DETERMINATION OF THE TOTAL EFFICIENCY IN THE ENGINE WITH DIRECT INJECTION OF THE PETROL

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Abstract
In the paper is presented six tribes of engine’s work which is charged mixture: laminar, homogenous, homogenous lean homogeneously – laminar, laminar heating the catalyst. Then was described a direct fuel injection which is applying in Mitsubishi gasoline direct-injection (GDI) engines, where were included: regulation of mixture’s composition, load’s lamination (which was showed and described) and functions of single – phase and diphase injection. The graph of overall efficiency showed us its distinct growth in a range of 750 – 2700 r.p.m

Next is presented a mathematics model of mixture’s creation in combustion chamber. This is the process which were included:
• mass of gas in combustion chamber
• difference of pressures between fuel injection and gas pressure in combustion chamber
• fuel’s evaporation.

In the end the paper conclusions were drew out from problems, which were discussed.

1. Introduction

We can observe, in last years, very intensive development of the motorization. It requires higher and higher environmental protection and decreasing of the fuel consumption or increasing of the engine power without changing engine’s overall dimensions.

Nowadays, during the engine’s work, we can distinguish the six kinds of the feed:[1]

• laminar mixture,
• homogeneous mixture,
• weak homogeneous mixture,
• homogeneous-laminar mixture,
• homogeneous antiknock mixture,
• laminar mixture which heating up the catalyst.

The change of kind of the admission during engine’s work takes place without discontinuity of the turning moment, thus it is invisible for the car driver. The Figure 1 presents stages of the engine’s work in compliance with the different kinds of the admissions and phases of the injections.[2]

The moment of the transition from the laminar mixture to homogenous mixture is when engine reaches about 3500 rpm. what is related to the GDI model speed of 115 km/h.

2. The mathematical model of mixture’s creating inside the combustion chamber

Mass of gas inside the chamber is determined by inflow exhaust gas or hot air from the cylinder during compression process and outflow of mixture consisting of gas and
evaporated fuel to the cylinder and increase of fuel mass in gaseous state. Change of gas amount in this small volume can be defined as follows:[3]

The single-phase injection
A – stoichiometrical homogeneous mixture \((\lambda=1)\), such a kind of the feed is possible in all kinds of the ranges, B – weak or homogeneous mixture with \(\lambda=1\) and exhaust gases recirculation, such a kind of the feed is possible in the ranges C and D, C – laminar mixture with exhaust gases recirculation.

The diphase injection:
C – laminar mixture which heating up the catalyst, D – homogeneous-laminar mixture, E – homogeneous antiknock mixture.

**Fig.1. The characteristic of the turning moment with different kinds of the GDI engine's admission.**

\[
dm_c = F_1 \cdot u_1 \cdot \rho_1 \cdot dt - F_2 \cdot u_2 \cdot \rho_2 \cdot dt + dm_f
\]

\(m_c\) – mass of gas in the chamber,
\(F_1\) – cross section area of inlet duct which transfers hot charge from cylinder,
\(F_2\) – cross section area of duct (transfer of rich mixture to the cylinder),
\(u_1, u_2\) – inlet and outlet velocity,
\(\rho_1, \rho_2\) – inlet and outlet density of charge

During injection process fuel is delivered to the mixing chamber as a result of pressure difference \(p_w\) in electronic injector and \(p_c\) in mixing chamber.

\[
\Delta m_p = i \cdot C_D \cdot F_w \cdot \sqrt{2 \cdot \rho_p \cdot \Delta p \cdot \Delta t} \quad \text{where pressure amounts: } \Delta p = p_w - p_c
\]

\(i\) – amount of injector’s holes
\(F_w\) - mean area of the injector’s hole
\(C_D\) – coefficient of flow losses
\(P_w\) – pressure of injected fuel
\(P_c\) – pressure in mixing chamber

Change of the liquid droplet mass is defined by the Spalding equation:

\[
\frac{dm_f}{dt} = -\pi \cdot d_k \cdot \frac{k_v}{C_{pv}} \cdot Nu \cdot \ln(1 + B_M)
\]

\(d_0\) – diameter of fuel droplet,
\(k_v\) – heat conductivity of vapor,
\(C_{pv}\) – specific heat vapor,
\(Pr\) – laminar Prandtl number for continuous phase,
\(F\) – correction of Frossling coefficient during mass exchange:
\[ F = \frac{1}{B_M} \cdot \ln(1 + B_M) \]

\( B_M \) – dimensionless number of mass exchange

The first droplets of fuel delivered to the cylinder begin evaporate from the start of injection to the mixing chamber because of initial evaporation temperature of gasoline amounts about 320K.[10]

\[ \frac{dm_{fr}}{dt} = \frac{m_{fr} - m_{vfr}}{\tau_v(t)} \]

\( \tau_v \) – characteristic time of the fuel evaporation with droplet diameter \( d \)

\( f_n \) – index representing total mass of fuel vapor

\( f_p \) – index representing of total fuel mass

\( \tau_v = \frac{\rho_f D_{32}}{4\lambda_f} \left[ \frac{1}{3} c_{sf} \ln \left( \frac{T_c(t) - T_f}{T_c(t) - T_s(\rho_{\lambda})} \right) + \frac{1}{2} \frac{h_{f}(T_c(p_c))}{T_c(t) - T_c(p_c)} \right] \)

\( D_{32} \) – mean Sauter diameter of fuel droplet

\( C_{pf} \) – specific heat of fuel (for petrol \( C_{pf} = 2.4 \) KJ/KgK at \( p=1 \) bar and \( T=298 \))

\( T_f \) - temperature of delivered fuel in K

\( T_s \) – saturation temperature of liquid fuel at current pressure in chamber

\( T_c \) – temperature of charge in chamber

\( h_f \) – evaporation heat of fuel (350 KJ/kgK, for petrol)

\( \lambda_f \) – fuel heat conductivity (W/mK)[10]

On the basis of presented mathematic model the further analysis were made. They related to:

- mass of gas in the combustion chamber,
- the pressure differences between inlet fuel and the gas pressure inside the combustion chamber.

3. Direct petrol’s injection applicable into Mitsubishi GDI engines

Regulation of the mixture’s content in GDI engine is diphase.[1] In the range of the little loads filling of the cylinders is the same, and the enrichment or weaken of the mixture depends on the dose of the fuel.

In the period of the engine’s work with high load the mixture’s content depends on the opening of the throttle. It allows to fly in a necessary quantity of the air in order to keeping the excess of the air on the level \( \lambda = 1 \). The fuel is injected to the suctioned air. In the case of little load or engine’s work with rotational speed of the idle running, combustible mixture prepared in the cylinder is very weak (30-40 air fuel ratio).

In the GDI engine the processes of combustion of weak and enrich mixtures are different. In the case of the combustion of very weak mixture, the process of combustion of the laminar charge was ensured by engine’s construction. In order to reach this objective same elements were matched:[4]

- the form of the fuel injection jet,
- the edge and position of the round hollow in the piston head,
- the moment of the fuel injection and the whirling of the charge in the combustion chamber.
The lamination of the charge inducing, that mixture which is collecting around sparking plug is richer than mixture that can be find closer the walls and the bottom of the combustion chamber. This combustion process in the Mitsubishi GDI engine is presented below. (see Figure 2.)[5]

Presented visualization concerned the process of injection and combustion during the engine’s work (with laminar mixture) – the scientific research was made in Cracow University of Technology. The register was made for the engines of 2400 r.p.m. with partial load. Specific fuel consumption was equal 238 [g/kWh].

![Figure 2. The combustion of the laminar mixture.](image)

The photo presents the beginning phase of flame development for 18° OWK after GMP.
The high swirl in the combustion chamber can be very clear seen because of the nature of flame.

Near by the walls the clean air is collecting - in consequence the heat losses of combustion are decreasing, but the temperature inside the chamber of combustion is increasing. This phenomenon is a reason of increase of the N0x contents in exhaust gasses.[6] In order to prevent such a situation it was necessary to introduce recirculation of the exhaust gasses in engine’s admission circulation to avoid high temperature inside the chamber of combustion. During such a conditions, the moment of fuel injection is appropriate in the end of compression stroke. Injected jet of fuel is very breaking up and creates kind of the mist, which is dislocating on the surface of the cavity inside the piston head. That constructional detail does not hinder during creating the conical jet of the fuel which is necessary while engine’s work with high load. The round cavity inside the piston head has very special shape and the edge which directed the charge’s swirl. During the engine’s GDI work with high load or with max. power and high rotational speed, fuel’s injection is in the early phase of air stroke flow. The fuel jet is conical, which favour the creation of the homogenous charge of the well mixed fuel with air. In that stage of the engine’s work the fuel saving is decreasing, but it is an inevitable result of the high load. The Figures 3 and 4 present functions of the single- phase injection and the diphase injection, where the diphase fuel’s injection is applicable:[7]

- after engine’s starting in order to warming up of the catalyst,
- in the range between admission of the laminar mixture and homogeneous mixture,
- with full load and delay admission in order to avoid the knocking combustion.

The fuel pump applicable to the admission of the GDI engine, obtains direct drive from engine. Its injection’s pressure is equal 5 Mpa. It is not so much, but the constructors ensure that the break-up of injection fuel is appropriate.

In the analytical model of fuel’s injection presented on the chart 4 depends on:[5]

- rotational speed of the engine,
- the ignition’s lead ankle,
- the time of injection,

The time of injection divides on to 4 stages:
• time t1 from the moment of injection to the contact of the jet with the piston head (contents air resistance);
• time t2 from the moment of entry into curvature of the piston head to the half of the length of curvature (contents frictional resistance of the fuel jet);
• time t3 from the half of the length of curvature of the piston head to the exit moment of the fuel jet from the piston head (contents the air resistance and the frictional resistance);
• time t4 – from the moment of exit from the curvature of the piston head to the moment of reach the port between sparking plug points).

![Fig.3. Dependence of the moment of injection on function $^6OWK$ and rotational speed.](image)

![Fig.4. Dependence of the pressure on the rotational speed of the single-phase injection and the diphase injection](image)

On the basis of the calculated time of the injection we can estimate the ankle of fuel injection’s lead under the given rotational speed.

The Figure 5 presents the ankle of fuel injection’s lead for different injection’s pressures (5, 8, 10 Mpa), in the function of rotational speed of the crankshaft with consideration of the ankle of ignition lead.

As a result of presented analysis it appears that the specific fuel consumption and consumption per hour is decreasing in the range of the rotational speed 750 – 3000 r.p.m.

The change of the total efficiency of the GDI engine was estimated on the basis of the
rotational speed and engine’s load. Results were presented on the Figure 6.

Fig. 5. The angle of fuel injection’s lead depending on the engine’s rotational speed with consideration of the angle of ignition lead.

Fig. 6. The dependence of total efficiency $\eta_o$ on two cases, stratified charge, without stratification of the charge, as a function of the engine’s rotational speed.

4. The comparison of the speed’s characteristic and the flexibility of the Mitsubishi GDI and Alfa Romeo JTS engine’s

The Figure 7 presents the comparison of two engines speed characteristic: GDI and the modern Alfa Romeo - JTS. The GDI max engine’s power is about 95 kW whereas JTS is over 120 kW. In the JTS engine max rotational moment is reached when the rotational speed is about 3200 (revolutions/min). Also we can see that the JTS engine has higher fuel’s injection pressure and better compression degree.

$$e_M = \frac{M_{0\text{Max}}}{M_{o\text{(NeMax)}}}$$ – the moment of the flexibility

$$e_N = \frac{n_{N\text{(max)}}}{n_{M\text{(max)}}}$$ – the flexibility of the rotational speed

$$e_C = e_M \times e_N$$ – total flexibility
<table>
<thead>
<tr>
<th>Engine’s GDI flexibility</th>
<th>Engine’s JTS flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_M = 174(Nm)/160(Nm) = 1.087$</td>
<td>$e_M = 200(Nm)/180(Nm) = 1.111$</td>
</tr>
<tr>
<td>$e_N = 5180/3950 = 1.311$</td>
<td>$e_N = 6200/3300 = 1.878$</td>
</tr>
<tr>
<td>$e_C = 1.08 \times 1.311 = 1.42$</td>
<td>$e_C = 1.111 \times 1.878 = 2.08$</td>
</tr>
</tbody>
</table>

**Fig. 7.** The speed characteristic of Mitsubishi GDI engine’s and Alfa Romeo JTS engines

5. The pressure of fuels injection in Alfa Romeo engine

The high pressure pump of the 2.0 JTS engine with three pistons is driven by the exhaust valve’s distribution shaft with proper distance washer.

The different phases of pump’s work are characteristic for such a system:

- during the idle running the pressure is about 50 bar,
- during the work it is reaching to 100 bar,
- max pressure made by the pump is 120 bar.

The electromagnetic injectors are directed by controller, which controls engine’s work. The injector has one hole of fuel’s injection, which is placed on axis with the injector under the angle of inclination $60^\circ$.

6. Conclusions

- The idea of gasoline direct injection is modern but very developed, whatever still aspire to increase of the injection’s pressure.
- The air – cooling inside the cylinder is a result of the evaporating of the injected fuel. This phenomenon reduces a danger of the knocking combustion.
- The lack of a fuel inside the head race during the filling increases the filling factor and decreases the contents of the hydrocarbons during the starting of the cold engine.
• The increasing of the compression degree improves the charge’s exchange.
• The characteristic feature of such engines is very stable combustion during the low rotational speeds of the idle running.
• Thanks to the possibility of the application of the multiple fuel injections in to the cylinder, we can direct the combustion process during its appearance.
• The total efficiency is improved during the engine’s work with the laminar mixture (the fuel’s consumption was decreased about 40%). Very high total flexibility of the 2.0 JTS engine improves the ride comfort and the capacity of the elevations overcoming.

References

[5] Praca Doktorska „Określenie sprawności ogólnej silnika ZI z uwarstwionym ładunkiem przy zastosowaniu bezpośredniego wtrysku paliwa” Bronisław Sendyka, Mariusz Cygnar, 2002
[8] „Układy zasilania silników o zapłonie iskrowym i samoczynnym” – Andrzej Sochan 2002
[10] BOSCH – „s40/v40 Proces spalania GDI”