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THE ANALYSIS OF THE ECFM-3Z COMBUSTION MODEL IN THE MARINE 4-STROKE ENGINE FOR THE EXHAUST GAS COMPOSITION

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Abstract

The paper presents ECFM-3Z combustion model analysis in the marine, 4-stroke diesel engine. The purpose of the modeling was to determine the composition of the exhaust gas. This composition depends on the composition of the combustible mixture, combustion time and thermodynamic conditions prevailing in the engine cylinder during the working process. Mentioned parameters are variable in time and space, and therefore require the use of 3-dimensional model based on the finite volume method, taking into account the fuel injection, brake-up and evaporation, mixing with air, auto-ignition and combustion. All models presented in the literature are adapted to the parameters of relatively small engines. Different marine engine parameters require significant modifications taking into account the heat exchange with the structural elements of the engine, leakage through piston rings and energy losses by friction. It should also be noted that dimensions of the marine engine require careful optimization of spatial moving meshes according to computation time and quality of results. Paper presents influence of mixing time, start of injection and autoignition delay on modeling results of the exhaust gas composition.

Key words: *marine engine, multidimensional model, mixing time, autoignition delay, ECFM-3Z combustion model*

1. Introduction

The aim of the design development of marine piston engines is the reduction of fuel consumption and the reduction of toxic compounds emissions into the atmosphere. These objectives require the knowledge of parameters of phenomena occurring in engine cylinders during its operation. Parameters of the combustion process in the engine cylinder determine the composition of the exhaust gas. The assessment of phenomena, resulting in the emissions of toxic compounds into the atmosphere, requires a multi-dimensional modeling of the propagation of flame in the engine cylinder. This process is made up of many co-existing physical phenomena. Mentioned phenomena's are the injection of fuel into the engine cylinder, fuel brake-up and evaporation, mixing with air, autoignition and flame propagation in a heterogeneous combustible mixture. It should be noted, that the result of the combustion process occurring are a number of chemical reactions. Chemical reactions are determined by temperature and pressure in the engine cylinder but also by the composition of the combustible mixture, the combustion chamber geometry, the phenomena of heat transfer, gas movement, leaks by the piston-rings-cylinder liner system etc.

Many models of combustion processes are developed. In the last 10 years increasingly popular in the modeling of combustion processes are Coherent Flame Models (CFM) [1]. CFM models describe the combustion process on the assumption that the scale of chemical reactions is many times smaller than the scale of the turbulent flow. This enables the separation of both phenomena models. It's further assumed that chemical reactions take place only in a very thin surface layer of the flame, which the shape and the location depend on of the turbulent flame propagation phenomena. CFM model was modified by Colin and Benkenida [2] in 2004. Mentioned model, named Tree Zone Extended Coherent Flame Model (3Z-ECFM), allows obtaining correct results of modeling for diesel engines. Mobasheri et al. [3], [4] apply 3Z-ECFM model to develop a strategy for fuel injection into the engine cylinder to reduce the NOx and the soot emissions. Moreover, authors tested and optimized the split fuel injection into the engine cylinder with capacity of 2.5dm^3. Authors present Homogeneity Factor, a new parameter for supporting the air–fuel mixing and the combustion process in diesel engines. Taghavifar et al. [5] use 3Z-ECFM model to modification the structure of the combustion chamber of a small engine to changing the mixture formation, the combustion initiation and emissions. The 3Z-ECFM model is useful to predict of exergy parameters of a small dual fuel, high speed diesel engine [6] and real time predict of the NOx emission [7]. The 3Z-ECFM model with Eulerian–Lagrangian Spray Atomization model were used to simulation of primary break-up and atomization processes also [8].

Presented works show wide possibilities of modeling of the combustion processes using the model 3Z-ECFM. It should be noted that engines used in shipbuilding are significantly different from small, on-road engines and engines used in the automotive industry. Main differences are i.e. relatively low speed of marine diesel engines, the large stroke in relation to the cylinder bore, the ignition of fuel before TDC (top dead center), the boost pressure greater than the exhaust gas pressure for all loads of the engine, higher compression ratio and a large heat exchange surface in relation to the cylinder volume. These differences cause that default settings of the 3Z-ECFM model allow the calculate parameters of the combustion process only on a small scale. The model of the combustion process in the marine engine cylinder was presented in [9]. Default settings of the 3Z-ECFM model allow to correct modeling of thermodynamic parameters of the combustion process. Modeling of the combustion process in the marine engine cylinder to assess the composition of the exhaust gas requires a modification of mentioned model parameters.

The main purpose of the study is the analysis of selected 3Z-ECFM model parameters to assess the composition of the exhaust gas from the marine diesel engine. Following parameters of the 3Z-ECFM model of the combustion process are taken into account in the presented analysis: start of injection angle (SOI), the autoignition delay and the intensity of fuel and air mixing (mixing time).

2. The 3Z-ECFM model description

Phenomena occurring in the engine cylinder were modeled as the Euler description [10]. The model base of the combustion process in the engine cylinder is a geometric grid, including the shape of the cylinder with the air intake duct, the outlet duct and exhaust and inlet valves. Analysis and selection of spatial grid parameters are presented in [11]. Parameters of the laboratory engine are presented in Tab.1. Evaporated fuel is mixed with air in the engine cylinder. To modeling these phenomena the k-ε model [12] was used. The combustion process was described by the ECFM-3Z model. In the present model, the autoignition delay (τ) is determined by air temperature (T), the density of the mixture (ρ) and the molar concentration of oxygen ([O_2]) and fuel ([$Fuel$]) for all cells of grid by the following equation [13]:

$$\tau = 4{,}804 \cdot 10^{-8} \cdot [O_2]^{-0{,}53} \cdot [Fuel]^{0{,}05} \cdot [\rho]^{0{,}13} \cdot e^{\frac{5914}{T}} \ , \qquad [1]$$

The autoignition delay, calculated according to equation 1 was delayed from 0 to 43% during the analysis. The composition of the exhaust gas depends on mixing time of fresh fuel and fresh air before combustion. The phenomenon of mixing was defined by standard 3Z-ECFM model equations [13]. The mixing time was changed from 0 to 420% in comparison to the standard parameters of the mixing time during presented analysis. The Dukowicz fuel evaporation model [14] and TAB fuel brake-up model [15] are used. The dipper description of the combustion model was presented in [9].

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	–

3. Results

An application of standard values of the autoignition delay and the mixing time in the 3Z-ECFM model allows obtaining correct results of pressure distribution in the cylinder compared to measured values. Please note that measured values essentially concern pressure on the indicator cock. Mentioned pressure value differs from the pressure values in the engine cylinder [16]. The left side of Fig.1 shows pressure characteristics in the cylinder for the default 3Z-ECFM model values and direct measurements.

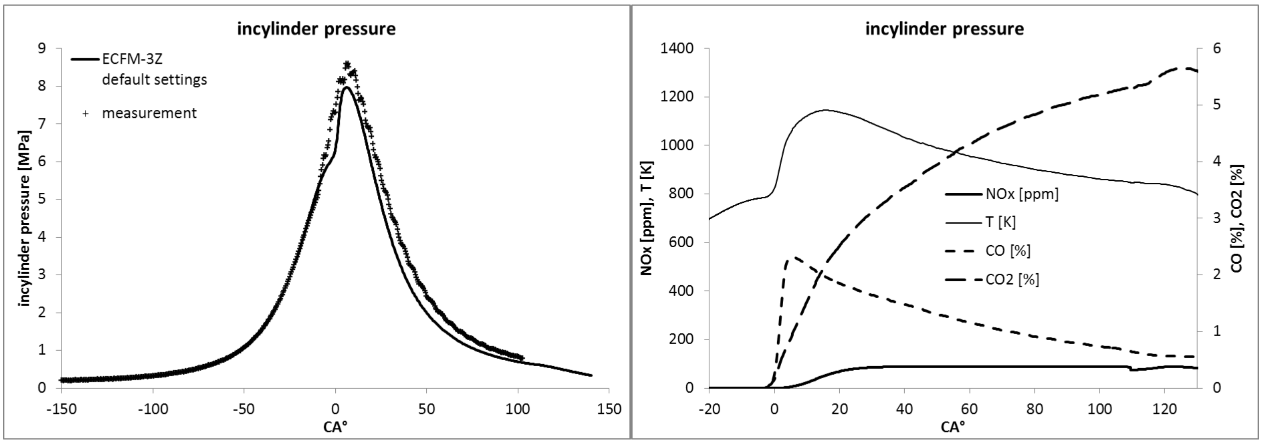

Fig.1 Results of in cylinder pressure measurement and ECFM-3Z model calculation results with default values

According to presented results, the maximum measured pressure is greater about 8.3% than the calculated value. It should be noted that results of modeling require the correct selection of parameters such as SOI, characteristics of fuel injection into the cylinder and fuel consumption, determine geometric dimensions of the fuel injector and injected fuel stream and the pressure and temperature of charge air. The method of selection of these parameters is presented in [9]. This model is valid only in appearance. Analysis of results of toxic compounds fractions in the exhaust gas show significant discrepancies with the measured values. The right side of Fig.1 presents results of temperature distribution as a function of CA (crankshaft angle). Presented results are average values for the entire cylinder volume. Calculated fractions of nitric oxide (NO), carbon monoxide (CO) and carbon dioxide (CO_2) in the exhaust gas are presented also. Tab.2 presents the comparison of measured fractions of listed chemical species in the exhaust gas with the calculated values. For comparison, the average values of the weight fractions for the entire volume of the exhaust gas duct and the crank angle between 110° after TDC and 140° after TDC. According to presented results calculated NOx fraction is many times lower than the measured fraction. Calculated CO fraction is higher than the measured CO fraction. The reason for this is too low modeling combustion temperature, in the comparison to real conditions.

Tab.2. Mass fractions in the exhaust gas and maximum in cylinder pressure

Parameter	NOx [ppm]	CO [ppm]	CO_2 [%]	p_{max} [MPa]
Measurement	788	715	6.3	8.5
Model with default values (SOI -21°)	78	5782	5.44	7.79

Presented results support the conclusion, that obtaining values of calculated average pressure for the entire cylinder volume, similar to measured values, do not allow for proper modeling of the composition of the exhaust gas. The use of default 3Z-ECFM model parameters results in a lower combustion temperature than expected. As a result, incomplete fuel combustion occurs (increase of CO fraction in the exhaust gas) and the NOx fraction in the exhaust gas decreases.

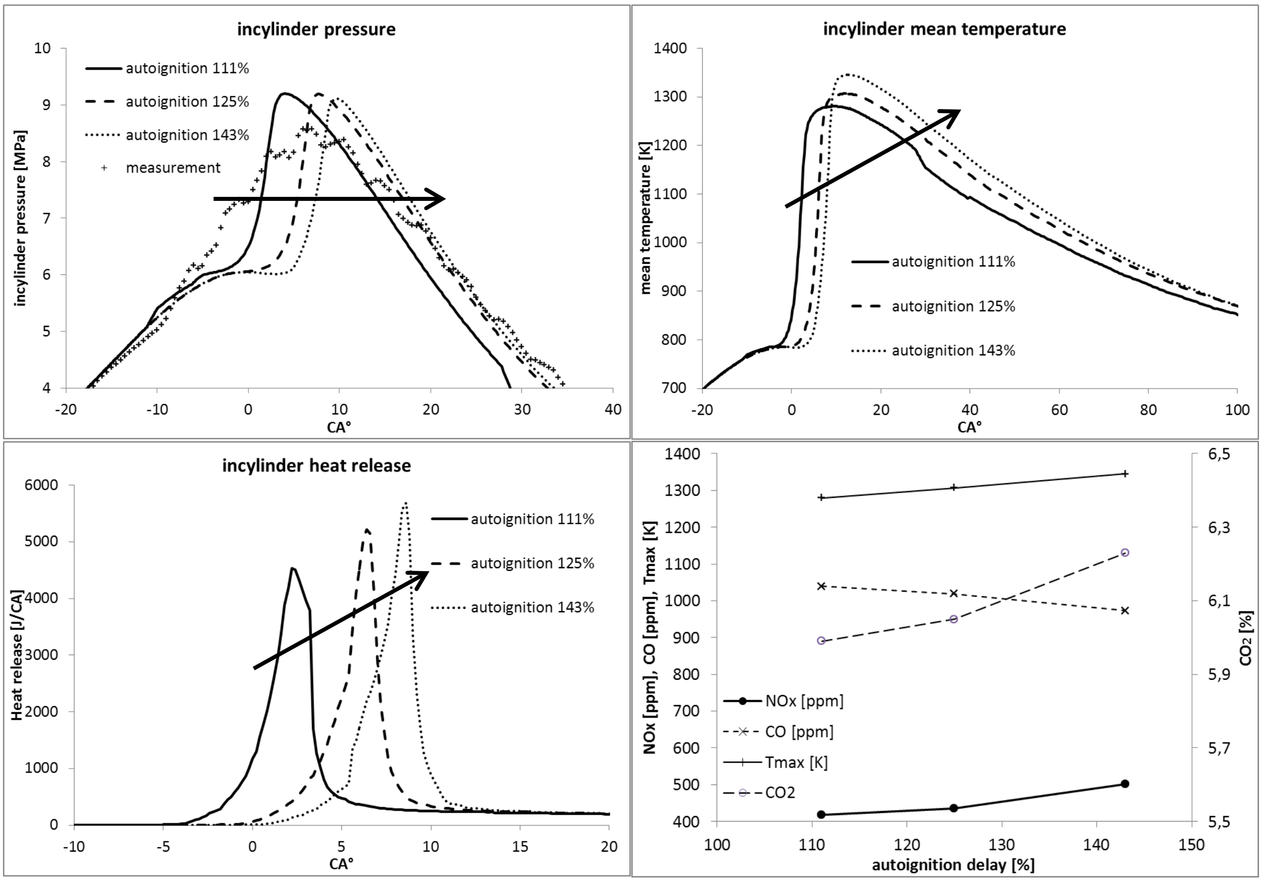

Fig.2 Influence of the autoignition delay on modeling results

The way to increase calculated temperature of the combustion process is the earlier SOI and the autoignition delay. Such a set of model parameters can result in approaching the calculated value of NOx and CO fractions to measured values. The autognition delay causes the greater part of fuel evaporates before autoignition. The effect of this is the increase of the effect of combustion controlled by chemical kinetics and the reduction of the influence of the diffusion in the combustion process on calculation results. The autoignition delay in the 3Z-ECFM model can be carried out by limiting the flow of energy from the in-cylinder air into vaporized fuel (increase of the mixing time). The physical interpretation of this parameter is the extension of the heat flow from air to evaporated fuel, caused by improper selection of parameters of fuel injection process into the cylinder. Presented Eq.1 is an empirical equation, adapted for modeling of the autoignition delay in a relatively small piston engines. Extension of mixing time parameter causes fuel autoignition delay and thus increases of heat release rate in the initial stage of the combustion.

Fig.2 presents the influence of autoignition delay changes on the value of mass fractions of NOx, CO and CO_2 in the exhaust gas. Characteristics of average temperature and average pressure for the entire cylinder volume and the intensity of the heat release from the combustion process are presented also. Data comes from calculations for the engine load equal 220kW at 750rpm, the SOI -21° and the mixing time equal 400% of default model values.

According to presented results, the increase of the autoignition delay shifts the combustion process on the expansion stroke. The result of this is the intensification of the combustion process, despite the slight decrease of pressure in the cylinder. The 43% increase of the autoignition delay results the increase of the maximum heat release by 26%. Effect of this is the increase of average temperature of the combustion process by 60K. The increase of combustion process temperature causes the increase of the NOx mass fraction in the exhaust gas. The increase of temperature promotes the oxidation of CO to CO_2. For this reason, Fig.2 presents increase of the CO_2 fraction in the exhaust gas with a decrease of the CO fraction.

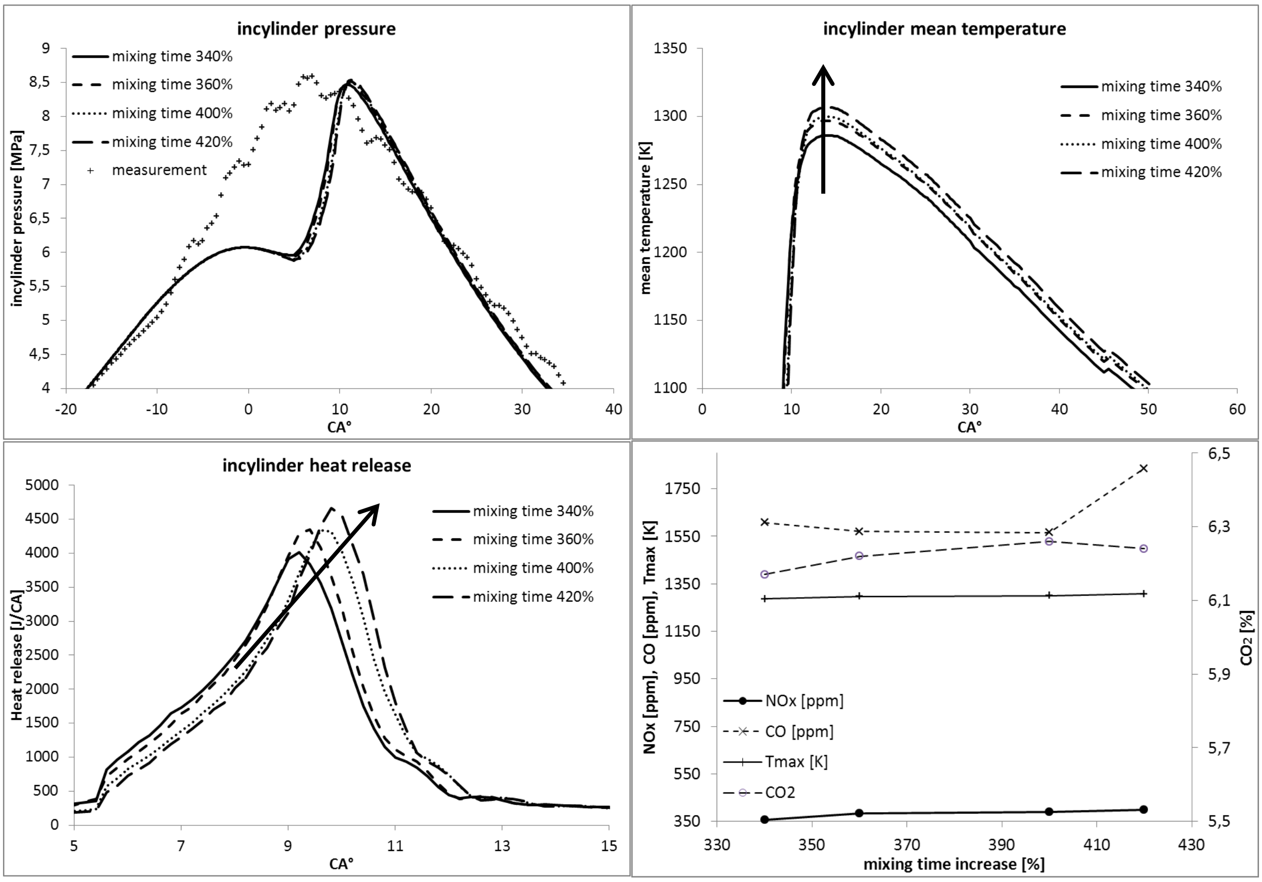

Fig.3 Influence of the mixing time on modeling results

Fig.3 presents the influence of the mixing time parameter on modeling results. These results correspond to the engine load equal 220kW at 750rpm, the SOI -18 ° and the autoignition delay equal 143% of standard values of the model. According to presented results changing the mixing time does not change the characteristic of pressure in the engine cylinder. This means that the change of this parameter is not visible during the in-cylinder pressure analyze. Therefore it can be concluded that it is possible to adjust parameters of the model of the combustion process, which result is changes in the calculated composition of the exhaust gas without modifying the characteristic of in-cylinder pressure. Increasing the mixing time causes a slight increase in the intensity of the combustion process. The increase of the mixing time by 80% (from 340% to 420% of the default value) causes the increase of the maximum heat release by about 16%. The effect of this is the increase of combustion process temperature. Mentioned temperature increase is not as large as in the case of increasing the autoignition delay. It should be noted that the increasing the mixing time will slightly slow down the combustion process. Increasing the mixing time of more than 400% moves the combustion process in the direction of the expansion stroke, and causes slight deterioration of the combustion process. The result of this is the increase of CO fraction in the exhaust gas with the constant value of the NOx fraction in the exhaust gas. The conclusion is that the mixing time increasing over 400% will not affect the growth of the NOx fraction despite the increase of the intensity and temperature of the combustion process. It should be noted that the increase of the SOI angle does not cause a qualitative change dependances presented on Fig.3. Therefore, it can be assumed that 400% of the default value of the mixing time is the adjustment limit for this type of the engine.

An important parameter for the composition modeling of the exhaust gas is SOI (start of injection angle). This parameter can be measured directly by static experiment or estimated by the analysis of the in-cylinder pressure characteristic. Both methods are not accurate therefore, the influence of the SOI value on the modeled exhaust gas composition was considered also.

Fig.4 presents influence of the SOI angle on modeling results. Presented results correspond to the engine load equal 220kW at 750rpm, the mixing time equal 420% and the autoignition delay equal 143% of default model values.

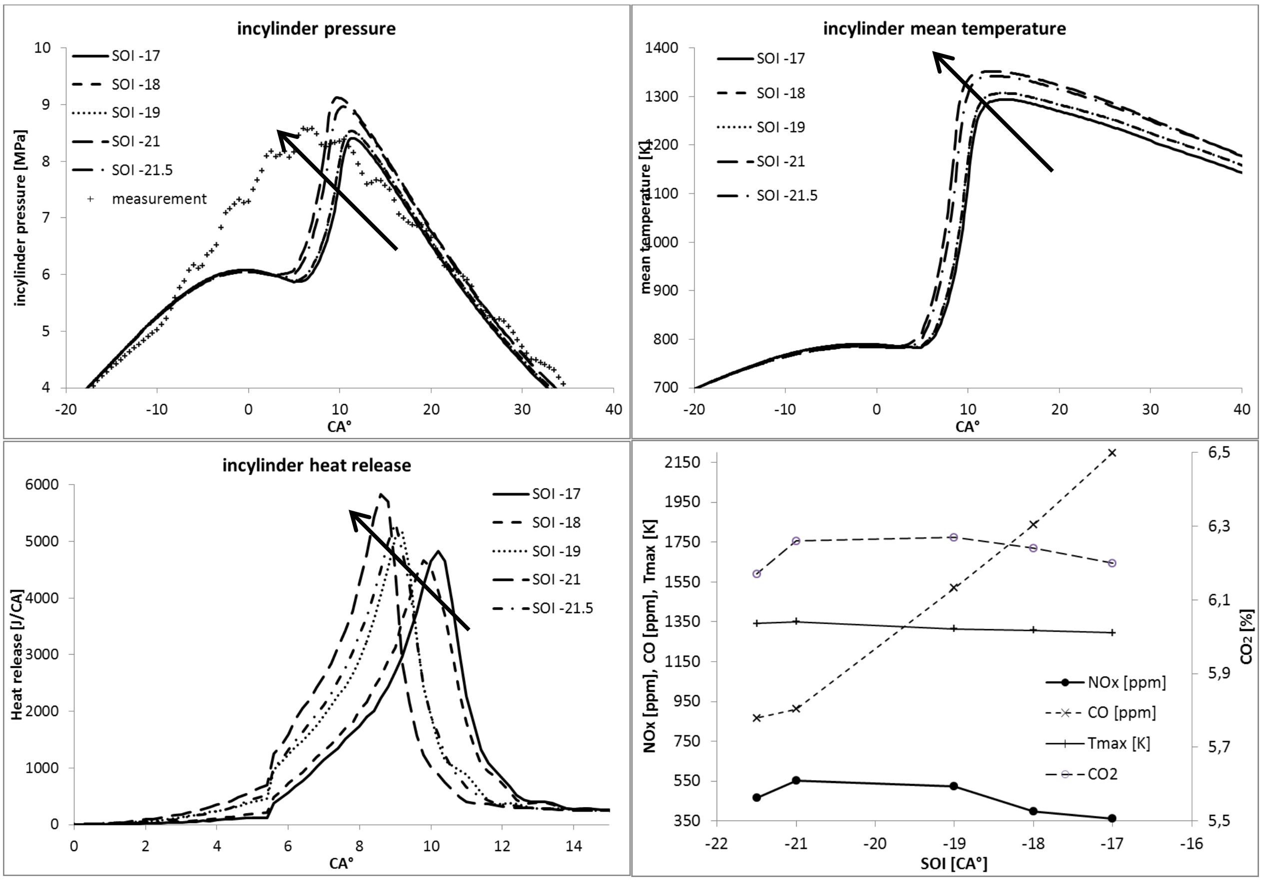

Fig.4 Influence of the SOI angle on modeling results

The increase in the distance between the SOI and the TDC causes early autoigniton of fuel. The result of this is the intensity change of the combustion process. The analysis of heat release characteristics shows that at the SOI equal to 18°CA, mentioned combustion intensity is the lowest. It should be noted that this is the value of the SOI measured on a real object and a significant delay of the combustion is caused by maximum considered values of the mixing time and the autoignition delay. As expected, the increase of the SOI angle reduces the NOx fraction in the exhaust gas. This is due to the slowdown in the combustion process and the reduction of combustion temperature. The result is a deterioration of the combustion process, resulting in a rapid increase of the CO fraction in the exhaust gas. Analysis of obtained results of the CO_2 and the NOx fractions shows that there is a certain interval of the SOI angle, that the contents of both of chemical species are the largest. The conclusion is that a significant delay of SOI does not result in the expected limitations of the NOx fraction in the exhaust gas.

4. Conclusions

The paper analyzed the effect of the SOI angle, the autoignition delay and the mixing time on modeling results of the combustion process. The purpose of the modeling was the validation of the 3Z-ECFM model in terms of the composition of the exhaust gas of marine diesel piston engine. The analysis allows drawing following conclusions:

– Default settings of 3Z-ECFM model parameters do not provide correct results of modeling the combustion process in the marine piston engine. Required modification resulting in the increase of temperature of the combustion process. This can be achieved by delaying of the autoignition of the combustible mixture.

– The greatest impact on changing of modeling results has changes in the autoignition delay and the SOI angle. Earlier fuel injection and/or the autoignition delay increase the intensity of the combustion process.

– The validation of the combustion process model to assess the composition of the exhaust gas by analyzing the characteristic of combustion pressure is insufficient. According to obtained results it is possible to change the calculated composition of the exhaust gases without modifying the characteristic of the engine cylinder pressure. This can be done by adjusting the mixing time in the 3Z-ECFM model.

– The change of the SOI angle causes a rapid change of the CO content in the exhaust gas. For this reason, this value should be chosen with as high accuracy.

– Significant delay of the SOI does not result in the expected limitation of the NOx fraction in the exhaust gas. The certain interval of the SOI angle, that the contents of CO_2 and NOx in the exhaust gas are the largest was observed.

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