JOURNAL OF MECHANICAL AND TRANSPORT ENGINEERING
Vol. 70, no. 1 2018
DOI 10.21008/j.2449-920X.2018.70.1.04

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(Received 16 Nov 2017, Received in revised form 24 Mar 2018, Accepted 25 Mar 2018)

SIMULATION STUDY OF THE INJECTIOR LOCATION IMPACT ON THE COMBUSTION PROCESS THERMODYNAMIC INDICATORS OF A SPARK IGNITION COMBUSTION ENGINE

This article is an introduction to the comprehensive study of the impact of fuel injectors placement for an internal combustion SI engine with direct gasoline injection. Ultimately, the study will focus on the applications for a fuel supply system simultaneously injecting two liquid fuels, which will help identify the qualitative and quantitative phenomena related to fuel injection and combustion in a novel solution. Designing the system correctly requires performing simulator tests for simpler systems – with one injector placed in the combustion chamber. The article presents a study of the change in angular position of the injector as well as a change of its location in the combustion chamber.

Keywords:fuel injection, fuel mixing, combustion, simulation study

1. INTRODUCTION

At present there is a noticeable trend in the development of SI internal combustion engines designed for vehicles, which consists of optimizing the fuel injection and combustion processes. The aim is to reduce fuel consumption and harmful compounds emissions while maintaining the same engine efficiency, mainly in range of small and medium loads. Hence, new technical solutions for injection molding with increasing dosage accuracy as well as methods for shaping laminar and homogeneous-laminar fuel mixtures [Pielecha 2012].

This study presents the preliminary stage of research on simultaneous injection and combustion of differentiated liquid hydrocarbon fuels (using direct injection

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systems). The conclusions of the study will be used to determine a suitable fuel supply system solution of an internal combustion engine with two different fuels injected directly into the combustion chamber. The authors have already performed preliminary simulation tests confirming the possibility of injection and combustion of various fuels mixed directly in the cylinder [Sidorowicz and Pielecha 2017]. The most important conclusions regarding the applicability of this arrangement were as follows.

The research concerns the effects of using three different fuels in combination with gasoline for separate direct injection on spray and flammability of the mixture created directly before ignition.

It was shown that it is possible to shape the air excess ratio in the area of the spark plug by injecting different fuels. Isopentane and ethanol injected through a separate injector than the gasoline have various effects on the air-fuel mixture in the area of combustion initiation. The quantitative properties of the spray were presented and the effects described.

The air excess ratio value in the spark plug area depends on:

- fuel density – its increase causes limitation of the fuel outflow from the injector nozzle, and as a result – the limitation of fuel spray range,
- injection timing of different fuels – different fuel properties, which means: enthalpy of evaporation, density, specific heat and stoichiometric air/fuel ratio cause different flammability condition in the spark plug area.

2. STAGE OF RESEARCH PROGRESS CONCERNING THE ANALYZED CONCEPT

2.1. Introduction

Direct gasoline injection is a solution that very quickly replaces the indirect injection technology inSI engines. The share of direct injection engines in new SI-powered vehicles in the US market increased from 5% to 46% between 2009 and 2015. It is estimated that the share of these engines in all road vehicles will be over 50% by 2020 [Zimmerman et al. 2016]. There are many technical solutions for SI engines fuel injection, which have been used in commercial applications and have been extensively described in the literature. Unconventional power supply systems for spark-ignition engines using direct and indirect injection include:

1) multiple fuel injection,
2) water injection in SI engines,
3) a combination of direct and indirect fuel injection,
4) direct gasoline injection using two injectors.

Partial characteristics of the above described methods are included in subsequent sections of this work.

2.2. Injection of different fuels in SI engines

Venugopal and Ramesh [2014] analyzed the effects of using a mixture of gasoline and n-butanol formed through indirect injection. These studies show that separate fuel injection to the intake manifold lowers emissions of HC and CO, and the use of n-butanol as a second fuel increases the engine efficiency. Both effects depend on the engine load.

Elfasakhany [2016] used a mixture of petrol and acetone as supply for an SI internal combustion engine and compared its effects to using gasoline. The use of acetone as a fuel additive (fuel mixed before injection) improves the reactivity of the fuel/air mixture while having a positive effect on fuel efficiency and emissions.

2.3. SI engine water injection

Another unconventional solution is the indirect water injection system for the SI engine. For the first time this system has been used in series to power a BMW M4 GTS engine, as described by Böhma et al. [2015]. Water is not a fuel, but its use greatly influences the combustion process. The effects of water evaporation before and during the combustion process reduce fuel consumption and improve engine performance.

2.4. Indirect and direct fuel injection combination

The direct and indirect gasoline injection into the SI engine is thought to hold great potential. It is used as a solution in the engines of the VW Group [Heiduk et al. 2011] or Toyota [Ishiguro et al. 2013]. Depending on the engine load and engine speed, fuel is delivered through one or two injection systems to achieve optimum engine performance.

Many scientists have used similar fuel mixing systems in which fuels are supplied with separate injection systems. An example would be a system with a direct injection of gasoline and n-heptane supplied by an indirect injection system [Qian et al. 2016]. Depending on the type of petrol used (its octane number) and the relative amount of n-heptane added, the engine's resistance to knock, combustion efficiency and chemical composition of the exhaust gas changes accordingly.

2.5. Gasoline direct injection using two injectors

The literature analysis indicates that the use of either angled or reciprocal injection with two injectors was not investigated very often. Research on the feasibility of such solutions in the field of reciprocal injection was performed by Jelitto [2004], but it did not provide satisfactory results. The study involved gasoline injection using multi hole injectors. However, these studies have not resulted in changes to the fuel spray in the vicinity of the spark plug.

The concept of the fuel supply system using two high-pressure injectors directly in the cylinder was created in the Department of Combustion Engines. The technical adaptation of this solution for a combustion engine was described in the Master thesis by Dmowski [2015]. Research on the injection and spraying of gasoline in such a system was carried out by Borowski [2016]. One type of fuel was used for the study, but the proposed possibility of fuel spraying process control opens up new possibilities in the field of fuel mixing research.

The authors will focus on the using this system to identify the effects of the use of different fuels injected directly, independently of each other.

3. RESEARCH STAGES

The analysis of the test results aims to determine the quantitative and qualitative characteristics of fuel injection and combustion in an SI engine equipped with a custom designed injection system. In article [Sidorowicz and Pielecha 2017], the authors analyze the effect of using different fuels injected directly into the combustion chamber on theair excess ratio in the area near the spark plug. This study focuses on determining the position of the injectors that will allow to obtain an unambiguous direction of the changes in these quantities. This will allow to determine the effect of placing the injector (or injectors) on the fuel injection and spraying indicators. The research will be conducted in several stages, and the most important elements of this research are:

1) determining the effect of the location of one injector in the direct fuel supply system for the preparation of the fuel and the combustion of the fuel-air mixture,

2) determining the impact of the location of the two injectors in the direct petrol injection fuel supply system for dose preparation,

3) analysis of the influence of the single injector location on the fuel-air mixture combustion process,

4) estimation of the influence of the two injectors location in the supply system of two hydrocarbon fuels for dose preparation,

5) analysis of the influence of the two injectors location on the fuel-air mixture combustion process.

The proposed method of dividing the study into stages is a logical reasoning sequence when designing, analyzing and verifying novel fuel supply systems for various engine fuels with direct injection of light (liquid) hydrocarbon fuels. The methodology of the study involves simultaneously conducting both simulation and experimental tests. At each stage of the study, the results from both types of study can be used to make changes or corrections.

4. RESEARCH METHODOLOGY

The methodology of the study of all the above-mentioned stages includes parallel experimental and simulation analysis. Simulation tests will be conducted in the AVL Fire 2017 simulation environment. This environment allows CFD simulations to be performed on all the processes necessary to determine the effectiveness of the combustion system. These processes include the fuel injection and spraying process, the mixing process and the combustion process. In addition, results will be obtained regarding combustion quality in the form of nitrogen oxides and particulate matteremissions. The obtained simulation values will be verified in the further stages at the test stations: the constant volume chamber, the rapid compression machine and the one-cylinder test engine.

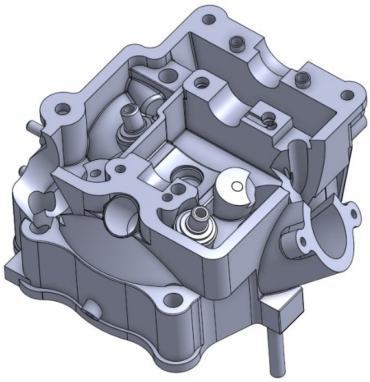
The initial step described in this article is to simulate fuel injection and spray using a single injector. However, the full study methodology will include a test of complete system with two injectors in the combustion chamber (Fig. 1).

a) b)

Fig. 1. Concept of the technical execution of the injection system: a) model of combustion chamber geometry together with injectors placed above it, b) model of the cylinder head to be placed in a constant volume chamber or a rapid compression machine

Experimental verification of the new combustion system is planned using a single-cylinder engine. Its design and development was performed at Institute of Combustion Engines and Transport (Poznan University of Technology). The engine head is adapted for fuel supply with two injectors, eliminating the use of two of the four engine valves (one inlet and outlet). The test engine design was created this way (Fig. 2). This project was executed and described in [Dmowski 2015]. In the next stage of technical work conductedon the analyzed system, activities related to the construction of such a system will be undertaken.

a) b)



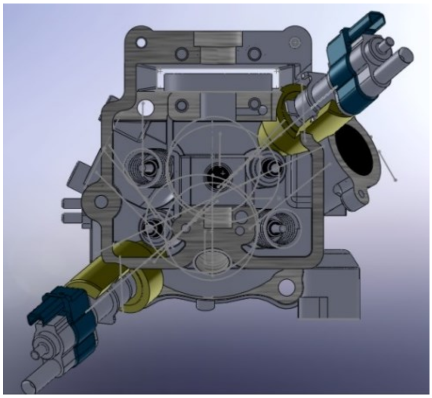


Fig. 2. The cylinder head model of the injection system with two injectors: a) camshaft view, b) layout model with injectors [Dmowski 2015]

5. THE IMPACT OF PLACING THE INJECTOR IN THE COMBUSTION CHAMBER ON THE THERMODYNAMIC FUEL INJECTION CONDITIONS

Simulation tests are carried out on a single-cylinder test engine, the cylinder head of which is shown in Fig. 2. This engine's technical parameters (Burgman) are shown in Table 1.

Table 1. Modeled engine technical data

Parameter	Unit	Value
Type	–	Piston engine, 4-stroke, spark ignition
Cylinder number	–	1
Displacement	cm^3	385
Compression ratio	–	10.2
Bore	mm	83
Stroke	mm	71.2

For this stage of the study (injection with one injector) a simulation model was prepared – geometry of the combustion chamber (Fig. 3).

a) b)

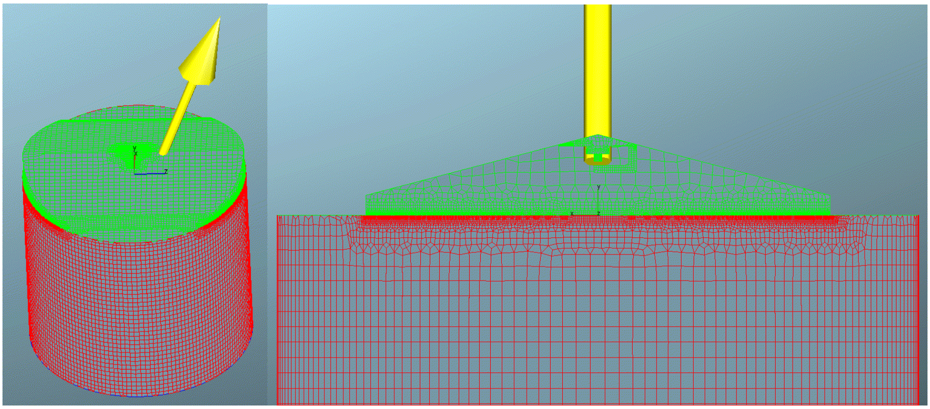


Fig. 3. The combustion chamber geometry adopted for the simulation: a) view of the injection site, b) cross section through the spark plug electrode

This phase focuses on the analysis of the classical, direct injection of liquid fuel (gasoline) in a spark-ignition engine. This test constitutes the base solution for considering further research stages in which the system will contain two gasoline injectors.

The analyzed case concerns fuel spraying. 2D (two-dimensional – average) and 3D (3D – local) results were generated for selected angular positioning configurations and alignment of the linear injector relative to the spark plug (Fig. 4).

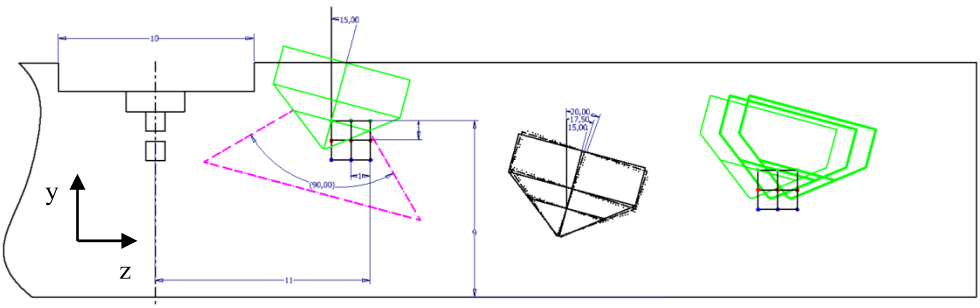


Fig. 4. The layout of the injector relative to the spark plug, together with the parameters used for the injection and combustion analysis (angle, distance)

The tests refer to the variable angular position of the injector and its changes in the plane y and z. The test variants are shown in Table 2.

Table 2. Test injector variants in the combustion chamber

Variable	Unit	Change value
y coordinate	mm	9; 10; 11
z coordinate	mm	7; 8; 9
angle	deg	15.0; 17.5; 20.0

Only a part of the simulation study (the total number of variants is 27) is presented in the article. Fig. 5a shows the preliminary results of the fuel spray analysis, taking into accountonly the linear change in the injector position (variable y according to Fig. 4). The most advantageous position is largely embedding it in the combustion chamber. In this case, the amount of evaporated fuel is the largest at a fixed angle of crankshaft rotation. This is due to the proper distance of the injector from the spark plug electrodes. This position prevents the jet from reaching the spark plug electrode and allows increasing the fuel evaporation.

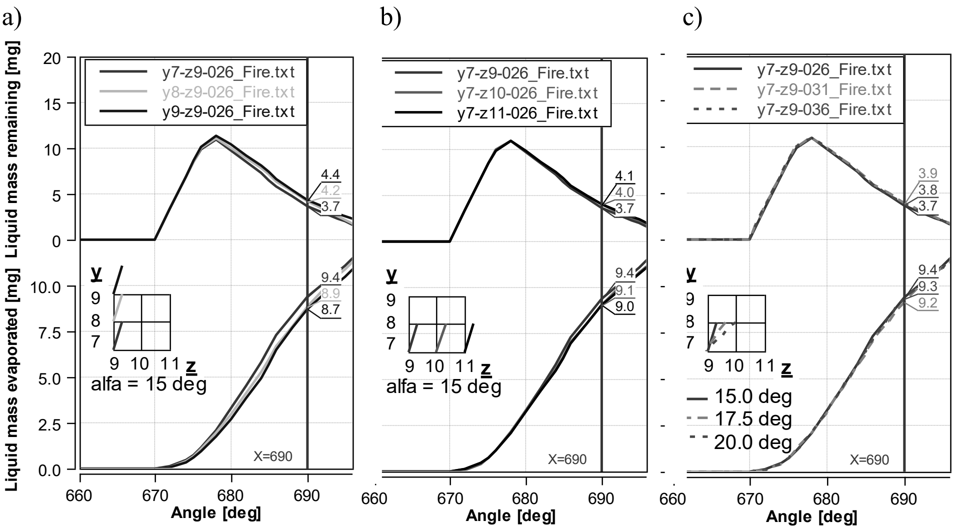


Fig. 5. Influence of change of injector position in the combustion chamber: a) change of the y coordinate (change of height), b) change of the z coordinate of the injector distance from the spark plug, c) change of the injector position angle in the combustion chamber

Repositioning the injector in the direction of the z-axis (Fig. 5b) results in higher evaporated fuel values, thus reducing the mass of the unevaporated fuel. Change ofthe z coordinate reduces the amount of unevaporated fuel by 7%compared to the y coordinate change, however, only at high values of this offset (from the spark plug). The values obtained by changing the y-coordinate (9 mm) are the best option, as further increasing the distance from the plug in the horizontal direction causes the spray to deteriorate. It may be assumed that it would be preferable to reduce the z coordinate, but this is not possible due to structural reasons (the minimum spark plug distance from the injector must be maintained).

Increasing the angle of the injector deflection from the assumed base angle (this was 15 degrees) causes the fuel spray to deteriorate (Fig. 5c). This is due to the fact that changing the angle can cause partial injection and fuel spray on the walls of the combustion chamber.

In further analysis, the results of local fuel spraying processes were also helpful. Figure 6 shows the isolation of the air excessratio constant value during the petrol injection depending on the crankshaft rotation angle in the selected geometric configuration of the injector.

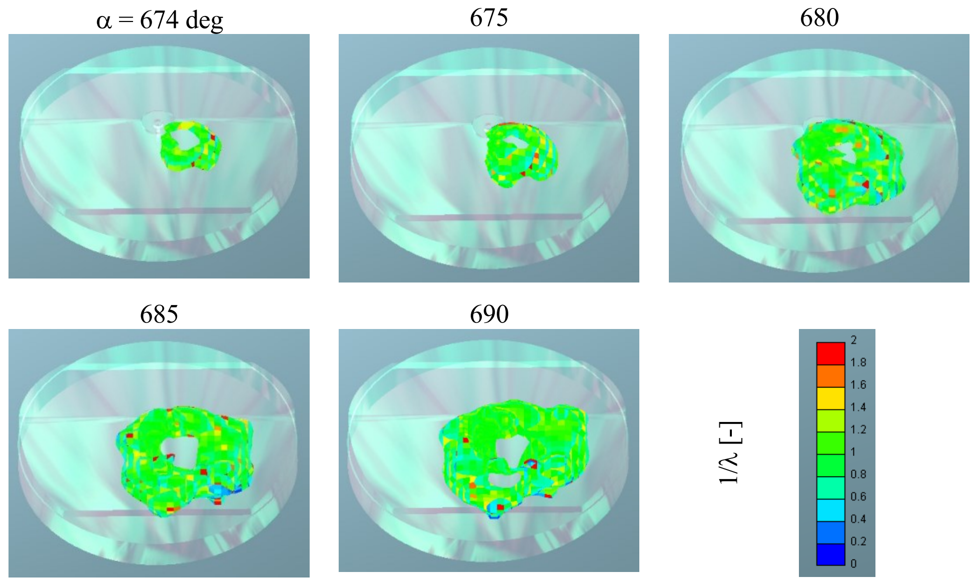


Fig. 6. Isolating the constant value of λ = 1 of the fuel dose development in the combustion chamber (injector position relative to the spark plug y = 7 mm, z = 10 mm, alfa = 15°)

As can be seen from the presented isoline, the proper positioning of the injector has specific effects on the development of the fuel dose in the combustion chamber. Thanks to the different positioning of the injector, it is possible to choose the most advantageous solution in terms of the effects of fuel injection and spraying.

Therefore, the first research stage must be supplemented with the combustion studies using the above-described variants (Table 2). However, it is expected that the best solution for combustion (maximum output values while maintaining the minimum values of harmful components emission) will be similar to the one analyzed. The final choice of the injector location should therefore take into account the weighed factors of the combustion indicators and the combustion products (exhaust emissions). Their selection is one of the elements of the next stage of research.

6. CONCLUSIONS

This article presents an outline of a research study on the impact of the injector geometry on the fuel atomization and combustion indicators. The information provided in the article describes the current research and application possibilities of unconventional injection and combustion systems for liquid fuels.

Current research focuses on the injection analysis in a one injector system. Analysis of the injector position choice (9 variants presented in the article) in this configuration (centrally placed spark plug) lead to the following conclusions:

a) the largest evaporated fuel mass value was observed for the injector position of y = 7 mm (the range of variation of this value is 8% at y = 9 mm);

b) moving the injector away from the spark plug axis (from z = 9 to z = 11 mm) results in lower fuel evaporation of up to 5%;

c) change in the injector angle causes the least change in fuel evaporation: at an angle of 15° this value is the highest and decreases by about 3% at the angle of 20°.

The presented conclusions indicate the importance of the injector spatial position in the combustion chamber. In further research these results will be complemented by the influence of the injector's position on the combustion process indicators. Both the thermodynamic process indicators and the emission indicators will be analyzed.

The one injector combustion system configuration will be used as the reference point for testing the system with two injectors. The research plan is to test such a system in terms of the injector positions selection in relation to the injection process itself and the fuel atomization as well as in relation to the combustion process. These solutions will be compared with the simultaneous analysis of all process indicators (injection and combustion). Multivariate simulations will allow for a wide range of results (27 test configurations). Next, they will be subjected to an optimization process in order to search for the optimal solution.

Continuation of the subsequent research stages will contribute to testing and identifying of the new combustion system. This system will allow the cylinder to be supplied with various fuels that will be mixed directly in the combustion chamber.

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ACKNOWLEDGEMENTS

The study presented in this article was performed within thestatutory research (contract No. 05/52/DSMK/0265).

SYMULACYJNE STUDIUM WPŁYWU UMIEJSCOWIENIA WTRYSKIWACZA NA PRZEBIEG WSKAŹNIKÓW TERMODYNAMICZNYCH SPALANIA W SILNIKU ZI

Streszczenie

Artykuł jest wstępem do kompleksowych badań wpływu umiejscowienia wtryskiwaczy paliwa zasilającego silnik spalinowy o ZI wyposażony w bezpośredni wtrysk benzyny. Docelowo studium skupiać się będzie na wnioskach dotyczących układu zasilającego dwoma różnymi paliwami płynnymi równocześnie, co przyczyni się do zidentyfikowania jakościowego i ilościowego zjawisk związanych z wtryskiem i spalaniem w nowatorskim rozwiązaniu. Poprawne zaprojektowanie układu wymaga przeprowadzenia badań symulacyjnych dotyczących układów prostszych – z jednym wtryskiwaczem umieszczonym w komorze spalania. W artykule zaprezentowano studium obejmujące zmianę kątowego położenia wtryskiwacza oraz jego zmianę położenia w komorze spalania.

Słowa kluczowe: wtrysk paliwa, mieszanie paliw, spalanie, badania symulacyjne