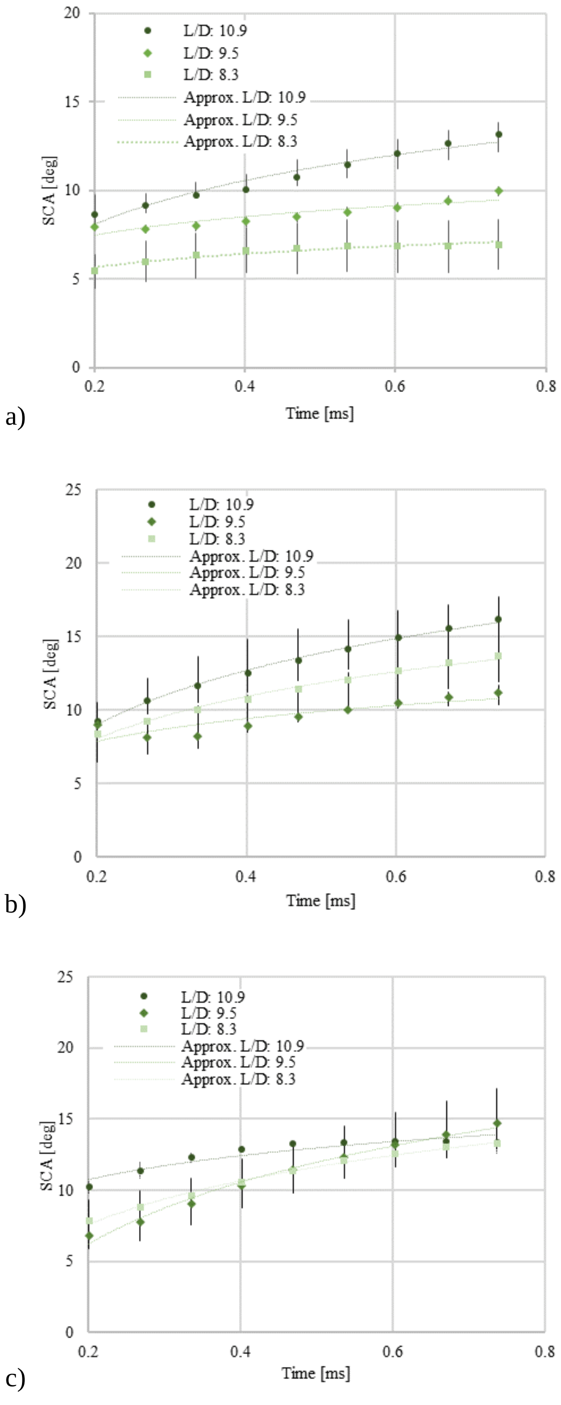


Fig. 6. The characteristics of SCA in the early stage of injection in dependent of different L/D ratio and opening pressures: a) 15 MPa, b) 25 MPa, c) 35 MPa

Figure 6 presents the SCA characteristics between 0.2 and 0.7 ms. The first three measurements (at time 0–0.1 ms) were omitted from the analysis due to the difficulty in calculating the SCA of a very small fuel spray.

For the SCA, as for the diesel STP, an approximation method was applied using an appropriate mathematical function to determine the change in the L/D for the SCA during the early spraying stage. The best fit of the SCA experimental results was obtained for the logarithmic function according to the general equation (2).

$$\mathrm{SCA(t)} = a \ln(t) + b \quad (2)$$

where: SCA – spray cone angle; a, b – the regression coefficients, t – time [ms].

The coefficient of determination R^2 for the determined cone angle characteristics was calculated and amounted to 0.82–0.99. The resulting R^2 calculations demonstrate a very good fit between the experimental results and the chosen logarithmic function.

Table 4. The coefficients of regressions SCA equations

P_o	L/D	a	b	R^2
15 MPa	10.9	3.56	13.80	0.95
	9.5	1.52	9.89	0.82
	8.3	1.10	7.42	0.91
25 MPa	10.9	5.34	17.58	0.99
	9.5	2.70	11.67	0.92
	8.3	4.15	14.72	0.99
35 MPa	10.9	2.43	14.66	0.88
	9.5	6.28	16.32	0.98
	8.3	4.42	14.71	0.99

Based on Fig. 6 and Table 4, it was observed that the SCA increases during the early stage of spraying. The highest SCA was obtained for the L/D = 10.9 for all P_o considered.

By reducing the diameter of the injector outlet, the fuel-wall friction force of the orifice increases in the wall layers, leading to an intensification of the shear forces of the spray layers. The occurrence of shear forces is a result of the viscosity effect of the diesel. Consequently, the increased disturbances occur in the injected diesel spray as a result of the intensification of the shear forces of the spray wall layers. The increased disturbance in the orifice and the smallest diameter of the outlet orifice under consideration resulted in the formation of droplets in the cloud, which lost their velocity faster and deviated from the jet axis due to the increased gas density in the CVC. Therefore, for the L/D = 10.9, a larger SCA was generally observed compared to the values of L/D = 9.5 and 8.3. A reduction in the L/D, i.e. an increase in the diameter of the injector outlet, results in a reduction in the SCA during the early stage of spraying. This is due to the occurrence of less turbulence in the spray and the formation of droplets in the cloud with greater mass and volume, which require more time to atomize and decelerate by the prevailing increased gas density in the chamber.

Conclusions

This paper presents the experimental research on the geometry of the diesel spray injected into the cylinder of a marine engine. It should be noted that the measurement of the fuel injection and spray process in marine diesel engines requires a specialised laboratory bench fitted with equipment capable of simulating the conditions in a marine engine cylinder and measuring equipment with a wide measurement range.

On the basis of the analysis of the experimental results of the macrostructure of the diesel spray injected into the constant volume chamber, the following conclusions were drawn:

– STP and SCA of the marine diesel engine spray are time-dependent.
– The increase in the diesel STP over time in the early stage of spraying has the character of a power function, while the SCA, as a function of time, takes the character of a logarithmic function.
– The geometry of the spray pattern of diesel in the early stage of spraying is influenced by the change in the geometry of the injector outlet expressed by the L/D ratio.
– An increase in the L/D ratio of the outlet orifice resulted in an increase in the value of the cone angle of the spray over time considered.

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Nomenclature

CVC	constant volume chamber
D	outlet orifice diameter
L	outlet orifice length
P_b	backpressure in the chamber
P_o	injector opening pressures
SCA	spray cone angle
STP	spray tip penetration
UPS	Unit Pump System

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