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MODELLING OF THE INJECTION AND COMBUSTION PROCESSES IN THE GASOLINE DIRECT INJECTION ENGINE

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Preliminary notes
The paper presents modelling of the injection process by means of *KIVA* program. The elaborate mathematical models used in calculations describing the processes occurring inside the engine cylinder make it possible to create complicated virtual models reflecting real conditions in a satisfactory way. The accuracy of calculation results is determined by the quality of input data, which can be obtained based on model investigations. Based on the modeling of injection and combustion processes in the GDI engine, presented in the work, the basis for a broader analysis of the gas-dynamic phenomena was obtained.

Keywords: *GDI engine, stratified charge, visualization*

Modeliranje procesa ubrizgavanja i izgaranja kod motora s direktnim ubrizgavanjem

Prethodno priopćenje
Rad prikazuje modeliranje procesa ubrizgavanja pomoću KIVA programa. Složeni matematički modeli koji se koriste u izračunima i koji opisuju procese koji se odvijaju unutar cilindra motora omogućuju generiranje kompliciranih virtualnih modela koji odražavaju stvarne uvjete na zadovoljavajući način. Točnost rezultata proračuna određena je kvalitetom ulaznih podataka, koji se mogu dobiti na temelju ispitivanja s modelom. Na temelju modeliranja procesa ubrizgavanja i izgaranja u GDI motoru, predstavljenih u radu, dobivena je osnova za širu analizu plinsko-dinamičkih pojava.

Ključne riječi: *GDI motor, slojevito punjenje, vizualizacija*

1 Introduction

Constructors of gasoline engines are faced with higher and higher requirements as regards ecological problems and increase in engine efficiency at a simultaneous decrease in fuel consumption. Satisfaction of these requirements is possible due to recognition of the phenomena occurring inside the engine cylinder, choice of suitable optimal parameters of the fuel injection process, and determination of geometrical shapes of the combustion chamber and piston head.

By the use of simulation program KIVA 3V possibilities of up-to-date methods of calculation of changes of temperatures, pressures during the process of stratified charge combustion were presented. The elaborate mathematical models used in calculations, describing the processes occurring inside the cylinder of the engine, permit to create complicated virtual models reflecting the real conditions in a satisfactory way. Correctness of calculation results is determined by the quality of input data which can be obtained basing on model investigations.

Another advantage is the possibility of computer simulation of the phenomena occurring in the cylinder and elaboration of mathematical models which permit a very quick calculation of the parameters we are interested in. Application of such a kind of calculation methods helps in determinations of preliminary structural assumptions and creates a possibility of designing arbitrary shapes of co-working parts in order to choose the best solutions.

Combination of computer methods and model investigations with test bed investigations gives an exact description of the processes occurring in the cylinder and gives a chance of a considerable decrease in costs of productions and modification of elements of a gasoline engine.

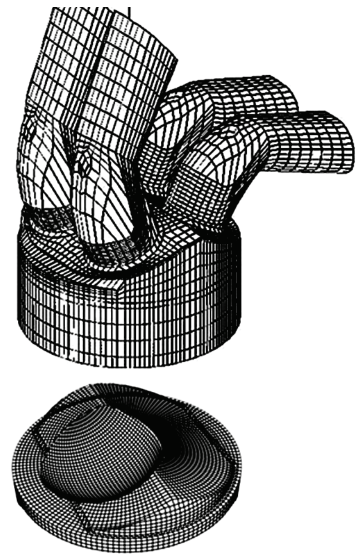

Figure 1 Mesh of the cylinder at 60 ATDC and geometrical model of a piston

2 Modelling of the injection and combustion process by means of programme KIVA 3V

The programme for computer modelling and simulation of combustion engine KIVA 3V possesses a large, developed, graphic interface which may additionally consider the inflow and outflow system and create complicated curved surfaces describing, as in our case, the head of the piston. For such a complicated system as the combustion chamber Mitsubishi GDI the commercial programme KIVA 3V in the Laboratory Los Alamos describes fully the physical and thermodynamical processes inside the cylinder [1, 3, 5]. In Fig. 1 is shown a mesh of one cylinder at 60 after top dead center and geometrical model of a piston of a gasoline engine type 4G93GDI of the firm Mitsubishi.

2.1 Parameters of the calculation model

During the compression stroke, the injector (located between the two intake pipes) delivers highly pressurized fuel. The fuel is injected towards the piston bowl and is turned by its wall to the spark plug. However, the injection time should be strictly defined depending on the engine speed and the ignition angle [3]. In the analysed mode, the injection angle was 75° before TDC and the duration of the process was 32° CA. The parameters of fuel injection:

- Rotational speed:	2000 rpm
- Total time of injection duration:	2 ms (≈30°)
- Mass of injected fuel per cycle:	0,0255 g
- Injector position:	$\gamma = 60°$
- Ignition moment:	15° before TDC
- Direct fuel injection	75° before TDC
- Total time of injection duration:	2 ms (≈32°)
- Injection path:	sinusoidal
- Sauter's mean diameter SMD:	50 µm

For computer simulation of the injection and combustion process in a gasoline direct injection engine of 1,8 mm^3 capacity, S=44,5 mm travel and cylinder diameter D=81 mm the module PISA (Piston Engine Simulator) in the programme Phoenics, based upon the programme KIVA 3V was used. Fig. 2 shows the section of the geometrical net of the combustion chamber of a GDI engine with a characteristic outline of the piston head permitting rebouncing of the fuel jet and outline of the edge of the head. Whereas the orthogonal net BFC (Body Fitted Coordinates) was formed by 1864 calculation cells. The initial parameters were obtained by means of a simulation programme of the zero-dimensional model of a 4-stroke engine [4].

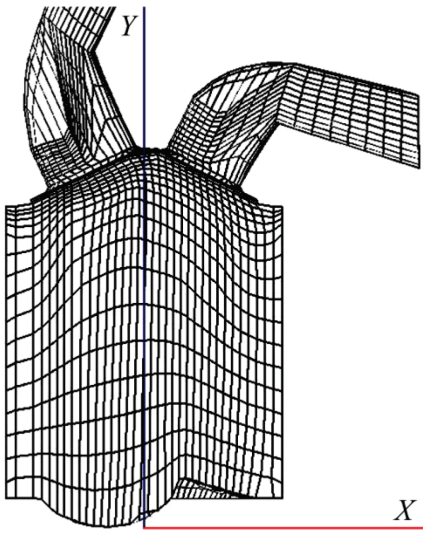

Figure 2 Mesh of the cylinder at 180 ATDC and geometrical model of a piston

The amount of injected fuel corresponded with the global coefficient of air excess λ = 1,512. Equal temperature of the combustion chamber walls about 500 K, and a lower temperature of the cylinder walls about 480 K and the piston 550 K can be adopted.

The carried out analysis concerned distribution of the gaseous phase of fuel, temperature and pressure in the cylinder during injection and combustion of stratified fuel-air mixture and content of toxic components.

2.2 Scheme of charge propagation

Using the CAD program a mode of charge stratification of ultra – lean combustion was elaborated considering the shape of the concave bowl of the piston and injection castor angle presented in Fig. 3.

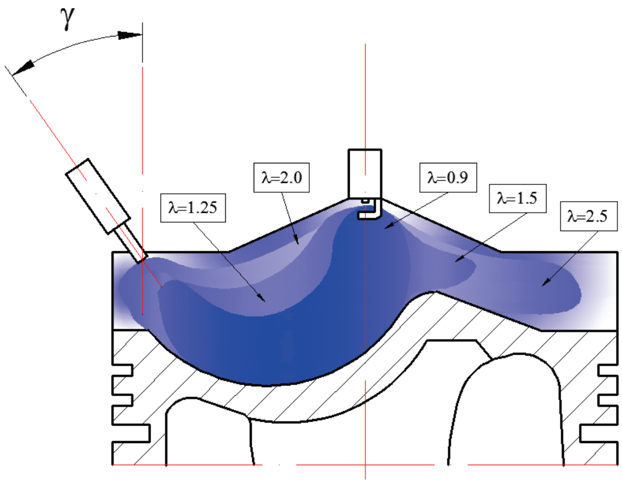

Figure 3 Variation of fuel mixture in combustion chamber (γ - angle of injector position**)**

The small spheric bowl in the piston shown in Fig. 3 works as a chamber and is located on the side of the inlet channel. The geometry of the bowl in the piston bottom is designed in such a way that the fuel sprayed from the injector falling on the concavity is directed under the ignition plug. High pressure of the injected fuel is thought to prevent formation of a fuel film on the piston bottom during refraction and supply of an adegnate rich dose of fuel under the ignition plug.

2.3 Analysis of pressure and temperature by use KIVA 3V

By the use of KIVA 3V for various coefficients of air excess was obtained the course of changes of pressure in the cylinder, presented in Fig. 4.

For determination of the decrease in fuel consumption a comparison of maximal values of combustion pressures of a homogeneous and stratified charge was made.

Stratification of the charge was chosen in such a way that 5 zones of different coefficients of air excess λ occurred, as shown in Fig. 3.

At the assumption of equal volumes of charges of λ = 0,9 and λ = 1,9 a subsidiary calculation coefficient of air excess λ_z = 1,113. Combustion of such a stratified charge gives maximal combustion pressure and temperature equal to the pressure and temperature of a homogeneous charge of $\lambda = 1$.

Fig. 5 shows traces of pressure changes in the cylinder for various coefficient of air excess λ.

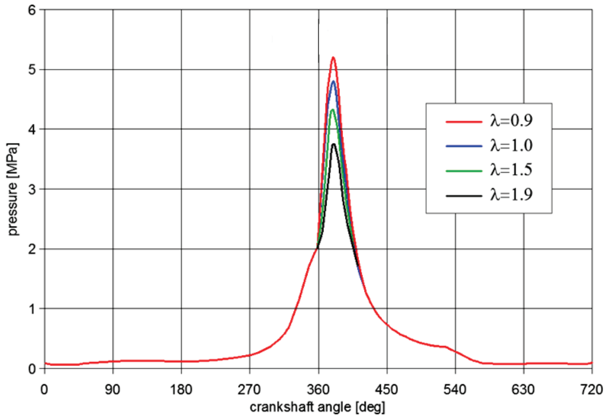

Figure 4 Traces of pressure changes in the cylinder for various coefficient of air excess λ

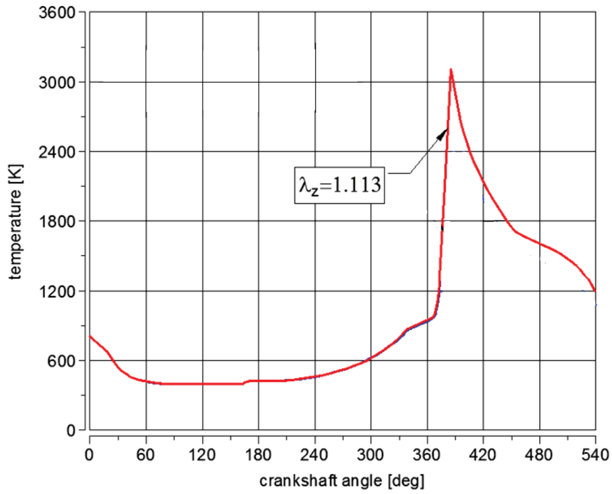

Figure 5 Traces of temperature for a substitutive coefficient of air excess λ_z =1,113

In the enclosed illustrations (Figs. 6 ÷ 8) of temperature changes inside the cylinder of the GDI engine from the moment of injection till the end of the combustion process are shown.

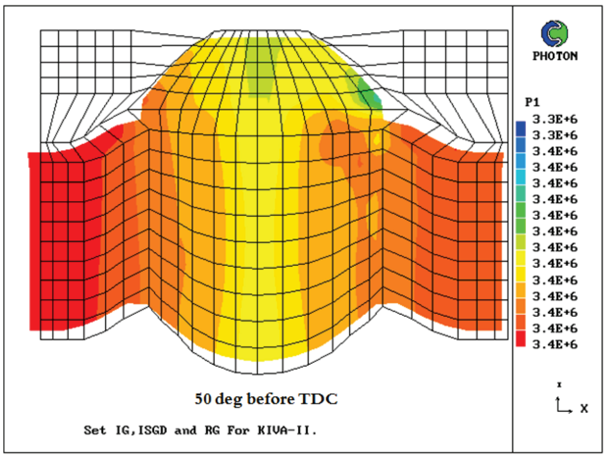

Figure 6 Diagram of combustion pressure for 50° before TDC

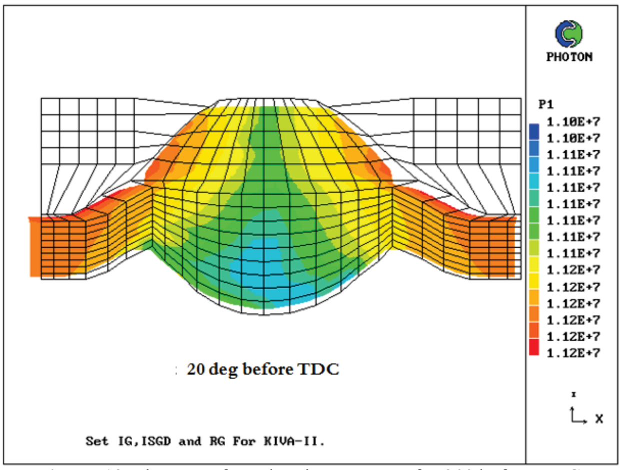

Figure 13 Diagram of combustion pressure for 20° before TDC

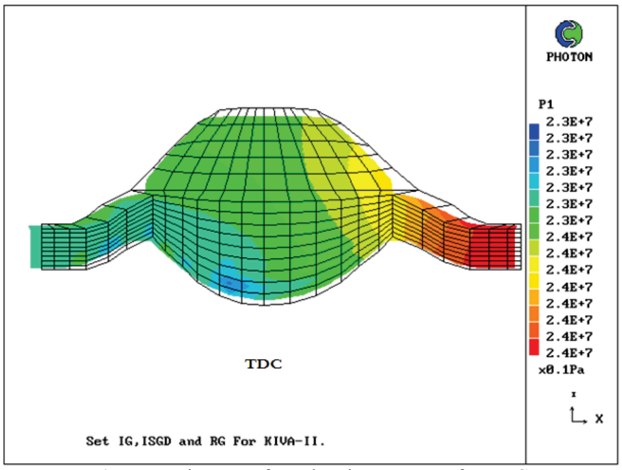

Figure 7 Diagram of combustion pressure for TDC

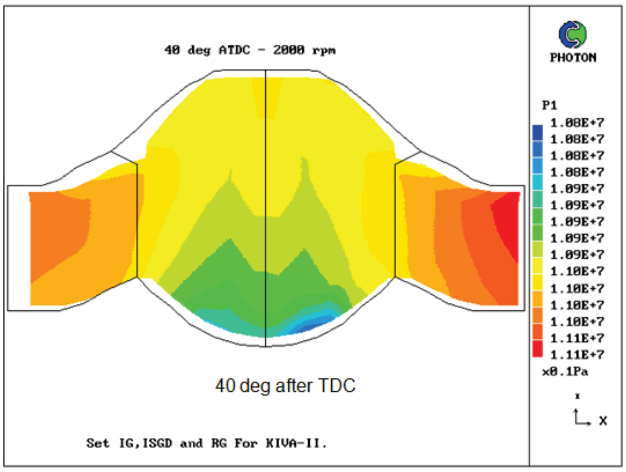

Figure 8 Diagram of combustion pressure for 40° after TDC

On the basis of the obtained results it may be claimed that combustion of lean stratified mixture in the GDI engine proceeds in a stable way. Combustion iniciated by the jump of ignition spark near a rich mixture creates positive conditions for further combustion of a stratified charge.

2.4 Analysis of participation of the gaseous phase

The enclosed illustrations (Figs. 9 ÷ 12) show the changes in the participation of the gaseous phase inside the cylinder of the gasoline direct injection engine from the moment of injection till the moment of ignition.

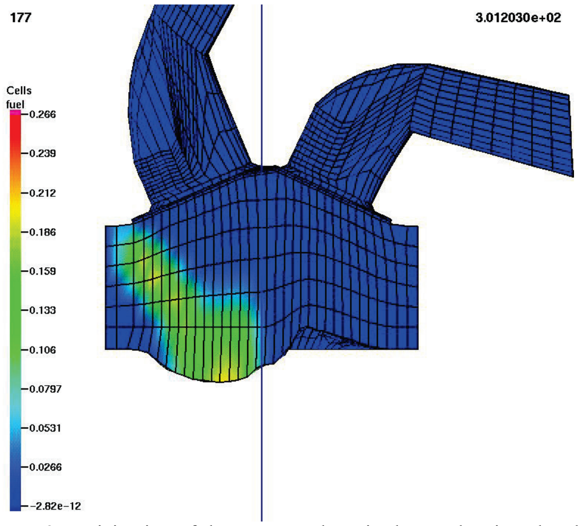

Figure 9 Participation of the gaseous phase in the combustion chamber in the stratified charge mode at 2000 rpm and 60° before TDC

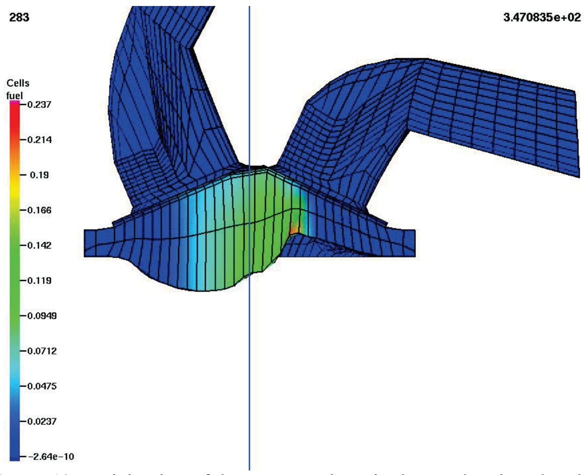

Figure 10 Participation of the gaseous phase in the combustion chamber in the stratified charge mode at 2000 rpm and 13° before TDC

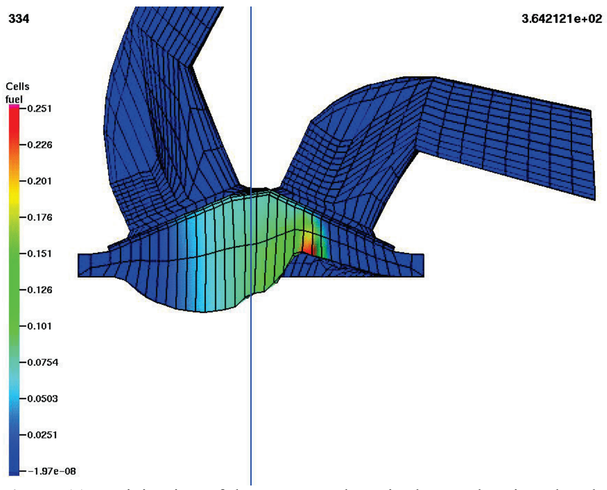

Figure 11 Participation of the gaseous phase in the combustion chamber in the stratified charge mode at 2000 rpm and 4° after TDC

The amount of injected fuel corresponded to the global coefficient of air excess $\lambda = 1{,}512$.

Near TDC, some liquid fuel flows to the squish region and sometimes cannot be burned. When the jet is in motion, fuel vaporizes and there is more vapour at its boundary than inside the jet. Due to the limitations of this paper, the distribution of fuel-air equivalence ratio cannot be presented.

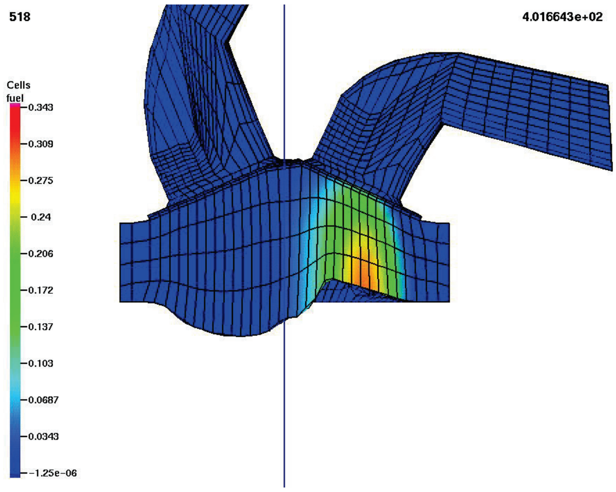

Figure 12 Participation of the gaseous phase in the combustion chamber in the stratified charge mode at 2000 rpm and 40° after TDC

It follows from the analysis that individual drops evaporate quickest outside of the fuel jet where a better contact with the hot gaseous charge exists. Maximal mass participation of the gaseous phase (vapours) of the fuel in the whole charge takes place inside the jet with regard to a great number of drops which were in contact with the hot charge. Locally maximal participation of the gaseous phase of the fuel at piston position 60° before TDC is 0,26 (Fig. 9) what corresponds to the coefficient of air excess $\lambda = 0{,}891$. With regard to rebouncing of the fuel jet from the head of the piston a transient increase in participation of the gaseous phase to the value of about 0,26 takes place. In consequence of ignition in the central top point of the head (4° before TDC) and formation of a pressure wave, the core of the gaseous phase of fuel is partly shifted towards the piston. The fuel in the area of the spark plug gets completely combusted (Fig. 11).

2.5 Analysis of temperature distribution in the cylinder

Temperature distribution in the engine cylinder is closely connected with the change of temperature of a fuel drop. For the model KIVA the change of fuel drop temperature is determined on the basis of the equation of balance of energy [2]:

$$\frac{1}{3}\pi r^3 \rho_k c_k \frac{\mathrm{d}T_k}{\mathrm{d}t} - \pi r^3 \rho_k \dot{R} L(T_k) = \pi r^2 Q_k , \tag{1}$$

where:
r - radius of fuel drop
$L(T_k)$ - evaporation heat at given temperature T_k
c_k - specific heat of drop
ρ_k - fuel density.

In the enclosed illustrations (Figs. 13 ÷ 16) temperature changes inside the cylinder of the GDI engine from the moment of injection till the end of the combustion process are shown.

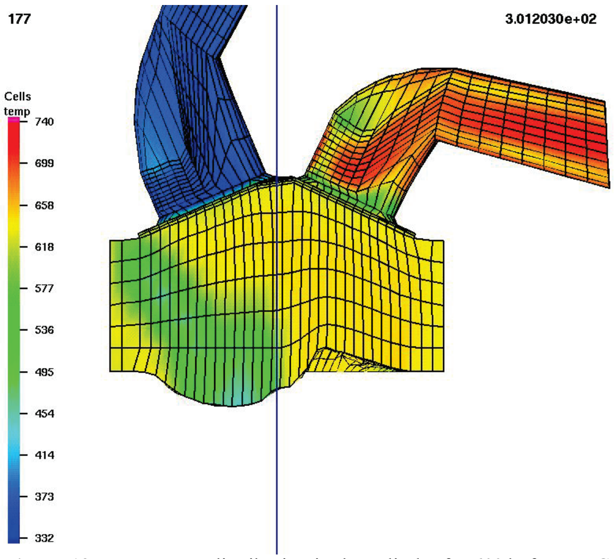

Figure 13 Temperature distribution in the cylinder for 60° before TDC

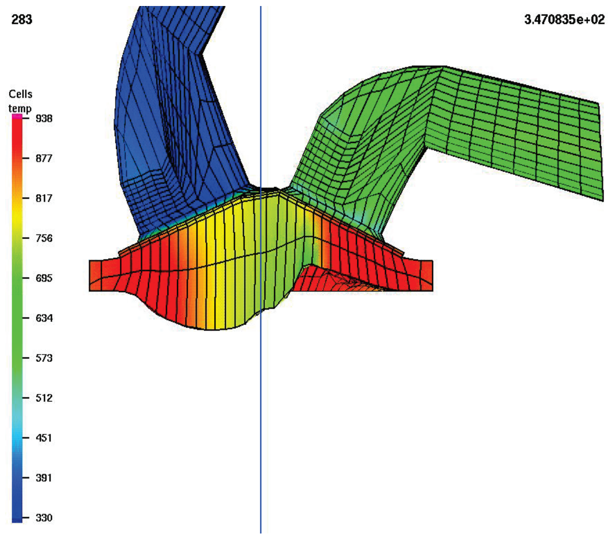

Figure 14 Temperature distribution in the cylinder for 13° before TDC

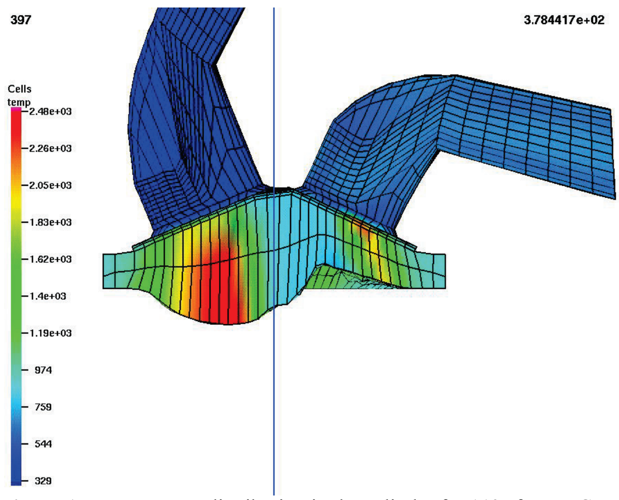

Figure 15 Temperature distribution in the cylinder for 11° after TDC

During the injection process, one can observe a decrease in the temperature of the charge where there is liquid fuel, which is caused by a vaporization process. When the piston is near TDC, the temperature of the charge in the squish region is higher than in the centre of the combustion chamber. The process of combustion during the stratified charge mode is irregular. As a result of fuel and gas conductivity, the regions with fuel vapour surrounding liquid fuel ignite first. This can also be observed during the visualization process. The distribution of temperature shows the entire process of combustion and proceeds in a different way than in conventional engines with a homogeneous charge. At the very end of this process the charge in the middle of the combustion chamber burns as a result of a higher temperature and vaporization of the fuel jet.

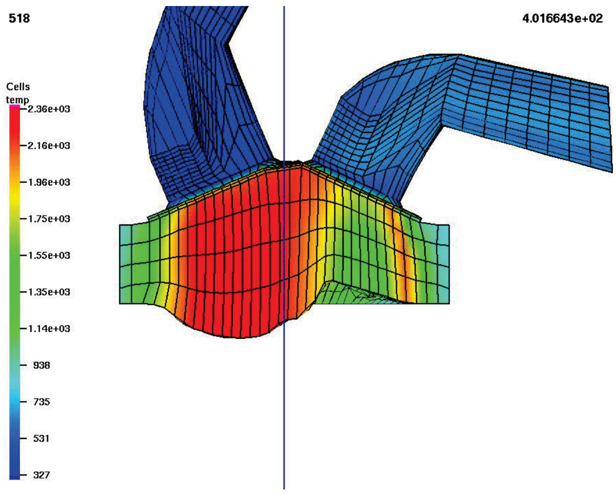

Figure 16 Temperature distribution in the cylinder for 40° after TDC

However, near the spark plug, the air excess coefficient is sufficient to begin the combustion process. The ignition of the spark plug took place at 10° before TDC.

3 Conclusion

Increase of charging temperature in the combustion chamber was observed during injection process while liquid fuel is exposed to vaporization process. When piston is near TDC temperature of charge in a squish region is higher than in the centre of combustion chamber. Process of combustion during stratified charge mode is irregular, as a result of conductivity of fuel and gas, first of all are ignited the regions with fuel vapour surrounding liquid fuel. It can be observed also during visualization process. Distribution of temperature shows the whole process of combustion and it proceeds in another way than in conventional engine with homogeneous charge. Just at the end of this process the charge in the middle of combustion chamber burns as a result of higher temperature and vaporization of fuel jet.

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