# STUDY OF STRATIFICATION OF CNG MIXTURE IN A HIGH CHARGED SI ENGINE

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***Abstract***

*The burning of CNG mixture can occur in very small range of the compression pressure and lean mixture composition. The increased compression pressure requires a big pressure of CNG injection Even for lean mixtures the maximum combustion pressure reaches value near 200 bars. For very lean mixtures and higher compression ratios the misfire occurs, on the other hand for rich mixtures and high compression ratios the detonation is observed. For part load the fuel is injected during the compression stroke, which should form a bigger concentration of fuel near spark plug. The timing of injection should correlate with the piston position BTDC and engine speed in order to enable the adequate stoichiometric mixture near the spark plug during the ignition. The stratification of the charge depends on the location of the injector and the angles of injection nozzles and on the shape of the piston crown. The motion of the injected gaseous fuel required the adequate profile of piston head to turn the fuel stream directly to the spark plug. The flat piston causes that small part of fuel reaches the cylinder cavities and the increase of HC is observed. The paper performs results of calculations of the work engine parameters for 3 types of the piston shapes. The calculations were carried out in the 3-dimensional space with full engine geometry for the same engine speed and injection time. The simulations of CNG injection and combustion process were carried out for motorcycle engine SUZUKI DR-Z400S*

***Keywords**: transport, SI four-stroke engine, fuelling*

## 1. INTRODUCTION

The European automotive corporations have worked on a new direct injection of compressed natural gas in SI engines with high charging bigger than in diesel engines. It is assumed that charging ratio reaches value about 2.8, which is not met in automotive engines. By applying of high supercharging system the pressure of the end of compression process can be higher than 40 bars and is almost 1,5 time bigger than in diesel engines with direct fuel injection. For these reasons the maximum value of combustion pressure can reach 180 bars. The increased compression pressure requires also a big pressure of CNG injection. Till now on the automotive market there are not the gas injectors with sufficient flow rate through the nozzles for the low loads with injection during compression stroke enabling to get the stratified charge and also for full loads at high engine speeds.

Naturally aspirated SI engine filled by the natural gas has lower value of thermodynamic efficiency than diesel engine. The experiments conducted on SI engine fuelled by CNG with lean homogeneous mixtures ($\lambda\approx1.4$) show, that in many cases it causes a faulty ignition and for this reason the better solution is the concept of the stratified charge with CNG injection during the compression stroke [5].

## 2. GAS INJECTION FLOW RATE

The flow rate of gas through the injector depends on the difference of pressure between two mediums and total cross section area of the nozzles. The pressure changes in the cylinder during piston motion and in the injection pipe with controlled injection pressure it is assumed to be of constant value. The author did some calculations in order to determine the required flow area of the gas injector for some engine operation loads and speeds. It was assumed that a lift of injector needle and flow area occurs in a sinus function of total time of the injector opening. The normalized valve area (the full opening valve area is treated as one) in a function of normalized angle (the total angle of the valve opening is referred to 1 radian) of opening injector is presented in Fig.1.

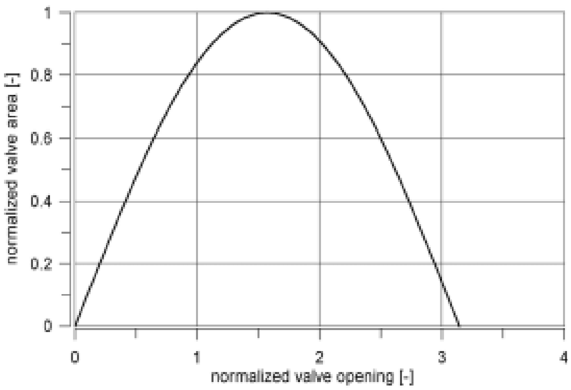


*Fig. 1. Normalized opening area of the injector*

The calculations of the required injector flow area were done on the assumption of given engine power and total engine efficiency. The required dose $m_p$ of CNG is obtained from the following equation:

$$m_p = \frac{60 \cdot N_e}{W_p \cdot \eta_0 \cdot i \cdot n} \cdot \tau \tag{1}$$

where:

- $N_e$ - engine power [kW],
- $W_p$ - calorific value of fuel (for natural gas $W_p$=46 788 J/kg),
- $\eta_0$ - total engine efficiency,
- $i$ - number of cylinders
- $n$ - engine speed [rpm],
- $\tau$ - correction factor for engine type (0.5 for 4-stroke and 1.0 for 2-stroke engine).

For smaller injector nozzle area causes the flow with sonic velocity [4]. The non-dimensional subsonic flow mass coefficient for given pressure ratio $P=p_c/p_{inj}$ is obtained from the following formula:

$$\psi = \varphi \sqrt{\frac{1}{RT_c} \frac{k}{k-1} P^{\frac{2}{k}} \left(1 - P^{\frac{k-1}{k}}\right)} \tag{2}$$

where $k=c_p/c_v$ is a heat coefficient ratio. The non-dimensional sonic flow mass coefficient can be calculated from a simplest formula:

$$\psi = \varphi \sqrt{\frac{k}{RT_c} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{3}$$

where: $\varphi$ - coefficient of flow restriction through the nozzle,
$R$ - gas constant (molar number for CNG it was assumed $M_{CNG}$=16 as for $CH_4$),
$T_c$ - temperature in the cylinder.
For given injection time the required flow area of the nozzle is obtained from the dependency:

$$F_{inj} = \frac{m_p}{t_{inj} \cdot p_{inj} \cdot \psi} \tag{4}$$

and velocity of the flowing gas to the cylinder:

$$u_{inj} = \frac{m_p R T_c}{p_{inj} F_{inj}} \tag{5}$$

On the given theoretical consideration and conducted calculations the results were obtained for different injection pressure of CNG in the engine with the following working parameters:
1: 200 kW/5000 rpm, $\alpha_{inj}$ =120 deg CA; $p_{cyl}$ =2 bars
2. 50 kW/3000 rpm, $\alpha_{inj}$ =120 deg CA; $p_{cyl}$ =2 bars
3. 50 kW/5000 rpm, $\alpha_{inj}$ =50 deg CA; $p_{cyl}$ =25 bars.

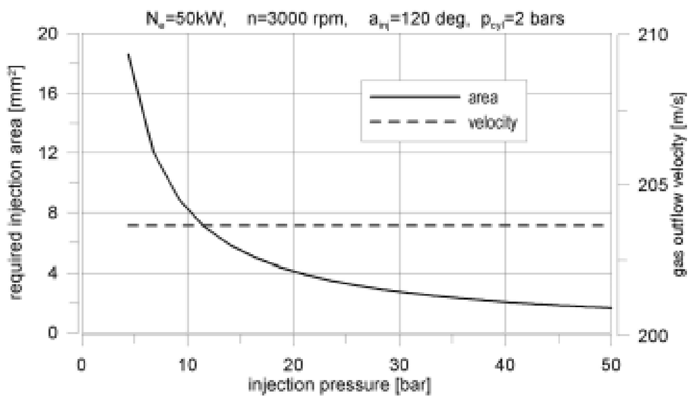


*Fig.2. Required injection area and velocity of gas outflow at power 50 kW/3000 rpm for CNG injection during induction stroke for different injection pressure*

In calculations the total engine efficiency was assumed to be 35%. The results of calculations of the required flow areas and injection velocities for the second case are shown in the Fig.2 for given above engine working parameters and injection parameters. For full load with lower cylinder pressure the outflow of the gas from the injector is sonic and there is needed the bigger nozzle area at lower injection pressure. On the other hand the higher gas pressure about 40 bars can reduce the flow area to 6 – 7 mm$^2$. At middle loads this value can be reduced to 2 mm$^2$ and for this case the sonic flow also occurs. For part loads with charge stratification the sonic flow through the nozzle occurs at injection pressure higher than 45 bars with minimum flow area 4 mm$^2$.

## 3. ENGINE CALCULATION MESH

Before any engine design and experimental tests every time the simulations of work cycle is needed. The Cracow University of Technology will provide tests with direct injection of CNG on one- cylinder motorcycle four-stroke engines SUZUKI DR-Z400S adopted for this target. This modern engine with capacity of 400 cm$^3$ and bore/stroke ratio = 90mm/62,6mm and compression ratio ε=12 will be equipped with gas injector located between two inlet channels. The simulation will enable to define the correct location of the injector. The cylinder with pentroof combustion chamber and 4 valves has the spark plug located in the middle of the cylinder head. The first step has been done by carrying out the simulation of injection in the stratified mode and combustion process in order to check the assumed injection parameters. The simulation parameters of the gas injection are presented in Table 1. The whole process of the engine work was done in 3-dimensional space by using the program KIVA3V [2]. The source code of the program was modified by author with applying for gas injection, because the original version was released for liquid fuel injection only. For the simulation tests there were prepared three calculation meshes of the cylinder: the first with the flat piston, second with wedge piston and third with the bowl piston.

*Table 1. Injection parameters*

| | |
|---|---|
| Dose of CNG fuel | 0,0350 g/cycle |
| Beginning of the injection | 105 deg CA BTDC |
| Duration of the injection | 60 deg |
| Ignition point | 11 deg CA BTDC |
| Cone of fuel jet | 60 deg |
| Number of nozzles | 1 |

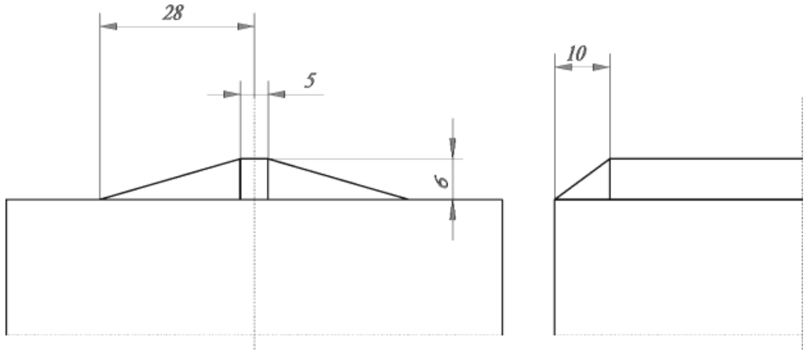


*Fig. 3. Piston wedge geometry in case 2*

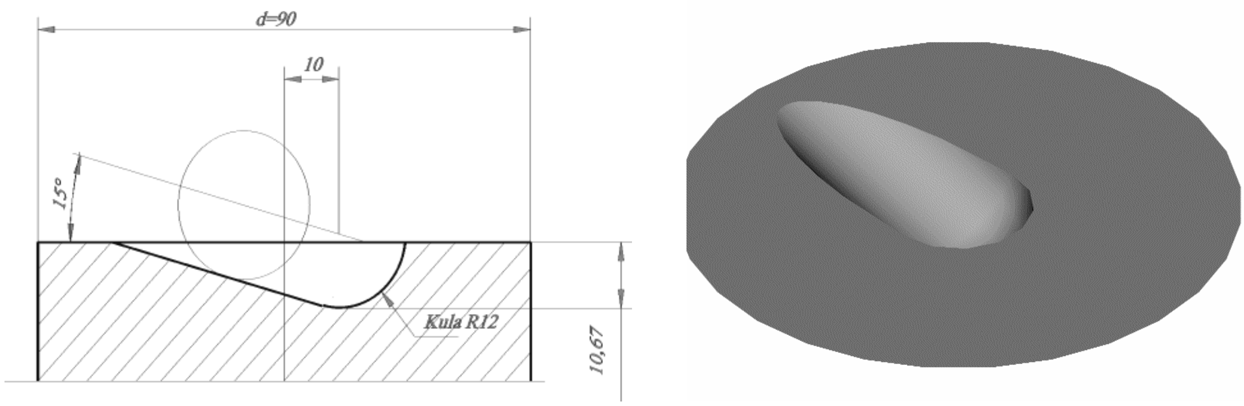


*Fig. 4. Piston bowl geometry in case 3 (piston bowl)*

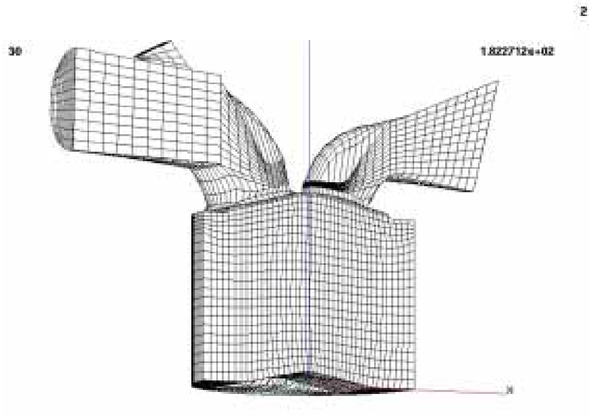

*Fig.5. Cylinder mesh in case 2 wedge piston)*

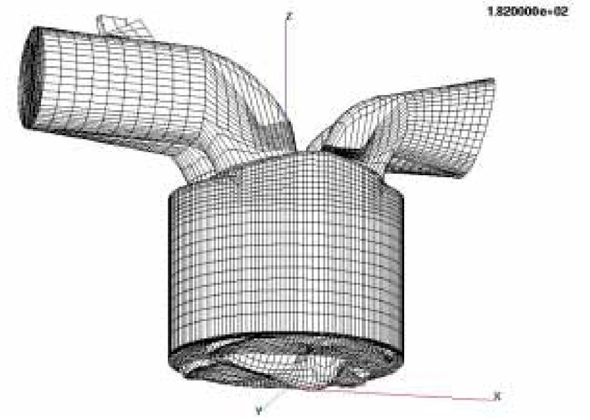

*Fig.6. Cylinder mesh in case 3 (piston bowl)*

The mesh of the engine with the flat piston contains 62 838 vertices and 62 811 cells. It was assumed, that the injector had only one nozzle with flow area amounted 2 mm$^2$. The other types of the meshes contain respectively: second case: 54721 cells and 54748 vertices and third case: 61177 cells and 61204 vertices. Direction of the CNG jet to the spark plug in the stratified mode requires the optimal piston shape, which causes a rebound of the fuel stream to the cylinder head. The two shapes of the piston taken for the calculation are shown in Fig. 3 (piston wedge) and in Fig.4 (piston bowl), respectively. In order to obtain the satisfied results with a big precision, the mesh of the cylinder should contain smaller cells and this increases the cells amount. On the other hand the big amount of cells increases the calculation time.

## 4. MESH ADAPTATION

The praparation of the cylinder mesh and the calculation were carried out in Linux operation system with 64-bit precision. The program was written in Fortran77 language and can be modified by the user. The each layer of the cells on the cylinder walls should be on the same level (the same dimension of *z*-axis) because of mesh adaptation during the piston motion. The cylinder mesh was created from two blocks: the lower modified by piston shape and the higher (combustion chamber) with smaller height dimension of the cells. The profile of the piston crown was defined by mathematical functions as well the bowl and the wedge. At the beginning of the mesh creation the moving surface was created as flat with default numbers of mesh vertices and their *x*, *y, z* dimensions. The author gave an additional procedure in order to create the deflection of lower part of the cylinder by using the mathematical functions. The original values of the *x* and *y* vertices position were unchanged after reshaping of the blocks. The modification of the *z* values of the first mesh layer was done by using the following dependencies:

$$z_1(i,j) = z_0(i,j) + \Delta z(i,j) \tag{6}$$

and the all vertices in the lower block containg *m* layers change their *z*-axis position according to the formula:

$$z_k(i,j) = z_1(i,j) + (k-1)\frac{z_m(i,j) - z_k(i,j)}{m} \tag{7}$$

where: $\Delta z$ is the calculated increment of the piston height to the flat shape, *i, j* – indices of the vertex in x and y axis, *0* – index of the initial shape, *1* – index of the modified shape, *k* – index of the layer in the lower block and *m* – number of the layers in this block. In the case 3 the scallops of the piston were created to obtain the clearence between valves and the piston.

## 5. INITIAL CONDITIONS

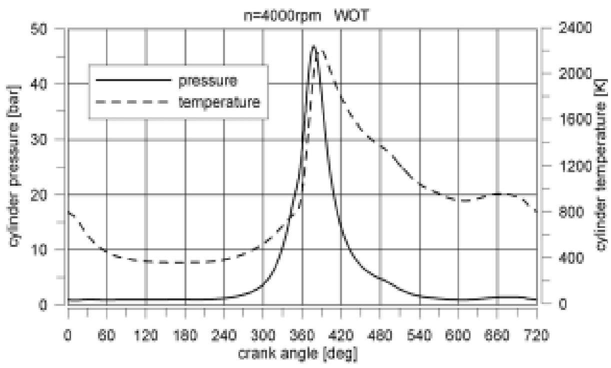


*Fig.7. Cylinder pressure and temperature at 4000 rpm*

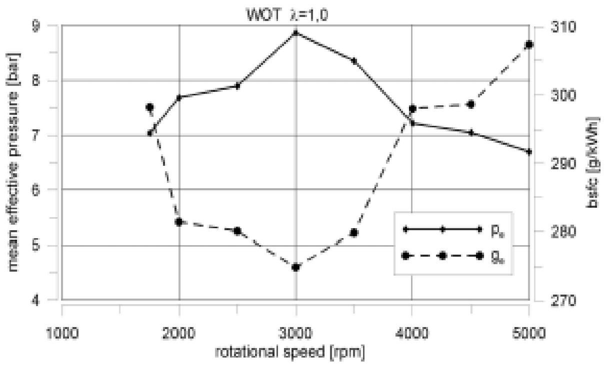


*Fig.8. Mep and bfsc at 4000 rpm and WOT*

Before the 3-dimensional simulation the additional computer program based on zero-dimensional code enabled the calculation of the working parameters of the naturally aspirated engine fuelled by CNG at different rotational speed and full load. The results of this calculations were taken as the initial parameters: pressure and temperature in the cylinder and gas velocity in the ducts for CFD calculations. Variation of the calculated cylinder pressure and temperature are shown in Fig.7 at 4000 rpm and WOT. Fig.8 presents the mean effective pressure and specific fuel consumption for the same operation in function of the rotational speed.
The simulation of the CNG injection and ignition process by using of modified KIVA code was carried out after closing of inlet valves at 110 deg BTDC.

## 6. CALCULATION RESULTS

Simulation of the injection process during compression stroke was done at engine speed 4000 rpm. The target of this test was to assess the proper injection parameters: start of injection and setting of the injector angles to the main axis. The stream of lean fuel mixture with $\lambda \approx 1.0 - 1.5$ should reach the spark plug in the moment of ignition. The temperature of the gas fuel injected into the cylinder space amounted 333K. Only diffusion of the fuel into the cylinder charge occurs with lowering of the charge temperature inside the core of the jet.

### 6.1. FLAT PISTON

The first case of the injection during compression stroke was considered with horizontal orientation of the fuel jet 70 deg to the cylinder axis. The shortening of the duration of the injection causes higher velocity of the stream for the same dose of fuel. With almost horizontal stream the fuel reaches the piston surface. After rebounding from the piston surface and cylinder walls the fuel jet spreads on the head walls and in favourable conditions the mixture with appropriate concentration of fuel reaches the spark plug (Fig.9 at 96 and 76 deg BTDC). The ignition mixture at high loads is easier than at stratified mode. The detailed chemistry of the ignition of CNG fuel is required in simulation of combustion process and production of exhaust pollutants [1].

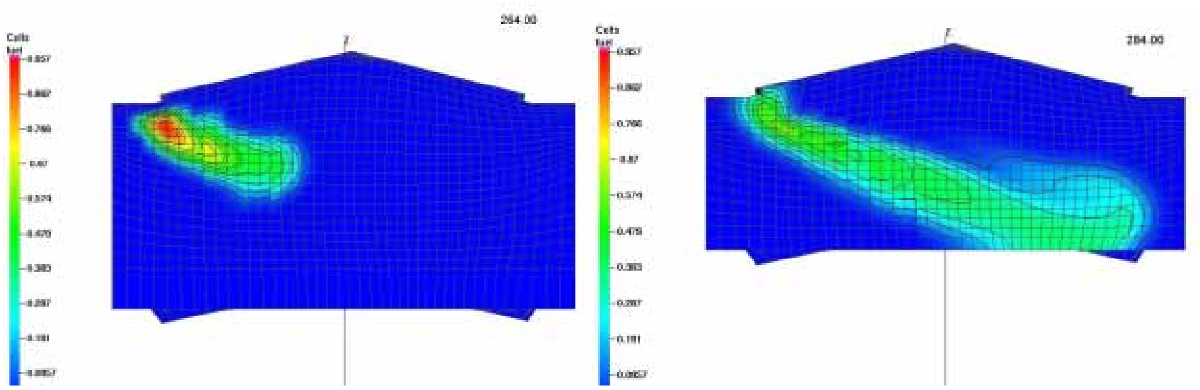

*Fig.9. CNG mass ratio in the engine with flat piston at 96 and 76 deg BTDC at 4000 rpm*

### 6.2. PISTON WITH WEDGE SURFACE

The injection of the CNG in the case with wedge piston was simulated in the same way as in the first case (70 deg to the z-axis) with start of injection at 105 deg BTDC. The CNG mass concentration during injection process is presented in the Fig.10, 11 and 12 at 79, 36 deg BTDC and 34 deg ATDC, respectively. The ignition process was simulated by adding additional anergy (50 mJ) in the cells where the spark plug electrodes are located. The increase of temperature in this place (center of the combustion chamber) is shown in Fig.13. The combustion process is observed by an increase of OH radicals after ignition process (Fig.14) and increase of nitrogen oxide which is observed at 34 deg ATDC (Fig.15). The non-complete CNG combustion is shown in Fig.16 which causes small increase of the cylinder pressure and mean temperature (Fig.17).

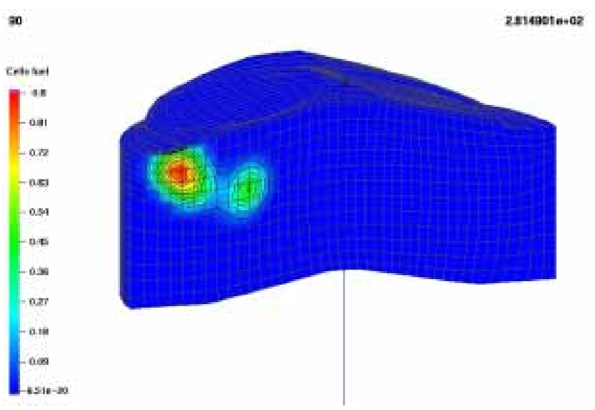

*Fig.10. CNG mass concentration at 79 deg BTDC*

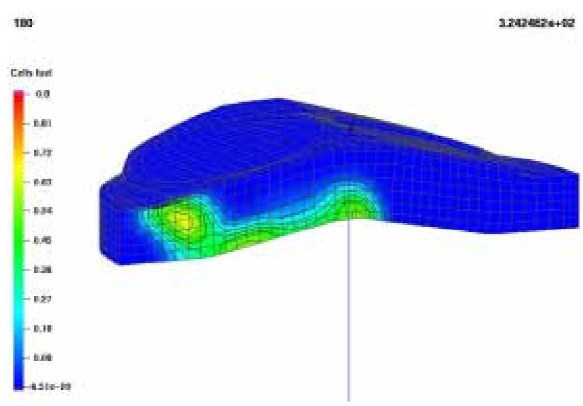

*Fig.11. CNG mass concentration at 36 deg BTDC*

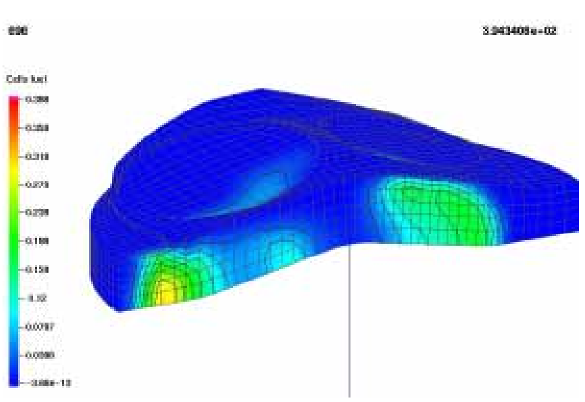

*Fig12. CNG mass concentration at 34 deg ATDC*

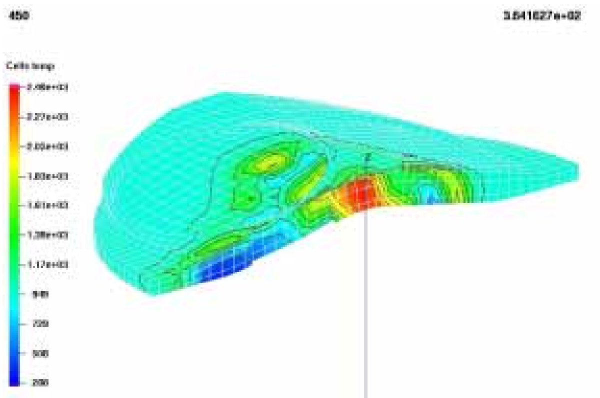

*Fig.13. Temperature distribution at 4 deg ATDC*

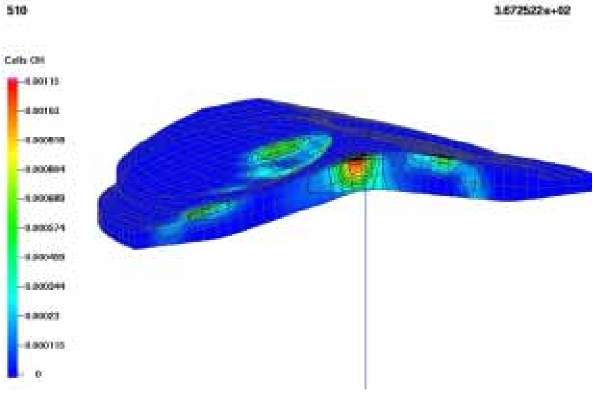

*Fig.14. OH radical mass concentration at 7 deg ATDC*

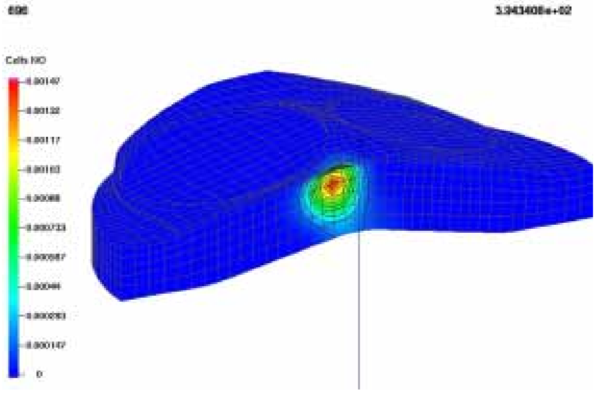

*Fig.15. NO mass concentration at 34 deg ATDC*

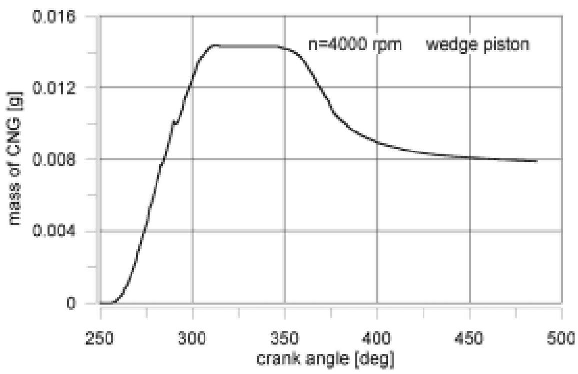


*Fig.16. Total mass of CNG in cylinder*

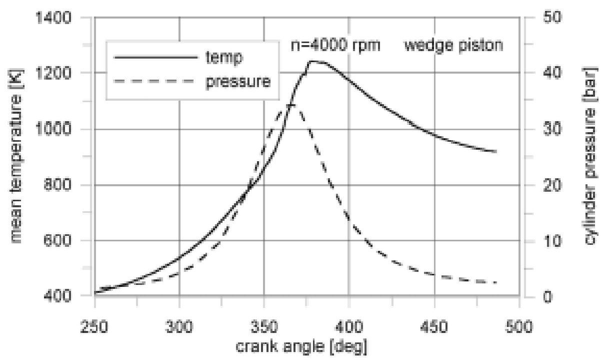


*Fig.17. Mean temperature and pressure in cylinder*

## 6.3. BOWL PISTON

The simulation of CNG injection to the cylinder with the bowl piston was carried out for two cases: with side injection and central injection of gaseous fuel. This paper shows only fuel propagation in the first case. The angle between the axis of the injector and the cylindfer axis amounted 70 deg with initial velocity of the spray 150 m/s. The CNG mass concentration in the charge for three crank angles 73, 28 and 0 deg BTDC is shown in Fig.18, 19 and 20, respectively. The length of the piston bowl is to long because the fuel reaches the cylinder head too late behind the spark plug, which is loacted in the central position.(Fig.20). The spark plug should be moved in *x*-axis with making the bowl shorter and with a smaller radius. The temperature of the charge increases during the ignition (Fig.21), however it does not cause the combustion of the lean mixture in this region. The change of the mass of CNG in a function of crank angle is shown in Fig.22 and variation of the pressure and temperature are shown in Fig.23. The compression of the mixture is only observed without fuel combustion.

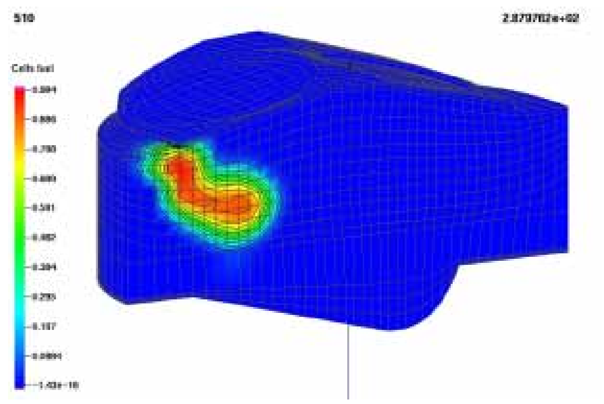

*Fig.18. CNG mass concentration at 73 deg BTDC*

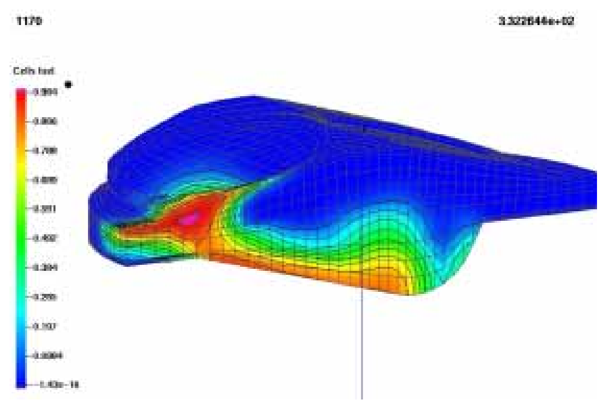

*Fig.19. CNG mass concentration at 28 deg BTDC*

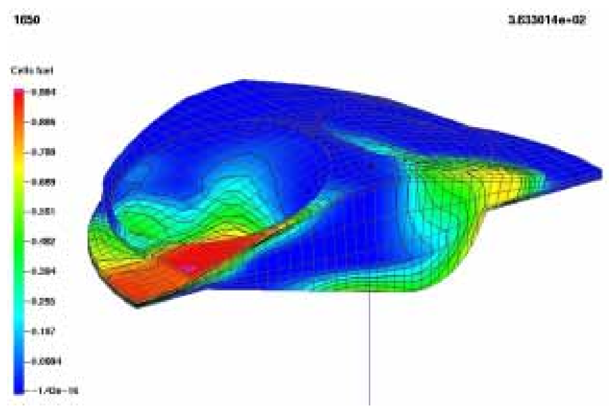

*Fig.20. CNG mass concentration at TDC*

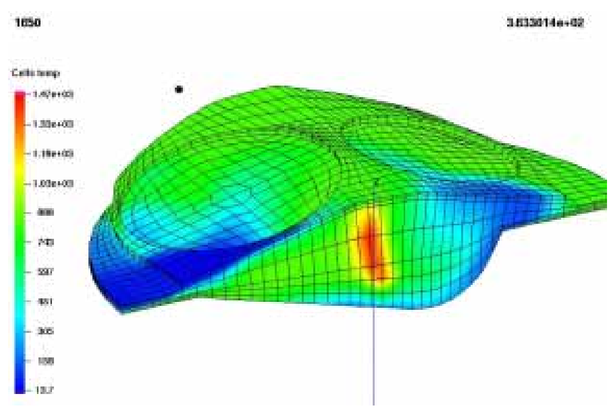

*Fig.21. Temperature in cylinder at TDC*

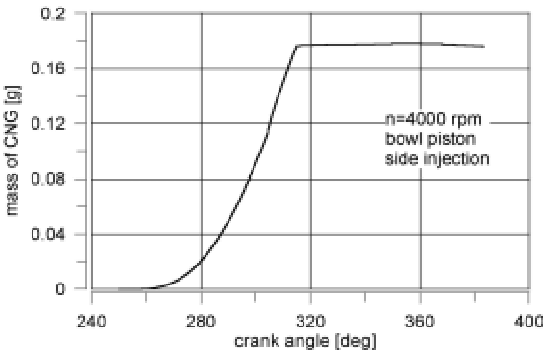


*Fig.22. Total mass of CNG in cylinder*

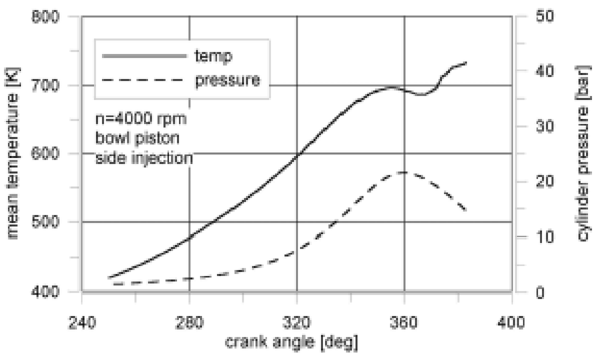


*Fig.23. Mean temperature and pressure in cylinder*

## 7. CONCLUSIONS

1. Location and settings of the gas injector influences much more on the possibilities of mixture ignition for stratified charge at lower loads. The direction of the fuel into the spark plug requires the making of the bowl shorter and with smaller radius.
2. Direction of the fuel stream can be also conducted by an additional air stream during fuel injection.
3. For the stratified mode the controlled injection parameters should be injection timing because the fuel propagation depends on the increasing pressure, charge velocity and rebounding on the piston surface.
4. Direct gas injection in high charged SI engines required the gas injectors with a big mass flow rate at sonic flow.

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