APPLICATION SPRAY GUIDED OF CHARGE FORMATION IN SI ENGINE WITH GASOLINE DIRECT INJECTION.

Bronislaw Sendyka¹, Sławomir Kudzia²,

¹ Prof. D.Sc., Ph.D., Eng Bronislaw Sendyka Cracow University of Technology e-mail: bsendyka@usk.pk.edu.pl
² M.Sc., Eng Sławomir Kudzia Cracow University of Technology, skudzia@o2.pl

ABSTRACT

In this paper has been described the structure of a gasoline direct injection engine. There has been shown the burning chamber structure of the engine of that type. There have been also presented constructional differences spray guided engines.

There have been compared the parameters of the spray guided engines and also external characteristics of the mentioned engines. In this paper there are also showed the influence of combustion chamber shape and the way of the charge formation on toxic fumes emission to the atmosphere.

There has been designated an influence of an angle of crank shaft on a direction of a fuel stream movement.

This paper also presents the analysis of chances of piezoelectric injectors use in such type of engines in order to give facilities for stratify mixture formation.

There is also shown mathematical model of injection, by means of which there has been described a movement of fuel stream in combustion chamber.

The results of calculations have been helpful for the analysis of the influence of fuel injection pressure on an extent of fuel spray in a the chamber and on the angle of injection outdistance that is necessary for obtainment of stratification of fuel, ensuring the stable work of the engine.

Keywords: Gasoline Direct Injection, Spray Guided, Fuel Injection

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. 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 [1].

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.

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 [3]. 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 [4].](image)

Other conception of charge formation has been proposed by Volkswagen Concern in SI 2.0 FSI engine with gasoline direct injection (Fig. 3).

![Fig. 3. Burning chamber of VW 2.0 FSI engine with spray guided direct injection [5].](image)

In this engine there is also used model of charge formation with help of fuel stream. Fuel, that is injected into the burning chamber, is directed not towards a piston bottom but towards a spark plug. Relatively long way between the spark plug and the injector causes that air motion fixed by means of properly shaped inflow collector plays an important part in process of charge formation. The injector is placed in the burning chamber under the pressure of 11 [MPa]. Due to air whirl near spark plug electrodes there is accumulated a combustible cloud of air-fuel mixture. After ignition there is thermally isolating air coat between burning mixture and the piston walls, that decreases heat radiating through the walls of engine mounting. In order that engine work in stratified mixture may be realized there must be closely maintained: adequate parameters of fuel injection, the shape of burning chamber and internal flow of mixture in a piston. Therefore in stratified mixture mode work some valves controlling the air flow in inflow collector completely close its lower part. Because air flows only topside of the collector that cross-section is smaller, there is a rise of air flow speed. In the piston a stream of inducted air is “coiled up” proper shape of a piston bottom strengthens this effect. Maximal opening of a throttle has an influence on decrease of waste of inducted air flow. The development of FSI conception is turbocharged 2.0 TFSI engine (Fig. 4.), that in comparison with the FSI, works only in homogenous mixture mode. Among more important changes in construction of this engine should be mentioned: shape of a piston bottom and materials of which it has been made – these are characteristic of higher resistance. The higher resistance of materials is imposed by greater increase of engine power, that is obtained by using turbocharged when are maintained gabarits of FSI engine.

![Fig. 4. Burning chamber of VW 2.0 TFSI engine with spray guided direct injection [5].](image)

2. THE COMPARISON OF WORK PARAMETERS OF SI ENGINES WITH GASOLINE DIRECT INJECTION

External characteristics of the engine were prepared with full opening of the throttle, in other works with full load, so it can be say, that during making the characteristics show above, all engines had been working in homogenous mixture mode.

Fig. 5 shows external characteristics of VW 2.0 FSI engine. This engine achieves maximal power of 110 kW with speed of 6000 rpm. Its maximum torque is 200 [Nm] with speed of 3500 rpm.

Fig. 6 shows external characteristic of turbocharged 2.0 TFSI engine. The development of FSI engine conception is a turbocharged 2.0 TFSI engine (Fig. 4.), that in comparison with the FSI engine works only in homogenous mixture mode.
Drawing a comparison between works of both engines it may be designated an influence of turbocharged of SI engine with gasoline direct injection on its operating parameters. A fundamental influence, that is exerted by turbocharged FSI engine is an increase of power value and torque. The most important change is the value torque according to the speed of a crank shaft (Fig. 4). Maximal torque of TFSI engine with value of 280 [Nm] is approachable in the range from 1800 rpm to 5000 rpm. This characteristic much better improves an elasticity of engine work. A car provided in TFSI engine has greater speed-up than the one provided in FSI engine. Maximal power of 147 [kW] achieves in the range of torque from 5000 rpm to 6000 rpm.

On Fig. 7 there is presented external characteristic of a Renault F5R 2.0 IDE engine. Its maximal power with value of 103 [kW] occurs at crank shaft speed of 5500 rpm. Maximal moment with value of 200 [Nm] achieves at 4100 rpm.

From the comparison of work parameters of spray guided injection engine issues the fact, that despite different conceptions of the charge formation in burning chamber, they have similar performances. The FSI engine has slight higher maximal power. Although maximal torque trends the same level, it occurs at different speeds. Using of turbocharged much better improves the performances of SI engine with gasoline spray guided, but it limits possibility of its work in stratified mixture mode.

Using in CGI engine the dynamic charge improves the course of torque at higher speed, and this has an influence on increase of power in this range of speed.
The external characteristic of CLS 350 CGI engine showed in Fig. 8 that displacement volume has value of 3500 [ccm], has been referred to the displacement volume of 2000 [ccm] in order to compare easier with the remaining engines showed in this paper.

3. 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.9.

![Fig. 9. Schematic diagram of mixture stratification in spray-guided direct injection engine; a,b,c – zones of stratify fuel ignition dose, d – zone of homogenous charge.](image)

Diagram shown in Fig. 10 presents three work modes of that engine according to the speed engine and load.

![Fig. 10. Dependence of engine load value from the mode of its work.](image)

3.1 Parameters of the F5R engine

The model engine and process of charge forming are characterized through following parameters:
- winch radius of a crank \( R_w = 0.0465 \) [m],
- diameter of a cylinder \( D_c = 0.0827 \) [m],
- compression coefficient \( \varepsilon = 10.5 \),
- displacement volume \( V_{ss} = 1998 \) [cm\(^3\)],
- slenderness of a connecting rod \( \lambda_c = 1/3.5 \),
- diameter of an injector nozzle \( d_o = 0.2 \) [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 \( P_{ks} = 1.5 \) [MPa],
- stoichiometric constant for gasoline combustion \( \lambda_t = 14.7 \),
- air density \( \rho_g = 1.27 \) [kg/m\(^3\)],
- fuel density \( \rho_f = 775 \) [kg/m\(^3\)],
- total volume of a cylinder \( V_w = 555 \) [cm\(^3\)],
- volumetric efficiency \( \eta_v = 0.75-0.9 \),
- air fuel coefficient of homogenous charge
  - mode I \( \lambda_h = 1.60 \),
  - mode II \( \lambda_h = 1.35 \),
  - mode III \( \lambda_h = 1.10 \),
- volume of zone „a“ ignition dose \( V_a = 0.008 V_w(\alpha) \),
- volume of zone „b“ ignition dose \( V_b = 0.027 V_w(\alpha) \),
- volume of zone „c“ ignition dose \( V_c = 0.065 V_w(\alpha) \).

3.2 Initial velocity of the fuel stream and the stream of fuel flow through an injector

The compression in an engine occurs during polytrophic transformation, 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]**

\[
\eta_p = \frac{\log(P_{ks}) - \log(P_{ps})}{\log(\varepsilon)} = 1.22
\]  

**compression coefficient**

\[
\varepsilon = \frac{V_{ks} + V_{ss}}{V_{ks}}
\]

\[
V_{ks} = \frac{4}{\eta_p}
\]
burning chamber volume
\[ V_{ks} = \frac{V_{ss}}{4 \cdot (\varepsilon - 1)} = 55.5[cm^3] \]  
(3)

total volume of a cylinder
\[ V_w = V_{ks} + V_{Sz}(\alpha_o) \]  
(4)

variable volume of a cylinder resulting only from displacement volume
\[ V_{Sz}(\alpha_o) = \pi \cdot D_{c}^2 \cdot R_w \left[ 1 - \cos(\alpha_o) + \frac{\lambda}{2} \sin(\alpha_o) \right] \]  
(5)

compression pressure
\[ P_{ps} \cdot \left( \frac{V_{ss}}{4} + V_{ks} \right)^{\eta_p} \]
\[ P_c \left( V_{ks} + V_{Sz}(\alpha_o) \right)^{\eta_p} \]  
(6)

On the ground of the equal (7) [7] 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. 11.

\[ U_0 = C_{D} \cdot \sqrt{2 \cdot \frac{P - P_c(\alpha_o)}{\rho_{p}}} \]  
(7)

fuel mass injected to a cylinder
\[ m_g = \frac{V_u}{4} \cdot \rho_g \cdot \eta_v \]  
(9)

fuel mass injected to a cylinder during a suction stroke
\[ m_{ps} = \frac{m_g}{\lambda_z} \cdot L_z \]  
(10)

fuel mass injected to a cylinder during a compression stroke
\[ m_{pc} = \frac{m_g}{\lambda_h} \cdot L_z \]  
(11)

fuel mass of zone “a” of ignition dose
\[ m_{ph} = \frac{m_{ps} \cdot V_u}{V_w(\alpha_o) \cdot \lambda_a} \cdot (\lambda_h - \lambda_a) \]  
(12)

Fig. 12. Dependence of the fuel flow stream through the injector from an angle of injection advance.

### 3.3 An angle of injection advance

On the ground of value of flow stream through the injector that has been presented in Fig. 12 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.

air mass sucked in a cylinder [8]
\[ V_{gs} = \eta \cdot \rho \cdot \lambda_v \cdot \lambda_a \cdot \lambda_z \]  
(9)

fuel flow stream through an injector
\[ q = \pi \cdot \frac{d_i^2}{4} \cdot U_0 \cdot \rho_p \]  
(8)

The decrease of initial velocity of the fuel stream, shown in Fig. 11, results from the increase of the compression pressure alongside with a piston motion towards TDC (top dead center). 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. This dependence is shown in Fig. 12.

![Fig. 11. Dependence of initial velocity of the fuel stream from an angle of injection advance.](image)

![Fig. 12. Dependence of the fuel flow stream through the injector from an angle of injection advance.](image)
### 4. 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 homogenous mixtures, that are enriched only with stratify ignition dose.

4. Homogeneity of poor base mixture in spray-guided direct injection engine depends mainly from cone angle of fuel stream. Increase of value of this angle principally causes improvement of this parameter.

5. Correlation between a inclination injector angle in relation to a symmetry axis of a cylinder and a cone angle of fuel stream has a decisive influence on the course of fuel motion.

6. Mutual relations of the injector and the ignition spark plug in the engine with spray guided direct injection working in homogenous mixture mode has a little influence on size its work parameters.

### 5. REFERENCES

[1]- www.members.fortunecity.es
[4]- www.netzeitung.de
[5]- www.audi.it

### NOMENCLATURE

- $\alpha_0$: angle of injection advance [deg]
- $C_D$: flow coefficient through injector
- $D_c$: diameter of a cylinder [m]
- $d_o$: diameter of an injector nozzle [m]
- $\varepsilon$: compression coefficient
- $\lambda_s$: 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]
- $n$: speed engine [1/min]
- $n_p$: average exponent of polytrophic
- $\eta_v$: 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]
- $R_w$: winch radius of a crank [m]
- $\rho_g$: air density [kg/m$^3$]
- $\rho_p$: fuel density [kg/m$^3$]
- $U_0$: initial velocity of fuel stream [m/s]
- $V_w$: total volume of a cylinder [m$^3$]
- $V_a$: volume of zone „a” ignition dose [m$^3$]
- $V_b$: volume of zone „b” ignition dose [m$^3$]
- $V_c$: volume of zone „c” ignition dose [m$^3$]
- $V_{sz}$: displacement volume [m$^3$]
- $V_{ss}$: variable volume of a cylinder resulting [m$^3$]