MULTIPOINT SPARK IGNITION ENGINE OPERATING ON LEAN MIXTURE

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INTRODUCTION

Experiment on multipoint spark ignition engine operating on lean mixture was carried out in the Institute of Internal Combustion Engines and Control Engineering of Częstochowa University of Technology. The results of research concerning the influence of spark plugs number and their location in SI engine on the performance of this engine are presented in the paper. The article also describes the numerical modelling of a combustion process performed with KIVA-3V [2], which was compared to an experiment. This software allows three-dimensional flows modelling in the chamber of any geometry of the IC engines, taking also turbulence and heat transfer into consideration.

RESEARCH OBJECT

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, with a 120 mm cylinder bore, had a new cylinder head designed with four valves and multiple spark plug locations – 8 spark plugs (see Fig. 1) [4]. A carburettor was used for fuel supply and excess air factor was set to λ = 1.2-2.0. The engine was connected to an electrical brake so the engine could operate on constant speed 1000 rpm. The ignition system includes eight transistor modules with low-resistance ignition coil per spark plug. This system allows choosing any spark plug number and location.

The high-speed data acquisition system that was designed and constructed at the Institute of Internal Combustion Engines and Control Engineering was used during measurements [3, 5].

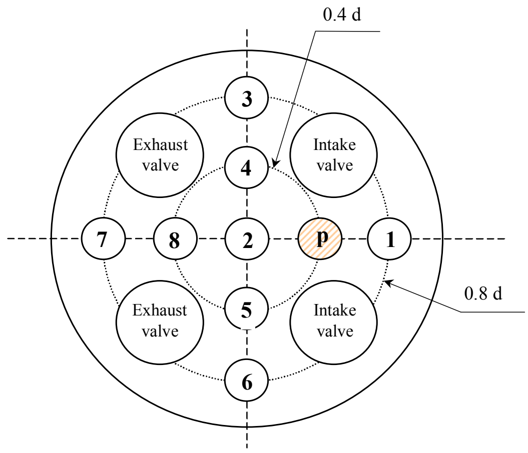

Fig. 1. Spark plug location legend (p – pressure transducer – Kistler model 6061B)

RESEARCH COURSE

The research was conducted in full engine load and after heat stabilisation, which means after boiling the cooling liquid (evaporation based cooling system). Taking the earlier research into consideration [4], measurements were done for central spark plug (No 2), four spark plugs (No 2, 4, 5 and 8) and all spark plugs. Data logging was performed for each one degree of crank angle for 95 consecutive engine cycles with the use of specialised software [5]. Simultaneously measurements of other quantities, which were essential for further analysis [3], were done. Measurements were conducted for five values of excess air factor (λ = 1.2, 1.5, 1.6, 1.8, 2.0). Richer mixtures were not applied because of knock occurrence, which took place at λ = 1.0-1.1.

At each excess air factor, ignition advance angle was optimised in order to achieve the best parameters of engine work. Indicated work, indicated efficiency and non-repeatability of the following cycles were especially taken under consider. Toxic components in exhaust gas concentration were measured during the research using exhaust-gas analyser RADIOTECHNIKA AI9600.

RESULTS OF THE EXPERIMENT

IGNITION ADVANCE ANGLE OPTIMIZATION

6° CA before TDC at λ = 1.2 was the most suitable ignition advance angle in the aspect of work, power and indicated efficiency. At λ = 1.5 and 1.6 the most suitable ignition advance angle was 10° CA before TDC, at λ = 1.8 it was 12° CA before TDC and at λ = 2.0 it was 14° CA before TDC. With the increase of mixture depletion the ignition must occur earlier in order to achieve a correct combustion process (Fig. 2).

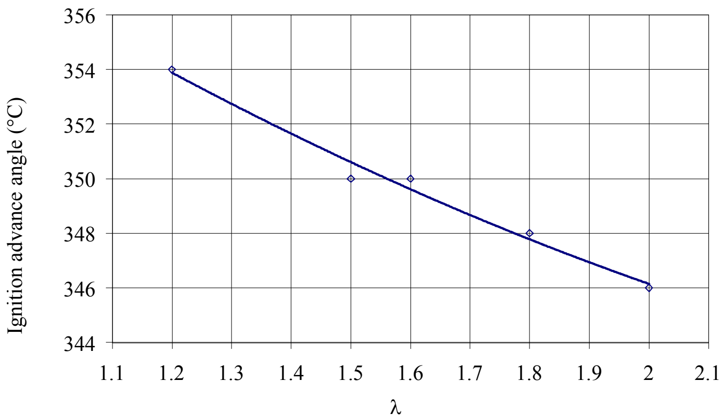

Fig. 2. Optimal ignition angle versus excess air factor

The value of ignition advance angle on one hand is limited by engine performance and on the other hand by toxic components concentration in exhaust gas, especially nitric oxides concentration, which increases with an increase of ignition advance angle value. In some spark plugs configurations, higher value of ignition advance angle was favourable but a significant increase in NO_x concentration also occurred in those cases.

MIXTURE DEPLETION AND ENGINE WORK PARAMETERS

A set of mixture depletion on test engine performance characteristics for each combination of spark plugs location was made after the determination of the optimum ignition advance angle values. The variation of indicated work, indicated efficiency, combustion duration and non-repeatability cycles were analysed. The non-repeatability factor was determined at the maximum cylinder pressure using the following dependency:

$$COV_p = \frac{\sigma_{p\max}}{\bar{p}_{\max}} \qquad (1)$$

where:

σ_p – maximum cylinder pressure standard deviation,
$\bar{p}$ – mean maximum cylinder pressure.

The combustion duration was shown as an angle between the ignition moment and the time when 100% of fuel was burned. The analysis results are depicted in the figures below.

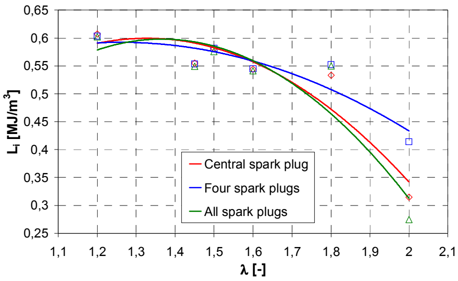

Fig. 3. Indicated work versus excess air factor

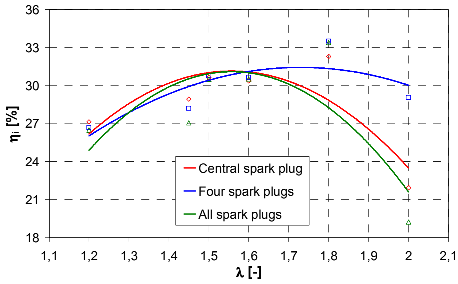

Fig. 4. Indicated efficiency versus excess air factor

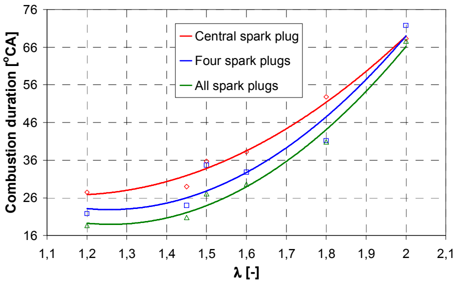

Fig. 5. Combustion duration versus excess air factor

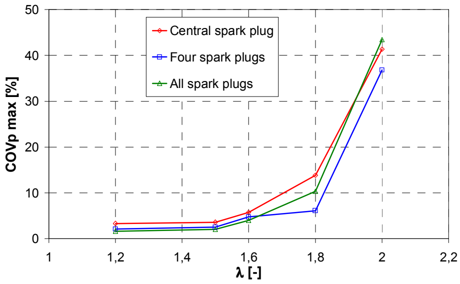

Fig. 6. Non-repeatability of engine cycles versus excess air factor

From the figures it follows that an engine's performance decreases with a mixture depletion increase (Fig. 3) although a distinct work decrease occurs only at high excess air factor (λ = 2.0). In this case a deterioration of engine work parameters is caused by significantly longer combustion duration (Fig. 5) and high cycle non-repeatability with misfire (Fig. 6). Combustion duration was approximately 70° CA and the pressure dispersion around its mean value was up to 43.4% (for all spark plugs).

The indicated efficiency of an engine (Fig. 4) increases at the initial range of λ and achieves its maximum (33.5% – all spark plugs) at λ = 1.8, and then decreases to the value of 29.1% (four spark plugs) and 19.2% (all spark plugs) at the maximum excess air factor (λ = 2.0).

The foregoing graphs depict the very favourable setting in the aspect of engine work parameters, which is the central location of four spark plugs at λ = 1.8. The maximum indicated efficiency of 33,5% occurs in this case and work and power decrease is low in comparison with richer mixtures.

TOXIC COMPONENTS EMISSION

Toxic components concentration of test engine exhaust gas was measured during the research. The concentrations of nitric oxides NO_x, hydrocarbons HC and carbon oxides CO were measured.

Carbon oxide concentration in the whole range of mixture depletion was at a stable level of 0.06%. In order to present the mixture composition's influence on nitric oxides and hydrocarbons emission Fig. 7 was presented.

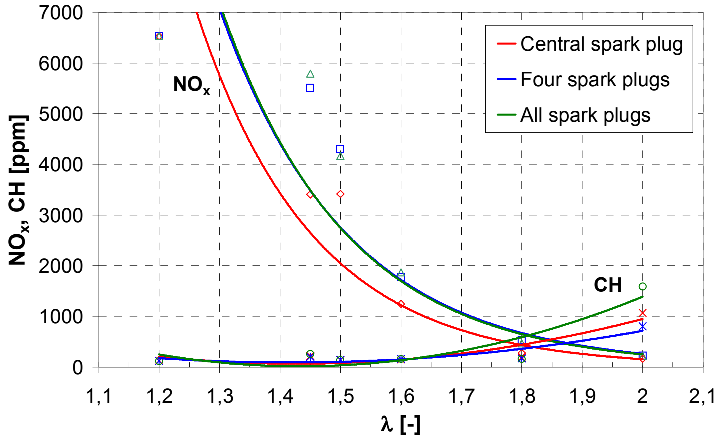

Fig. 7. Mixture composition influence on NO_x and HC emission

Nitric oxides concentration in exhaust gas of the test engine in the range of λ = 1.2-1.6 does not decrease below 1000 ppm. Only at excess air factor λ = 1.8-2.0, the nitric oxides concentration in exhaust gas is lower than 550 ppm. The lowest concentration of this compound was obtained at the maximum mixture depletion, and for one centrally located spark plug it was 160 ppm.

The significant increase of unburned hydrocarbons concentration at λ = 2.0, is the result of a very long-lasting combustion process and high cycle non-repeatability which occurs in this case. The highest CH emission was obtained at the least favourable configuration of all spark plugs. This effect cannot be explained on the basis of the conducted research, however, at the front flame distribution in a cylinder unfavourable influence on combustion process is probable.

For very lean mixtures of λ > 1.8, the four centrally located spark plugs configuration gives the lowest CH emission of less than 800 ppm.

MODELLING OF COMBUSTION PROCESS USING KIVA-3V

Combustion process modelling was realised for two configurations of spark plug number and location: one central spark plug (No 2) and two spark plugs (No 2 and 8). Geometric mesh, which described the shape of combustion chamber, was made in the cartesian co-ordinate system (see Fig. 9). The numerical study was carried out for excess air factor equal to 1.8 because, according to the experiment results, it was the most favourable setting of mixture composition.

The numerical simulations began at 220° CA and finished at 494° CA. This meets the test engine valve timing (the intake valves closure and the start of exhaust valves opening).

Fig. 8. Geometric mesh in cartesian co-ordinate system depicted for 50° CA after TDC

During the modelling attention was focused on pressure and temperature in the cylinder and on nitric oxide evolution during the combustion process. KIVA-3V software presents the analysis results in text files that are *dat.thermo*, which concerns pressure and temperature values and *otape12*, which concerns the nitric oxide concentration in cylinder gas.

COMPARISON OF EXPERIMENTAL RESULTS WITH NUMERICAL MODELLING RESULTS

Modelling results are shown graphically using GMV postprocessor [1]. Pressure and temperature (all cylinder volume mean values) in function of crank angle curves were made. The results of pressure and temperature modelling and experimental results were compared. The modelled engine nitric oxide distribution was specified in the function of crank angle. These values are actual and averaged for all the combustion chamber volume values.

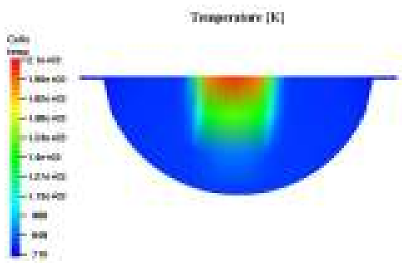

Fig. 9. Temperature distribution in TDC for central spark plug ($\alpha_{ignition}$ = 348° CA)

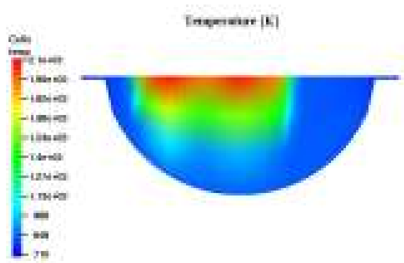

Fig. 10. Temperature distribution in TDC for two spark plugs ($\alpha_{ignition}$ = 348° CA)

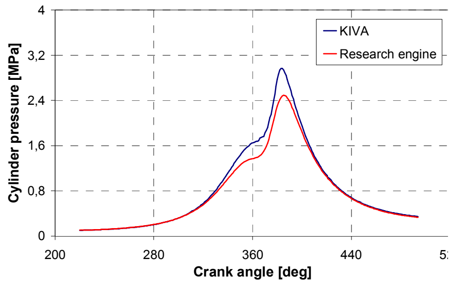

Fig. 11. Pressure in cylinder for central spark plug

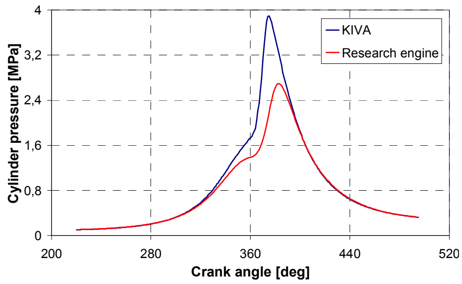

Fig. 12. Pressure in cylinder for two spark plugs

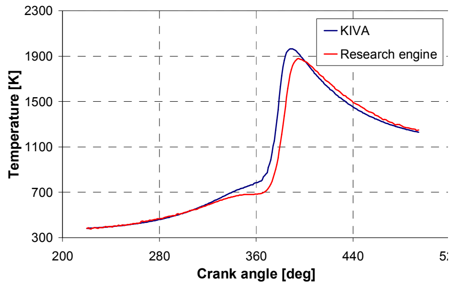

Fig. 13. Temperature in cylinder for central spark plug

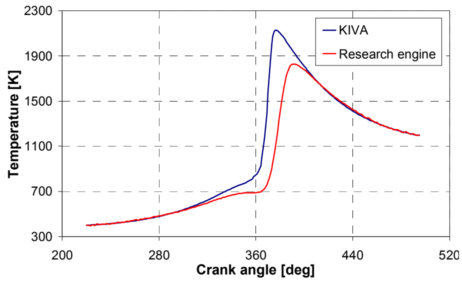

Fig. 14. Temperature in cylinder for two spark plugs

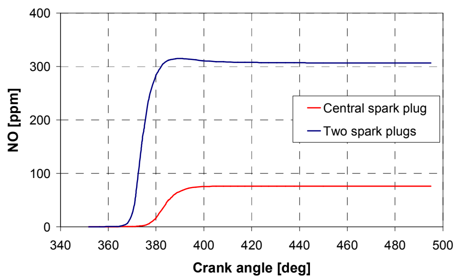

Fig. 15. NO distribution in cylinder versus crank angle for two configurations spark plugs number and location

Significantly faster flame propagation in case of two spark plugs results from figures 9 and 10. Even at the TDC a greater part of charge has a temperature higher then 1500 K. The good representation of this effect is the determination of a percentage share of temperature higher than 1500 K zone in all cylinder volume – Fig. 16. 50% share of this zone for one spark plug configuration is achieved at 380° CA and for two spark plugs configuration for 372° CA, which is 8° CA earlier.

In the two spark plugs configuration, the modelled pressure is higher (Fig. 12) and its maximum (3.9 MPa) occurs earlier (375° CA) than in one spark plug configuration (p_{max} = 2.9 MPa at 384° CA) – Fig. 11. Lower pressure values at little differences of spark plugs configuration were obtained in a real engine. For one spark plug the pressure is 2.5 MPa at 386° CA, and for two spark plugs it is 2.7 MPa at 384° CA.

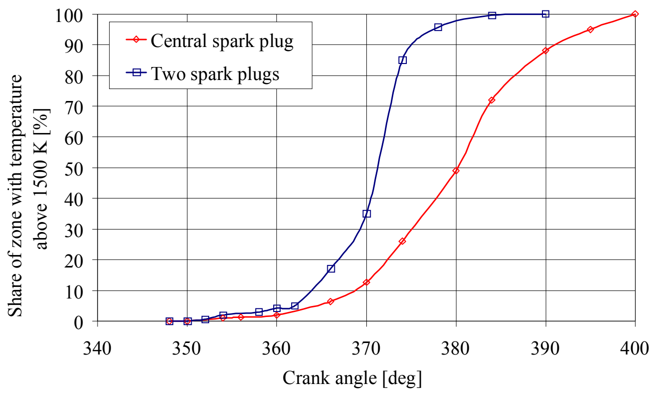

Fig. 16. Percentage share of temperature higher than 1500 K zone in all cylinder volume

The maximal combustion temperature of the modelled engine (Fig. 13 and 14) are at a higher level than in the experimental engine. The greatest differences are for two spark plugs configuration, where the temperature of the simulated process equals to 2130 K at 377° CA, and the combustion temperature calculated on the basis of the indicated diagram [3] equals to 1830 K at 390° CA. In the case of one spark plug, the differences are smaller because the modelled temperature is 1960 K at 390° CA, and in the real engine the temperature is 1880 K at 395° CA.

The numerical analysis of a combustion process shows an increase of nitric oxide concentration in exhaust gas in case of higher number of spark plugs – Fig. 15. For this mixture composition centrally located one spark plug is characterized by NO concentration of 80 ppm, and for two spark plugs the concentration is 310 ppm at 494° CA (exhaust valves opening). It is because of a higher maximum combustion temperature values.

Nitric oxides concentration in the experimental engine exhaust gas was measured and it was 280 ppm for one central spark plug and 400 ppm for two spark plugs.

CONCLUSIONS

Research into SI engine powered by mixture of λ = 1.2-2.0 show that increase in number of active spark plugs causes decrease of non-repeatability rate, increase of indicated pressure and efficiency. It also shortens the combustion duration. Significant improvement is obtained for four spark plugs (No 2, 4, 5 and 8) located centrally in combustion chamber. At this spark plug configuration, excess air factor value of 1.8 allows maximal indicated efficiency of 33.5%, indicated work equals 0.552 MJ/m^3 and is a little lower than 0.6 MJ/m^3 obtained at richer mixtures. Non-repeatability of the following cycles with reference to the maximum pressure in the cylinder equals to 6.13%. Exhaust gas toxicity is at a low level.

Numerical modelling of the combustion process in SI engine confirms a good influence of applying two spark plugs in a cylinder (standard version of KIVA does not allow modelling of more than two spark plugs). It increases flame propagation velocity. It is important during lean mixture combustion because applying that kind of mixture causes a decrease in combustion speed and deterioration of engine parameters. Figures 11 and 14 show a comparison of experimental results with numerical modelling results. In two spark plugs configuration the numerical model reveals higher pressures in the cylinder and a faster increase of those pressures with relation to one spark plug configuration. The maximum pressure angle amounts to 384° CA (central spark plug in KIVA) and 375° CA (two spark plugs in KIVA). The discrepancy between pressures and between temperatures during combustion can be caused by a different exponent of the compression polytropic curve values, which gained higher values in the numerical model than in a real engine. Figure 15 depicts nitric oxide concentration in the cylinder of KIVA engine. It shows that an increase in fire points number causes an increase in nitric oxide concentration.

Good results were obtained during the verification of the mathematical model using KIVA-3V software with a real engine. Processes in experimental engine combustion chamber were well reflected in computer simulations. Modelling results and experimental results confirm a good influence of a spark plugs number increase especially for lean mixtures burning.

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 KIVA Program for Engines with Vertical or 3. Canted Valve, Los Alamos National Laboratory LA-UR-97-689, February 1997.
3. **Cupiał K.**: „SILNIK" wersja 2001.5 – program do opracowywania wykresów indykatorowych, Instytut Maszyn Tłokowych i Techniki Sterowania, Częstochowa 2002.
4. **Cupiał K., Kociszewski A.**: Wielopunktowy zapłon w silniku ZI, Międzynarodowa Konferencja Motoryzacyjna AUTOPROGRES-KONMOT 2002.
5. **Gruca M.**: „LCTXR" – program do rejestracji i analizy sygnałów, Instytut Maszyn Tłokowych i Techniki Sterowania, Częstochowa 2001.

SUMMARY

The results of an experiment on multipoint spark ignition engine operating on lean mixture (λ = 1.2-2.0) were presented in the paper. The research concerned the influence of spark plugs number and location on the following performance characteristics of this engine: the indicated work, indicated efficiency and the cycle's non-repeatability. The article also described a modelling of the combustion process in this engine, which was performed with KIVA 3V. Those simulations were compared to the experiment.