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A model of a fuel spray parameter in a marine diesel engine

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This work presents an empirical model of one of the main parameters describing fuel spray evolution in a marine diesel engine – spray cone angle in the early stage of spray formation. The model was formulated based on experimental data obtained in a constant volume chamber with optical access. Laboratory experimental studies were conducted to determine the parameters of fuel spray in marine diesel engine-relevant air densities. The Mie scattering spray visualization technique was employed to capture the propagation process of the liquid fuel. Furthermore, a model of the evolution over time of the spray cone angle is formulated, where the existing literature models of the spray cone angle are defined as constant. The calculation results for the spray cone angle were verified against the experimental data for the spray cone angle.

Key words: *marine diesel engine, marine fuel injector, fuel spray, mathematical model, spray cone angle*

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1. Introduction

Piston internal combustion engines with compression ignition (CI) are the dominant types of engines used for propulsion in the marine sector. Among those engines, one can distinguish low-speed two-stroke engines and medium- and high-speed four-stroke engines. It is essential to note that marine engines can differ significantly in design from those used in automotive applications [3, 14].

Despite ongoing efforts to implement alternative fuels and propulsion systems aboard marine ships, marine diesel engines continue to primarily burn heavy fuel oil (HFO) and marine diesel oil (MDO) [21, 25]. These fuels can differ in physical properties, such as density and viscosity, compared to conventional diesel oil. The combustion of these fuels produces exhaust gases containing nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon oxides (CO_x), and particulate matter (PM), which significantly contribute to air pollution in the maritime environment [10, 23]. Pollution resulting from marine engine emissions was the driving force behind the introduction of Annex VI to the MARPOL 73/78 Convention by the International Maritime Organization (IMO), which regulates permissible emission levels. Notably, the IMO has announced plans to reduce total greenhouse gas emissions from maritime transport by 50% by 2050, compared to 2008 levels [11].

Considering the trend towards introducing alternative fuels and achieving low-emission targets in compression-ignition marine engines, there is a growing need to conduct research on fuel spray behavior [22, 26].

The processes of fuel injection and atomization in internal combustion engine cylinders are critical, as they directly influence air-fuel mixing, ignition, and combustion behavior. Moreover, the distinct structural characteristics of marine diesel engines with direct fuel injection, in contrast to those used in the automotive sector, necessitate a detailed understanding of the fuel injection and spray formation processes that occur inside the cylinders.

The formation of the fuel spray injected directly into the cylinder of a marine diesel engine depends on the injector nozzle's design parameters, fuel properties, and the conditions existing during injection [8]. One of the key parameters responsible for jet and droplet disintegration is the air density to which the fuel is injected.

When the fuel is injected at high pressure into the combustion chamber of a marine diesel engine, it is atomized into droplets and forms a characteristic conical spray shape. The shape and internal structure of the atomized fuel spray influence subsequent combustion processes inside the cylinder. The fuel spray propagates deeper into the chamber, increasing in both axial and radial directions. The fuel spray geometry is described by parameters that define its outer dimensions and internal structure. These parameters are classified into macro- and micro-groups. Macro parameters include the spray tip penetration (STP) and spray cone angle (SCA), whereas a typical micro-parameter used for evaluating atomization quality is the mean droplet diameter. The structure of the fuel spray pattern in the cylinder depends on the injector design features and operating pressure parameters. For example, higher injection pressure improves break-up of the fuel jet, but may also increase spray penetration and the risk of fuel impingement on the cylinder walls [18]. The authors [18] also presented the results of a study on the effect of the SCA on NO_x and soot emissions. As the SCA increased, NO_x emissions decreased, whereas soot emissions increased. On the other hand, changes in nozzle geometry affect the angle of the fuel spray. Tang et al. [20] demonstrated the influence of different nozzle k-factor on the spray angle as a function of time, for fuel injection pressure of 200 MPa and a backpressure of 5 MPa. It should be noted that the k-factor is defined as the ratio of the difference between the inlet and outlet diameters of the nozzle to its length [20]. Their study showed that for all tested nozzles, the fuel spray angle decreased rapidly within the first 0.1 ms, corresponding to the initial phase of injection. After approximately 0.2 ms, the spray cone angle stabilized. This spray behavior is characteristic of high injection pressures. Moreover, it was found that an increase in the k-factor results in a linear increase in the average fuel spray angle. Therefore, the ability to predict the structure of the injected fuel based on injection conditions and fuel type becomes important.

The values of fuel spray parameters are typically determined using models that combine physical principles with empirical relationships derived from experimental data [12]. These models typically consider the type of fuel, nozzle outlet diameter, and injection and ambient conditions. As a result, they are well correlated with the specific conditions under which they were developed. Therefore, applying these models to different conditions – such as alternative fuel types or other nozzle geometries – may not be valid under different conditions.

STP models account for the temporal and spatial variability of the fuel spray as it propagates into the cylinder. The SCA of the atomized spray is typically described as a constant value of a fully developed fuel spray, which remains unchanged over time [1, 4, 9]. From a general perspective, the mathematical models of SCA described in the literature include fuel and gas density in the cylinder, as well as the geometrical parameters of the fuel spray injector.

This is due to the fact that at high fuel injection pressures, the spray cone angle reaches a steady value very quickly after the start of injection, as observed in the test results described by [16, 20]. In [12], Kegl et al. proposed a model to calculate the spray angle of mineral diesel and rapeseed oil biodiesel. In developing the spray cone angle model, the authors considered the change of this parameter over time. It should be noted that the injection pressure was 17 MPa.

Marine diesel engines feature cylinders of much larger size than those used in automotive applications [17]. As such, effective combustion requires that the correct amount of fuel be delivered and atomized in the whole chamber volume. To maximize combustion efficiency, the fuel must be evenly distributed throughout the large combustion chamber. A high-viscosity spray injected into the marine diesel engine cylinder undergoes both primary and secondary break-ups influenced by chamber backpressure, nozzle geometry, and initial spray velocity. Due to the large scale of the marine diesel engine spray, changes in the SCA during the early stage of fuel spray development may be considerable.

In marine diesel engines with autoignition, the combustion process initiates with the injection and subsequent creation of a small portion of an air-fuel mixture capable of autoignition. The fuel injection begins shortly before the piston reaches top dead center (TDC), and the ignition is usually initiated before the entire volume of fuel is introduced. The injection continues during the initiated combustion process, significantly influencing the further characteristics of late-stage combustion and emissions. Consequently, analyzing the early development and radial expansion of the fuel spray during the initial stages of injection is crucial for creating an air-fuel mixture capable of autoignition.

The purpose of this study is to develop a new mathematical model that describes changes in the SCA of a marine diesel engine fuel injector as a function of time. To achieve this, high-speed imaging was employed in a series of experimental tests.

2. Experimental setup

The experimental setup consisted of three main modules [5–7]:

- a constant-volume chamber
- a visualization system based on a high-speed camera and global illumination to record the Mie scattering signal
- a pressure fuel supply system for the injector.

The test constant-volume chamber was cubic in shape and provided optical access from two sides. It is worth noting that the constant-volume chamber system is a fundamental piece of experimental research equipment in studies on fuel atomization and combustion. The marine diesel fuel injector was mounted on top of the chamber and tilted in relation to the chamber axis to increase the spray observation distance. The main design parameters of the chamber are presented in Table 1 and in [5]. The record propagation of fuel spray was carried out through one of the chamber's viewing windows, while the remaining three were covered to minimize light reflections.

Table 1. The main design parameters of the constant-volume chamber [5]

Parameter	Unit	Value
Length/width	mm	200 × 200
Diameter of the viewing window	mm	100
Number of access windows	–	4
Maximum backpressures	MPa	5

The parameters and methodology were included earlier in [5–7]. The chamber was filled with inert nitrogen gas during the tests. The tests were conducted at ambient temperature. Two levels of backpressure conditions were considered (p_B): 3.2 MPa and 4.3 MPa. A marine diesel fuel injector was used for the four-stroke marine diesel engine. An investigation was conducted on three different nozzle outlet diameters: 0.285 mm, 0.325 mm, and 0.375 mm, corresponding to L/D ratios of 10.9, 9.5, and 8.3, respectively. All the nozzle holes had a cylindrical shape. The spray analysis was performed using a single active nozzle hole, while the other holes were plugged. A commercial diesel fuel was used in the study and measured before the tests. The density was 816.1 kg/m³ (at 40°C) and the viscosity was 2.35 mPa·s. The injector's opening duration was 40 ms, and was calibrated to open at three different pressures (p_o): 15 MPa, 25 MPa, and 35 MPa.

To visualize the spray evolution inside the constant-volume chamber, image acquisition was performed using a high-speed camera (Photron SA1.1), operating at 15,000 frames per second. Two 250 W halogen lamps were used to illuminate the chamber. Sample images obtained during the experiment are shown in Fig. 1. The marine fuel injector was supplied with fuel by a high-pressure common-rail system, which maintained a pressure of approximately 50 MPa upstream of the injector. The system featured a specialized solenoid valve with a short opening time of 10 ms mounted before the fuel injector. Fuel pressure was measured using a piezoresistive pressure sensor (Kistler 4067E) [13]. Each test was repeated three times to eliminate gross errors and to confirm the correctness of the measurement method. The macrostructures of the diesel spray were analyzed using DaVis 8.4 software from the recorded images.

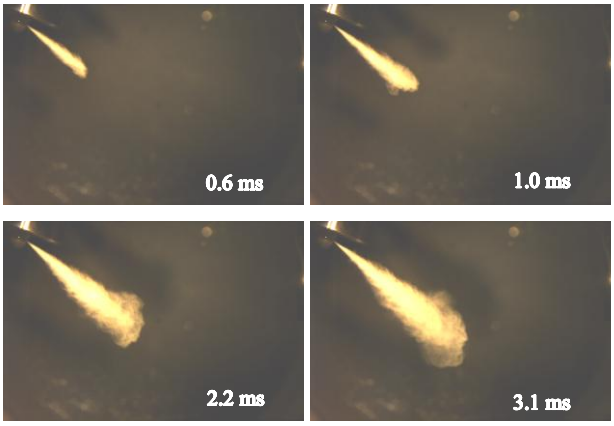

Fig. 1. The example raw images of diesel fuel spray captured at different times after start of injection, L/D: 10.9, p_o: 15 MPa, p_B: 4.3 MPa

3. Results and discussion

One of the macro parameters of the diesel spray from a marine diesel engine injector is the spray cone angle (SCA). It should be noted that SCA (together with STP) is a parameter that provides information about the volume (assuming axial symmetry of the spray) occupied by the atomised fuel within the cylinder space. The top of the cone is located at the injector nozzle outlet, while its base corresponds to the leading edge part of the spray front. The SCA of the diesel fuel spray is defined as the apex angle whose arms mark the outer boundary of the spray. The definition of SCA is illustrated in Fig. 2.

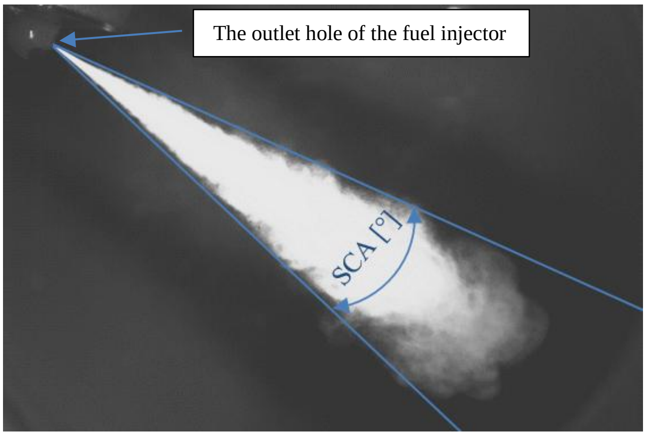

Fig. 2. The definition of SCA

In the experimental tests, the injection and atomization of diesel fuel from an injector into a constant-volume chamber were recorded. The propagation of the fuel spray was recorded from the start of injection until the end of the process. Fig. 3 presents sample results of SCA measurements from three repetitions. Significant differences in the shape of the recorded fuel spray were observed between 0 and 0.134 ms. As a result, the large discrepancy in spray cone angle values during this period made the analysis unreliable. Therefore, the first three measurements were excluded from further analysis of the early stage of the fuel spray development.

According to the results in Fig. 3, the SCA of the diesel fuel spray increases over time. From the start of injection, the spray penetrates the chamber at a high initial velocity, driven by the pressure differential between the injection pressure and the chamber's backpressure gas. The greater this pressure difference, the more kinetic energy is imparted to the fuel. As the spray continues to propagate, it undergoes secondary break-up, leading to a widening of the spray cone angle. This growth continues up to approximately 1.2 ms, after which the cone angle stabilizes. The duration of this development phase depends on the specific injection conditions.

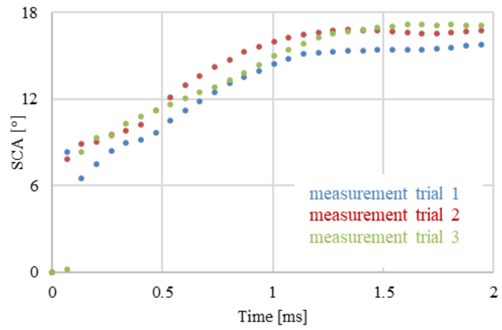

Fig. 3. The spray cone angle for L/D: 10.9, p_o: 15 MPa, p_B: 3.2 MPa

Figures 4, 5, and 6 present the arithmetic mean of the SCA over time for different L/D ratios, opening pressures (p_o), and backpressures in the constant-volume chamber (p_B). It should be noted that the analysis of the SCA characteristic was conducted [7], but only for a single backpressure condition in a constant-volume chamber. The average was calculated from three experimental trials for each injection condition. The error bars for each point represent the maximum and minimum spray cone angle values relative to the mean for that case.

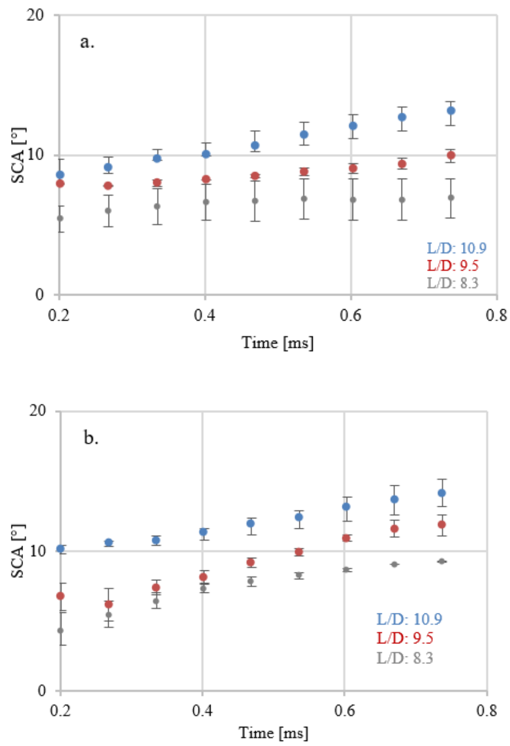

Fig. 4. The selection example of SCA results depending on L/D for p_o: 15 MPa, p_B: a) 3.2 MPa b) 4.3 MPa

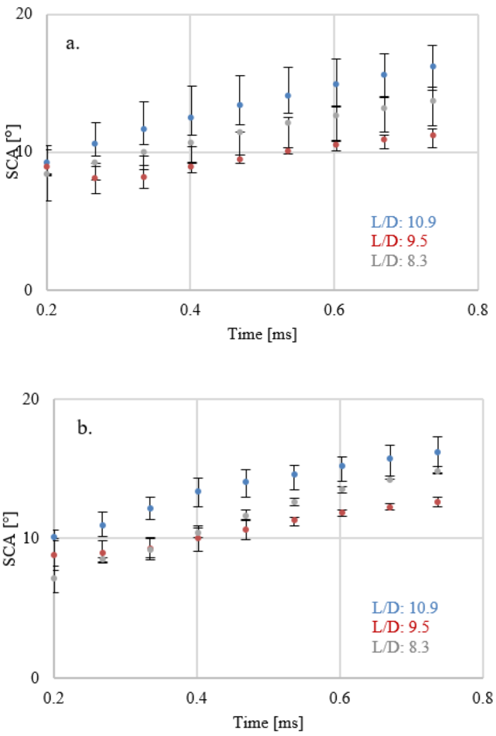

Fig. 5. The selection example of SCA results depending on L/D for p_o: 25 MPa, p_B: a) 3.2 MPa b) 4.3 MPa

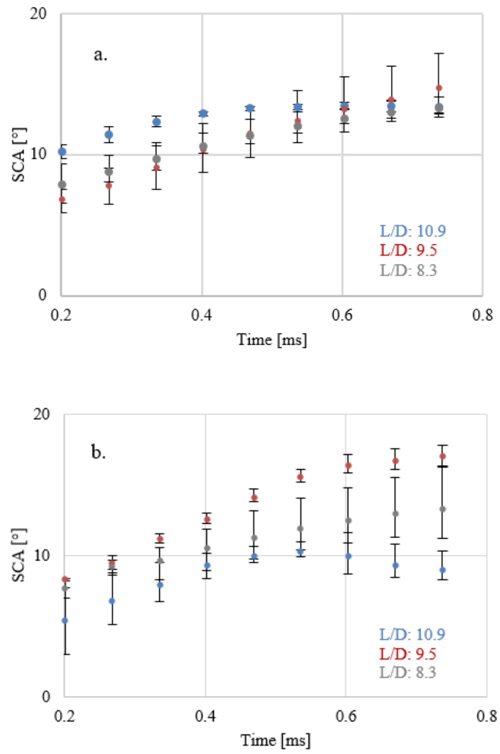

Fig. 6. The selection example of SCA results depending on L/D for p_o: 35 MPa, p_B: a) 3.2 MPa b) 4.3 MPa

First, the influence of marine diesel injector geometry on the SCA of injected diesel fuel during the initial phase of injection was analyzed. According to the results presented in Figs. 4–6, an increase in the L/D ratio of the fuel injector resulted in an increase in the spray cone angle. The largest value of spray cone angles was recorded for the L/D ratio of 10.9 in most observed cases. Decreasing the L/D ratio, which implies an increase in the outlet hole diameter, resulted in smaller spray cone angles, due to changes in flow conditions within the nozzle. A change in the geometry of the injector nozzle orifice (i.e., a change in the L/D ratio) affects the initial spray behavior because the mass flow rate is altered [15]. Moreover, it influences the possibility of decay or development of turbulence and cavitation in the flow along the nozzle [2].

For an opening pressure of 35 MPa and backpressure 4.3 MPa, the decrease in cone angle was observed for L/D = 10.9, as shown in Fig. 6b. This pressure combination created highly favorable conditions for fuel jet break-up. Droplets at the spray boundaries likely evaporated, and smaller droplets were more rapidly decelerated by the increased chamber backpressure. The presented results confirm the influence of the outlet hole geometry on the initial spray structure.

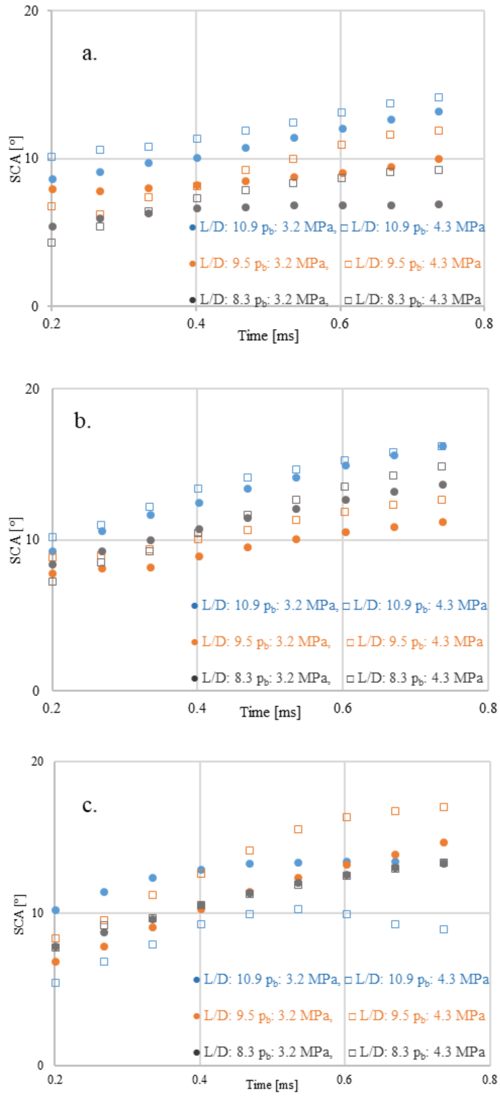

Fig. 7. The SCA results depending on L/D and p_b for : p_o: a) 15 MPa, b) 25 MPa, c) 35 MPa

Based on the experimental results presented in Fig. 7, it can be concluded that an increase in aerodynamic resistance in the constant-volume chamber has a significant influence on the propagation of the injected fuel. In this work, and partly in previous works [5–7] on the atomization process of diesel oil from a marine engine injector, the effect of backpressure in a constant-volume chamber on macro parameters was analyzed. Figure 7 presents the experimental results of SCA, considering all factors, including L/D ratio, opening pressures, and backpressures (3.2 MPa and 4.3 MPa). According to the presented experimental results, the area occupied by the injected and atomized diesel spray increases with the increase of the gas pressure in the constant-volume chamber. This is a typical trend in the formation of fuel spray geometry when the gas density in the constant-volume chamber is increased [5–7, 19]. This behavior of fuel spray is consistent with the predictions of the general atomization theory for high-pressure fuel injectors.

A higher gas density leads to the more rapid dissipation of the initial axial spray energy, promoting radial dispersion and disintegration of droplets, thereby increasing the spray cone angle. Furthermore, a decrease in spray velocity is observed, which is attributed to the increased aerodynamic forces in the constant-volume chamber at a backpressure of 4.3 MPa compared to a backpressure of 3.2 MPa. Furthermore, increasing the opening pressure also contributes to greater SCA values, as evidenced in Fig. 7. As part of earlier analyses of selected data, the velocity of the fuel spray in the initial stage was investigated [5].

3.1. Model of spray cone angle

Based on the analysis of the experimental results, presented in the previous section, it was noticed that the SCA changes over time during the initial phase of injection. In addition, the value of this SCA will be influenced by the changing diameters of the outlet holes, the backpressures in the constant-volume chamber, and the injector opening pressure. This became the basis for developing a mathematical model to predict the temporal variation of the spray cone angle of a diesel spray from a marine engine injector during the initial stage of injection.

The mathematical model of SCA was constructed using a general modeling approach based on the collected experimental data. First, the modeling problem was formulated, and simplifying assumptions were defined. The goal was to develop a time-dependent mathematical model of the SCA evolution during the early stage of fuel injection. The following assumptions were made: constant fuel density and viscosity, and constant test temperature. In the next step, the model variables were defined as: L/D ratio, backpressure (p_B), and opening pressure (p_o). Based on the analysis of the experimental results, the general form of the model was identified as nonlinear with a logarithmic character. A preliminary analysis of the approximation of results to the selected mathematical function was presented in earlier work [7]. Therefore, logarithmic approximation was applied. The final form of the model was adopted as Equation (1):

$$\mathrm{SCA} = \mathrm{A} \cdot \ln\left[1 + (\mathrm{L/D})^{\mathrm{C}} \cdot \mathrm{p_o^B} \cdot \mathrm{p_B^D} \cdot \mathrm{t}\right] \quad (1)$$

Parameters A, B, C, and D are coefficients adjusted to fit the function to the experimental results.

Table 2 presents the standard errors and 95% confidence intervals. It can be observed that the estimated model parameters A, B, C, and D fall within these intervals. To construct the nonlinear time-dependent mathematical model of SCA, an optimization function was used to minimize the coefficient of determination (R^2). The *NonLinearModelFit* function from Mathematica software was applied [24]. The coefficient of determination R^2 for the time-dependent SCA model during the early stage of fuel spray was 0.987. To validate the model, the computed results were compared with the experimental data.

Table 2. The parameters of the mathematical model

Parameter	Determined value of parameter	Standard error	Confidence interval 95%
A	4.94	0.23	4.49–5.38
B	0.87	0.04	0.80–0.95
C	2.75	0.07	2.60–2.89
D	0.70	0.09	0.52–0.88

As shown by the results, the model-predicted SCA values (derived from Eq. (1)) are in close agreement with the experimental values. The mean relative errors between the experimental and modeled SCA results range from 5.1% to 16.6%. The example results from the computations were compared with the experimental data (Fig. 8).

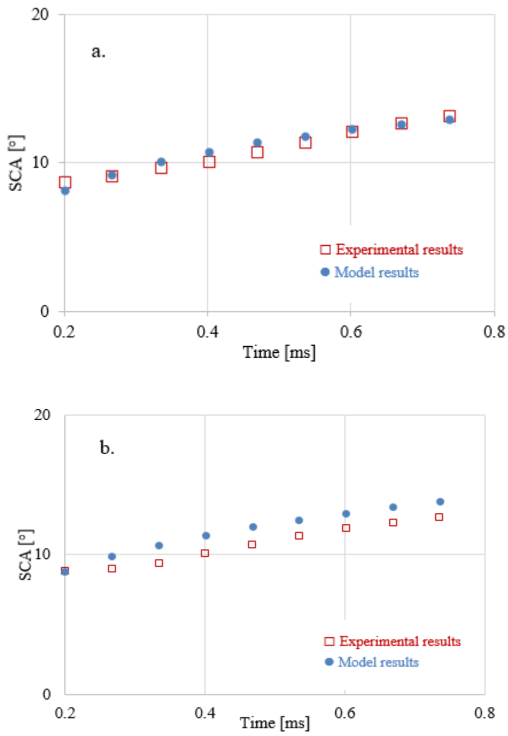

Fig. 8. Example results from the computations were compared with the experimental data: a) L/D: 10.9, p_o: 15 MPa, p_B: 3.2 MPa, b) L/D: 9.5, p_o: 25 MPa, p_B: 4.3 MPa

4. Conclusions

This article presents the results of experimental investigations of the diesel fuel spray formation by a marine diesel engine injector. The focus was on the early stage of spray development, as it is a crucial period for the initial air-fuel mixture formation and its spontaneous autoignition. The primary considerations concerned the influence of various nozzle orifices, backpressures in the constant-volume chamber, and opening pressures of the marine diesel fuel injector on the behavior of the spray cone angle (SCA) of diesel fuel spray. Based on these results, the following conclusions can be drawn:

- The SCA for diesel fuel injection from a marine diesel engine injector changes over time in the early stage of spray formation in a repeatable manner, which correlates with the nozzle dimensions and injection conditions
- Increasing the L/D ratio of the injector nozzle orifice leads to an increase in SCA
- Increasing the gas density in the constant-volume chamber results in an increase in the SCA.

The final outcome of this study is a formulated mathematical model for calculating the time-varying SCA for a marine injector during the early spray stage of diesel fuel injection. The model accounts for the L/D ratio of the injector orifice, variations in fuel pressure during injection, and changes in backpressure in the constant-volume chamber. Therefore, the presented mathematical model of SCA can be used for a rough estimation of the SCA when one of these parameters changes. The data generated by the model can be used as an input for 3D computational fluid dynamics (CFD) modeling of injection and atomization processes for the considered marine injector. It should be noted that this model was formulated based on specific values of experimental parameters; therefore, it shouldn't be applied outside the considered ranges of those parameters without prior validation.

The results presented in this article were obtained as part of doctoral research work.

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Nomenclature

CFD computational fluid dynamics
CI compression ignition
SCA spray cone angle
STP spray tip penetration
TDC top dead center

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