COMPUTATIONAL ANALYSIS AND EXPERIMENTAL RESEARCH INTO LEAN MIXTURE COMBUSTION IN MULTI-SPARK PLUG SI ENGINE

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Abstract

Simulation and experimental research into combustion in multi-spark plug SI engine results are presented in the paper. The outcome of experiment and computational analysis of lean mixtures (excess air number values λ = 1.8) combustion in engine with one, four and seven spark plugs are compared. The results of both the numerical calculations and the experimental research confirmed that applying four spark plugs favourably influences the parameters of lean mixture combustion. The verification of mathematical model applied in KIVA-3V and the real engine was satisfying. The comparison of experimental and numerical research revealed good qualitative conformity of modelled pressure courses with pressure registered on real engine, and in the case of one spark plug the conformity was not only qualitative but also quantitative.

The numerical simulations of combustion process reflects the phenomenon occurring in the combustion chamber of the research engine, which is confirmed by the case of seven spark plugs and its negative influence on combustion parameters of both the experimental and the model engines. The measurements results confirm the favourable influence of applying four spark plugs mostly in the case of lean mixture combustion.

Keyword*: SI engine, multipoint spark plug, spark plug location, lean mixture, numerical modelling*

1. Introduction

Introducing more rigorous toxic components emission standards forces the piston engine design development. Lean mixture combustion can lead to efficient decrease in toxic component emission and increase in engine efficiency. However it is connected with problems such as decrease in flame propagation velocity or high level of engine work non-repeatability. These inconveniencies can be partly overcome by applying multi-ignition among others [6, 7, 8].

2. Combustion modelling

Numerical modelling was performed in KIVA-3V code [2]. The software enabled 3D flow in piston engine combustion chambers of various geometry modelling taking turbulence and heat exchange into consideration. The geometric mesh (Fig. 1) of modelled combustion chamber was designed on the basis of S320 ER spark ignited test engine geometry [3, 4]. The simulation of combustion process was performed for liquid fuel (gasoline) at excess air number equal λ = 1.8. It was the most favourable setting of mixture composition in experimental engine [5] and for three active spark plugs configurations as follows: 1, 1-2-3-4 and all seven spark plugs. These spark plugs configurations were chosen on the basis of previous research – [5]. Location of spark plugs in combustion chamber is depicted in Fig. 2.

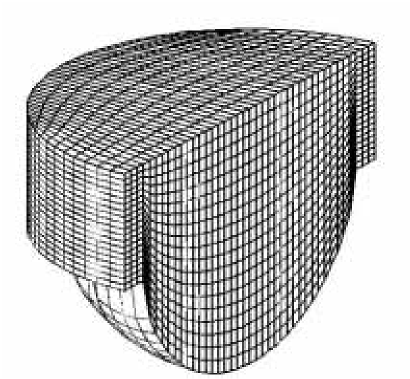

Fig. 1. Geometric mesh in Cartesian co-ordinate system

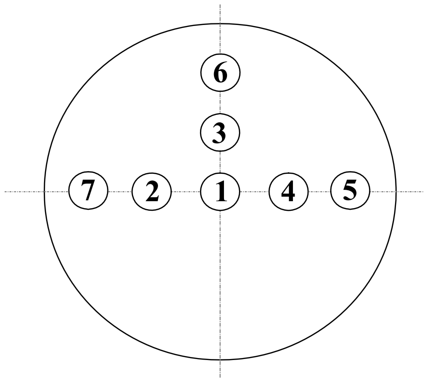

Fig. 2. Spark plugs location legend

The combustion process analysis started at 220°CA (crank angle) and finished 494°CA, which corresponds to experimental engine camshaft phases, which are inlet valves closure and beginning of outlet valves opening. The ignition advance angle was set at 348°CA for λ = 1.8.

The output data was presented in graphical form as screenshots generated by GMV [1] postprocessor and as pressure and temperature courses (mean values for cylinder volume) in function of crank angle.

Following figures present temperature distribution in combustion chamber of modelled engine for chosen active spark plugs configuration as well as pressure and temperature courses in function of crank angle. The spatial temperature distribution is depicted at crank angle equal 5° after Top Dead Centre.

Temperature distribution as well as pressure and temperature courses in function of crank angle at excess air number equal 1.8 are shown in figures 3 to 7.

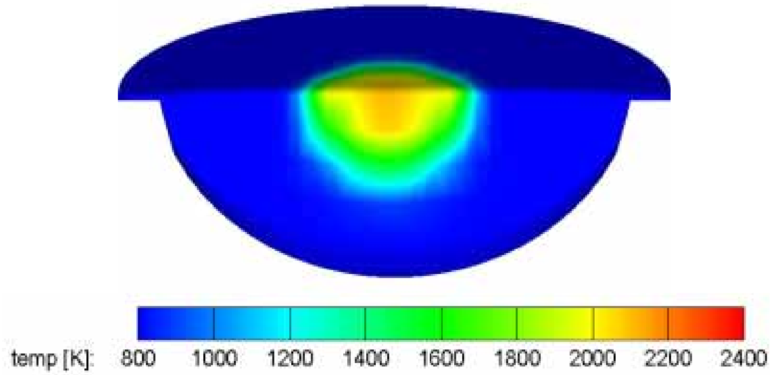

Fig. 3. Temperature distribution for one spark plug at λ = 1.8 and 5°CA after TDC

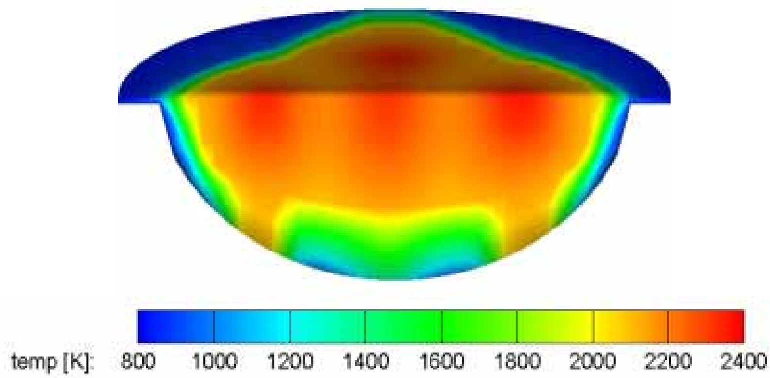

Fig. 4. Temperature distribution for four spark plugs at λ = 1.8 and 5°CA after TDC

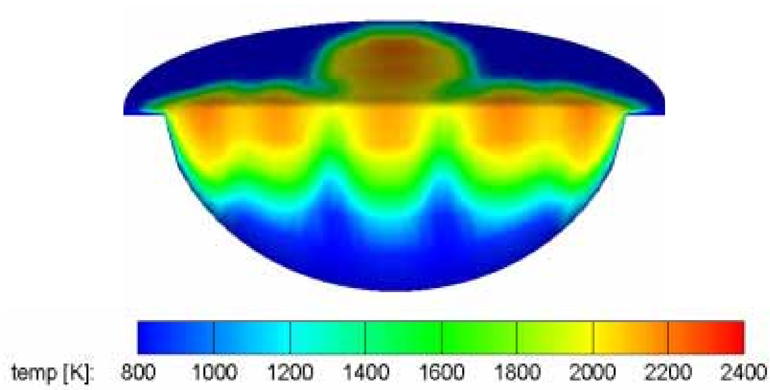

Fig. 5. Temperature distribution for seven spark plugs at λ = 1.8 and 5°CA after TDC

Fig. 4 reveals that applying four spark plugs made the combustion process faster as greater fuel fraction was burnt and high temperature of 2000K is obtained. The maximal temperature in cylinder has also been increased and at 5°CA after TDC it gained the value of 2400K in case of four active spark plugs and 2100 K in case of one active spark plug Fig. 3.

Further increase in active spark plugs to seven spark plugs caused decrease in combustion speed and in maximal values of temperature to 2100 K – Fig. 5.

Fig. 6 and 7 present pressure and temperature courses (mean value for cylinder volume) in function of crank angle.

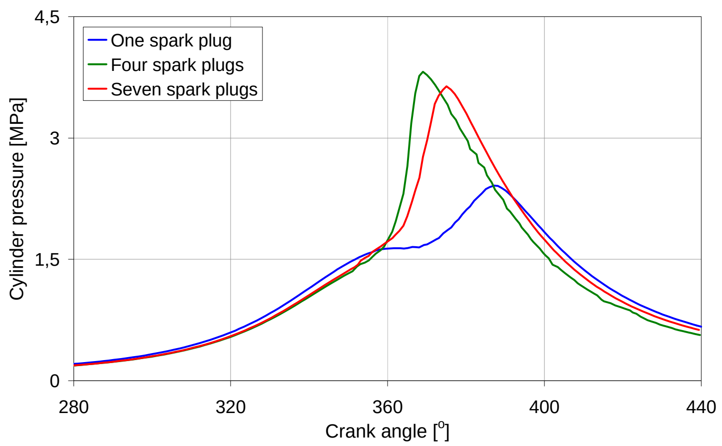

Fig. 6. In cylinder pressure courses for three spark plugs configurations at λ = 1.8

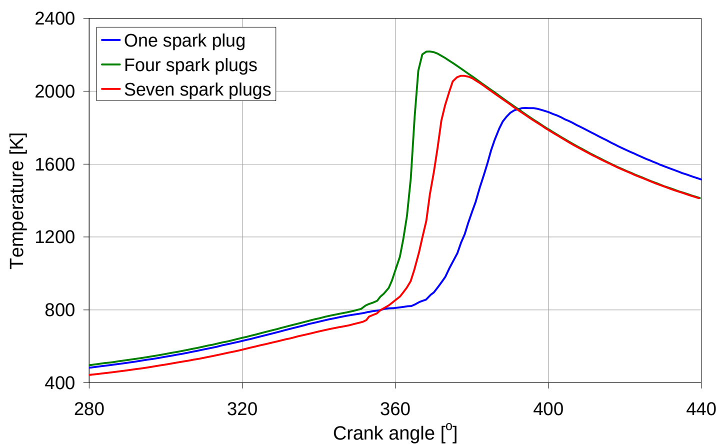

Fig. 7. In cylinder temperature courses for three spark plugs configurations at λ = 1.8

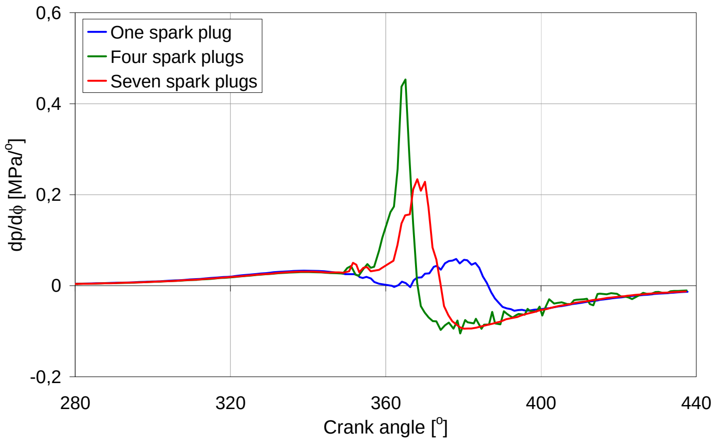

Fig. 8. Pressure growth speed courses in function of crank angle for three spark plugs configurations at λ = 1.8

It can be noticed that the combustion process for one spark plug was very elongated in time. The maximal pressure of 2.4 MPa was obtained at 388°CA (Fig. 6), however the maximal temperature of 1910 K was obtained at 396°CA – Fig. 7. Applying more spark plugs caused increase in combustion speed and in maximal values of pressure and temperature. The most significant increments are observed in case of four spark plugs. In such configuration the maximal pressure gained the value of 3.8 MPa at 369°CA and the maximal temperature gained the value of 2220 K at 369°CA. More than 50% growth of maximal pressure value was obtained in comparison with combustion process initiated by one spark plug. Moreover the pressure growth speed ($dp/d\phi$) increased more than seven times as it gained the maximum value of 0.059 MPa/° in the case of one spark plug and 0.45 MPa/° for four spark plugs – Fig. 8. Increasing the number of active spark plugs to seven has unfavourably influenced the combustion process in engine model. The combustion has been delayed, significantly less charge is burnt at the same piston position (Fig. 5) in comparison to the case with four active spark plugs – Fig. 4. The pressure in the cylinder gained the maximal value of 3.6 MPa at 375°CA (6°CA later than in the case of four active spark plugs) – Fig. 6. The maximal temperature was 2080K at 378°CA, which is 9°CA later than for four active spark plugs – Fig. 7. The pressure growing speed was almost two times lower in this configuration (0.45 MPa/° for four spark plugs and 0.23 MPa/° for seven spark plugs) – Fig. 8.

3. **Comparison of numerical modelling results with experimental results**

The research object was a diesel engine (S320 ER – WSW ANDORIA), which was adapted to the spark ignition engine powered by liquid fuel. This engine of 120 mm cylinder bore, had new cylinder head designed with four valves and multiple spark plug locations [4]. A carburettor was used for fuel supply and excess air number was set to λ = 1.2 ÷ 2.0. The engine was connected to an electrical brake and thanks to it the engine could operate on constant speed 1000 rpm. The most favourable setting of mixture composition was excess air number equal λ = 1.8 for four central spark plugs 1-2-3-4 (Fig. 2) – [5].

Pressure variation in the engine cylinder was registered during the engine work for three above mentioned spark plug configurations. The comparison of mean pressure courses from 95 cycles is depicted in Fig. 9. Similarly as in the engine model, the lowest pressure was obtained for one spark plug. The maximal pressure value in this case was 2.5 MPa at 384°CA. Increasing the number of active spark plugs to four caused the maximal pressure increase to the value of 3.1 MPa. The maximal pressure also occurred earlier (377°CA). Seven spark plugs activation did not resulted in further pressure increase. In contrary, the pressure value decreased to the value of 3.0 MPa and occurred at the same crank angle equal 377°CA.

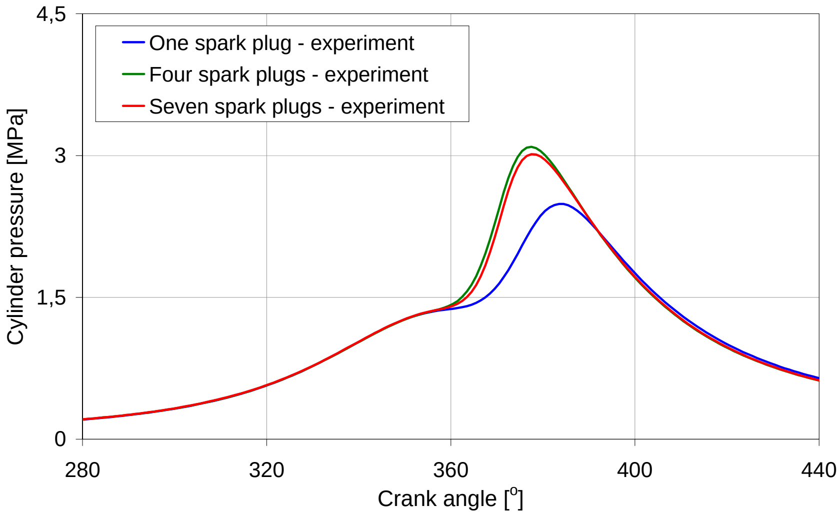

Fig. 9. In-cylinder pressure courses for three spark plugs configurations at λ = 1.8 for experiment

Fig. 10 depicts the in-cylinder pressure growth speed (*dp/dϕ*) of the test engine. It can be noticed that the increase in active spark plugs accelerates the combustion process. The pressure growth speed increased from maximal value of 0.09 MPA/° in the case of one spark plug to the value of 0.17 MPa/° in the case of four spark plug. It is also seen that introducing seven active spark plugs did not result in the pressure growth speed increase as it gained the same value as in the case of four active spark plugs (0.17 MPa/°). The maximum value occurred slightly later than in the case of four spark plugs.

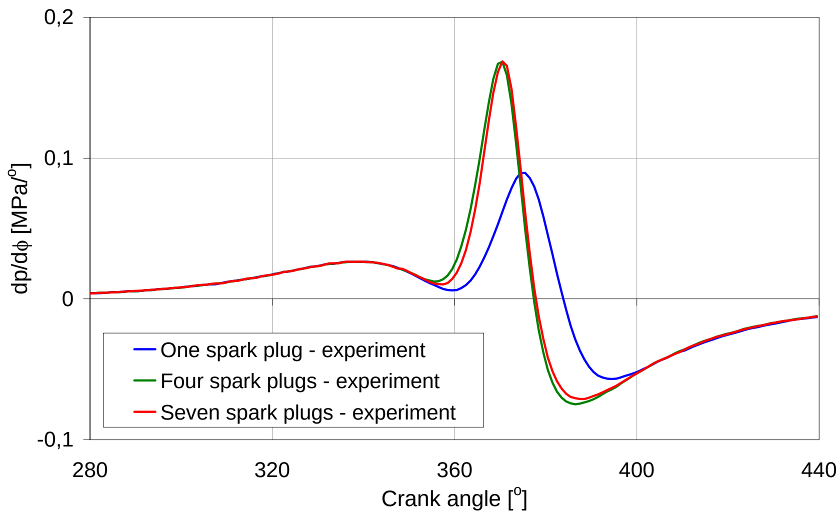

Fig. 10. Pressure growth speed courses in function of crank angle for three spark plugs configurations at λ = 1.8 for experiment

The courses of pressure obtained as a result of numerical modelling and as a result of experimental research were compared. The comparison is shown in Fig. 11-13. It can be noticed that the numerical simulation represented the case with one spark plug located central in the combustion chamber in the most realistic way – Fig. 11. The results are convergent both the qualitatively and even quantitatively. The maximal pressure recorded during experimental research gained the value of 2.48 MPa (mean value of 95 engine work cycles) at the crank angle equal 385°. The maximal pressure value obtained as a result of numerical modelling gained the value of 2.42 MPa at 387°CA.

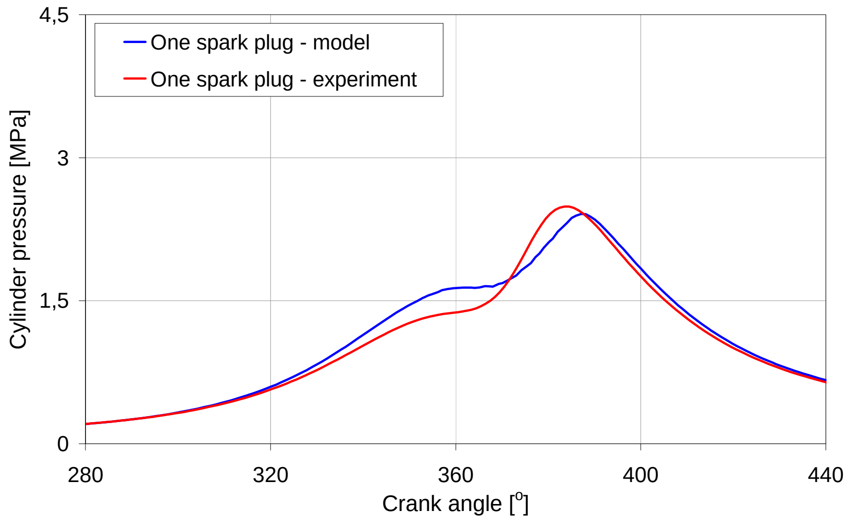

Fig. 11. In-cylinder pressure courses for one spark plug at λ = 1.8 for model and experiment

In the case of the next two configurations the differences between experimental and numerical research are more significant. The pressure values obtained during numerical calculations are greater in comparison to experimental results and their maximal values appear earlier. In the case of four spark plugs configuration (Fig. 12) the maximal pressure for modelled engine was 3.8 MPa at 370°CA, and for the test engine it was 3.1 MPa at 378°CA. In the case of seven active spark plugs (Fig. 13) the differences are slightly lower and pressure values are 3.6 MPa at 375°CA – numerical modelling and 3.0 MPa at 378°CA – experimental research.

It should be emphasized that both the experimental and numerical research confirm the unfavourable influence of applying seven spark plugs on combustion process. It shows how the KIVA-3V code is advanced and how great potential in modelling of phenomenon occurring in piston engine during combustion it has.

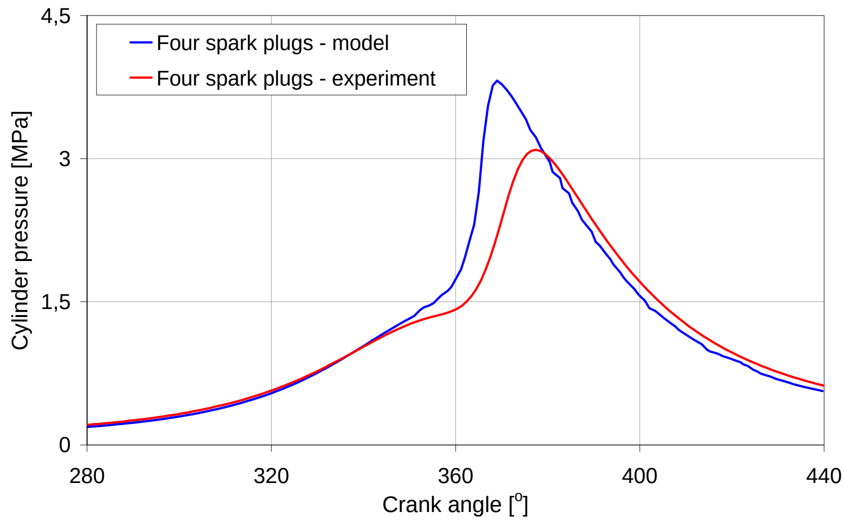

Fig. 12. In-cylinder pressure courses for four spark plugs at λ = 1.8 for model and experiment

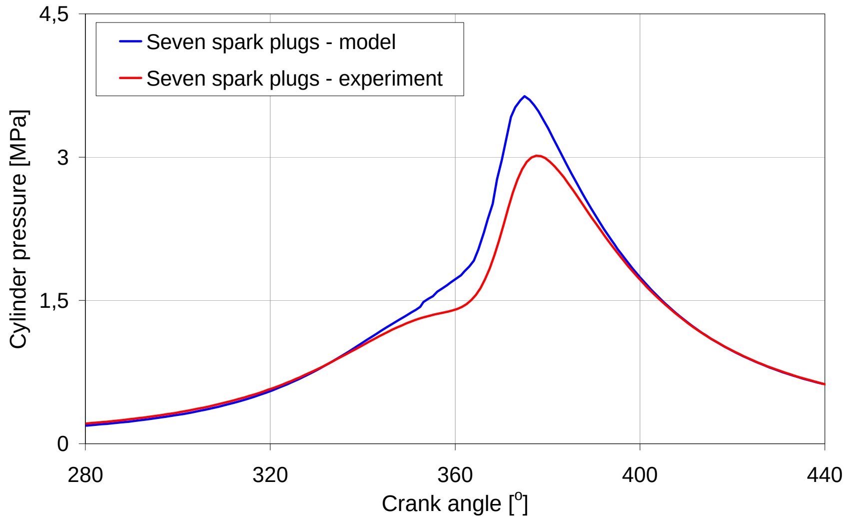

Fig. 13. In-cylinder pressure courses for seven spark plugs at λ = 1.8 for model and experiment

4. Conclusions

Numerical modelling of combustion in multi-spark plug engine proved that improvement in lean mixture combustion process can be obtained by increasing the number of active ignition points. Modelled engine work cycle in case of one active spark plug was impossible to be realized in practical applications. The combustion lasted very long and pressure growth speed $dp/d\phi$ gained low values, which did not exceeded 0.06 MPa/°. Applying four active spark plugs caused significant acceleration of combustion process and increase in maximal values of pressure and temperature. The highest values of maximal pressure 3.8 MPa and temperature 2220 K as well as the highest pressure growth speed 0.45 MPa/° were obtained in this configuration of spark plugs.

For seven active spark plugs the modelled engine work parameters deteriorated. The maximal pressure in the cylinder decreased to the value of 3.6 MPa at 375°CA (6°CA later than in the case with four active spark plugs). The maximal temperature decreased to the level of 2080K at 378°CA, which is 9°CA later than in the configuration with four active spark plugs. The pressure growth speed also decreased (almost two times) to the level of 0.23 MPa/°.

As conclusion it can be stated that numerical modelling results confirmed the favourable influence of applying four active spark plugs in lean mixtures combustion. The main disadvantage of such mixtures, which is very long combustion, has been overcome.

The comparison of experimental and numerical research in the configuration with only one spark plug revealed good qualitative and quantitative convergence of modelled pressure courses and pressure courses recorded on the test engine. The other spark plug configurations is characterized only by qualitative convergence as the calculated values differ from the measured ones. The pressure courses are qualitatively similar but their maximal values for the modelled engine are higher and occur earlier mostly in the case of four spark plugs. It means that in the range of very lean mixtures the combustion speed in the engine model is greater than in the real engine.

It can be stated as conclusion that the numerical model verification with the use of KIVA-3V produced satisfying results. The numerical simulations of combustion process reflects the phenomenon occurring in the combustion chamber of the research engine, which is confirmed by the case of seven spark plugs and its negative influence on combustion parameters of both the experimental and the model engines. The measurements results confirm the favourable influence of applying four spark plugs mostly in the case of lean mixture combustion.

References

[1] Abraham J., Magi V., *GMV, General Mesh Viewer*, Los Alamos National Laboratory LA-UR-952986, March 1995.
[2] Amsden A.A., *KIVA-3V: A block-structured computer program for 3-D fluid flows with valves, chemical reactions, and fuel sprays*, Los Alamos National Laboratory, Group T-3, March 1997.
[3] Cupiał K., Kociszewski A., Jamrozik A., *Multipoint spark ignition engine operating on lean mixture*, Teka Komisji Motoryzacji i Energetyki Rolnictwa, Polska Akademia Nauk Oddział w Lublinie, Tom III, s. 70-78, Lublin 2003.
[4] Cupiał K., Kociszewski A., *Measurements and 3D modeling of combustion in multipoint spark ignition engine*, Journal of KONES. Internal Combustion Engines, Vol. 9, No. 3-4, s. 80-87, 2002.
[5] Kociszewski A., *Spalanie mieszanek homogenicznych w silniku tłokowym z zapłonem wielopunktowym*, Praca doktorska, Politechnika Częstochowska, 2004.
[6] Löhner K., Müller H., *Gemischbildung und Verbrennung im Ottomotor*, [in:] List H., *Die Verbrennungskraftmaschine*, Springer-Verlag, Wien - New York, 1967.
[7] Quader A. A., *Lean combustion and the misfire limit in spark ignition engines*, SAE Paper 741055, 1974.
[8] Yamamoto H., Horita S., Matsuoka T., *Surrounding combustion process (SCP) – new concept for lean burn engine*, SAE Paper 920058, 1992.