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Evaluation of the Liquid Fuel Spray Parameters Based on Experimental Research and Numerical Simulation for the Piezoelectric Injectors

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Abstract

The paper presents an attempt to apply a simulation method in the investigations into liquid fuel atomization generated from piezoelectric gasoline injectors used in modern high-pressure injection systems. Individual stages of the simulation research have been discussed and an experimental verification of the method has been carried out. The results of the simulation and experimental research of the injection of liquid fuel have been presented in the form of influence of air backpressure on the fuel spray atomization and fuel propagation.

Keywords: fuel injection, simulation method, optical research

1. Introduction

Simulation based methods related to engine processes are a very important tool that determines the development of this field of technology. Their application to a large extent allows a reduction and optimization of the research process. Currently, there are many software applications that simulate the in-engine processes [9] used in the investigations of the liquid fuel injection and combustion processes [2, 5, 6].

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One of these is a software package – FIRE by AVL. It allows solving problems related to the modelling of chemical and physical processes occurring in combustion engines. This package contains an ESET simulating the processes of injection and atomization of liquid fuels [1].

The parameters of the injected fuel spray are very important in the aspect of combustible mixture formation, particularly in the case of gasoline piezoelectric injectors. Their main advantage is the ability to generate multiple fuel doses in relatively short dwell times. Piezoelectric injectors are applied in gasoline direct injection systems of the second generation in HPI (High Precision Injection) in the BMW engines [7, 8].

The research problem consisted in applying an optical method of observation and digital analysis of the obtained images of the fuel spray development and its simulation in order to determine the comparative indexes based on which the authors could carry out an objective evaluation of the course of the fuel injection and atomization processes. A particularly important issue was the explanation of how the basic parameters of the gasoline injection (injection pressure, injection duration) influence the changes of selected comparative indexes determinable for a spray of injected fuel. The authors also aimed at collecting appropriate research material that would serve to determine the functional relations among the said parameters and the values of the comparative indexes [11, 12, 13]. Digital simulation allows forecasting the processes of injection and atomization of fuel.

2. The Basics of the Calculation Method

The investigations into fuel atomization cover multiphase phenomena and require a simultaneous numerical solving of equations for the liquid and gaseous phases. In most cases the calculations related to the liquid atomization are based on the method referred to as Discrete Droplet Method [1, 4]. This method solves differential equations of distance (trajectory), momentum, heat and mass of individual fuel droplets.

A force acting on a fuel particle equals:

$$m_d \frac{du_{id}}{dt} = F_{idr} + F_{ig} + F_{ip} + F_{ib} \tag{1}$$

where: m_d – mass of the fuel particle, u_{id} – velocity vector of the fuel particle, F_{ig} – force covering gravity and buoyancy – formula (6), F_{ip} – force of pressure, given in form (7), F_{ib} – other external forces (electrostatic and magnetic forces), F_{idr} – motion resistance determined as:

$$F_{idr} = D_p \cdot u_{irel} \tag{2}$$

where D_p – is a function of aerodynamic resistance defined as:

$$D_p = \frac{1}{2}\rho_g A_d C_d \left|u_{rel}\right| \tag{3}$$

where C_d – drag coefficient, being the function of Reynolds number Re_d and the cross section area of particle A_d.

In the FIRE software for the determining of the drag coefficient for an individual sphere Schiller-Naumann formula was applied [1]:

$$\begin{cases} \frac{24}{Re_d}(1 + 0,15Re_d^{0,687}) & Re_d < 10^3 \\ 0,44 & Re_d \geqslant 10^3 \end{cases} \tag{4}$$

The Reynolds number was presented with the consideration of liquid viscosity μ_g:

$$Re_d = \frac{\rho_g \left|u_{rel}\right| D_d}{\mu_g} \tag{5}$$

where ρ_g – gas density.

F_{ig} is a force covering the influence of gravity and buoyancy:

$$F_{ig} = V_p \cdot (\rho_p - \rho_g) \cdot g_i \tag{6}$$

where ρ_p – particle density, g_i – apparent gravity, V_p – particle volume.

F_{ip} is a force of pressure given in the form:

$$F_{ip} = V_p \cdot \nabla_p \tag{7}$$

Quantity F_{ib} contains other external forces (electrostatic and magnetic forces). Putting relations (2)-(7) into equation (1) and dividing it by the mass of particles m_d we obtain a formula for the acceleration of a particle:

$$\frac{du_{id}}{dt} = \frac{3}{4}C_D\frac{\rho_g}{\rho_d}\frac{1}{D_d}\left|u_g - u_d\right|\left(u_{ig} - u_{id}\right) + \left(1 - \frac{\rho_g}{\rho_d}\right)g_i \tag{8}$$

that after integration allows determining of the particle velocity:

$$\frac{dx_{id}}{dt} = u_{id} \tag{9}$$

where x_{id} – vector of particle location.

For the determination of the droplet disintegration a half-empirical model was used (sheet model) in order to determine the initial conditions of the spray (thickness, velocities and duration of the droplet disintegration – Fig. 1).

For the simulation the following input data are needed: number of fuel doses, external and internal diameter of the injector hole, properties of the injected liquid, external and internal angle of the fuel spray cone and difference of injection pressures. Thickness of the spray h is calculated based on:

$$h = \left[\frac{A \cdot 12 \cdot \dot{m}_l \cdot \mu_l}{\pi \cdot \rho_l \cdot d_{out} \Delta p} \cdot \frac{(1 + X)}{(1 - X)^2}\right]^{0,5} \tag{10}$$

$$X = \frac{(d_{out} - 2 \cdot h)^2}{d_{out}^2} \tag{11}$$

where h [m] – spray thickness, X [-] – the ratio of the air cone to the total area, d_{out} [m] – external hole diameter, m_l [kg/s] – fuel flow rate, μ_l [kg/(ms)] – dynamic viscosity of the liquid, ρ_l [kg/m^3] – liquid density, Δp [Pa] – difference of pressures, A [-] – constant, A = 400, θ [deg] – half of the angle of the external cone.

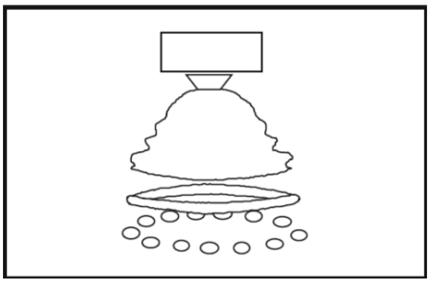


Fig. 1. Stages of the fuel spray disintegration

The length of the liquid disintegration is obtained from the Clark and Dombrowski equations [1]:

$$B_L = B \cdot \left[\frac{\rho_l \cdot \sigma \cdot \ln(\eta/\eta_0) \cdot h \cdot \cos\theta}{\rho_g^2 \cdot v_{rel}^2}\right]^{0,5} \tag{12}$$

where $\ln(\eta/\eta_0)$ [-] – parameters determined experimentally, $\ln(\eta/\eta_0) = 12$, v_{rel} [m/s] – relative velocity between the liquid and the gas, ρ_g [kg/m^3] – gas density, σ [N/m] – surface tension, B [-] – constant, standard B = 3.

The above equations were used for the simulation of the liquid fuel atomization with the use of piezoelectric gasoline injectors. The results of the simulation of the fuel atomization have been shown in Fig. 2. The simulation tests were carried out for a piezoelectric outward-opening injector used in the second generation direct injection systems.

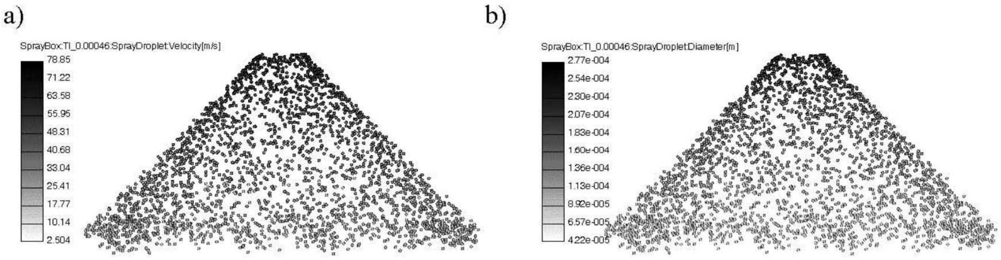


Fig. 2. Simulation results of the fuel spray development: a) droplet velocity, b) droplet diameter (P_{inj} = 20 MPa; t_{inj} = 0.5 ms; for time t = 0,46 ms after the onset of the injection)

3. Research Methodology

For the verification of the simulation tests a test stand has been used (Fig. 3) composed from a high pressure gasoline injection system with a high pressure pump and a feed pump. Piezoelectric gasoline injector was placed in the measurement chamber with adjustable air pressure within the range of 0-4.0 MPa. The location of the injector allows observation of the fuel spray atomization cone. More detail about test stand one can find in the paper [10].

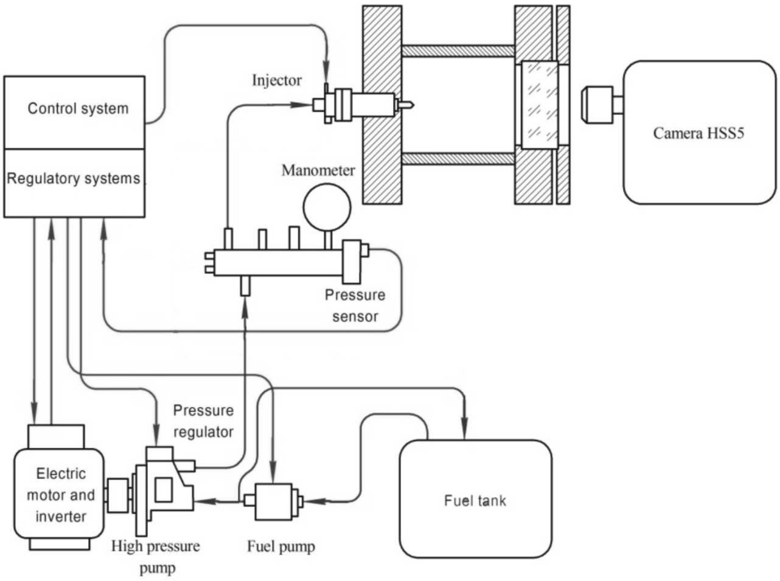


Fig. 3. Fuel atomization tests stand

The high-speed camera High Speed Star 5 by LaVision used for the tests (up to 250 000 frames/s) was fitted with a monochromatic CMOS image converter. The recording speed was limited to 10 000 frames per second (time resolution 100 us) in order to obtain the image resolution of 512×512 pixels (pixel size 17×17 um). The spectral range of the recording was 380-800 nm.

A computer device (sequencer) controlled the operation of the system that generates various signals to the actuators. It allows activation of the operation of the individual elements of the test system: opening of the inlet and outlet of the air supply, adjusting the injector and generating an electric impulse to initiate the recording process.

The tests were performed for two pressures of the injected fuel 5 and 20 MPa (Table 1). These values were selected as the boundary ones occurring in modern injection systems. They however set a new stage in the development of these systems. The tests were performed for a variant that allowed linear-range recording – perpendicular injector position against the axis of the camera (Fig. 4).

Table 1

The test parameters of the fuel injection into a chamber with backpressure

No	P_{inj} [MPa]	P_{air} [MPa]	t_{air} [^oC]	t_{fuel} [^oC]	P_{inj}- P_{air}- t_{air}- t_{fuel}
1	5	0.5	20	20	HPI-50-5-20-20
2		1.5			HPI-50-15-20-20
3	20	0.5			HPI -200-5-20-20
4		1.5			HPI -200-15-20-20

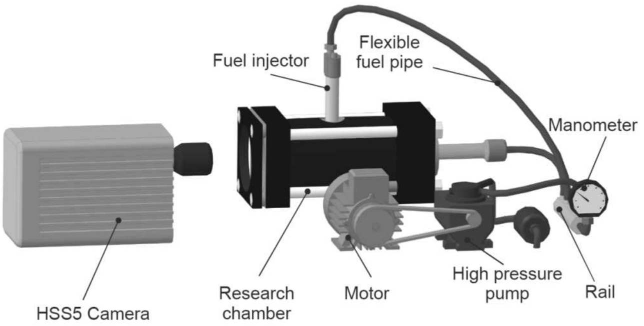


Fig. 4. The location of the injector and the recording of the fuel spray in the chamber

The analysis of the fuel spray penetration, its atomization and velocity was developed with the use of the DaVis software by LaVision. The authors also used software of own design based on the Command Language CL [3]. The methodology of this kind of research has been already described by authors in the papers [11, 12, 13].

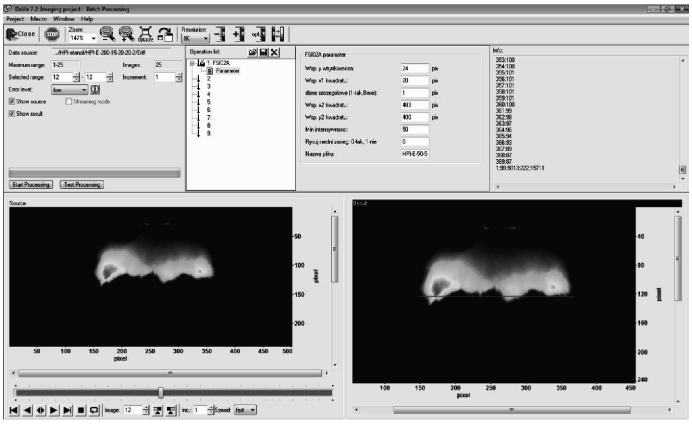
The linear spray penetration was determined according to the following algorithm (Fig. 5):

a) the initial point of the fuel outflow from the injector was determined in the coordinates of X and Y;

b) the values of the fuel spray penetration were determined for an individual image analyzing the width of the fuel spray of the injected fuel based on its luminance;

c) the value of the average fuel spray penetration of the injected fuel was determined;

d) including the time between the subsequent images the values of the velocities of the front of the fuel spray of the injected fuel were determined.



Zoom: 147%
Resolution: 1K

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Maximum range: 1-25
Images: 25
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FSI02A parameter
Wsp. y wtryskiwacza: 24 pix
Wsp. x1 kwadratu: 20 pix
dane szczegolowe (1-tak,0-nie): 1 pix
Wsp. x2 kwadratu: 483 pix
Wsp. y2 kwadratu: 400 pix
Min intensywnosci: 50
Rysuj sredni zasieg: 0-tak, 1-nie 0
Nazwa pliku: HPI-E-50-5-

Info:

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353;100
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365;94
366;93
367;89
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1;99.9013;222;15711
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Image: 12
Inc.: 1
Speed: fast

Fig. 5. The determining of the linear spray penetration with the DaVis software

The linear fuel spray penetration was determined as the distance of the fuel spray from the point of its outflow from the injector, related to the average values from the individual distances of the fuel spray within one image. Linear fuel spray penetration denotes a perpendicular setting of the camera axis to the axis of the injector.

The velocity of the fuel spray was determined as an average fuel spray penetration related to the duration of the fuel injection. From the geometry of the injector we know, that the spray angle amounts to 90°. Taking into account the fact that the analyzed image is flat, the actual value of the spray front velocity was obtained from the fuel spray penetration extended by the value resulting from the geometrical relations (Fig. 6).

4. Investigations of the Influence of the Backpressure on the Fuel Spray Penetration

Figure 7 shows the recorded fuel spray penetration and the simulation of the fuel injection for the pressure of 5 MPa and for the backpressure of 0.5 MPa and time 0.5 ms from the onset of the injection. Thus calculated values of the velocities have been presented in Fig. 8. The increase in the backpressure causes a significant

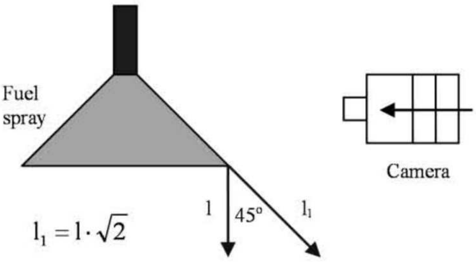


Fig. 6. Geometrical analysis of the fuel spray and the determining of the actual velocities of the injected fuel spray front

reduction in the fuel spray velocity. After 0.2 ms a clear reduction of the fuel spray velocity takes place. After the end of the injection the changes are imperceptible.

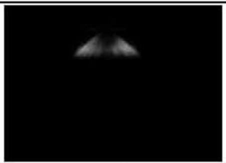
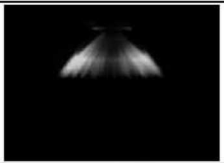
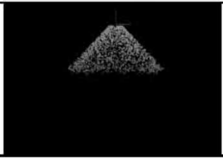
	Fuel pressure P_{fuel} = 5 MPa, air pressure P_{air} = 0.5 MPa		
Time [us]	100	300	500
Tests			
Simulation			

Fig. 7. Images of the fuel penetration during high-pressure gasoline injection to the chamber with a backpressure and the simulation of the injection (t_{inj} = 500 us)

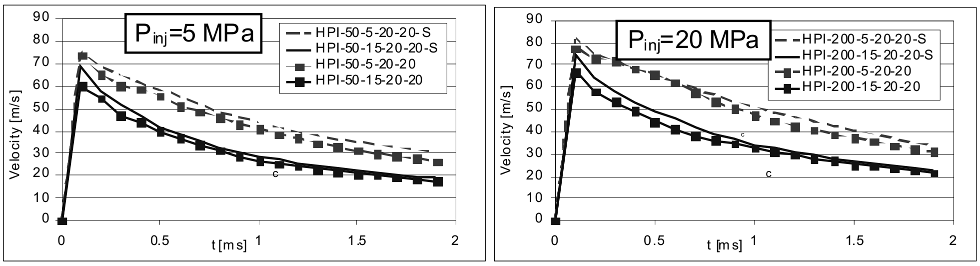


Fig. 8. Comparison of the results of the simulation (— lines) and the test stand investigations (-■- lines) related to the influence of the backpressure and fuel injection pressure on the velocity of the front of the fuel spray (P_{inj} = 5; 20 MPa; t_{inj} = 500 us; backpressure P_{air} = 0,5; 1,5 MPa)

5. Simulation Model Appropriateness Assessment

In the analyzed investigations the authors obtained a high level of compatibility of the simulation results with the actual values of velocity of the fuel spray. The discrepancies are the highest in the initial phase of the injection, which could result from the inaccuracy of the optical methods of determining of the beginning of the fuel spray and its penetration.

A detailed analysis of the fuel spray penetration has been presented below. A growth of the backpressure (Fig. 9) clearly reduces the penetration of the fuel spray. The coding of the courses is as shown in Table 1. The nature of the changes of the fuel spray penetration when injected under the pressure of P_{inj} = 20 MPa does not change in comparison to the injection at the pressure of P_{inj} = 5 MPa. The values of spray penetration are different though. The maximum measured values of the spray penetration at the pressure of 5 MPa and the backpressure of 0.5 MPa are 50.2 mm and at the pressure of P_{inj} = 20 MPa and the same backpressure are 58.7 mm. At the injection pressure of 20 MPa a growth in the backpressure from 0.5 to 1.5 MPa results in a reduction of the spray penetration by 30%. The maximum changes amount to 33% at the injection pressure of 5 MPa and the backpressure growth from 0.5 to 1.5 MPa.

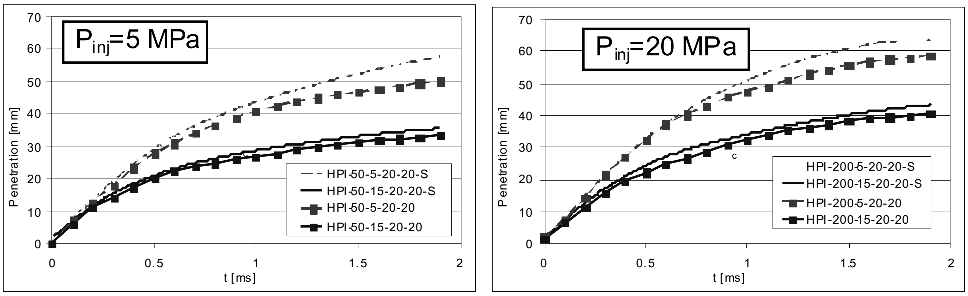


Fig. 9. Comparison of the simulation results (— lines) and test bed results (-■- lines) of the influence of the air backpressure on the injected fuel spray penetration (P_{inj} = 5; 20 MPa; t_{inj} = 500 us; backpressure P_{air} = 0.5; 1.5 MPa)

The fuel spray penetration calculated during the simulation is bigger. It results from the fact that the observation of the droplets of small diameter is complicated and not always recorded with the optical methods. The maximum difference between the simulation results and the fuel spray penetration tests amount to approximately 12% (for P_{inj} = 5 MPa and backpressure 0.5 MPa, for time t_1 = 1.9 ms from the onset of the injection). A growth in the injection pressure and the backpressure results in a reduction of the difference between the results of the simulation and the tests. During the first phase of the injection (approximately from time 0.7 ms) we do not observe significant differences in the fuel spray penetration in the simulation and the actual tests. After this time changes occur in the obtained penetration levels of the fuel spray. The lower the air backpressure the higher the said changes.

6. Conclusions

Based on the conducted test and simulations of the fuel spray the authors have observed as follows:

1. The simulation allows a detailed determination of the parameters of the fuel spray provided the input parameters of the fuel spray and the geometry of the injector were taken into account.

2. The fuel spray penetration calculated during the simulation is bigger. It results from the fact that the observation of the droplets of small diameter is complicated and not always recorded with the optical methods.

3. During the first phase of the injection (approximately from time 0.7 ms) we do not observe significant differences in the fuel spray penetration in the simulation and the actual tests. After this time changes occur in the obtained penetration levels of the fuel spray. The lower the air backpressure the higher the said changes.

4. Air backpressure is much more impactfull on the fuel spray penetration than the fuel injection pressure.

5. The maximum values of the velocity of the fuel spray front were determined in the initial phase of the injection and amounted to approximately 80 m/s. As the backpressure grew by 1 MPa the maximum values of the said velocity reduced by approximately 15%. Higher injection pressures result in changes in the maximum spray front velocity by 6%. After 0.2 ms from the onset of the injection, a clear reduction of the fuel spray front velocity takes place.

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