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Fuel injection rate shaping and its effect on spray parameters in a direct-injection gasoline system

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Abstract The presented test results contain an analysis of the variable control of fuel flow from high-pressure gasoline injectors. To control such a system, the cRIO 9063 system and NI-driven module were used. This system allows controlling a piezoelectric injector with a time-varying needle height, which affects the time-varying fuel flow during a single-time opening of the injector needle. The tests were carried out in a constant volume chamber with a constant fuel dose ($P_{inj} = 15$ MPa and $q_o = 17.4$ mg), with two values of medium back pressure: $P_b = 1.0$ and 1.5 MPa as well as different injector opening times (resulting from equal doses of fuel). Analyses of changes in linear and radial fuel spray range as well as the fuel spray volume were made. It has been found that injection rate-shaping allows to control the fuel flow from the injector at a variable needle height. A reduction of the linear range of the spray by 50% and a radial range by 40% compared to conventional settings within a specified time from the start of the injection was achieved. The surface area of the spray is limited by a maximum of 60% compared to the settings at the maximum control voltage. The use of injection rate-shaping may be an effective method of controlling the variable fuel flow from the injector and may allow the replacement of multi-stage fuel injection.

Keywords Fuel injection · Fuel spray · Rate-shaping · Optical research

1 Introduction

The split fuel dose injection is a method for controlling the combustion process and the associated exhaust emission. The first scientific works on the research of injection systems in CI engines using rate-shaping appeared several years ago (Egnell 2000; Juneja et al. 2004; Wickman et al. 2000).

Such shaping of the injection process has been utilized in compression-ignition engines using electromagnetic (Hountalas et al. 2002; Tanabe et al. 2005) or piezoelectric injectors (Lee et al. 2006; Shen et al. 2014) for several years. The initially available simulation methods of time-varying fuel flow modeling (Boggavarapu and Singh 2011; Hountalas et al. 2002; Juneja et al. 2004; Winklhofer et al. 1992) have now taken quite complicated shapes regarding the start of injection (Macian et al. 2014; Mancaruso et al. 2017; Rottmann et al. 2009; Zhou et al. 2018) and the way it ends (Koci et al. 2015).

A detailed analysis of piezoelectric injector operation was presented by Le et al. (2014). The authors of this work have shown that the “dynamic surface control” allows accurate reproduction of partial and full injector opening. Research on the rate-shaping system using a new injector concept at a maximum diesel pressure of 250 MPa was conducted by Grzeschik and Laumen (2014). The modular HiFORS injector contains a two-stage hydraulic servo system which transforms the actuation voltage of a single piezo

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actuator into a corresponding injection pressure. Macian et al. (2014) analyzed experimental tests with prototype injectors operating in *direct-acting rate-shaping* mode. They were conducted in the context of auto-ignition delay in the CI engine and combustion conditions. It has been shown that the partial needle lift causes a slight shortening of the second-stage ignition delay. It was found that non-conventional injection rate profiles (boot and ramp) have a significant impact on the premixed phase of the combustion (OH).

Publications on the use of rate-shaping in gasoline engine systems are few. Such research was led by Payri et al. (2018), among others, using a solenoid-driven gasoline direct-acting injector, obtaining high compliance of model and experimental results (differences below 5%).

The presented literature analysis does not indicate a wide use of this injection method in SI engine systems. Such a solution can be widely used in spray-guided systems, where fuel injection occurs immediately before the ignition (Bisht 2019). This article attempts to apply this injection technique in a direct petrol injection system (using outward-opening piezo injectors).

2 Motivation

The presented literature analysis indicates that the tests of fuel atomization indexes carried out in relation to the spark-ignition engine injectors using the rate-shaping system have only been made on individual systems. This paper demonstrates the benefits of using such an injection system in relation to gasoline systems along with the quantitative and qualitative differences determined using conventional injection and injection rate-shaping.

3 Research method

3.1 Test objects and apparatus

Analysis of the fuel atomization process was carried out using a constant volume chamber. The test stand schematic is shown in Fig. 1. The exact description of the test stand used can be found in the publication by Pielecha (2018).

During the injection process tests, the following parameters were recorded: electrical signals of the injector control (voltage and current curves) and images of fuel atomization in a plane parallel and perpendicular to the axis of the injector. This research methodology enabled the analysis of linear and radial fuel spray atomization indicators. An outward-opening injector was used in the conducted tests. The main

Fig. 1 Test stand schematic used in injection rate-shaping tests

feature of such a solution is its outwards motion when the needle moves. Using this injector type creates a fuel spray in the shape of an empty cone, with air contained in the middle.

The cRIO9063 module and 9215 and 9751-driven systems from National Instruments were used to generate electrical signals controlling the injector. This made it possible to control the *outward-opening* Siemens high-pressure piezoelectric petrol injector in the voltage range from $U = 90$ to $U = 170$ V. Measurements of voltage and current were carried out using current clamps Pico TA 018 and direct voltage measurement (voltage 1:20 divider was used—Pico TA 197) operating at 20 MHz.

Optical analysis was carried out using a LaVision HSS5 camera with a Nikon 50 mm lens, 1:1.4 (1.4 aperture) at 20 kHz (image size 304×192 pix). The actual image size was $133.7 \text{ mm} \times 84.5 \text{ mm}$, which corresponds to $1 \text{ pix} = 0.44 \text{ mm}$. Each test was repeated three times. Image processing was carried out using the DaVis software from LaVision.

The initial conditions of the fuel injection process and its atomization are given in Table 1.

The tests were carried out at various fuel injection conditions. The settings in which the following aspects were implemented were used:

- (1) maximum opening of the injector needle – standard settings of the system,

Table 1 Initial conditions for fuel injection and atomization tests

Parameter	Unit	Value
q_o (fuel quantity)	mg	17.4
P_b (back pressure)	MPa	1.0 or 1.5
Fuel injection pressure	MPa	15
Fuel	–	Gasoline (RON95)

Table 2 Fuel injection process research plan

No	Point designation	Parameters (U, t)	Fuel dose
1	Max. opening	$U = 170 \text{ V}, t = 0.7 \text{ ms}$	17.4 mg
2	Min. opening	$U = 120 \text{ V}, t = 1 \text{ ms}$	
3	Rate-shaping	$U = 90/170 \text{ V}$ (at $0.4 + 0.45 \text{ ms}$), $t = 0.85 \text{ ms}$

Fig. 2 Injector power supply control for electric signals with various fuel injection strategies

Fig. 3 Selected repeatability test results of current and voltage signals

Table 3 Selected fuel atomization sequences with various methods of forcing the injector opening

t [ms]	$U = 170$ V $t_{inj} = 0.7$ ms	$U = 120$ V $t_{inj} = 1.0$ ms	$U = 90/170$ V $t_{inj} = 0.85$ ms	$U = 170$ V $t_{inj} = 0.7$ ms	$U = 120$ V $t_{inj} = 1.0$ ms	$U = 90/170$ V $t_{inj} = 0.85$ ms
	$P_b = 1.0$ MPa			$P_b = 1.5$ MPa		
0.2						
0.4						
0.6						
0.8						
1.0						
1.2						
1.4						
1.6						
1.8						

- (2) small injector needle opening assumed,
- (3) control in the system with variable injector needle opening time – *rate-shaping*.

The differentiated injector opening forced the necessity to set a constant fuel dose value. Based on preliminary tests, different injection times were determined at different injector control voltages in order to obtain the same fuel dose. The fuel dose was set at 0.023 ml/injection ($m_f = 2.3$ ml/100 injections $\cdot 0.757$ g/cm³ = 17.4 mg/injection). A constant fuel dose was injected at three different system settings; this forced

Table 4 Selected fuel atomization sequences with various methods of forcing the injector opening (radial fuel spray)

t [ms]	$U = 170$ V $t_{inj} = 0.7$ ms	$U = 120$ V $t_{inj} = 1.0$ ms	$U = 90/170$ V $t_{inj} = 0.85$ ms	$U = 170$ V $t_{inj} = 0.7$ ms	$U = 120$ V $t_{inj} = 1.0$ ms	$U = 90/170$ V $t_{inj} = 0.85$ ms
	$P_b = 1.0$ MPa			$P_b = 1.5$ MPa		
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

the necessity to change the fuel injection time. The range of the test conditions variation is presented in Table 2.

The constant supply voltage setting with the minimum injector opening was $U = 120$ V. However, in order to achieve a small needle lift in the rate-shaping system (and keep it in that position for a short time), it was necessary to further reduce the initial voltage to $U = 90$ V (short-term voltage pulse by $U = 120$ V did not allow the injector needle to rise low). Minimal opening of the injector at voltage $U = 90$ V resulted in a very long injection time in order to reach the constant fuel dose value. Therefore, it was found that it was possible to vary the voltage values (minimum and in rate-shaping mode) in order to obtain a variable fuel flow.

Fig. 4 Image processing and determining the geometric indicators of the fuel spray geometry

3.2 Evaluation of electric signals

Using the NI cRIO9063 system, voltage rise times were set, which resulted in obtaining 120 V ($t_{inj} = 1$ ms) or 170 V ($t_{inj} = 0.7$ ms) for constant injector opening. Fuel injection while implementing the *rate-shaping* mode required a low voltage signal (90 V), followed by 170 V. These times were set at 0.4 ms and 0.45 ms, respectively (total fuel injection time in *rate-shaping* was 0.85 ms). The above sequences are shown in Fig. 2. The injection times of all sequences were chosen so that the mass of injected fuel was at a constant value.

Electrical signal settings required assessment of their repeatability. This was necessary to determine the repeatability of the fuel flow from the injector. For this purpose, 30 repetitions of fuel injection were performed, showing only a few examples of the results in Fig. 3.

Fig. 5 Test results on the linear fuel spray penetration and the coefficient of variation of this range related to the atomization time (three repetitions) for three fuel injection methods and an air back pressure of: **a** $P_b = 1.0$ MPa, **b** $P_b = 1.5$ MPa

3.3 Fuel atomization test results

3.3.1 Fuel spray tests in a plane parallel to the injector axis

Tests of geometric indicators of the fuel spray were carried out in relation to the spray range, plane surface area of the spray exposure and its width. The research used Pb95 gasoline with a composition compliant with that gasoline type for PKN ORLEN.

The results of optical tests regarding image registration in a plane parallel to the injector axis are shown in Table 3. Different structures of fuel outflow are visible with different injection methods. Increasing air back pressure limits the range and area of the fuel spray. The injection carried out in the rate-shaping system indicates a different fuel atomization characteristic. The limited range in the initial phase is caused by limiting the opening of the injector needle (outward-opening). The following sequences, however, indicate a similar range to conventional injection with a lower value of forcing voltage.

3.3.2 Fuel spray tests in a plane perpendicular to the injector axis

Using the test stands presented (Fig. 1), it was possible to simultaneously record images of fuel atomization in a plane parallel and perpendicular to the injector axis. Using the plane perpendicular to the axis of the injector, it was possible to determine the radial range and the corresponding surface area of the fuel spray.

Preliminary analysis of the test results presented in Table 4 indicates the existence of a circular and rectangular structure. Similar injection images (similar physical phenomenon) were obtained and explained in the paper by Pielecha (2018). High values of the injector supply voltage (high rise of the injector needle) result in a rectangular structure; however, a small opening of the injector (regardless of the back pressure of the medium) causes only the creation of a circular structure. The use of injection rate-shaping delays the formation of a rectangular structure only in the first phase of fuel injection (limited opening of the injector needle).

Fig. 6 Test results on the fuel spray area (plane parallel to the axis of the injector) and the coefficient of variation of this area related to the atomization time (three repetitions) for three fuel injection methods and an air back pressure of: **a** $P_b = 1.0$ MPa, **b** $P_b = 1.5$ MPa

3.4 Pictures analysis techniques

The recorded images were further processed in order to obtain fuel atomization indicators at various injection conditions.

Fig. 7 Analysis of the fuel spray geometric indicators with three injection methods and different back pressure values for: **a** linear fuel spray penetration S_L , **b** spray surface area A_L , **c** fuel spray width W_L

Tests of spray indicators were carried out for each of the samples and the following parameters were determined (Fig. 4):

- fuel spray range; was defined as the maximum distance from the atomizer to the adopted luminance limit of the spray image. Preparation of images for the assessment of the spray range consisted of selecting a research area (using image masking) and subtracting the measurement background (measurement noise). The linear or radial range of the spray was determined with this method.
- fuel spray area; determined as the number of pixels with a given range of image luminance intensity.
- the width of the spray was determined based on an assessment of the linear range of the spray, assuming the size of the coordinate perpendicular to the range of the spray.

4 Analysis of the geometric quantities of fuel spray

4.1 Assessing the geometric quantities of linear liquid fuel spray penetration

The research methodology presented above was used to determine the linear range of sprayed fuel. The analysis was carried out at three values of injector supply voltage: corresponding to the maximum injector opening ($U = 170$ V), minimum opening ($U = 120$ V), and the rate-shaping system ($U = 90/170$ V). The analysis was carried out for three repetitions of fuel injection. At the same time, the repeatability of this value range was determined for three values of the linear range at each point in time of the injection process. The results of these tests for conventional injection and rate-shaping at two values of medium back pressure are presented in Fig. 5. Preliminary analysis indicates varied values of the linear range depending on the value of the control voltage. The use of variable voltage value $U = 90/170$ V results in the initial limitation of the linear spray range, however, the maximum opening of the injector in the second part of the fuel injection eventually causes its significant increase.

In tests on internal combustion engines, it is assumed that the value of the coefficient of variation (CoV) related to the average indicated pressure should not exceed 3.5%–5% (King and Böcker 2012; Subic et al.

Fig. 8 Test results of the fuel spray radial penetration and the coefficient of variation of this range related to the atomization time (three repetitions) with three fuel injection methods and with an air back pressure of: **a** $P_b = 1.0$ MPa, **b** $P_b = 1.5$ MPa

Fig. 9 Test results of the fuel spray surface area (plane perpendicular to the axis of the injector) and the coefficient of variation of this area related to the atomization time (three repetitions) with three methods of fuel injection and an air back pressure of: **a** $P_b = 1.0$ MPa, **b** $P_b = 1.5$ MPa

2012) or the value of 10% (Heywood 1998). The coefficient of variation (CoV) is often used by authors in their statistical analysis of cylinder images. Huang et al. (2003) used this coefficient to also determine the combustion duration variation ($CoV = 6\text{--}12\%$), the rise of maximum pressure as well as the combustion products: CO, CO₂, CH₄ and NO_x (2–15%). The CoV was also used in the optical analysis of the obtained images. Chen et al. (2014) performed an optical analysis of the flame speed propagation (based on the data of 250 cycles) at different values of flow turbulence. A value of $CoV = 49.7\%$ was obtained (at a low turbulence value) and 25.1% at high turbulence. A wide analysis of the flame stability based on the CoV value was performed by Zhang et al. (2013). In this article; however, the flame contour change analysis was performed (using 2000–9000 images). As a result, a CoV value of less than 4% was found. Taking into account the above assumptions, an analysis was performed, including the determination of the linear range coefficient of variation $CoV(S_L)$. It has been shown that only at the initial injection time the value of the variation index is high and then reaches values below 5%. The initial large value of this factor is the result of optical tests in which the spray range is calculated on the basis of recorded images at a frequency of 20 kHz (initial small range values generate large errors).

The obtained $CoV(S_L)$ values below 5% mean high repeatability of the fuel spray linear range, and therefore, the obtained results may be used for further analysis.

The analysis of the injected fuel sprays surface area (in a plane parallel to the injector axis) – A_L indicates the existence of significant differences in the determination of this quantity at different values of the control voltage. The values of the linear range S_L and the fuel spray surface A_L are similar in quality. The results of these comparisons at two values of medium back pressure are presented in Fig. 6. Additionally, the CoV coefficient of variation of both tested values was also taken into account.

A comparative analysis of the linear range (S_L), surface area (A_L) and the width (W) of the fuel spray for different fuel injection methods is presented in Fig. 7. The assessment of the average linear range (at time of t around 2 ms) indicates obtaining the maximum range with the control signal with $U = 170$ V (maximum opening of the injector needle). This value is about 12% higher in relation to the injection with a voltage of $U = 120$ V and with rate-shaping injection (Fig. 7a). The maximum differences in range and rate-shaping values are obtained after ($t = 0.5$ ms) the first injection phase (the time of the first injection phase is $t_{inj} = 0.4$ ms). With a lower back pressure P_b , the maximum linear range difference was 48%, while for the higher pressure it was 47%. These values are similar. Similar relationships were expected during the

Fig. 10 Analysis of the fuel spray geometric indicators with three injection methods and two medium back pressure values for: **a** radial spray penetration, **b** spray surface area (plane perpendicular to the injector axis)

analysis of the spray surface area and spray width (Fig. 7b, c). The maximum differences in the surface area of the spray are 63% at the injection time $t = 0.5$ ms (with a higher medium back pressure). This value is three times greater than changes in time $t = 2$ ms (Fig. 7b). The spray width W_L is similar in its characteristic to the spray range (Fig. 7c). In this case, the largest changes are observed at $t = 0.5$ ms from the injection start and they are 40% in relation to the maximum needle opening value at the two values of air back pressure.

4.2 Assessment of geometrical quantities of radial fuel spray penetration

Similar to the analyzes carried out to assess the linear range, additional analyzes were performed in relation to the radial range of the fuel spray. The radial range (S_R) and the surface area in this cross-section (A_R) were determined. Analysis of the radial range at three repetitions can be used to assess their repeatability. This is indicated by the determined radial range non-repeatability ratios of less than 5%. For injection rate-shaping, changes in radial range in the initial phase are very large (large values of $\text{CoV}(S_R)$).

In the initial injection phase, the range was clearly reduced in relation to both conventional injection ranges (at both low and high supply voltage) regardless of the medium back pressure value—Fig. 8.

The analysis of the surface area A_R (perpendicular to the injector axis) is shown in Fig. 9. Due to the differences resulting from the obtained geometrical indicators of the fuel spray, the $\text{CoV}(A_R)$ values sometimes exceed 5% (at low medium back pressure). Higher values of the back pressure P_b confirm the high repeatability of determining the spray surface area during fuel injection.

A comparative analysis of the main geometric (radial) spray indicators is shown in Fig. 10. The maximum changes in radial range are (Fig. 10a), respectively: at medium back pressure $P_b = 1.0$ MPa equal to $\Delta S_R = 40\%$ (in relation to the max range); at $P_b = 1.5$ MPa— ΔS_R was 61%. The radial range of fuel injection at $t = 2.0$ ms is the largest at maximum needle opening ($U = 170$ V). However, during injection rate-

Fig. 11 Radial distribution of the surface area of the fuel spray at $t = 0.5$ ms ASOI at different values of back pressure (1.0 MPa and 1.5 MPa): **a** linear distribution, **b** radial distribution

shaping, the spray range is greater than the minimum (at $U = 120$ V). Similar changes are also shown by the spray surface area (cross-section perpendicular to the injector axis)—Fig. 10b. In this case, the (radial) surface area limitation is about 50% at $t = 0.5$ ms from the start of fuel injection.

Determining the relative changes in geometric indicators also required the calculation of the radial width W_R of the spray. This width was defined as two times the average range value determined in a full 360-degree angle:

$$W_R = 2 \cdot \frac{\sum_{i=1}^{360} S_{Ri}}{360} \quad (1)$$

The average spray width value determined on the basis of the spray radial range is obtained with a small error with the circular structure of the radial range (Table 4). With a quadratic structure, the medium range is affected by a much larger error resulting from the spray structure (Table 4—quadratic structure). The same conclusions were also obtained in the paper by Pielecha (2018).

The qualitative and quantitative distribution of the fuel spray in both of its cross-sections is shown in Fig. 11. These data were compared for the time value of $t = 0.5$ ms after the start of the fuel injection.

Analysis of the linear and radial profiles indicates similar values of reducing the surface area in both linear and radial cross-sections. These results are consistent with those shown in Fig. 7 (spray cross-section parallel to the injector axis) and Fig. 10 (cross-section perpendicular to the injector axis). This means that by changing the injector supply voltage, it is possible to obtain a time-varying fuel flow. This injection is smaller (smaller radial range) than during constant voltage of $U = 120$ V.

5 Conclusions

Research on the possibilities of shaping the fuel flow from high-pressure gasoline injectors requires determining the usefulness of injection rate-shaping. Such injection allows shaping the range and width of the fuel spray during the injection of gasoline (or light hydrocarbon fuels). The NI control system used

together with the Driven system enables effective control of the variable rise of the piezoelectric fuel injector needle in the opening time range close to 0.4 ms. The non-repeatability of the voltage control in the constant values range (90 or 170 V) is about 5%.

The tests and their optical analysis indicate that the use of injection rate-shaping allows to achieve:

- (a) in relation to the parallel cross-section of the spray: a maximum reduction by about 50% of the spray range, by 60% of the spray area and by 40% of the spray width;
- (b) in relation to the perpendicular cross-section of the spray: a reduction of 40% in the range of the spray and a reduction of its area by about 50%.

The obtained changes in geometric indicators when using injection rate-shaping allow finding promising options for controlling the range and shape of the injected fuel spray. Such large changes in geometric indicators can be used to effectively control the variable fuel flow from the injector to create a stoichiometric mixture around the spark plug.

The presented issue of time-varied fuel flow can be an effective method for replacing multi-stage fuel injection. This can be achieved using the following features of such a control system:

- (a) spray range reduction and thus keeping more fuel near the spark plug (spray-guided injection),
- (b) limiting the increase of fuel droplets size when closing and subsequently opening the injector normally,
- (c) fuel injection time reduction, especially significant at high engine speeds.

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