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MODELING OF GASOLINE FUEL SPRAY PENETRATION IN SIDI ENGINES

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ABSTRACT−The paper presents a research on the fuel injection and atomization depending on the thermodynamic quantities inside the cylinder of a combustion engine. With the use of piezoelectric outward-opening injectors the changes in the geometrical quantities of the atomized fuel in the aspect of its injection were determined. The studies concerning the influence of the individual quantities on the fuel spray penetration injected by the outward-opening injectors comprise a synthesis of the injection and atomization tests. Own mathematical equation describing the fuel spray penetration was proposed. The exponents (equation coefficients) related to the influence of the fuel pressure, air backpressure, charge density and time of fuel spray development were determined with the coefficient of determination 0.9797, indicating a congruence of the experimental data with the values obtained on the basis of the mathematical equation.

KEY WORDS : Fuel injection, Fuel atomization, Fuel spray penetration modeling

1. INTRODUCTION

In spray-guided mixture formation systems as a result of proximity of the injector and the spark plug, kinetic and geometric interactions between the fuel spray (or fuel sprays in split injection) and the mixture ignition occur. Hence, recognizing the fuel spray parameters, and in particular its penetration in the time up to 5.0 ms after the start of injection, is a key issue allowing to interpret fuel atomization during fuel injection.

In spray-guided charge formation systems a reduction of the fuel consumption and exhaust emissions is possible through an extension of the engine working space with charge stratification (Schwarz *et al*., 2006; Van Basshuysen, 2009). VanDerWege *et al*. (2003) indicated the possibility of obtaining a stratified charge at high loads (effective pressure above 0.5 MPa and engine speed above 4000 rpm) through application of split injections. He also indicated an improvement in the quality of the homogenous mixture obtained under high engine loads through the use of a wide spray cone angle of the injected fuel with an injector centrally located in the combustion chamber. In the spray-guided system the losses during the combustion and heat release are smaller, which gives chances for further reduction of fuel consumption.

The formation of a combustible mixture starts with the introduction of air into the cylinder working space and subsequently injection and atomization of the fuel. For the above reason, the quantities that decide about this process are:

- Air movement inside the cylinder,
- Conditions of the fuel injection, fuel disintegration and evaporation,
- Concentration of the reactants of the process.

The investigations performed by Befrui *et al*. (2002) indicate that the ambient pressure and variable thermodynamic parameters of air have a partial impact on the structure of the fuel spray cone (Figure 1).

Beard (according to Martin *et al*., 2010) confirmed that the control of the injection and atomization of fuel as well as air movement near the spark plug are important issues in the study of physical phenomena accompanying direct gasoline injection.

The necessary elements ensuring the flammability of the mixture near the boundary between the fuel spray and the air are: proper air movement, repeatable geometric parameters of the fuel spray and precise control of its injection. Schwarz *et al*. (2007) indicated existence of a certain fuel spray cone that is independent of the combustion chamber and does not depend on the charge movement.

The above-mentioned investigations indicate a certain regularity of the air influencing the geometry of the spray: in spray-guided charge formation systems the geometry of the spray is not changed as a result of variable influence of the air inside the cylinder.

The distribution of the gaseous phase is particularly

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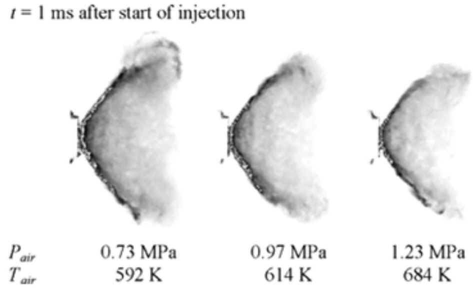

Figure 1. Images of the fuel spray taken with the LIF method showing the engine operating conditions (t_{inj} = 1.5 ms, P_{inj} = 20 MPa, P_{air} – air backpressure; fuel: isooctane) (Befrui *et al*., 2002).

important due to the potential proximity to the spark plug. Such a location of the injector and the spark plug is conducive to quick fuel evaporation and limits the possibility of using the penetration of the vapour for stratification of the charge. Spatial convergence of the liquid and its vapour phases during the whole fuel injection phase allows both, the lean and the stoichiometric mixtures, to be burnt without the necessity of significant change of the ignition angle. As the studies (Itoh *et al*., 2006) show, spray-guided mixture formation allows for the use of injection angle of the smallest advance. Itoh *et al*. (2006) and Fan *et al.* (2012) showed that this type of injection should end at approximately 30-25ºCA before TDC (in the studies multi hole injectors were used, thus the fuel spray penetration was greater than in case of outward opening injectors analyzed in this paper). The ignition takes place approximately 10ºCA after the end of the injection (for the charge formation system using the piston crown, the analogical data is: 40-50ºCA before TDC and 20-30ºCA after the end of the injection). This means that the spray-guided mixture formation allows for a significant stratification of the charge, thus for burning very lean mixtures (λ approximately 4). This is possible in the presented solution utilizing outward opening injectors, as the time between the start of the injection and the ignition is considerably reduced due to directing the fuel spray (the initial lateral surface of the fuel spray cone) onto a spark plug.

Fuel atomization is often tested in a constant volume chamber (Wislocki *et al*., 2011; Skogsberg *et al*., 2007). This allows for reflection of typical conditions of the average engine load when the stratified charge is formed (backpressure approximately 0.6 MPa, fuel temperature 363 K, air temperature 293 K). Skogsberg *et al*. (2007) using the MIE method have shown the directions of movement of the atomized fuel (Figure 2). In the initial phase of the injection the air is pushed out by the atomized fuel. Due to the fact that the relative air density under the resistance forces acting on the atomized fuel is high, a negatively oriented vortex is generated (Figure 2 (a)). As the fuel spray has a shape of a hollow cone, the air taken in

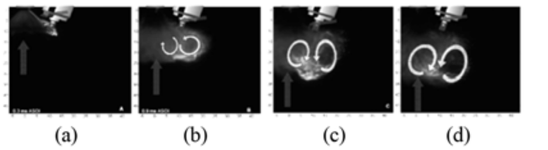

Figure 2. Distribution of the liquid phase in the vicinity of the spark plug during the injection of fuel (images taken using the MIE flat exposure method; t_{inj} = 0.7 ms, m_f = 10 mg) (Skogsberg *et al*., 2007).

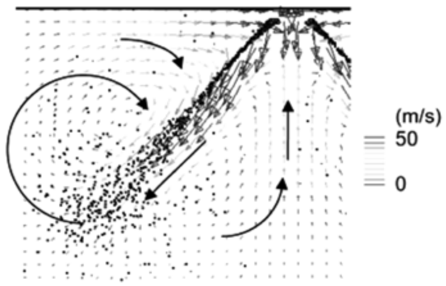

Figure 3. Simulation research of the distribution of the charge and air velocity field during injection into the constant volume chamber (q_{inj} = 35 mg/s, P_{inj} = 20 MPa) (Kim *et al*., 2008).

is drawn upwards (Figure 2 (b)), which was also shown by VanDerWege *et al*. (2003). Next, in combination with the resistance forces, the other vortex is generated. These vortices, depending on the backpressure, partially reduce the penetration of the atomized fuel.

Supplementary to the above studies may be the work of Kim *et al*. (2008) in which the charge swirl velocity was determined during the injection of the fuel spray. The tests were conducted at the injection pressure of 20 MPa (injection to a constant volume chamber). The distribution of the velocity field has been shown in Figure 3. A recirculation zone forms in the lower part of the spray, where the charge swirl plays a dominant role. The air outflowing from the inside of the hollow cone generates an uptake of the charge upwards and outside, toward the injector.

The velocity of the outflow of fuel in the vicinity of the injector needle is approximately 150 m/s (based on own research) and up to 200 m/s (Kim *et al*., 2008) depending on the pressure of the injected fuel and the piston backpressure. The velocity of the moving air leading to the swirling of the atomized fuel spray (end of its cone) is approximately 5-10 m/s as shown in Figure 3.

Currently, most of the empirical models refer to geometrical parameters of the fuel spray generated by diesel fuel injectors. Taking the studies of Hiroyasu and Arai (1990) into account, the fuel spray penetration was determined based on the following dependence:

for $\tau < \tau_{break}$ $$S = 0.39 \cdot \left(\frac{2 \cdot \Delta P}{\rho_f}\right)^{\frac{1}{2}} \cdot \tau \qquad (1)$$

for $\tau > \tau_{break}$ $$S = 2.95 \cdot \left(\frac{\Delta P}{\rho_f}\right)^{\frac{1}{4}} \cdot (d_o \cdot \tau)^{\frac{1}{2}} \qquad (2)$$

where t_{break} denotes time after which a continuous fuel spray disintegrates into droplets, which is:

$$\tau_{break} = \frac{29 \cdot \rho_f \cdot d_o}{(\rho_{back\text{-}press} \cdot \Delta P)^{\frac{1}{2}}} \qquad (3)$$

where: ΔP – pressure difference between the injector and air backpressure [Pa], ρ_f, $\rho_{back\text{-}press}$ – fuel and gas densities [kg/m^3], d_o – injector hole diameter [m], τ – time [s].

The fuel spray penetration given by Dent (1971) is based on the following formula:

$$S = 3.36 \cdot \left(\frac{\Delta P}{\rho_{back\text{-}press}}\right)^{0.25} \cdot (d_o t)^{0.5} \cdot \left(\frac{294}{T_{back\text{-}press}}\right)^{0.25} \qquad (4)$$

where: $T_{back\text{-}press}$ – denotes backpressure air temperature.

There is no extensive research on the empirical formulas of the fuel spray penetration injected by outward opening injectors used in the spray-guided system. Knowing empirical equations of the fuel spray penetration makes it possible to predict of actual penetration on the basis of a few selected parameters. It also enables construction of appropriate combustion chamber. For this reason in the paper the spray penetration was determined on the basis of tests taking into account input data such as: P_{inj}, P_{back}, and t_{inj}.

2. METHODOLOGY OF RESEARCH

The test stand (Figure 4) incorporated a high-pressure gasoline injection system fitted with high-pressure feeding pumps. The piezoelectrically controlled gasoline injector was placed in the closed chamber with a controlled backpressure in the range of 0-4.0 MPa. Positioning of the injector allows for recording of images of the injection from the side (for the analysis of axial fuel spray penetration) and from the bottom of the spray (for the observations of radial spray penetration).

Tests of fuel spray were conducted according to the parameters in Table 1.

In the research a high-speed camera – High Speed Star 5 by LaVision fitted with a CMOS monochromatic image converter has been used. The recording speed was limited

Table 1. Conditions of conducting.

P_{inj} [MPa]	t_{inj} [ms]	P_{back} [MPa]
5	0.5; 0.6	0.5; 1.0; 1.5; 2.0
10	0.5; 0.6	0.5; 1.0; 1.5; 2.0
20	0.5; 0.6	0.5; 1.0; 1.5; 2.0

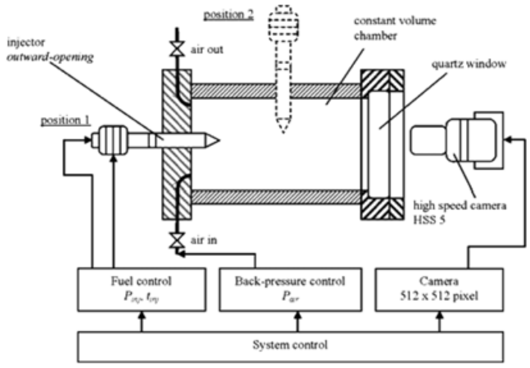

Figure 4. Schematics of the stand measuring the geometrical parameters of the fuel spray position 1: linear penetration, position 2: radial penetration.

to 10000 frames per second (time resolution 0.1 ms) in order to obtain a maximum image resolution of 512 × 512 pixels (diameter 80 mm per 512 pixels; 1 pixel = 0.156 mm). The camera operated in the spectral wavelength of λ = 380-800 nm (luminance from 0 to 1024 counts).

A sequencer – a computer device generating control signals to the actuators (electromagnetic valves) – was used for the system operation control. It facilitated the control of the operation of several elements of the research system such as opening of the supply and exhaust of control air, release of electrical impulse in the injector and completion of the recording process.

The research was conducted for different values of injection pressure: 5, 10 and 20 MPa. These values have been chosen as boundary ones characteristic of the modern injection systems (Drake *et al*., 2010; Bae and Oh, 2012). The measurements were carried out in a closed research chamber with the backpressure in the range of 0.5, 1.5 MPa; in all cases duration of injection was variable (0.5 and 0.6 ms). Image recording was carried out in two ways. The first consisted in positioning of the camera perpendicularly to the injector axis – it allowed the analysis of the axial fuel spray penetration. In the other – the camera was positioned parallel to the injector axis and allowed radial spray penetration analysis (Figure 4).

The analysis of the spray penetration, spray area and changes of the spray velocity was processed on the computer with the use of DaVis program implemented by own software developed on the basis of Command Language CL. The fuel spray penetration was determined according to the algorithm:

(1) the initial position for the fuel outflow from the injector was determined from the X and Y coordinates.
(2) for a single image the fuel spray penetration values were determined resulting from the analysis of the entire width of spray of the injected fuel and based on its luminance.
(3) the velocity of the medium penetration of the fuel dose was determined.

(4) time intervals between taking subsequent images were taken into account and velocities of the penetration of the injected fuel spray front were determined.

3. GASOLINE ATOMIZATION IN HIGH-PRESSURE SYSTEMS

The parameters of atomized liquid spray can be divided into macroparameters (external) and micro-parameters (internal). The basic parameters characterizing the macrostructure of atomized fuel are: penetration, area, velocity and level of asymmetry (unevenness) of the spray.

High-pressure injection (spray-guided) was analyzed using piezoelectric injectors. Using outward opening injectors, the authors obtained an injection in the form of a hollow cone. Due to a characteristic design of the injector nozzle of outward opening and of the needle lift from 30 μm (Warnecke *et al.*, 2006) to 36 μm (Marchi *et al.*, 2010) the authors indicated a possibility of maintaining identical fuel dose at different fuel pressures, which allows influencing the injected fuel atomization.

In the tests the authors analyzed the operation of the injectors in order to determine the fuel spray longitudinal and transverse penetration (in reference to the injector) as well as the cross-section area of the fuel spray. The fuel spray penetration and area (flat exposure) were tested at the injection pressure values from 5 MPa to 20 MPa (Figure 5, 6). The assumed values of the air backpressure (0.5 and 1.0 MPa) resulted from the engine operating conditions. The possibility of injection control (fuel pressure) in order to obtain a desired atomization level (fuel spray penetration and area) ensues, among the others, from course of the

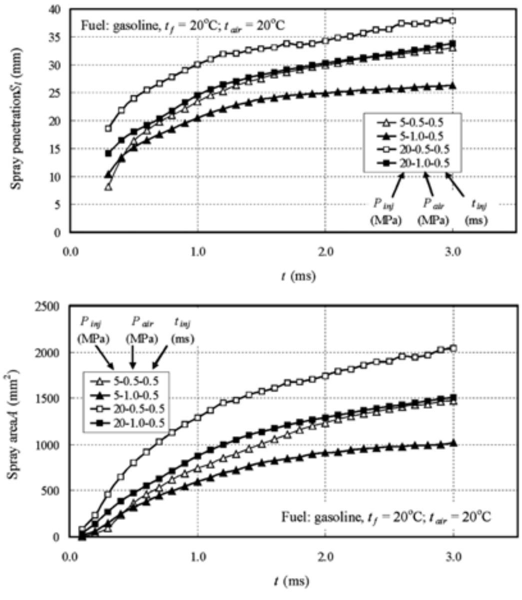

Figure 5. Analysis of the fuel spray penetration (a) and area (b) for a constant injection time $t_{inj} = 0.5$ ms (the other, variable parameters are shown in the graphs).

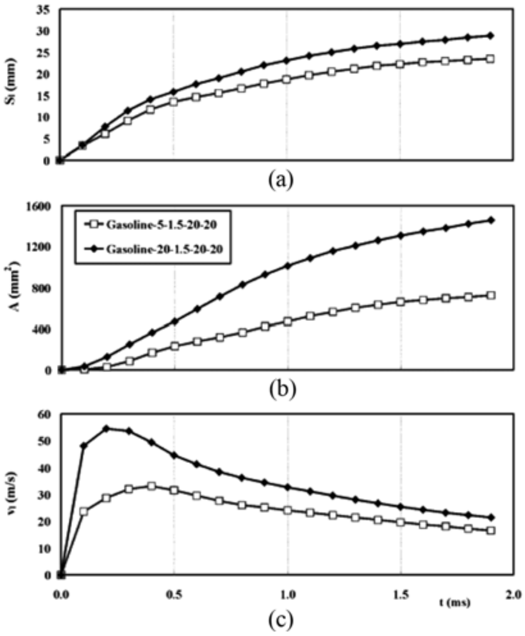

Figure 6. Influence of the conditions of the fuel injection on the geometrical indexes of the fuel spray: a) penetration, b) area, c) velocity; (t_{inj} = 0.5 ms, P_{inj} = 5 and 20 MPa, P_{air} = 1.5 MPa, t_f = 20ºC, t_{air} = 20ºC) coding: fuel type – P_{inj} [MPa]-P_{air} [MPa]-t_{air} [ºC]-t_f [ºC].

penetration and area curves at the injection pressure of 20 MPa with the air backpressure of 1 MPa being similar to the penetration curve at the injection pressure of 5 MPa with air backpressure of 0.5 MPa. This means that it is possible to obtain identical fuel spray penetration and the same area at different fuel injection conditions (different P_{inj}) and different conditions inside the cylinder (different P_{air}). It is worth noting that the quantitative similarity of these fuel sprays (here: penetration, angle and area) not necessarily is in line with the qualitative similarity (P_{inj}, P_{air}). The control of the injection and atomization of fuel in order to form the charge before combustion is possible when these fuel sprays are similar in terms of quantity and quality.

If we know the geometrical angle of the fuel spray cone, we can determine the actual fuel spray penetration S_l (Figure 7 (a)) i.e. the distance that it covers. This angle enables us to assess whether the fuel spray penetration is greater than the one determined on the basis of flat fuel spray exposure recorded by the camera. Despite the differences, in relevant literature regarding this type of injectors, it is a general principle that the fuel spray penetration is determined along the injector axis. In tests on single hole gasoline injectors and multihole diesel injectors there is no need to take the fuel spray angle into account (in the authors' research on fuel spray atomization from typical gasoline injector (Zhao *et al.*, 1999) and diesel injectors, the fuel spray penetration was determined

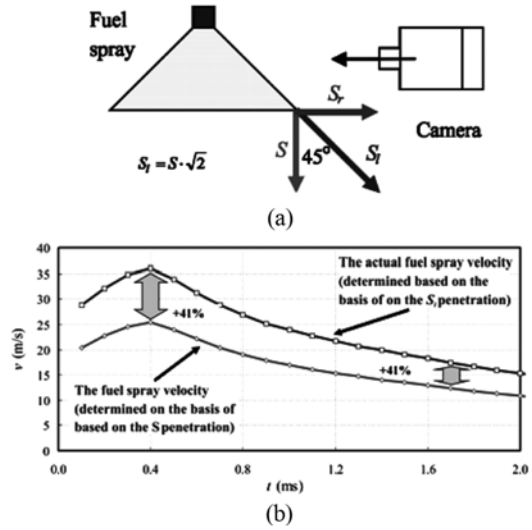

Figure 7. Determination of the fuel spray velocity: a) taking into account the actual fuel spray penetration, b) based on the fuel spray penetration and direction of fuel outflow from the injector (P_{inj} = 5 MPa, t_{inj} = 0.5 ms, P_{air} = 1 MPa).

individually for each fuel spray). Based on the fuel spray penetration and injection time from the outward opening injector, the velocity of the fuel spray front was determined (Figure 7 (b)).

Including the fuel spray penetration S_l in the research allows to determine the actual velocity of the outflowing fuel. The use of the literature-based method of the determination of the fuel spray penetration (quantity S in Figure 7 (a)) and calculation of the fuel spray velocity on this basis gives incorrect values. This error amounts to 41%, which results from the value of $\sqrt{2}-1$.

The control of the process of fuel injection and atomization requires that the fuel atomization and mixture formation take place in the vicinity of the spark plug. In order to obtain a stratified charge we do not need much time from the start of the injection to the spark plug discharge. Yet, if we want to obtain a combustible mixture (high ignition probability), we need to control the injection time so that the spark plug electrodes are at the tip of the fuel spray cone of the ignition dose (particularly important in a split injection system).

The information on the linear and radial fuel spray penetration is not sufficient to determine the spatial fuel spray location enabling the mixture ignition. Experimental research on fuel atomization indicates a varied time of fuel spray development and its reaching of the location that guarantees contact with the spark plug (location that is different from the linear or radial penetration) (Figure 8).

Similar conclusions related to the obtainment of the ignitability of the mixture formed by the outward opening injectors were drawn in the above-mentioned studies (Chen *et al*., 2011; Peterson *et al*., 2011). On the basis of improper

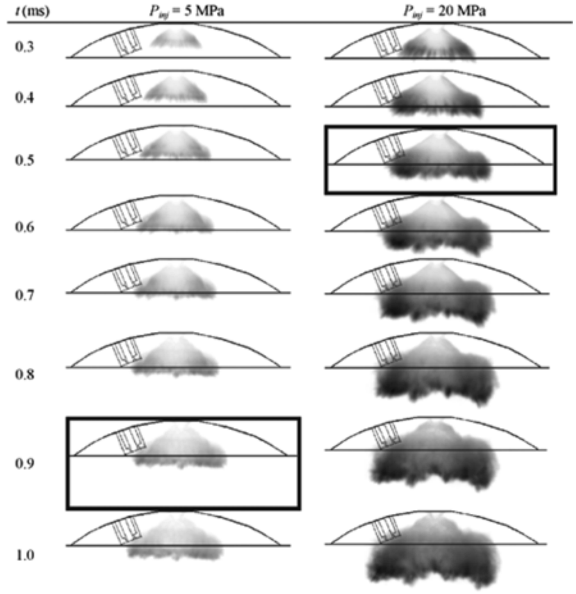

Figure 8. Sequences of injected fuel sprays depending on the injection pressure until contact with the spark plug (t_{inj} = 0.6 ms, P_{air} = 2 MPa, no fuel dose division); images that show the contact of fuel with the spark plug have been put in frames; experimental research.

ignitability (misfire) of the charge in the cylinder in Waltner *et al*. (2006), the authors indicated the values of the ignition angle (counted from the moment of injection to the spark plug discharge) that lead to the misfire.

It is worth noting that the results of the research presented in Figure 8 refer to the injected fuel without division of fuel dose, which means that the time refers to the whole fuel dose.

4. RESULTS AND DISCUSSION

The above-presented analysis of fuel atomization served to determine the influence of the individual input quantities on this process. The input quantities of the fuel injection and atomization are fuel pressure, air backpressure with its parameters (density and temperature) and the time of the fuel spray development.

In the research on the fuel spray development the influence of the fuel pressure, air backpressure and injection time on this process were determined (Figure 9). The research on the geometrical parameters of the fuel spray indicates that there exists a dependence between the fuel pressure, the air backpressure and fuel penetration (within the range of fuel pressure changes of 5 to 20 MPa and air backpressure of 0.5 to 1.0 MPa): an increase in the fuel pressure by 5 MPa results in an increase in the fuel spray penetration by 2-5% in the range from 0.5 ms to 3.0 ms after the start of the injection. Greater changes were obtained at lower values of the air backpressure. Such a

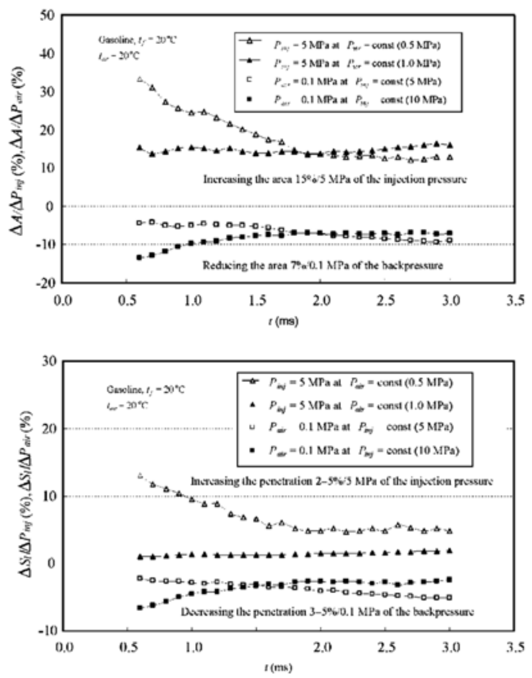

Figure 9. Changes in the fuel spray area (a) and penetration (b) after unit changes of the fuel injection and air backpressure settings during the injection into the constant volume chamber (t_{inj} = 0.5 ms, P_{inj} = 5 and 10 MPa, P_{air} = 0.5 MPa and 1.0 MPa; negative values denote a reduction of the quantity).

result was obtained for the fuel injection pressure of 5 or 20 MPa. Upon increasing by 0.1 MPa the backpressure of air up to which the fuel injection takes place, the fuel spray penetration was reduced by 3-5%. We need to note that greater backpressure values make the changes more repeatable in the whole range of fuel injection: from its start to the selected time after its end. Lower backpressure values indicate lack of stability of the penetration due to different values of *dS/dP* in the initial phase of fuel atomization. In the next stage of fuel atomization (in Figure 9 after 1.8 ms) we can observe a stabilized fuel spray penetration at a lower content of the air inside the chamber.

The linear fuel spray penetration is of great importance for the multihole injectors. For injectors with conical fuel spray formation, the linear penetration does not provide sufficient information to enable the control of the fuel injection. Because of a small distance from the fuel outflow to the spark plug, the knowledge of the radial penetration S_r (beside the linear penetration S_l) is desired (compare with Figure 6 (a)). It is important to know the relations between the linear and radial penetration because the fuel spray cone is formed spatially (Figure 10).

The analysis of the ratio of the linear to radial penetration indicates that the linear penetration constitutes approximately 47% of the radial penetration. Under the conditions without air backpressure they should be identical (because of the shape of the cone of the angle of 90°) and amount to S_l/S_r = 0.5. Increase in the injection pressure results a short time after the start of the injection (up to 0.5 ms) in reduction of the S_l/S_r value. This means that in this time window the radial penetration plays the dominant role. After the time of approximately 0.8 ms, linear penetration starts increasing faster than the radial one, and reaches a value approximately 12% greater than the average of 0.47. An increase in the fuel injection pressure (dark lines in Figure 10) causes that at a later time of atomization process the significant direction of the fuel spray development is linear. Similar is the influence of the air backpressure: its increase results in an increase in the linear penetration as compared to radial penetration (increase in S_l/S_r index). This means that in the combustion chamber the cone of the atomized fuel is 'flattened'. Thanks to such a formation of the fuel spray, it is possible to delay the injection without the need to take into consideration the fuel spray contact with the piston crown.

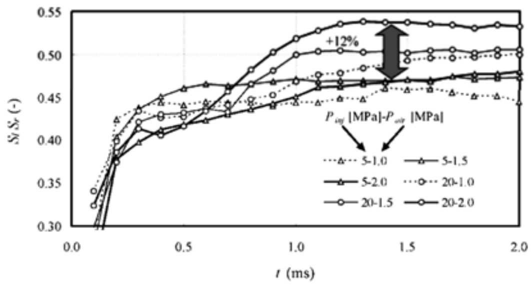

Figure 10. Influence of the fuel pressure and air backpressure on the relative changes of the linear and radial fuel spray penetration (t_{inj} = 0.6 ms).

The obtained results may constitute basis for the creation of an equation describing the fuel spray penetration depending on the basic process parameters in a high pressure gasoline injection realized by an outward opening injector. By determining linear fuel spray penetration S_l and utilizing knowledge of S_l/S_r ratio (Figure 4) it is also possible to define the radial fuel spray penetration. On this basis it is possible to get essential information about development of fuel spray in the combustion chamber.

Fuel spray penetration S_t described with a mathematical equation (5) requires that the following initial conditions be preserved:

- In the description the fuel injection pressure P_{inj}, air backpressure P_{air}, air density ρ_{air} and fuel spray development t are taken into account.
- The subject of the description is gasoline; for other fuels additional tests are required.
- The fuel spray penetration must be determined for the basic air temperature value (20°C) in a constant volume chamber and for a constant fuel temperature (20°C) operating in the injector, hence the mathematical form of the equation does not include the change in the

temperature of the liquid and the air (the change in the air density results from the change in its pressure).
- The time of the fuel spray development needs to be limited to 4 ms after the start of the injection.

The analysis of the relevant literature on the description of the fuel spray allows for a proposal of the equation structure whose all components are independent quantities. As the subject of the research is medium pressure injection, the making and assumption of the fuel and air pressure difference and defining this difference with a single exponent e.g. $(P_{inj} - P_{air})^z$ may not be appropriate. In the above expression small values of air backpressure Pair inside the cylinder would not be reflected. Hence, the following formula was proposed:

$$S_t = (P_{inj})^a \, (P_{air})^b \, (r_{air})^c \, t^d \tag{5}$$

where: P_{inj} – fuel pressure [MPa], P_{air} – air backpressure in the constant volume chamber [MPa], ρ_{air} – air density at a given temperature [kg/m^3], t – time of fuel spray development [ms].

Determination of coefficients a, b, c and d requires optimization methods. The optimization criterion has been presented in a form subject to minimization of decision function $f(U)$ expressed as a sum of squares of the differences of the individual values of the fuel spray penetration depending on the fuel injection pressure, air backpressure, air density and fuel atomization time as determined experimentally and through formula (5).

The mathematical model contains decision variables, limitations and optimal decision:
- Decision variables: a, b, c, d – exponents of the individual quantities influencing the fuel spray penetration.
- Limiting condition (determining the range of the admissible solutions) S_l: a, b, c, $d \neq 0$, these can be negative and positive values except zero (zero value eliminates a given component from the equation – denotes lack of its influence on the fuel spray penetration; in the model quantities that trigger changes in the fuel spray penetration have been taken into account).
- Optimum decision: $U(a, b, c, d)$ fulfills the limiting condition for which decision function $f(U)$ reaches a minimum:

$$f(U) = \sum_{i=1}^{n} (S_{l_i} - S_{t_i})^2 \rightarrow min \tag{6}$$

where S_{t_i} – denotes the calculated value of the fuel spray penetration for given quantities (P_{inj}, P_{air}, ρ, t), S_{l_i} – denotes the test value of the fuel spray penetration for the same values of P_{inj}, P_{air}, ρ, t; i – subsequent value.

The task was solved using 360 values of the fuel spray penetration obtained from the measurements of fuel atomization. For the solution of the optimization task, a generalized method of reduced gradient implemented in the MS Excel (Solver module) was used. This is a method

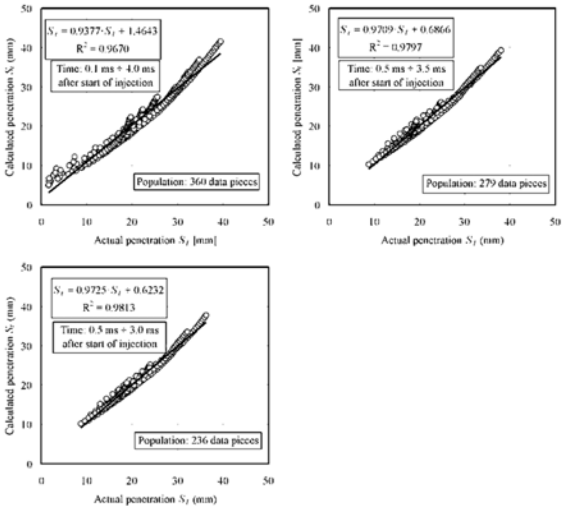

Figure 11. Analysis of the spread of the actual penetration (S_l) and calculated penetration (S_t) including: a) the total research population in the injection time range from 0.1-4.0 ms, b) partial population in the injection time range from 0.5-3.5 ms, c) partial population in the injection time range from 0.5-3.0 ms.

of solving for non-linear programming tasks with non-linear limitations.

The solution of the optimization task is obtaining such coefficients of equation (1) for which the sum of the squares of deviations ($S_l - S_t$) is minimum.

The task formulated in such a way, in the range of variables of the measurement data from 0 to 4.0 ms, enabled the obtainment of a solution regarding determination coefficient $R^2 = 0.967$ (Figure 11 (a)).

The analysis of the graph allows a statement that the greatest deviations of the results of measurements and calculations of fuel spray penetration occurred in the initial (up to 0.5 ms) and final (from 3.5 ms to 4.0 ms) period of fuel atomization. That is why the coefficients of equation (1) were calculated for a reduced amount of data (ranges in which the greatest deviations of values occurred were not included). As a result, the coefficient of determination had a value of 0.9797 (Figure 11 (b)) and the sum of the squares of deviations was 4 times lower. Upon further limitation of the measurement data (range from 3.0 ms to 3.5 ms), the value of coefficient R^2 grew to 0.9813 (change by 0.16%) – Figure 11 (c). The influence of the data reduction on the obtained values of coefficients of equation (1) has been shown in Table 2.

A small change of the coefficient of determination confirms that further elimination of measurement data from subsequent time windows has no influence on the final results of the optimization. A limitation of the amount of data from the range 0.5-3.5 ms to 0.5-3.0 ms did not significantly influence the calculated coefficients of the individual root values of equation (5) (maximum change

Table 2. Characteristic values determined in the optimization research of the fuel spray penetration.

Determined quantities	Range of atomization time [ms]		
	0-4.0	**0.5-3.5***	0.5-3.0
Coefficient *a*	0.302277	**0.296918**	0.292277
Coefficient *b*	–0.93265	**–0.95556**	–0.95727
Coefficient *c*	0.637195	**0.663871**	0.666642
Coefficient *d*	0.406825	**0.371403**	0.395186
The sum of squares of deviations	803.7864	224.044	157.8925
Equation of simple regression	$S_t = 0.9377 \cdot S_t + 1.4643$	$\boldsymbol{S_t = 0.9709 \cdot S_t + 0.6866}$	$S_t = 0.9725 \cdot S_t + 0.6232$
Coefficient of determination R^2	0.9670	0.9797	0.9813

* Bold – model selected for further application.

6.4% was recorded for coefficient *t* being the atomization time). Therefore, we should accept that the obtained equation:

$$S_t = (P_{inj})^{0.296918} (P_{air})^{-0.95556} (\rho_{air})^{0.663871} t^{0.371403} \tag{7}$$

is important for gasoline in the range of time 0.5-3.5 ms from the start of the injection, at the injection pressure range of 5-20 MPa and air backpressure range of 0.5-2.0 MPa.

The usage of the defined model of fuel spray penetration is valid for the presented ranges of input values. Extension of the model to all input values (P_{inj}, t_{inj} and P_{back}) might require further research. It might be stated, however, that in the conducted tests were applied conditions existing in combustion engines with outward-opening injectors, which enables extension of the application range of the defined model of fuel spray.

5. CONCLUSION

The investigations and analyses of the fuel injection and its atomization allowed the knowledge about these phenomena to be extended:

- The authors obtained analytical material allowing the dependence of the linear and radial penetration and velocity on the changes of the injected fuel pressure and air backpressure inside the cylinder to which the injection is realized to be determined.
- Based on the experimental analysis of the fuel injection, an equation was formed describing the fuel atomization including the changes of the fuel pressure, air backpressure, temperature and atomization time.
- The pressure of the injected fuel most significantly influences the fuel atomization indexes, particularly its penetration.

General conclusions were complemented with detailed ones, allowing a more precise comparison of the relations between the quantities of the fuel atomization process and the obtained indexes:

- An increase in the fuel pressure by 1 MPa (in the range 5-20 MPa) results in an increase in the linear fuel spray penetration by 5% in the time of 0.5-3.0 ms after the start of the injection and an increase in the fuel spray area by 3% (its flat exposure) determined on the basis of the flat image analysis; such changes are a result of an increase in the velocity of the fuel outflow from the injector, which results in a greater kinetic energy of the fuel and enables its greater penetration; the consequence is the increase in the fuel evaporation rate and a better charge homogenization.
- Upon increasing of the backpressure by 0.1 MPa, a reduction in the fuel spray penetration by 4% and its area approximately by 7% take place; an increase in the backpressure results in the increase of the charge density in the cylinder, thus in a reduction of the velocity of the outflowing fuel.
- Linear penetration constitutes on average 47% of the radial penetration, which denotes a necessity of taking this feature into account when designing combustion systems; at the same time such a shape of the fuel spray allows a significant delay of the injection without the contact of the fuel spray with the piston crown.

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