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Optimization of work parameters of gaseous SI engine

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Summary. Results of numerical analysis of methane combustion in SI engine are presented in the paper. Work parameters of engine fuelled with methane lean mixtures of λ = 1.4 for several ignition advance angles are compared. The results of analysis proved that using ignition advance 6° CA before TDC, caused that engine work parameters (pressure, temperature and pressure growth speed) are correct and optimal. Simultaneously, the emission of nitric oxide was decreased compared to early ignition advance angles.
Key words: SI engine, methane, numerical modelling, lean mixture.

INTRODUCTION

One of the research activities carried out in the Institute of Thermal Machinery is 3D modelling of combustion in spark ignition engine fuelled with gasoline, gas and lean mixtures this fuels [1-15]. The calculations are performed in KIVA-3V and AVL FIRE programs [16-22].

The paper aims an analysis of influence of the ignition advance angle to stationary gaseous engines parameters, operating at constant rotational speed and driving electric generators. Such engines can be fuelled with natural gas, biogas (waste dump gas, sewage gas) or mine gas as well as fuels containing methane. The containment of methane in above mentioned fuels differs according to the origin of the fuel. The natural gas contains approx. 98% of methane, biogas contains approx. 40-60%, and main gas obtained during the exploitation of the mine contains approximately 25-60% of methane. The containment of methane in mine gas differs for different coal deposits, the way it is exploited and time.

The paper is the continuation of numerical analysis of combustion in gaseous SI engine model fuelled with lean mixtures [23, 24].

MODEL OF ENGINE

The engine model was prepared according to the test engine data. The test engine was designed as the modified single-cylinder, high-pressure S320ER engine, which has been rebuilt in order to apply multipoint spark ignition [25]. The main engine parameters are presented in Table 1.

Table 1. Main engine parameters

Engine capacity	1810 cm^3
Number of cylinders	1
Cylinder alignment	horizontal
Cylinder diameter	120 mm
Crank throw	80 mm
Crankshaft length	275 mm
Piston stroke	160 mm
Compression ratio	8.5
Rotational speed	1000 rev/min

The application of multipoint spark ignition in the test engine allowed to fuel the engine with lean mixtures of liquid and gaseous fuels of air excess factor λ ≤ 2.0 [25].

The numerical modelling was performed in KIVA-3V program [26]. The software enabled 3D modelling of flow in piston engine combustion chambers of various geometry with taking turbulence and heat exchange into consideration.

The geometric mesh (Figure 1) describing the combustion chamber of the test engine was generated in the pre-processor of KIVA-3V package.

COMBUSTION MODELLING

The simulation of combustion process was performed for gaseous fuel (methane) at air excess factor value λ =

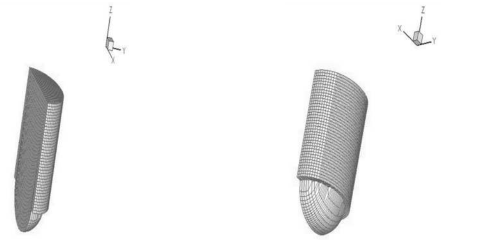

Fig. 1. Geometric mesh in cartesian co-ordinate system

1.4, one central spark plug and eight values of the ignition advance angles – 2, 4, 6, 8, 10, 12, 14, 16 deg CA before top dead center (TDC).

The chemical reaction of methane combustion model in KIVA-3V takes into account four kinetic reactions and six equilibrium reactions. The first kinetic reaction describes the oxidation of fuel and the following three reactions describe the NO formation according to extended Zeldowich mechanism [27].

$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O,$$
$$O + N_2 \Leftrightarrow N + NO,$$
$$N + O_2 \Leftrightarrow O + NO,$$
$$N + OH \Leftrightarrow H + NO.$$

The equilibrium reactions are [27]:

$$H_2 \Leftrightarrow 2H,$$
$$O_2 \Leftrightarrow 2O,$$
$$N_2 \Leftrightarrow 2N,$$
$$O_2 + H_2 \Leftrightarrow 2OH,$$
$$O_2 + 2H_2O \Leftrightarrow 4OH,$$
$$O_2 + 2CO \Leftrightarrow 2CO_2.$$

The coefficients of NO formation kinetic reaction rate are necessary to perform the calculations and they were chosen on the basis of the literature studies [28].

The results of numerical modelling are presented in graphical form. The distribution of temperature and nitric oxide concentration in the combustion chamber are presented using Tecplot 360 postprocessing software [29]. The courses of pressure, temperature, NO and CO_2 concentration (averaged values for the volume of combustion chamber) in function of crank angle are also presented.

NUMERICAL ANALYSIS RESULTS

The following figures depict the distribution of temperature and nitric oxide concentration in the combustion chamber, which occurred for the analyzed ignition advanced angles. Moreover, courses of pressure, temperature, NO and CO_2 concentration (averaged values for the volume of combustion chamber) in function of crank angle are depicted. The temperature distribution is presented at crank angle in TDC. The NO distribution is presented at crank angle corresponding with the maximal concentration of this compound.

The temperature distribution as well as pressure courses (averaged values for the volume of combustion chamber) in function of crank angle are depicted in Fig. 2 – Fig. 4.

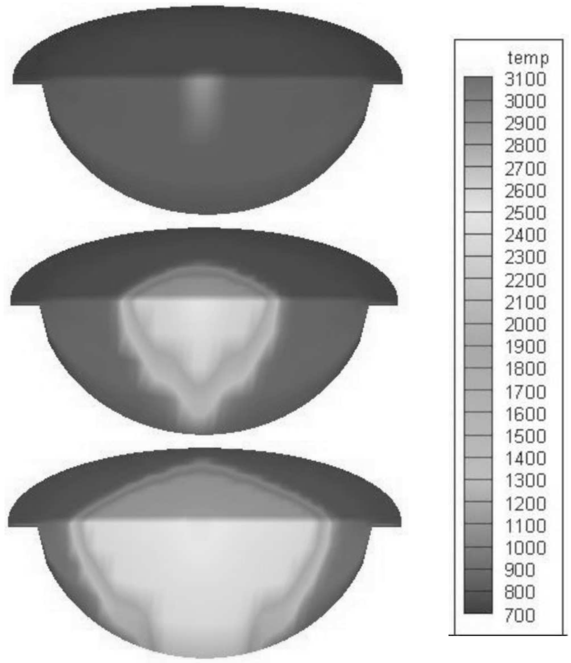

Fig. 2. Temperature distribution for three example ignition advance angles 2°CA, 10°CA, 16°CA before TDC

Fig. 2 reveals that the combustion process was intensified by increasing the ignition advance angle value. Greater portion of fuel was burnt at temperature above 2000 K. Such phenomenon is clearly seen in case of ignition advance angle equal 16°CA before TDC. In this case, the combustion process takes place in almost whole volume of the chamber.

Fig. 3 and 4 depict pressure and temperature courses (averaged values for the volume of combustion chamber) in function of crank angle.

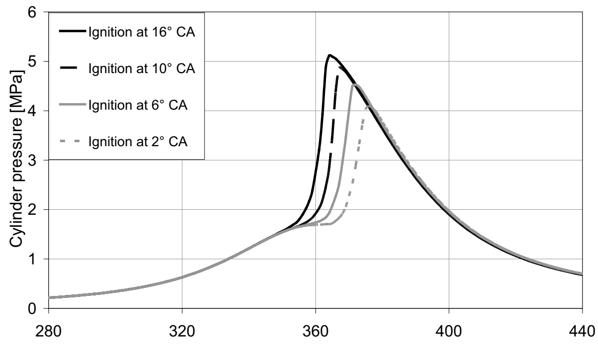

Fig. 3. In cylinder pressure courses for selected ignition advance angle values

In case of 2°CA ignition advance angle value, the pressure in the cylinder reaches its maximal value equal 4.1 MPa at 376°CA. The increase in the ignition advance angle to 16°CA before TDC causes the 24% increase in maximal pressure value.

The maximal pressure values occur earlier than in the configuration with 2°CA ignition advance angle value – the difference in crank angle are 12°CA. It proves that the combustion process was intensified for the configuration with earlier ignition. It is clearly seen on a chart depicting the

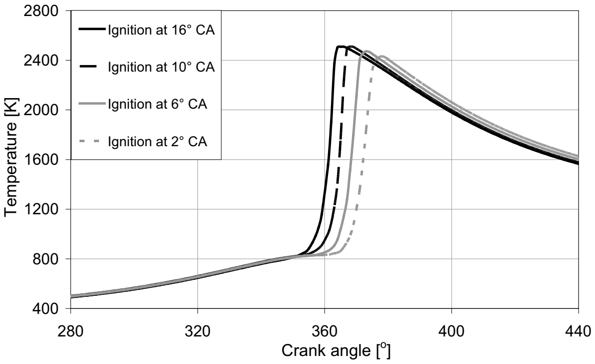

Fig. 4. In cylinder temperature courses for selected ignition advance angle values

pressure growth speed in the cylinder – Fig. 5. For case of 2°CA ignition advance angle value, this parameter reaches maximal value of 0.42 MPa/° at 372°CA. In case of 16°CA ignition advance angle value, *dp/dφ* is two times bigger and reaches the value of 0.84 MPa/° at 361° CA.

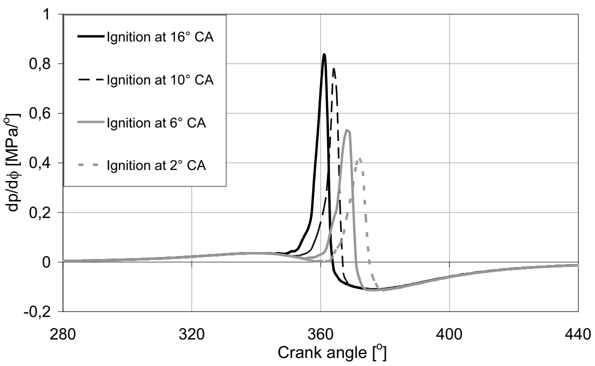

Fig. 5. Pressure increase courses in function of crank angle for selected ignition advance angle values

Taking into consideration the above mentioned data, it can be stated that configuration with more early ignition is not purposeful. The difference in maximal values of temperature (Fig. 4) is not significant. Although the acceleration of combustion process occurs, significant increase in pressure (Fig. 5) can lead to hard and noisy operation, which applies dynamic load to crankshaft and piston.

Increase the ignition advance angle value, causes increase in nitric oxide emission – Fig. 6 and 7.

Fig. 6 depicts the nitric oxide distribution in the combustion chamber for the three example ignition advance angles 2°CA, 10°CA, 16°CA before TDC. The pictures depict maximal values of nitric oxide concentration and which are prepared in the same scale. It can be noticed that increasing the ignition advance angle value significantly increases the NO concentration in the cylinder volume.

For 2°CA ignition advance angle value, the nitric oxide concentration (the averaged value for the volume of the combustion chamber – Fig. 7) reached its maximal value equal 2930 ppm at 394°CA. In case of 10°CA ignition advance angle value, the NO concentration increased by 65% up to 4850 ppm at 387°CA. For 16°CA ignition advance angle value, the NO concentration increased by 80% (5285 ppm) in comparison with case of 2°CA ignition advance angle.

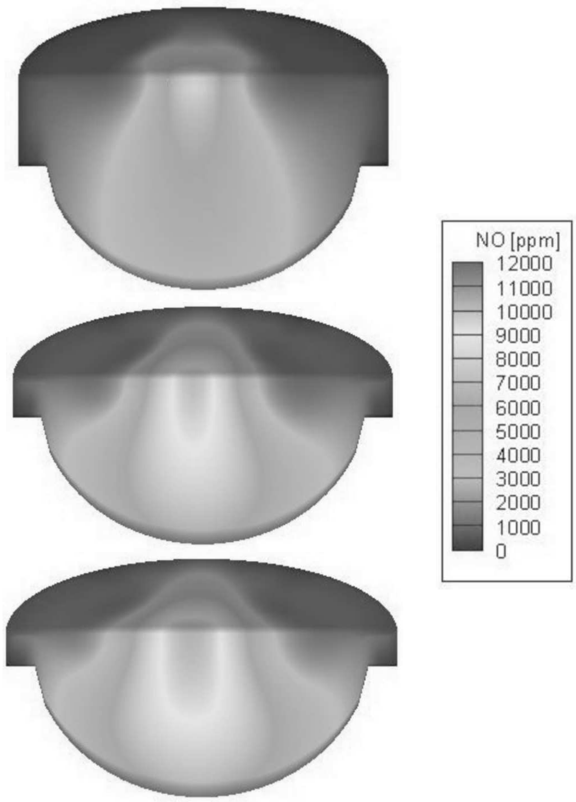

Fig. 6. NO distribution (actual maximum values at 46°, 28°, 25° CA after TDC) for three example ignition advance angles 2°CA, 10°CA, 16°CA before TDC

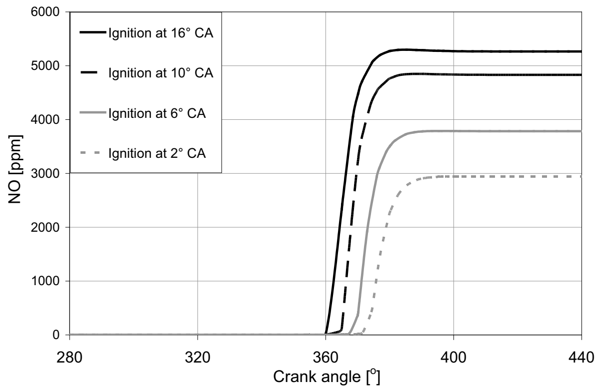

Fig. 7. Variations of NO concentration (mean values for cylinder volume) for selected ignition advance angle values

The above analysis proves, that increasing the ignition advance angle value to about 12°CA, 14°CA, 16°CA before TDC is not favourable. The pressure increase in the cylinder is too big, which can result in very hard engine operation and the nitric oxide emission increases significantly.

The chart depicted in Fig. 8. shows the variations of CO_2 concentration, which were occurred during modelled engine operation for all ignition advance angle values. The carbon dioxide emission values are mean values, calculated for the whole volume of cylinder. The maximal concentration of

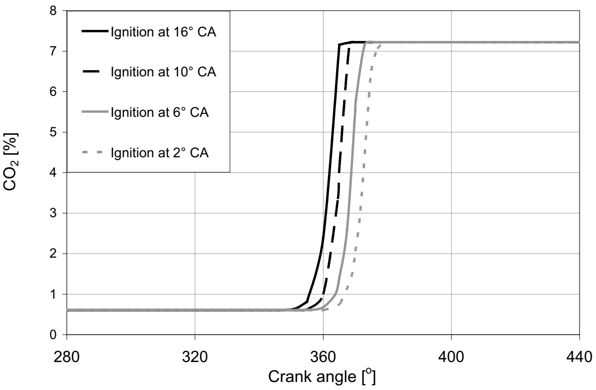

Fig. 8. Variations of CO_2 concentration (mean values for cylinder volume) for selected ignition advance angle values

this compound was 7,2% and was obtained at different crank angles depending on the value of ignition advance angle. With the increase of ignition angle, the maximal concentration of CO_2 was obtained faster.

The results of these tests were compared with those of a engine powered by a mixture of λ = 1.2 – Fig. 9-10. In this case (λ = 1.2) the optimal ignition advance angle was 2°CA before TDC.

The comparison shows that for the selected ignition advance angle much more preferred to use a leaner mixture. Although much smaller value of the pressure growth speed in this case, in the exhaust gas components is about 12% less CO_2 and up to almost 50% less nitrogen oxide.

CONCLUSIONS

The results of 3D modelling of methane combustion showed, that using earlier ignition advance angle caused very significant increase in NO emission, which gained even 80% for 16°CA ignition advance angle value. The difference in maximal values of temperature was insignificant. High values of pressure growth speed (maximal value of 0,83 MPa/°) can lead to noisy and hard engine operation.

The optimal value of ignition advance angle appears to be 6°CA before TDC. In this case model engine work parameters are proper and suitable to combustion lean gaseous mixture methane and air. The pressure in the cylinder reaches its maximal value equal 4.5 MPa at 372°CA and pressure increase is 0,53 MPa/°. Concentration of NO reaches its maximal value equal 3760 ppm at 387°CA and this is about 30% lower in comparison with case 16°CA ignition advance angle.

The results of numerical analysis can be used in stationary gaseous engines, operating at constant rotational speed and driving electric generators. Such engines can be fuelled with lean mixtures fuels containing methane and air.

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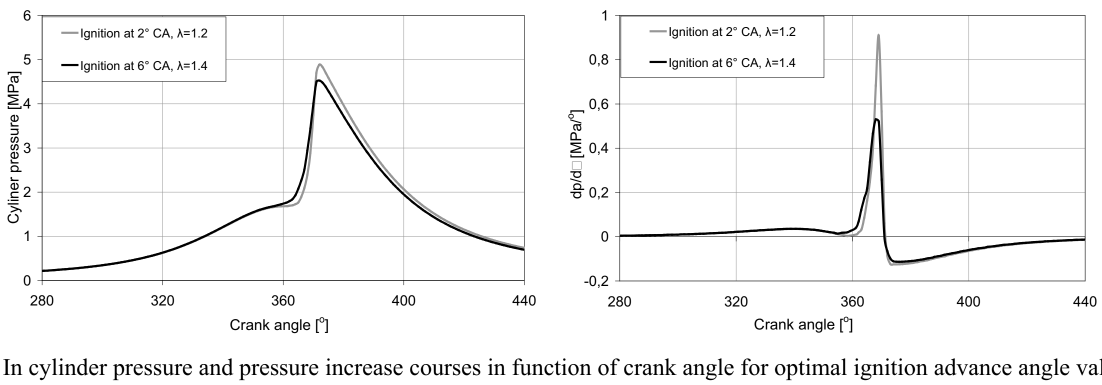

Fig. 9. In cylinder pressure and pressure increase courses in function of crank angle for optimal ignition advance angle values

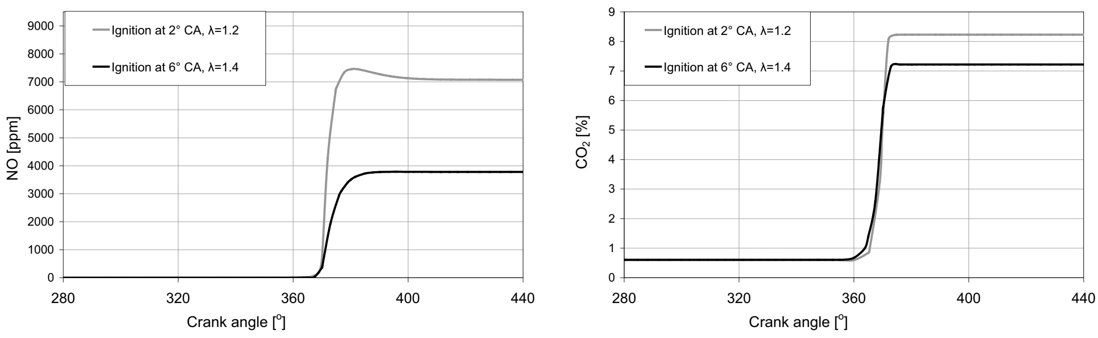

Fig. 10. Variations of NO and CO_2 concentration (mean values for cylinder volume) for optimal ignition advance angle values

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OPTYMALIZACJA PARAMETRÓW PRACY SILNIKA GAZOWEGO ZI

Streszczenie. Wyniki analizy numerycznej spalania metanu w silniku ZI zostały przedstawione w artykule. Parametry pracy silnika zasilanego ubogimi mieszankami metanu $\alpha = 1,4$ dla kilku różnych kątów zapłonu zostały porównane. Wyniki tej analizy udowodniły, że przy kącie zapłonu 6° OWK parametry pracy silnika (ciśnienie, temperatura i szybkość wzrostu ciśnienia) są poprawne i optymalne. Jednocześnie, emisja gazu azotowego zmniejszyła się w porównaniu z wcześniejszymi wartościami kąta zapłonu.

Słowa kluczowe: Silniki SI, metan, modelowanie numeryczne, uboga mieszanka.