ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1181719

THE ANALYSIS OF INFLUENCE OF FUEL SPRAY ANGLE ON NOx FRACTION IN THE EXHAUST GAS FROM MARINE 4-STROKE DIESEL ENGINE

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Abstract

The manuscript presents the analysis of influence of fuel spray angle on NOx fraction in the exhaust gas emitted from marine 4-stroke diesel engine. Analysis is based on computational fluid dynamic (CFD) model designed because of the motion mesh of combustion chamber of the marine engine cylinder and air inlet and exhaust gas ducts. Presented model consists of models of fuel injection into combustion chamber, breaking-up and evaporation of the fuel, mixing with air and turbulent combustion with heat transfer to construction elements of the engine cylinder. Mentioned CFD model is validated according to boundary and initial conditions taken from direct measurements. The chosen research object is laboratory 4-stroke turbocharged Diesel engine with direct injection of the fuel and mechanically controlled of both cylinder valves and the injector. The conclusion from the analysis is that the increase of fuel spray angle causes the increase of maximum speed of kinetic phase of the combustion and the decrease of maximum speed of diffusion phase of the combustion. The effect of this is the increase of maximum combustion pressure and the decrease of maximum combustion temperature. The result of presented changes in combustion process is the increase of NOx fraction in the exhaust gas. It should be noted that extended increase of the fuel spray angle cause close-up the fuel spray to the cylinder heads wall and the decrease of NOx fraction in the exhaust gas.

Keywords: *marine diesel engine, NOx fraction, spray angle, CFD model*

1. Introduction

The most popular source of the mechanical energy in the marine transportation is marine Diesel engine. In such engines, fuel is delivered to engine cylinders as a liquid. The geometry of fuel spray injected into the engine cylinder is of crucial meaning in a process of the combustion and the heat release [1]. Mentioned phenomena influence on the exhaust gas composition. Optimal shape of the fuel spray injected into the engine cylinder depends on the shape of the combustion chamber (the piston bottom) and the position of cylinder valves [2]. Reitz in his work [1] presents general guidelines for forming the combustion process to reduce emissions of NOx and soot. According to mentioned guidelines, the largest amount of NOx is formed in areas of the combustion chamber with temperature above 2000K during the combustion of lean mixtures. For this reason, the fuel injection process should proceed in such a way that said conditions occurred in the smallest volume of the combustion chamber. The piston engines constructor has the ability to interference in the fuel injection spray pattern by modifying the fuel injection time [3], injection pressure [2], dimensions and quantity of fuel nozzles' holes [4], the position of holes [5-7] and holes' shape [2]. The change of values of mentioned parameters causes changes in the combustion process and in the consequence of this change the exhaust gas composition.

The manuscript presents theoretical analysis of the influence of the fuel spray angle on the NOx fraction in the exhaust gas. Mentioned analysis is based on CFD (*Computational Fluid Dynamic*) model of the combustion process in the marine 4-stroke Diesel engine. The chosen research object is 3-cylinder laboratory engine with parameters, presented in Tab. 1.

Tab. 1. The laboratory engine parameters

Parameter	Value	Unit
Max. electric power	250	kW
Rotational speed	750	rpm
Cylinder number	3	–
Cylinder bore	250	mm
Stroke	300	mm
Compression ratio	12.7	–
Injector nozzle		
Holes number	9	–
Holes diameter	0.325	mm
Holes position diameter	7	mm
Holes position angle	150	deg.
Spray cone angle	6	deg.
Opening pressure	25	MPa

2. Model description and validation

Presented model was created based on the moving spatial mesh, covering the combustion chamber of the engine together with the air intake duct and the exhaust gas duct. Mentioned mesh consists of 1.5 million of finite volume elements (cells). The methodology of moving spatial mesh design was presented in [8]. The combustion model in Diesel engines cylinders consists of model of fuel injection, model of fuel brake-up and evaporation, model of fuel turbulent mixing with air and auto ignition and model of chemical kinetic combustion and the flame propagation. The shape of the fuel spray and the quantity characteristic of fuel injection were obtained by active experiment, which was described in [9] and [10]. The brake-up of fuel were described by WAVE model [11] with Wakisaka modification [12] and fuel evaporation by Dukowicz [13] mechanism. The auto ignition and combustion process were modelled by Tree Zone Extended Coherent Flame Model (3Z-ECFM) [14]. The calculation of turbulent flow was prepared by k-zeta-f model [15]. The iterative algorithm SIMPLE (*Semi-Implicit Method for Pressure Linked Equations*) has been used to pressure correction in cells. The energy and turbulent flow balance equations calculation were prepared using the „upwind" method and calculations of continuity flow equations were prepared by „central" scheme. In the 3Z-ECFM model, chemical reactions of combustion process occur in relatively small volume of the combustion chamber in the homogeneous mixture of air and fuel. The model assumed a substitute fuel composition in the form of a mixture of hydrocarbons having a molar ratio of carbon to hydrogen equals $C_{13}H_{23}$. Stoichiometric equations have been applied to calculation of mole fractions of chemical components used in thermal Zeldovich and "prompt" Fennimore mechanisms of the NOx formation. All presented calculations were prepared in AVL Fire package and full description of combustion model has been presented in [16].

The analysis and conclusions on the basis of CFD modelling results is possible only in the case of a positive validation of obtained results with results taken from direct measurements. According to the target of presented work and availability of laboratory, measurement results the validation of modelling results have been prepared based on characteristics of the combustion pressure in the engine cylinders and NOx fractions in the exhaust gas. The characteristic of combustion pressure was measured by pressure indicators installed in indicator valves of the research object. Obtained values of combustion pressure were recorded with frequency equals 720 probes per the engine crankshaft rotation. It should be noted, that obtained combustion pressure results are mean values for overall volume of the combustion chamber. For this reason, the verification of calculated results has been done by using mean pressure values in the overall volume of the spatial mesh, mapping the engine cylinder volume. Calculated NOx fractions in the exhaust gas with measured in the laboratory test values of NOx fractions have been compared also. The calculation and measurement results of combustion pressure in the engine cylinder and NOx fractions in the exhaust gas are presented in Fig. 1. Fig. 1a presents characteristics of the combustion pressures in the cylinder of the research object obtained by the modelling and direct measurements for the engine load equals 250 kW. The solid line presents the calculation results. According to presented results, the calculation error in relation to measurement values for the maximum combustion pressure equals 1.91%.

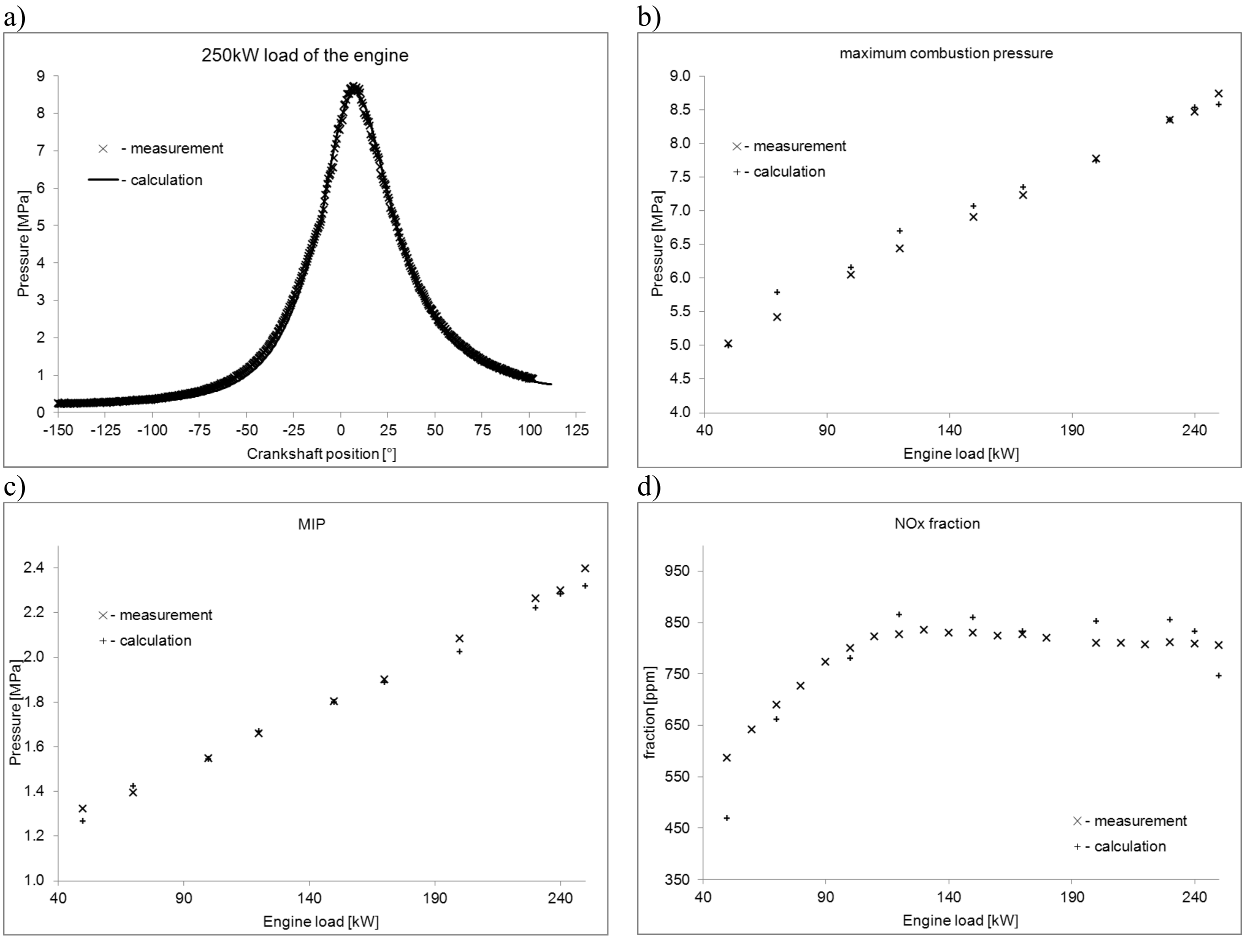

Fig. 1. Calculated and measured combustion pressure and the NOx fraction in the exhaust gas

Figure 1b and 1c presents the aggregate results of calculations and measurements of the combustion pressure in the engine cylinder. Presented results consist of validation of the maximum combustion pressure and the mean indication pressure (MIP) for all considered loads of the research object. According to presented results, the maximum error between calculated and measured MIP is observed for 50 kW load of the engine. For mentioned load, observed error equals 4.3%. The mean error for all considered loads equals 1.42% for the maximum combustion pressure and 1.13% for the MIP. Fig. 1d present results of measurements and calculations of NOx fractions in the exhaust gas. According to presented results, mean error of calculated values in relation to measured values for all considered loads of the engine equals 1.2%. It should be noted, that the maximum error is observed for the smallest considered load of the engine also.

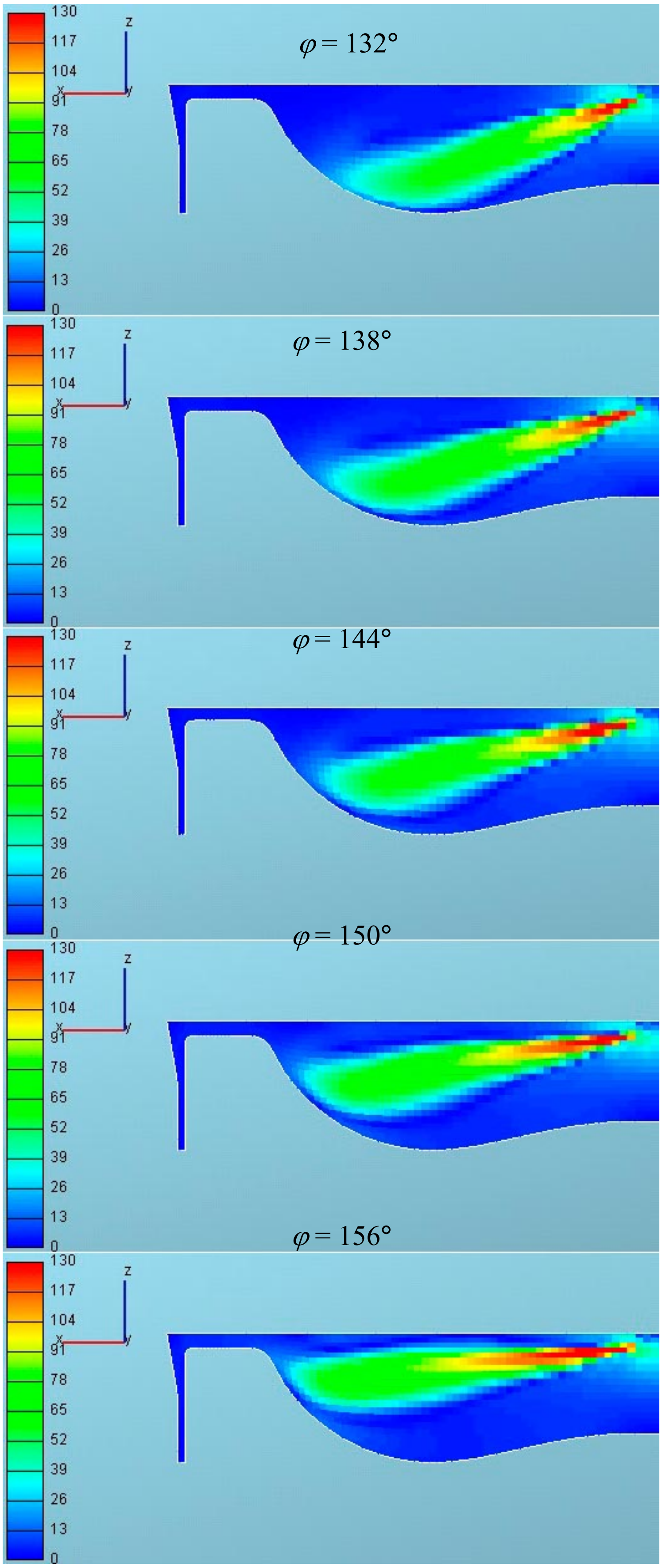

Fig. 2. Visualization of the fuel spray velocity distribution for 5° before the top dead centre of the piston position for considered spray angles „φ" in m/s

3. Obtained results

The fuel spray angle influences on the exhaust gas composition. It should be considered that mentioned angle must be selected based on geometric analysis of the combustion chamber, in particular the shape and position of the piston at the time of fuel injection.

In order to investigate the influence of the fuel spray angle on exhaust gas composition I prepare calculations using positively validated model of combustion in the engine cylinder. Calculations were conducted for beginning and boundary conditions taken from the direct measurement during research object operation at the load equals 250 kW. Calculations have been conducted for fuel spray angle „φ”, increased and decreased by 6° and 12° in relation to the nominal value of fuel spray angle, equals 144°.

Figure 2 presents cross section area of the engine cylinder with visualization of fuel spray velocity distribution for considered spray angles „φ” equals 132°, 138°, 144°, 150° and 156° respectively. Calculation results are presented for angular position of the crankshaft equals 5° before the top dead centre of the piston position.

Figure 3 presents influence of the fuel spray angle on calculation results of combustion heat release.

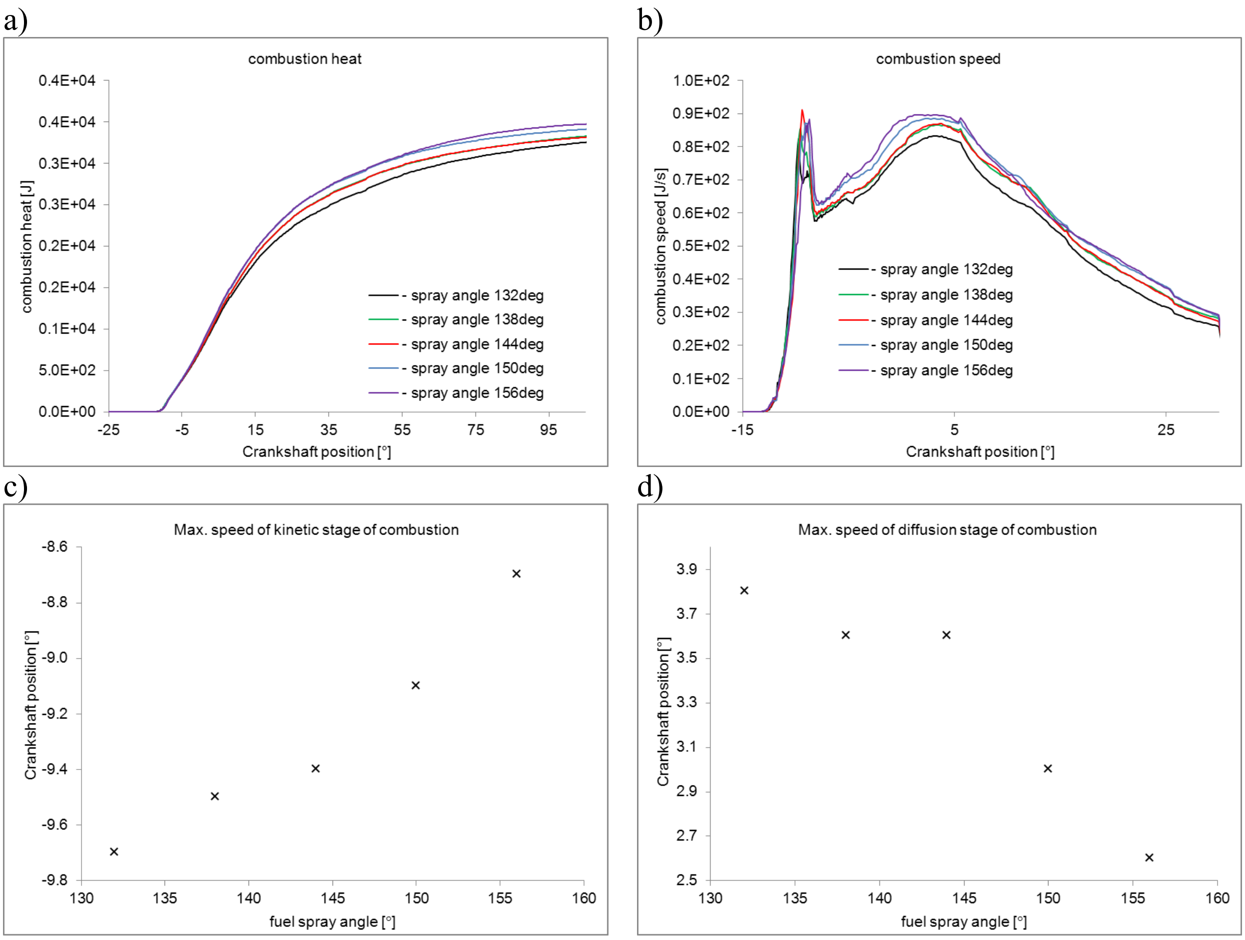

Fig. 3. Influence of the fuel spray angle on: a) heat and b) speed of combustion and maximum speed for c) kinetic stage and d) diffusion stage of combustion

According to presented results, the value of the fuel spray angle do not influence on fuel evaporation and auto-ignition process. The mass flow of evaporated fuel is not changed also. It should be noted that geometric parameters of the fuel spray influenced on the injection fuel pressure do not change also. Presented on Fig. 3 results confirm thesis that the value of the fuel spray angle influences on the combustion process. The increase of the fuel spray angle in considered range causes the extension of the kinetic stage of the combustion with not changed quickness of heat release. Analysis of the diffusion stage of the combustion presents the opposite trend. The increase of the fuel spray angle causes shortening of this stage of the combustion. Overall balance is that the increase of the fuel sprays angle increases of the combustion process speed. The effect of this is the increase of both temperature and pressure. Fig. 4 presents influence of the fuel spray angle value on temperature and pressure of the combustion process.

According to mentioned results, the increase of the fuel spray angle causes the increase of both presented parameters. Essential is fact that the injected fuel spray should be within the internal area of the combustion chamber. Injected fuel should not contact with combustion chamber surfaces. Direct contact of fuel with combustion chamber surfaces causes deterioration of the combustion process by cooling of the combustion mixture. Such situation is observed for maximum considered value of the fuel spray angle. According to results presented in Fig. 2 for injected fuel spray angle equals 156° the combustion mixture is near the wall of the cylinder head. This situation causes the slight decrease of combustion temperature in relation to the combustion of the fuel spray injected in 150° angle. Observed value of the MIP is similar for angle 150° and 156°.

a) b)

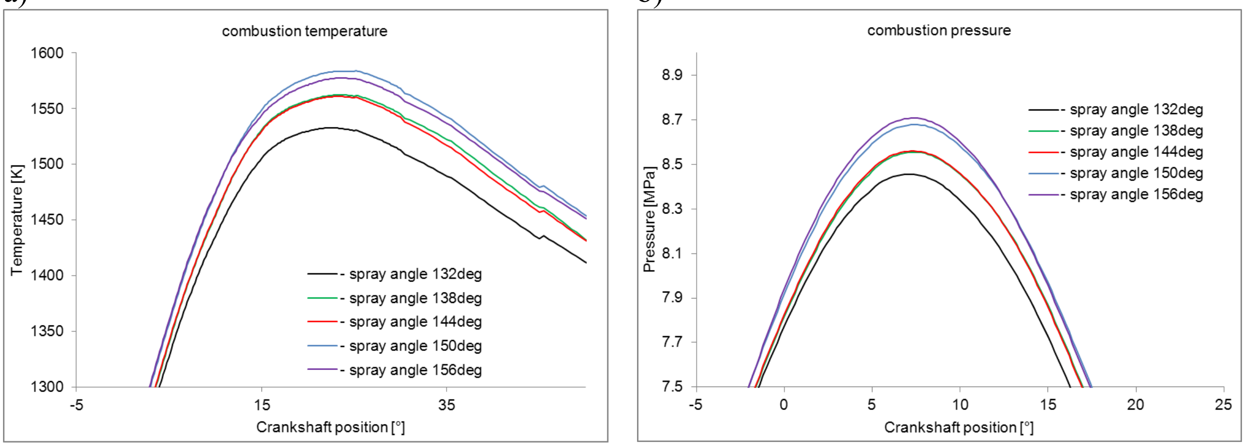

Fig. 4. Influence of the fuel spray angle on: a) temperature and b) pressure of the combustion process

It means that the effect of the combustion process acceleration in the case of maximum considered spray angle is compensated by cooling the flame by cylinder heads wall near combustion process. It should be pointed that changes of mentioned parameters are not large. The difference for extreme values of fuel spray angle equal 3% for the maximum combustion pressure and the MIP and 47K for maximum combustion temperature. Despite such small changes in thermodynamic parameters of the combustion process, the significant change in the NOx fraction in the exhaust gas is observed.

Figure 5 presents the influence of the value of the fuel spray angle on the calculated NOx fraction in the engine cylinder. The increase of temperature and pressure of the combustion process with the increase of the value of the fuel spray angle causes the increase of the NOx fraction in the combusted mixture. Naturally, small decrease of temperature, calculated for 156° of the fuel spray angle causes the decrease of the NOx fraction in the exhaust gas also.

4. Conclusions

The main goal of the manuscript is the analysis of the influence of the fuel spray angle on the NOx fraction in the exhaust gas emitted from the marine 4-stroke Diesel engine. Due to realize the presented purpose the CFD model of the combustion process in the engine cylinder was

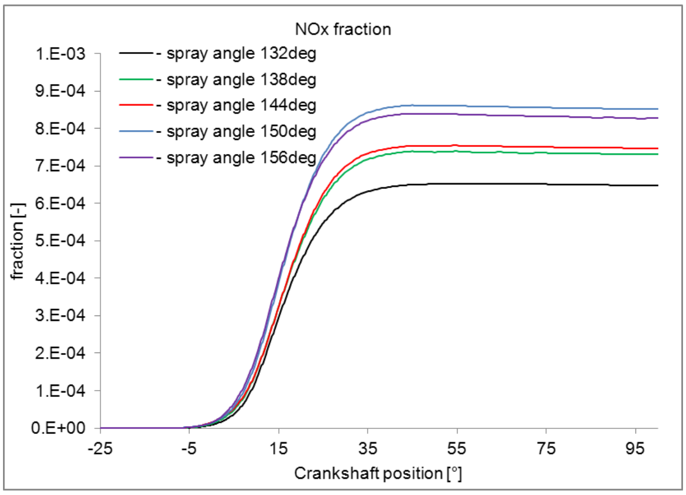

Fig. 5. Influence of the spray angle on the NOx fraction in the engine cylinder

conducted. Mentioned model consists of the fuel spray and the breaking-up model, the evaporation model and the model of mixing fuel witch fresh air and the model of auto ignition, the combustion and the turbulent propagation of flame with chemical kinetic calculations. The analysis of calculation results allows formulating following conclusions:

– the value of the fuel spray angle do not influence of the evaporation and the auto ignition process. All considered angles of the fuel spray gave the same auto ignition time,
– the value of the fuel spray angle influences of the combustion process. The increase of the fuel spray angle in considered range causes prolongation of the kinetic stage of the combustion with not changes speed of the heat release,
– the increase of the value of the fuel spray angle causes shortening the diffusion stage of the combustion process,
– the overall balance of presented phenomena is that the increase of the fuel spray angle causes the acceleration of the combustion process. The effect of this is the increase of temperature and pressure of the combustion process,
– the angular position of the injected fuel equals 156° is too close to the cylinder head wall. It causes slight decrease of the combustion temperature in relation to value of the fuel spray angle equals 150°. This observed effect is caused by cooling the combusted flame by construction elements of the engine cylinder,
– the increase of temperature and pressure of the combustion process with the increase of the fuel spray angle causes the increase of the NOx fraction in the combusted mixture. Naturally, the slight decrease of the combustion process temperature for the 156° of the fuel spray angle causes the decrease of the NOx fraction on the exhaust gas also.

Acknowledgments

The project was supported by the National Science Centre in Poland, granted on the basis of decision No. DEC-2011/01/D/ST8/07142.

The project was supported by AVL Company according to University Partnership Program and license of AVL Fire software.

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