Journal of KONES Powertrain and Transport, Vol.14, No. 4 2007

THE INFLUENCE OF SPRAY GUIDED CHARGE ON POSSIBILITY OF STRATIFIED MIXTURE FORMATION IN SI GASOLINE DIRECT INJECTION ENGINE

Bronisław Sendyka, Sławomir Kudzia

Section of Special Engines
Faculty of Mechanical Engineering
Cracow University of Technology
Al. Jana Pawła II 37, 31-864 Kraków, Poland
skudzia@o2.pl

Abstract

In this paper there has been described the structure of ZI gasoline direct injection engines in which there has been applied spray guided. There has been shown the burning chambers structure of the engines of that type. There has been also presented the modification range of ZI engines equipped with system of gasoline multipoint indirect injection in order to get the gasoline direct injection engine with spray guided.

The authors have described the block diagram of fuel supply system of this type of an engine which is being developed in Cracow University of Technology's Combustion Engine Department. Certain information about mechanical modification of engine is given. They have proposed model of fuel air mixture stratification in a combustion chamber of spray guided engine, in which base homogeneous mixture come into being out of the this chamber.

In this paper there has been also designated an influence of an angle of crank shaft on initial velocity of fuel stream and on flow intensity of fuel stream that flows through the injector. There also has been presented an influence of air fuel coefficient of homogeneous base mixture on the angle on a crank shaft of ignition charge.

Keywords: *SI engine***,** *gasoline direct injection, spray guided, mixture stratification, fuel stream.*

1. Introduction

The newest solution of SI gasoline direct injection, that cherish the greatest hopes on future, is a spray-guided direct injection engine. Just today this system is called as the second generation direct injection engines[1]. The essence of this solution is guiding a fuel stream directly towards spark plug electrodes. Distance between a spark plug and an injector is small, therefore there is not necessity of driving charge over an air stream or a surface of a piston floor. It has a direct influence on decrease of fuel waste in range of 10-15 %. In this system it is possible to generate very well stratify charge and to dose appropriate (in given conditions of work) portion of fuel. In mentioned solutions there is used injection pressure equal 20 MPa.

Towards better exploiting higher initial velocity of the fuel stream, that results from the above, there is planning use of piezoelectric injectors in such engines. Those injectors in confrontation with electromagnetic injectors have shorter reaction time. This characteristic is conductive to making several injections during one work cycle, and this has positive influence on stratify charge generating. The next factor having an influence on concentration adequately rich charge in vicinity of spark plug electrodes is a properly shaped burning chamber. Reduction of the chamber size in its upper part where the spark plug and the injector are fastened, makes the fuel stream injected in the final phase of compression stroke remain in that space without dispersion in a whole burning chamber. The chamber has the shape, that approximates a bell. The schematic diagram of this solution is shown in fig. 1.

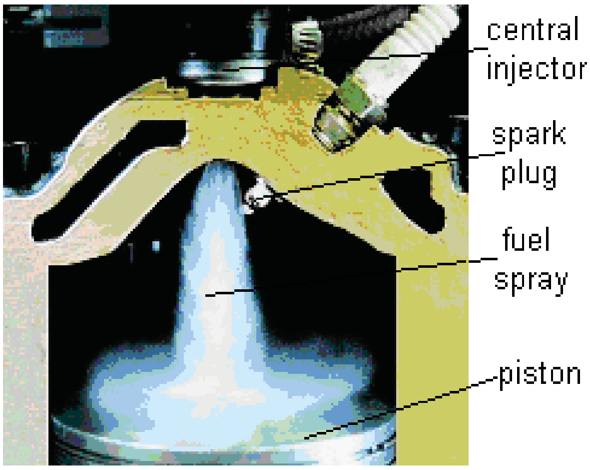

Fig. 1. The work scheme of Engine with Spray Guided Injection [2]

In fig. 1 it can be observed, that injected fuel stream flows between the spark plug electrodes. Similar scheme of burning chamber has been used in F5R (2.0 IDE) engine by Renault concern but there is one difference – this engine works only in homogenous mixture mode [2]. One of reasons of such state of affairs is the fact, that this engine is used for drive of sports cars.

This structure of a spark plug and an injector has been used in a burning chamber of CLS 350 CGI engine by Daimler- Chrysler concern. In this engine a piezoelectric injector is fastened top part of the chamber, diagonally in a short distance from the injector. This engine works in stratified mixture mode (fig. 2).

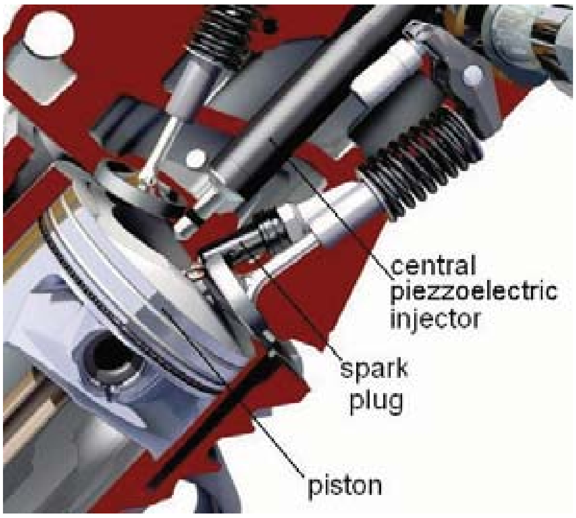

Fig. 2. Burning chamber of CLS 350 CGI engine with spray guided direct injection [3]

3. Modification of toyota engine head

One of more important elements of the engine modification is preparing in a head of serial engine with gasoline multipoint (indirect) injection additional holes which would enable to put into a combustion chamber some extra injectors of direct injection system.

In order to assure an appropriate tightness of the combustion chamber and water sheath of engine as well, there has been placed in holes been made earlier some bushes. These bushes have been fastened with help of special glue that is resistant to effect of high temperatures. There has been introduced high-tension injectors of serial produced 2.0 TFSI Volkswagen engine into the bushes. Their desirable feature is a position of a sprayer at an angle of 25° in relation to an injector axle. The injectors has been fastened in the head at an angle of 21° in relation to surface of adhesion to a cylinder block. Thanks of such configuration of the injector and its sprayer the fuel stream is lead directly to neighborhood of spark-plug electrodes. It is shown in fig. 3.

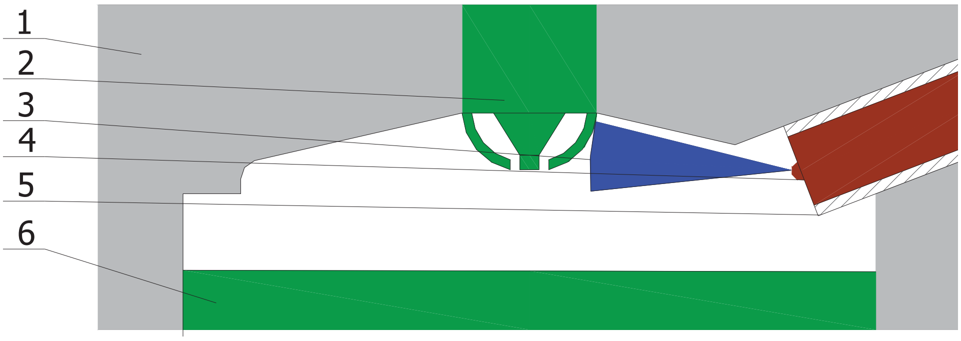

Fig. 3. The modified combustion chamber of the Toyota engine with spray guided fuel stream: 1- head, 2- spark-plug, 3- fuel stream, 4- injector, 5- leading bush, 6- piston

It is also possible to fasten the injectors with centrically located sprayers. Such solution allows on a change of way formation of ignition charge and consequently on estimation of the influence of spray guided charge on working parameters of ZI gasoline direct injection engine. The fixation way of the injector of gasoline direct injection system is shown in fig.4.

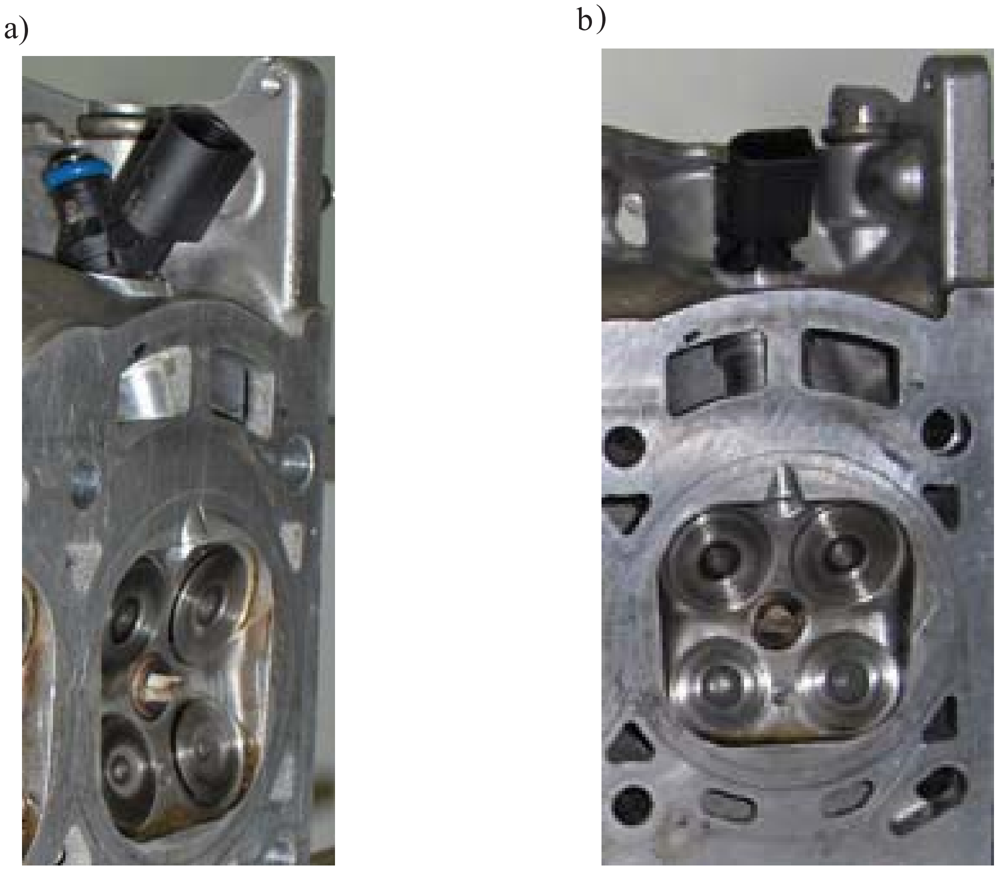

Fig. 4. Combustion chamber of the engine with spray guided charge, a- side view, b- front view

4. Model of fuel injection in the spray-guided direct injection engine

Schematic diagram of mixture stratification in spray-guided direct injection engine is shown in fig.5.

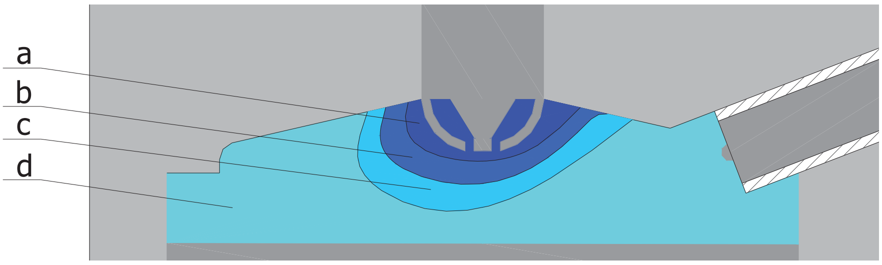

Fig. 5. Schematic diagram of mixture stratification in spray-guided direct injection engine; a,b,c – zones of stratify fuel ignition dose, d – zone of homogeneous charge

Diagram shown in fig. 6 presents three work modes of that engine according to the speed engine and load.

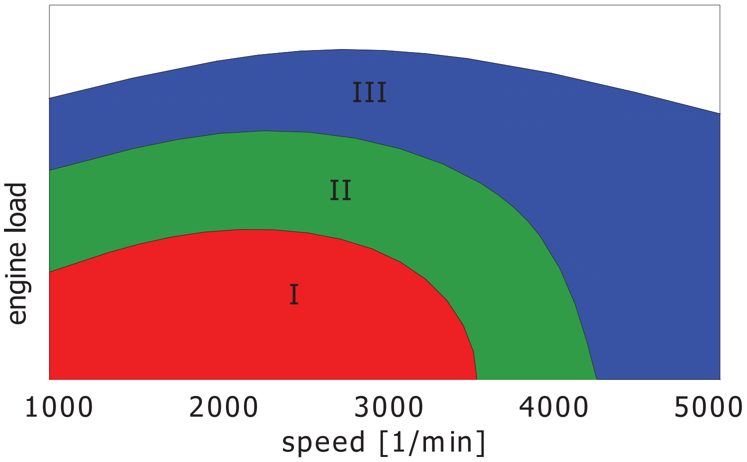

Fig. 6. Dependence of engine load value from the mode of its work

T Mode I – the engine works with ultra poor homogeneous mixture, that is generated by the fuel injection during compression stroke (zone „d" in fig. 5, for that λ=1,6), in the end of compression stroke there is injected stratify fuel ignition dose (zones „a", „b", „c" in fig. 5, for that λ_a=0.7, λ_b=0.8, λ_c=0.9).

Mode II – the engine works with poor homogeneous mixture, that is generated by the fuel injection during compression stroke (zone „d" in fig. 5, for that λ=1.35), whereas the fuel injection during compression stroke is a pilot dose that is indispensable for ignition of total charge (zones „a", „b", „c" in fig. 5, for that λ_a=0.7, λ_b=0.8, λ_c=0.9).

Mode III – the engine works with homogeneous mixture which composition is similar to stoichiometric; during compression stroke there is generated the charge which composition is similar to stoichiometric in whole burning chamber (zone „d" in fig. 5, for that λ=1.1); during compression stroke there is delivered fuel portion enriching the mixture in vicinity of the spark plug that improves burning conditions (zones „a", „b", „c" in fig. 5, for that λ_a=0.7, λ_b=0.8, λ_c=0.9).

4.1. Parameters of the engine

The model engine and process of charge forming are characterized through following parameters:

- winch radius of a crank Rw=0.0398 [m],
- diameter of a cylinder Dc=0.072[m],
- compression coefficient ε=11,
- displacement volume Vss=1296 [cm^3],

- slenderness of a connecting rod λ_s=1/3.5,
- diameter of an injector nozzle d_o=0.15 [mm],
- flow coefficient through injector C_D=0.46,
- injection pressure P=11 [MPa],
- pressure in the beginning of compression stroke P_{ps}=0.09 [MPa],
- pressure in the end of compression stroke P_{ks}=1.47 [MPa],
- stoichiometric constant for gasoline combustion L_t= 14.7,
- air density ρ_g = 1.27 [kg/m^3],
- fuel density ρ_p = 775 [kg/m^3],
- total volume of a cylinder V_w = 356.4 [cm^3],
- volumetric efficiency η_v = 0.75-0.9,
- air fuel coefficient of homogeneous charge,
  - mode I λ_h = 1.60,
  - mode II λ_h = 1.35,
  - mode III λ_h = 1.10,
- volume of zone „a" ignition dose
  $V_a = 0.008\ V_w(a_z)$,
- volume of zone „b" ignition dose
  $V_b = 0.027\ V_w(a_z)$,
- volume of zone „c" ignition dose
  $V_a = 0.065\ V_w(a_z)$.

4.2. Initial velocity of the fuel stream and the stream of fuel flow through an injector

The compression in an engine occurs during polytrophic transformation[4], therefore the change of pressure during this stroke , described through the equation (6), has been derived from the following equals (1)-(5):

average exponent of polytrophic [6]

$$n_p = \frac{\log(Pks) - \log(Pps)}{\log \varepsilon} = 1.16, \tag{1}$$

compression coefficient

$$\varepsilon = \frac{Vks + \frac{Vss}{4}}{Vks} \ , \tag{2}$$

burning chamber volume

$$Vks = \frac{Vss}{4 \cdot (\varepsilon - 1)} = 32.4[cm^3], \tag{3}$$

total volume of a cylinder

$$Vw = Vks + Vsz(\alpha_o), \tag{4}$$

variable volume of a cylinder resulting only from displacement volume

$$Vsz(\alpha_o) = \frac{\pi \cdot Dc^2}{4} \cdot Rw \cdot \left(1 - \cos(\alpha_o) + \frac{\lambda_s}{2} \cdot \sin(\alpha_o)^2\right), \tag{5}$$

compression pressure

$$Pc = \frac{Pps \cdot \left(\frac{Vss}{4} + Vks \right)^{n_p}}{\left(Vks + Vsz(\alpha_o) \right)^{n_p}} . \tag{6}$$

On the ground of the equal (7) [5] there has been estimated values of initial velocity of fuel stream, and results of these calculations has been presented in form of three-dimensional diagram and show in fig. 7.

$$U_0 = C_D \cdot \sqrt{2 \cdot \frac{P - P_C(\alpha_o)}{\rho_p}} . \tag{7}$$

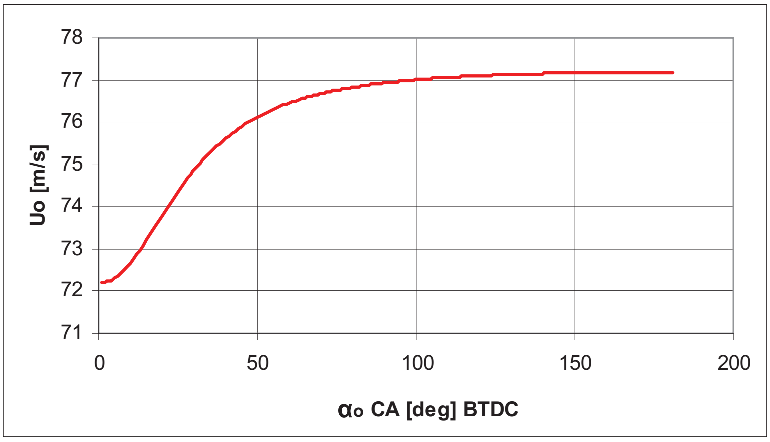

Fig. 7. Dependence of initial velocity of the fuel stream from an angle of injection advance

fuel flow stream through an injector

$$q = \frac{\pi \cdot d_o^2}{4} \cdot U_o \cdot \rho_p . \tag{8}$$

The decrease of initial velocity of the fuel stream, shown in fig. 7, results from the increase of the compression pressure alongside with a piston motion towards TDC (top dead center) [6]. The diagram presented below indicates the fact, that the injection pressure is the elementary parameter, which decides about initial velocity of the fuel stream in wall-guided direct injection.

The stream of fuel, that flows through the injector, is directly proportional to the initial velocity of the fuel stream, while it increases with growth of the injection pressure and an angle of injection advance [7]. This dependence is shown in fig. 8.

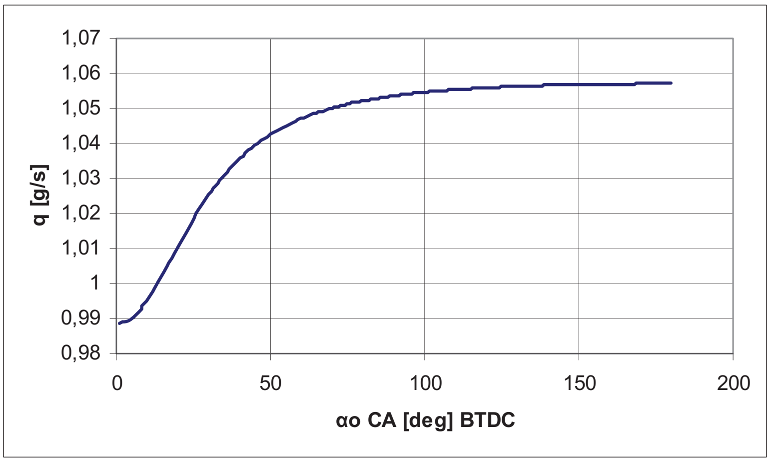

Fig. 8. Dependence of the fuel flow stream through the injector from an angle of injection advance

4.3. An angle of injection advance

On the ground of value of flow stream through the injector that has been presented in fig. 8 and mass of fuel injected to a burning chamber during a suction stroke (11) and compression (13) there have been calculated values of an injection pulse angle in each stroke [8]:
air mass sucked in a cylinder [8]

$$m_g = \frac{V_{ss}}{4} \cdot \rho_g \cdot \eta_v , \tag{9}$$

fuel mass injected to a cylinder

$$m_{pz} = \frac{m_g}{\lambda_z \cdot L_t} , \tag{10}$$

fuel mass injected to a cylinder during a suction stroke

$$m_{ph} = \frac{m_g}{\lambda_h \cdot L_t} , \tag{11}$$

fuel mass of zone „a" of ignition dose

$$m_{pa} = \frac{m_{ph} \cdot V_a}{V_w(\alpha_z) \cdot \lambda_a} \cdot (\lambda_h - \lambda_a) , \tag{12}$$

fuel mass injected to a cylinder during a compression stroke [9]

$$m_{pu} = \frac{m_{ph}}{V_w(\alpha_z)} \cdot \left[\frac{V_a}{\lambda_a} \cdot (\lambda_h - \lambda_a) + \frac{V_b}{\lambda_b} \cdot (\lambda_h - \lambda_b) + \frac{V_c}{\lambda_c} \cdot (\lambda_h - \lambda_c) \right], \tag{13}$$

$$m_{pu} = \int_{\alpha_0}^{\alpha_z} q d\alpha . \tag{14}$$

Thanks knowledge of ignition advance angle for particular values of the crank shaft of speed, it can be calculated the process of values changes of ignition advance angle for particular engine work modes, by means the equation (14). Results of calculations are set in fig. 9. From the diagrams shown in above figure results that enriching of base of fuel portion delivered into burning chamber during a compression stroke[10]. Then it causes the short of occurrence time of fuel injection and thus an injection advance crank angle.

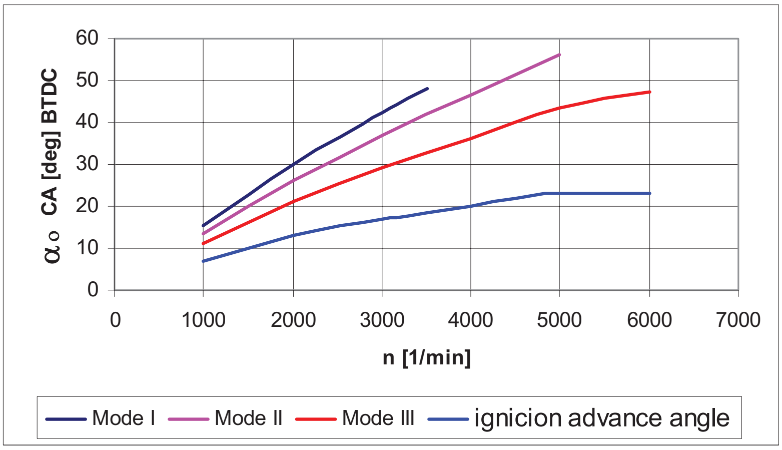

Fig. 9. Dependence of injection advance angle from speed engine and mode of work engine

6. System of power supply

Innovative technical solution which is being developed in Cracow University of Technology's Combustion Engine Department is next research stage in SI engine's spray guided direct injection. The main idea is of this research is implementation of two fuel systems. The first one, multipoint indirect injection system, is the basic fuel system of Toyota engine and its main task is creation of lean homogeneous mixture entering cylinder during suction stroke. The additional fuel system mounted on Toyota's engine is responsible for direct fuel injection during the compression stroke.

Its purpose is near spark plug mixture enrichment which facilitates ignition initiation. High homogeneity of base mixture is achieved trough extension of fuel vaporization time. Engine's Control Unit period will be replaced by adjustable unit which will be responsible for injection parameters control. With help of this unit such parameters as: pressure, advance angle, injection time can be adapted to variable engine's run condition. Total engine's efficiency increase is expected to be achieved with that solution presents Fig. 10. fuel injection system's block diagram.

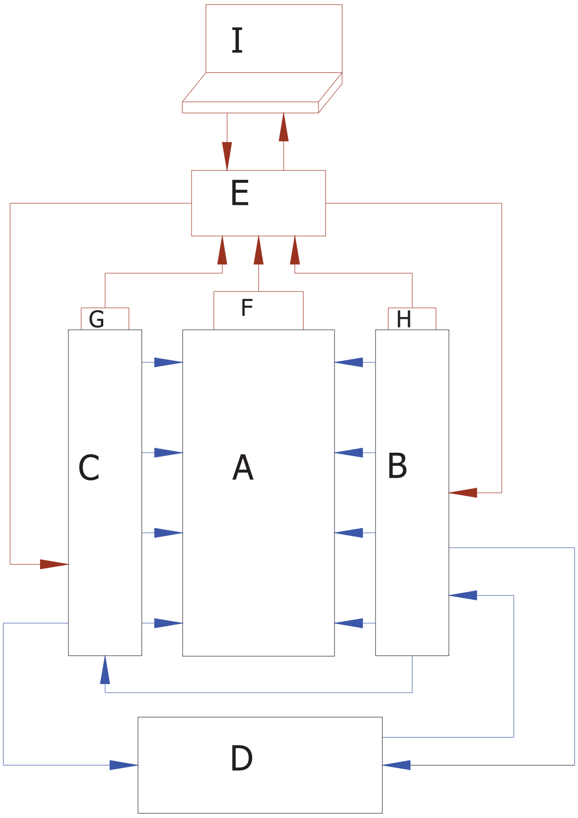

Fig. 10. Modified the engine's system block diagram. A- engine, B- MPI fuel system, C- direct fuel injection system, D- fuel tank, E- adjustable engine's control unit, F- engine's sensors, G- high-pressure fuel system's sensors, H- low-pressure fuel system's sensors, I- Personal Computer

5. Conclusions

1. In consideration of necessity absence of charge deflection from a piston floor and of not large space between a spark plug and an injector there is a possibility of stratify charge formation at high engine speed in spray-guided direct injection engine system.
2. Application of spray-guided direct injection system prevents a fuel film formation on a piston floor, especially at starting of a cold engine, and thus includes on decrease of hydrocarbons in exhaust gases.
3. Decrease of nitrogen oxides emission in spray-guided direct injection engine is possible thanks to combustion of homogeneous mixtures, that are enriched only with stratify ignition dose.

4. Homogeneity of base mixture in engine with spray-guided fuel injection can be achieved with use of indirect fuel injection.
5. Correlation between slope angle of injector in relation too cylinder axis and slope angle of sprayer against injector axis has significant influence an fuel flow direction.
6. Implementation of high-pressure fuel injection results in considerable fuel vaporization improvement due to fuel drops decrease. This solution gives additional advantage of injection time shortening.
7. Modification of existing engine into direct injection spray-guided injection will ease future application in commercial vehicles.
8. Enrichment of base mixture provoker's compression stroke fuel injection dosage decrease.

References

[1] BOSCH, *Bezpośredni wtrysk benzyny,* 2002.

[2] Majak, M., Rudak, Z., *Renault: spojrzenie w przyszłość*, „Auto" nr 4,1999.

[3] www.netzeitung.de

[4] Szargut, J., *Termodynamika*, 1998.

[5] Lumsden, G., Browett, C., Taylor, J., Kennedy, G., *Mapping Complex Engines*, Direct Injection SI Engine Technology 2004, SAE International 2004.

[6] Rychter, T., Teodorczyk, A., *Modelowanie matematyczne roboczego cyklu silnika tłokowego*, 1990.

[7] Sendyka, B., Kudzia, S., The analysis of power supply construction and burning process in engines with gasoline direct injection (GDI), KONMOT-AUTOPROGRES Zakopane, 2004.

[8] Sendyka, B., Kudzia, S. *Model of charge formation in spray guided direct injection engine,* "PTNSS KONGRES 2005" Bielsko Biała/Szczyrk, 2005.

[9] Sendyka, B., Kudzia, S. *Formation process of fuel-air mixture in wall-guided direct injection engine,* PTNSS KONGRES 2005 Bielsko Biała/Szczyrk, 2005.

[10] Sendyka, B., Kudzia, S., *Application spray guided of charge formation in SI engine with gasoline direct injection,* ICLAS, Kyoto, 2006.

NOMENCLATURE

C_D	flow coefficient through injector,	
Dc	diameter of a cylinder	[m],
d_o	diameter of an injector nozzle	[mm],
ε	compression coefficient,	
λ_s	slenderness of a connecting rod,	
L_t	stoichiometric constant for gasoline combustion,	
m_g	air mass sucked in a cylinder	[g],
m_{pz}	fuel mass injected to a cylinder	[g],
m_{ph}	fuel mass injected to a cylinder during a suction stroke	[g],
m_{pu}	fuel mass injected to a cylinder during a compression n stroke	[g],
n_p	average exponent of polytrophic,	
η_v	volumetric efficiency,	
P	injection pressure	[MPa],
P_c	compression pressure	[MPa],
P_{ps}	pressure in the beginning of compression stroke	[MPa],
P_{ks}	pressure in the end of compression stroke	[MPa],
q	fuel flow stream through an injector	[g/s],
Rw	winch radius of a crank	[m],

ρ_g	air density	[kg/m^3],
ρ_p	fuel density	[kg/m^3],
U_o	initial velocity of fuel stream	[m/s],
V_w	total volume of a cylinder	[cm^3],
V_a	volume of zone „a” ignition dose	[cm^3],
V_b	volume of zone „b” ignition dose	[cm^3],
V_c	volume of zone „c” ignition dose	[cm^3],
Vss	displacement volume	[cm^3],
V_{sz}	variable volume of a cylinder resulting	[cm^3].