Thermodynamic operating indicators of an SI engine with a rate-shaping type direct injection

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Abstract. The authors proposed a rate-shaping injection consisting of a time-controlled fuel dosing to allow better control of the injection process and also of the combustion process as a final result. The effects evaluation of applying such fuel injection control method should be based on the obtained engine operating indicators improvement analysis, especially the thermodynamic indicators. Selected injection strategies were implemented in an experimental engine model – a rapid compression machine (RCM). The observations of the processes inside the cylinder were carried out at the frequency of 10 kHz using the high speed camera. Indicator tests (AVL IndiModul) were performed with the same data acquisition frequency for further synchronization with the optical tests results. Comparative analyses of the effects of the direct injection system with a single fuel dose and rate-shaping system were performed. Combustion rates influencing the process thermodynamic indexes and resulting in differences in the results of optical tests were experimentally determined. The comparative assessment of the obtained results and analyses lead to the conclusion that the use of the rate-shaping system enables a significant increase in the combustion process control and enables the injection process control methods to be correlated with the operational indices of the model engine.

1. Introduction
The spark-ignition engines efficiency investigation results depend to a large extent on the combustion system design, which is the basic indicator of the system design quality. The exhaust emission depends in turn on its operation indicators [1–3].

Modern combustion systems allow for the structural engineering design of spark-ignition engines and compression-ignition engines to converge. The homogeneous fuel dose used so far (in MPI – multi point injection systems) is increasingly being replaced by a stratified dose (engines with direct injection).

Spark-ignition engines utilise various combustion systems and fuel injection technologies, as opposed to compression-ignition engines. The combustion systems of SI engines are divided into indirect injection systems to the intake manifold (low-pressure) and direct injection into the cylinder (medium-pressure). Using indirect injection causes fuel dose losses (fuel injection into the intake manifold) before it is delivered into the cylinder. Fuel injection should allow for the combustion of both homogenous and stratified fuel doses. Currently the main subject of research and development in this field focuses on obtaining an inhomogeneous (stratified) fuel dose, also enabling the combustion of lean mixtures. In this respect, the combustion systems of spark-ignition engines are similar to the combustion systems used in compression-ignition engines. The medium-pressure, direct, sequential petrol injection systems are currently the main research subject in these engines, because this injection...
strategy enables any quantitative and qualitative fuel dose shaping and affects its later combustion process.

2. The research problem

Research regarding gasoline direct injection systems, especially the fuel supply system, can be divided into several groups:

- related to increasing the fuel pressure,
- on the design of the injectors and the fuel atomization method,
- related to the injector placement in the combustion chamber,
- concerning its control method.

The FCA (Fiat Chrysler Automobiles), in a new prototype engine design with a 1150 cm$^3$ displacement, presented a solution based on placing the injector at a much higher tilt angle than is currently used. It was found that it is possible to avoid the collecting of moisture on the injector when using injection with a large fuel jet cone angle [4].

Small engines are not commonly equipped with an injection system with a centrally placed injector, because such a location would require reducing the diameter of the valves, also leading to a small engine operating range with the stratified dose [4]. The injection methods used in these engines are: "hollow cone" – at a pressure of 7–15 MPa, and multi-hole – up to 20 MPa. Increasing the fuel injection pressure to 35 MPa (from 20 MPa) allows an up to 3-fold reduction of the particle number emission from spark-ignition engines [5]. Sequential injection at such high pressure limits the spray range by 20% in relation to injection without dividing the dose [6]. The cited study also concludes that the injection of several doses of fuel, significantly before the piston reaches the TDC position, increases the particulate mass emission. The best results were obtained for the injection shortly before ignition (for a staggered dose) and with one dose injected well in advance (however, in this solution the piston crown wetting is often observed).

Research conducted by Audi confirms that the injector placement in the centre of the combustion chamber (or in its vicinity) has merit. Such combustion system construction combined with the Miller cycle is to result in increased thermal efficiency of the internal combustion engine [7].

The first scientific papers on simulation research using the rate-shaping technique of diesel fuel injection appeared at the beginning of the 21st century [8–10].

Current scientific works on rate-shaping fuel injection mainly concern injection systems of CI engines and are commonly based on simulation research. In the papers [11, 12], the authors analysed combustion and exhaust emission for an engine supplied with a kerosene and diesel oil mixture (kerosene-diesel). It has been shown that NO emissions are generally seen to decrease when boot injection rate-shapes are used instead of the conventional rectangular injection rate. Similar work was performed by Mohan et al. [13] obtaining the reduction of nitrogen oxide emissions, while using a rate-shaping injection. Research on the use of triangular rate-shaping strategies was also carried out by the authors of the papers [14, 15].

Experimental studies of piezoelectric injectors working in the rate-shaping system were conducted by Le et al. [16]. Using the LabView FPGA platform, closed-loop research with dynamic surface control was performed. Experimental tests in relation to model tests show 2.5% non-repeatability of the fuel dose per one injection. Similar research was conducted by Ferrari and Mittica [15].

Experimental research with prototype injectors operating in rate-shaping mode with direct control (direct acting) was analysed by Macian et al. [8]. This research was conducted in the context of combustion delay in the CI engine and the combustion conditions changes. 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 radicals).

The presented literature analysis does not indicate the use of this injection method in SI engine systems. For this reason, using the in-line outward-opening piezo-electric injectors, the authors attempted to apply this technique for the direct injection of gasoline.
3. Research methodology

3.1. Research method

To evaluate the possibility of shaping the injection characteristics of petrol and its combustion, the test-bench method was applied. The rate-shaping injection strategies selected for research were implemented experimentally using a model research engine (s.c. Rapid Compression Machine).

3.2. Test setup and measurement equipment

The fuel combustion process analyses were made using a rapid compression machine (figure 1). The diagram of the test bench is shown in figure 2. A detailed description of the test stand used is included in [17].

![Figure 1. Schematic of the test object for the combustion process analysis.](image1)

![Figure 2. The outline of the test bench used in the rate-shaping injection research.](image2)

In the research of the combustion process the following data were recorded: 1) electrical signals (voltage and current) of the injector control system, 2) variable signals (cylinder-pressure) and 3) combustion images. The cRIO9063 module and the National Instruments 9215 and 9751 Drivven systems were used to generate electrical signals for the injector control. This system enabled the control of Siemens high pressure petrol injector in the voltage range from 90 to 170 V. Measurements of voltage and current were taken using Pico TA 018 current clamps and direct voltage measurement (voltage divider 1:20 – Pico TA 197) sampled at 20 MHz.
The variable signals were recorded using AVL IndiModul, and further processing of the signals was done using the AVL Concerto software. Cylinder pressure history (AVL GM11D sensor with MicroIFEM amplifier), piston movement (Megatron LSR 150STR5k), injection time (TTL) and ignition time (TTL) were recorded at 20 kHz.

The optical analysis was performed using a LaVision HSS5 camera with a 105 mm UV-Nikon lens, 1:4.5, (shutter 8) at a frequency of 10 kHz (image size 512 × 512 pix). Image processing was done using LaVision DaVis software.

3.3. Methodology
The tests were performed for various fuel injection conditions. The parameters were selected so that: 1) the maximum opening of the injector needle – standard settings of the system, 2) assuming small opening of the injector needle, 3) injector system control with a time-based injector needle opening.

The fuel injection process research plan is presented in table 1 and in figure 3. The obtained variation of injector opening was used to investigate its impact on the combustion process. These tests were performed using the RCM at the test operating point, whose characteristics are given in table 2.

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

![Figure 3](image)

*Figure 3.* Control of electrical signals of the injector's power supply with various fuel injection strategies.

| No. | Parameter | Unit  | Value                  |
|-----|-----------|-------|------------------------|
| 1   | \(q\)     | mg    | 17.4 mg                |
| 2   | \(P_{in}\) | MPa   | 0.065 (overpressure)   |
| 3   | \(e\) (RCM) | –     | 11                     |
4. Combustion process test results

4.1. Combustion process optical observation results

The results of optical tests of recorded images with injection strategies as described in figure 3 were shown in table 3. The presented images have a time resolution of $\Delta t = 1$ ms. The first image was captured at the moment of ignition.

Table 3. The combustion process images for different fuel injection strategies.

| Strategy                          | Combustion process                      |
|-----------------------------------|-----------------------------------------|
| Minimum needle opening            | ![Image](image1)                         |
| $U = 120$ V                      | ![Image](image2)                         |
| $\Delta t = 1$ ms from SOI       | ![Image](image3)                         |
| Maximum needle opening            | ![Image](image4)                         |
| $U = 170$ V                      | ![Image](image5)                         |
| $\Delta t = 1$ ms from SOI       | ![Image](image6)                         |
| Rate-shaping                      | ![Image](image7)                         |
| $U = 90/170$ V                   | ![Image](image8)                         |
| $\Delta t = 1$ ms from SOI       | ![Image](image9)                         |

Analysis of the images presented in table 3 indicates the occurrence of flame in the whole combustion chamber only for the maximum injector supply voltage strategy. This is synonymous with the maximum injector needle opening. In the rate-shaping injector control strategy, the flame also covers the entire surface of the combustion chamber, however it occurs much earlier.

4.2. Combustion process indicators

The combustion process indicator analysis was performed using the following parameters: cylinder pressure and heat released. This data is shown in figure 4. It can be seen that the maximum cylinder pressure is obtained at the highest control voltage value (170 V) – figure 4a. Combustion analysis – for the other two strategies – indicates a lower maximum pressure of the process, but it reaches higher values later in the process. This characteristic contributes to a higher temperature in the cylinder in this phase of the process. This may result in a faster heating up of the catalytic converter and other exhaust aftertreatment systems. The heat release characteristic (figure 4b) indicates a relation to the cylinder pressure characteristic. Taking the analysis of images and the heat release process into account, it can be stated that these quantities are correlated with one another. Only the fuel injection with a low voltage (120 V) strategy demonstrates a different heat release characteristic (lower maximum values). The sudden drop in the heat released after reaching the maximum value is related to the specificity of a rapid compression machine construction (lack of a crank mechanism) and heat losses of the system.
The combustion process indicator analysis was performed relative to the maximum combustion pressure and the maximum heat release value and the times when it occurred (figure 5). The highest maximum pressure value was obtained for the injection control at a voltage of 170 V. The rate-shaping injection strategy leads to a combustion pressure value reduced by 10%. Combustion with the lowest voltage (120 V) injection control strategy achieves a maximum pressure value reduced by over 20% in relation to the maximum value for the 170 V strategy.

Similar conclusions were obtained from the analysis of the moment of maximum combustion pressure values occurring. The analysis of the maximum heat released values also indicates similar effects of the fuel injection strategies used. Injection implemented as rate-shaping obtains a maximum heat released value that is only 2.5% lower, despite the smaller maximum values of the combustion pressure. This indicates the possibility of rate-shaping type injection control regarding combustion process indicators. It is possible to limit the value of the maximum cylinder pressure with small losses of the maximum heat released value.

4.3. Optical indicators of the process
Based on the digital analysis of successive frames of the recording the physical indicators describing the flame formation and development in the combustion chamber volume were determined. These were: the instantaneous surface A [% or mm²] occupied by the flame relative to the total area of the combustion chamber (absolute or relative surface).

Advanced image processing techniques allow for a full flame development analysis. One of the additional parameters used in such analyses is the effective radius of the flame covered area. Its value is possible to determine based on the flame area; thus the effective radius equals:
\[ r = \sqrt{A/\pi} \]  

(1)

Using the effective flame radius size changes on the subsequent picture frames the flame velocity between two consecutive recorded pictures was determined:

\[ v = \frac{\Delta r}{\Delta t} \]  

(2)

where \( \Delta r \) is the effective radius growth, and \( \Delta t \) is the time between successive recorded images. As a result of such calculations, average values of the flame velocity distribution are obtained, regardless of the PIV method (based mainly on selected areas of the combustion chamber and the limited time range of flame development).

The coordinates of the points (pixels) occupied by the flame area make it possible to determine its geometrical centre. By using flat image exposure of a flame, it is possible to determine the coordinates of its centre on the same principle as is used to determine the centre of gravity of a flat figure of any shape. The \( x_o \) and \( y_o \) coordinates of the geometric centre of the flame radius are:

\[ x_o = \frac{\sum_{i=1}^{n} x_i}{\sum_{i=1}^{n} i} \quad \text{and} \quad y_o = \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} i} \]  

(3)

where \( x_i \) and \( y_i \) are the flame pixel coordinates, and \( i \) – the number of pixels taken up by the flame. The method of determining the flame area, the effective radius and the flame geometrical centre is shown in figure 6.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{The procedure for determining the flame area, the effective radius and the flame centre coordinates.}
\end{figure}

It was assumed that these indicators, determined for using a flat exposure of a spatial image, describe the propagation of the flame in a representative and sufficiently accurate manner [17]. The analysis included the flame area, the flame effective radius, its velocity and the coordinates of its centre (figure 7). The flame area analysis (obtained using images – table 3) indicates the largest flame area for the largest supply voltage strategy (170 V). A similar flame area and effective radius characteristics were obtained for combustion using the rate-shaping strategy. Only using the minimum supply voltage values in controlling the injector, which cause the least movement of the injector needle, resulted in a reduction in the size of the flame area and – by extension – its effective radius.

Analysis of the flame propagation rate, determined using the effective flame radius shows, that it remains within the same value range – up to a maximum of 10 m s\(^{-1}\). Combustion for the rate-shaping injection strategy is slightly different from the maximum voltage strategy. The coordinates of the flame centre were also used as an additional indicator.
The combustion process optical indicators determined based on the combustion process data for: a) the flame area, b) effective flame radius, c) effective flame radius change, d) change of the flame centre in the combustion chamber.

The analysis of figure 7d demonstrates the non-repeatable nature of this parameter. Combustion always begins at the spark plug, but the direction of the flame development is not easily predictable. It should be noted that this indicator allows assessing the repeatability of local values associated with the flame. It is not a substitute indicator, but indicates the actual development of the flame and the direction of its propagation.

5. Conclusions
A comparative assessment of the obtained results and analyses leads to the conclusion that the rate-shaping system enables a significant increase in the control of the combustion process. Combustion with the use of the rate-shaping strategy compared to the maximum control voltage value strategy (maximum opening of the injector) results in:

a) smaller maximum combustion pressure values (by 10%); although the occurrence of this value has been delayed,
b) similar maximum heat released values (the value obtained is lower than for the other strategy’s largest value by 2.5%),
c) slight changes in the flame area and a very similar effective flame radius,
d) slightly lower flame propagation velocity during its development, the obtaining maximum flame velocity values were smaller by about 2 m s\(^{-1}\).

Additionally, the performed analyses indicate the correlation of the injection control methods with the obtained model engine operational indicators.
Analysis of the test results indicates the possibility of using rate-shaping in high-pressure injection systems. Analysis of its use in systems with sequential fuel injection may result in much greater benefits than obtained in the analysed tests (without fuel dose staggering). Additionally, the assessment of ecological changes (based on the literature analysis in relation to CI engines with rate-shaping systems) may indicate the desirability of using this fuel injection system in spark-ignition engines.

Symbols and abbreviations

$A$ – flame area
$I$ – current
$P$ – pressure
$q$ – fuel dose
$Q$ – heat release
$r$ – flame radius
$SOInj$ – start of injection
$t$ – time
$U$ – voltage
$V$ – flame speed
$\varepsilon$ – compression ratio

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Acknowledgements

The study presented in this article was performed within the project 05/52/DSPB/0246 financed by Polish Ministry of Science and Higher Education.