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The influence of petrol injection parameters on the structure of geometry of fuel spray injected from outward-opening injectors

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ABSTRACT

The paper deals with the issue of determining the geometry of fuel spray generated by the outward-opening type of injectors. The design of the outward-opening type injector is the reason for the initial fuel flow taking a circular shape (an empty cone). With increasing pressure of the injected fuel this geometry changes into a square one. The aim of the research was to determine the conditions of these changes and to propose how to define the geometry in the form of an indicator z (accepting positive values – for circular geometry, and negative values – for square geometry) as well as to generalize the equation z_{eq} making it possible to determine the indicator of the fuel spray geometric structure changes. The defined indicator z shows that fuel injection pressure exceeding 15 MPa plays an important role in changing the geometric structure of the fuel spray. The back pressure of the medium into which the fuel is injected does not affect the determined value of the indicator. Additionally, an indicator of variation of radial penetration of the fuel spray CoV(S_r) and the indicator of linear to radial fuel spray penetration $S_l/S_{r\text{-}av}$ were determined, which only under certain conditions can replace the z indicator.

1. Introduction

Direct fuel injection is realized by different types of injectors: multi-hole and outward-opening injectors. The way fuel is atomised by these injectors is different than in the multi-hole atomisers and results in a different way of delivering fuel to the combustion chamber. The paper deals with the issue concerning determination of the fuel spray geometry generated by the outward-opening type of injectors. They are characterized by the formation of a cone-shaped fuel spray with a given angle of the apex (usually 90 degrees).

Works on stratifying the mixture in spark-ignition engines were started about 20 years ago. A broad spectrum of the issue of direct-injection technology was presented by Zhao et al. [1]. This analysis involved both multi-hole types of injectors: inwardly and outwardly opening. The combustion system with a similar supply method was also presented in paper [2]. The studies of combustion in direct injection fuel system were the subject of further research: the analysis of this process for multi-hole injectors was presented by Drake [3], and for the injectors of outward-opening type – by Alkidas et al. [4] and Achleitner et al. [5]. The latter work concerned the analysis of ignitability of the mixture taking into account the changes of the injection and ignition timing. Within the framework of the research the only analysis carried out was fuel spray penetration in the context of its reaching the spark plug. Implementation of this solution in manufactured versions of combustion engines was presented by Bock et al. [6] in 2008. The effect of the injection strategy on the ignitability of the mixture and the emission of exhaust components was presented in the work by Warnecke et al. [7].

The design of the outward-opening injectors is different from traditional internal-opening injectors and also different from the pintle type injectors. The design of the outward-opening injector was widely analysed in the works [7–9]. The fuel from the rail and high pressure pipe enters into the nozzle. This injector includes in its design the main part that opens the needle (upper nozzle gallery), which in the lower part has holes (usually four) to allow the flow of fuel. These holes at specific values of fuel and pressure of the medium cause a distortion of the geometry of the flowing fuel spray. The final fuel flow takes place within the scope of the angle of 360 degrees, since the final, lower part of the needle is built in the form of a full cylinder [10,11]. The opening of the needle according to different authors ranges from 35 μm [12] to 40 μm [13]. Variety of solutions of piezoelectric injectors of outward-opening type was presented by Arcomanis and Kamimoto [10]. These authors also presented alternative designs of the needle in the forms of a ring below the guides, a 3-passage guide and an inward seal band.

Gavaises et al. in their work [11] presented a simulation study in which the specificity of the design of the injectors with outward

Abbreviations: DISI, direct injection spark ignition; CoV, coefficient of variation; PIV, particle image velocimetry; CVC, constant volume chamber; CI, confidence interval

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Nomenclature

P_b	back pressure
P_{inj}	injection pressure
t	time
S_r	radial penetration
S_l	linear penetration
t_{inj}	injection time (energizing time)
z	indicators of the fuel spray geometry change from circular into a square geometry
W	width of spray

opening of the needle was taken into account. The fuel flow speed changes were indicated, occurring with the change of the angle of the cone of spray in the range of 50–70 degrees, and depending on the changes of the injector needle opening (needle lift up to 70 μm).

Early works on optical studies of fuel spray indicated the possibility of determining the radial penetration only during the analysis of the linear penetration in a plane parallel to the axis of the injected fuel spray [14]. Present solutions of injectors indicate the need of taking into account this penetration analysed for the axis perpendicular to the axis of fuel spray (outward-opening injectors). The authors of [15] by making analyses of fuel atomization in outward-opening injectors presented only the results of the tests of the linear penetration of fuel spray development. They identified problems in determining the penetration of a multi-part injection analysis.

Fansler et al. [16] analysing the atomisation of fuel from outward-opening injectors showed the relationship between the start of fuel injection and the ignitability of the mixture. The work presented the impact of the linear penetration of fuel spray on the ignitability of the mixture. A significant influence of the rate of fuel flowing from the injector on the position of the electric arc that appears on the spark plug electrodes was indicated. Similar tests using PIV and Mie methods were presented by Stiehl et al. [17]. The studies analysed the effect of combustion chamber geometry on the conditions prevailing during atomisation of fuel from the outward-opening injectors. Analyses were made mainly in relation to the linear penetration of fuel spray. Marchi et al. [18] analysed the change of fuel spray cone angle depending on the conditions of fuel injection and how a fuel dose is divided. These studies were carried out using different types of outward-opening injectors (positive-step inward seal band, negative and no-step).

Gavaises et al. [11] when modelling the fuel atomisation from the outward-opening injectors took into account the specificity of its design (simulations of several ways of "cutting out" the leading part of the injectors were made). Despite a wide analysis of the linear penetration, no changes in radial penetration of such a model were indicated. In the tests presented by Hermann et al. [12] the analysis of the linear and radial penetration of the atomised fuel was included. However, the radial penetration was determined on the basis of fuel spray width in a plane parallel to the axis of the fuel spray. The orthogonal projection was not analysed (in the plane perpendicular to the axis of the fuel spray). Similar results of research were presented by Choi et al. [19]. The authors [19] tested the penetration of liquid and vaporized fraction of fuel spray and the corresponding widths. Analyses were conducted using LIEF (laser-induced exciplex fluorescence) and PIV (particle image velocimetry) methods. Approximately 40 percent increase in the penetration of the vaporized fuel compared to liquid fuel was observed. Similar values of changes were obtained for fuel spray widths (representing vaporized and liquid phases). Research conducted by Kim et al. [20] concerned analysis of linear penetration of fuel spray in a combustion chamber. A comparison of the experimental tests and simulation tests was performed. The obtained high consistence of the model with the simulation tests enabled the analysis of the fuel distribution in the combustion chamber in the vicinity of the spark plug.

The tests of the radial distribution of the fuel spray were presented by Skogsberg et al. [21]. Their analysis involved the time range up to 1 ms. Such a short period of time from the start of the injection did not allow to observe the changes of the geometric structure of the fuel spray.

Oh et al. [22] in their tests showed a change of linear fuel spray penetration, depending on the pressure of the medium into which the fuel was injected. For the change of the pressure of the medium from 0.1 to 1.5 MPa, linear penetration was observed to be less than half of its previous value. The images taken with the use of PLIF technique allowed the authors to analyse only the linear penetration of fuel spray.

The analysis of the linear and radial penetration of gasoline for the second generation of petrol injection systems was presented by Zigan et al. [23]. By conducting the tests in two planes of fuel injection, the radial penetration was presented also taking into account the fuel spray width (on the basis of the plane parallel to the axis of the fuel spray). Despite this, the authors pointed out the non-uniformity of the fuel spray geometry in a plane perpendicular to the axis of out-flowing fuel. The analysis in the parallel and perpendicular planes was performed in two separate research modes. As the two planes of fuel spray were not recorded simultaneously, for the calculation of the radial fuel spray penetration current (parallel) exposure of the fuel spray was used.

The above analysis of the literature indicates the influence of the shape of the nozzle gallery on fuel atomisation. The presented studies relate mainly to fuel atomisation in a plane parallel to the axis of the injected fuel. Due to the lack of analysis of the shape of the fuel spray in a plane perpendicular to the axis of the fuel spray, tests were carried out which involve elements pointing to the importance of this issue. Within the study, the indicators to determine the shape of the obtained geometry of fuel spray were defined.

2. Tested object and conditions of research

The aim of the study was to determine the indicators of the changing fuel spray geometry: from circular to square, and to determine the conditions of the change taking into account fuel pressure and counter-pressure of the medium into which the fuel is injected.

The analysis of fuel spray penetration and changes of the geometry of out-flowing fuel spray was performed using an outward-opening type injector (Table 1) while supplying the injector with gasoline with the parameters shown in Table 2. The tests were carried out for variable values of the fuel pressure and variable counter-pressure of the medium, into which the fuel was injected.

The tests of the fuel spray geometry were done using a constant volume chamber. The internal volume of the chamber was 2.49 dm^3. The chamber had optical access on five sides, which enabled observation of the development of fuel spray in a plane parallel and perpendicular to the fuel spray axis. The optical diameter of the windows was 80 mm. The study used a high speed camera HSS5 by LaVision in two planes to record the fuel spray development (parallel and perpendicular). Using the image doubler it was possible to record the two penetrations of the fuel spray (linear and radial). This approach allowed for an assessment of both fuel spray penetrations at the same time. Two simultaneous images are formed on the halves of the matrix, which

Table 1
Fuel injector specification [5].

Injector	Outward-opening piezo-injector
Dynamic flow	14. 5 mg/inj ± 10% at 0.4 ms
Minimum dynamic flow	< 2 mg/str
Spray angle	90° ± 3°
SMD size	~15 μm
Opening/closing time	> 150 μs
Maximum voltage	190 V
System pressure	5–20 MPa

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