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Possibility of Improvement of Some Parameters of Dual Fuel CI Engine by Pilot Dose Division

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Abstract

The paper present a test results of dual fuel engine run on natural gas and diesel oil injected as a pilot dose. Determination of possibilities of engine's operational parameters improvement through division of the pilot dose was the main objective of the presented research. The first dose injected at ignition advance angle, the same as in case of operation on diesel oil only, has as its task to initiate process of combustion. The second dose, injected with changing delay when, as assumed, phase of combustion process is already in progress, has as its task to sustain combustion of gaseous mixture. Control of combustion process was attained through changes of injection delay angle of additional dose. Division of pilot dose effects in a considerable reduction of maximal heat release rate during combustion with simultaneous growth of average combustion rate of gas-air mixture. In result, it has been observed a growth of overall efficiency of the engine, reduction of NOx concentration in exhaust gases, and reduction of maximal combustion pressures. Simultaneously, emission of the CO and TCH was slightly worsened.

Keywords: *natural gas, dual fuel engine, pilot dose, thermal efficiency, combustion parameters*

1. Introduction

Nowadays, a search after alternative fuels suitable to internal combustion engines is observed in more and more extent. One from such fuels are various type gaseous fuels like: natural gas, biogas, by-product gases from manufacturing processes. Engines run on gas can operate according to two systems of combustion:

- spark ignition system (majority of applications),
- dual fuel system (limited number of applications).

In past, selection of such system was determined by considerable differences in price of the fuels mainly; by-product gases having low price of elementary energy and diesel oil with high unit costs. With considerable portion of diesel oil, cost of production of elementary energy in dual fuel engines was higher than production cost of energy in spark ignition engines. Difficulties in mechanical control of fuel charge quality in dual fuel engine constituted additional problem. In result, spark ignition engines can be found in majority of practical applications. This system requires, however, reduction of compression ratio to values of about ε = 9,0÷9,5, what results in reduction of thermal efficiency, comparing to compression ignition engines fueled traditionally (Fig. 1).

In dual fuel engine, to the cylinder is sucked in homogenous gas-air mixture, ignited due to injection of small pilot dose of diesel oil. Energetic fraction of diesel oil depends on implemented feeding system and size of engine, and can change in the following range:

- 1,5÷3,0% - the best stationary duel fuel engines with high power outputs,
- 3,0÷5,0% - generator type dual fuel engines with power outputs above 2 MW,
- 5,0÷10,0% - dual fuel engines with power outputs < 500 kW,
- 15,0÷30,0% - compression ignition engines adapted to dual fuel feeding.

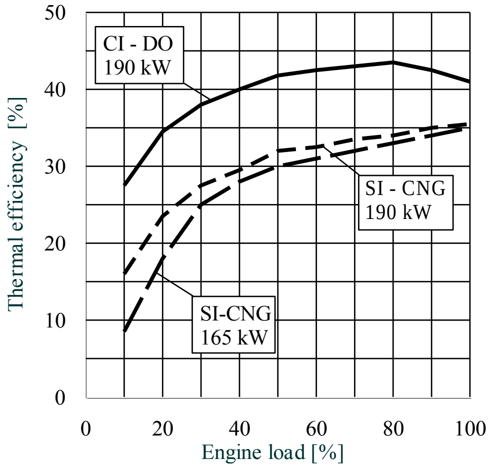

Fig. 1. Comparison of thermal efficiency of SI gaseous engines and CI engines fuelled traditionally [1]

The most advantageous conditions to combustion of gas in dual fuel engines are present near the point of maximal load. In such case the engine can be run on rich mixture with excess air ratio of λ_g=1,5÷2,0, characteristic of high combustion rate. As a rule, in such case the dual fuel engine features thermal efficiency higher than an engine run on diesel oil only.

One from the main problems of the dual fuel engines is reducing thermal efficiency at partial loads. It is connected with leaning of combustible mixture and worsening conditions of its combustion. When pilot doses are small, nearly entire liquid fuel evaporates during delay of self-ignition. Combustion time of pilot dose is very short and combustion runs violently. Good conditions of ignition and combustion are in the layer of gas-air mixture adhering to burning stream of liquid fuel. As combustion process of liquid fuel fades away, and front of flame recedes from the stream, combustion process runs more and more slowly. Cooling effect of cylinder walls has also disadvantageous effect here. At lean gas-air mixtures a fading of the flame can occur, what can have effect on efficiency and ecological parameters of the engine.

The main objective of the present work was to investigate a possibility of elicitation of combustion of gas-air mixture through division of pilot dose. Such possibility is offered by modern injection systems of Common Rail type, commonly used in contemporary compression ignition engines. In course of performed tests, dose of diesel oil was divided into two equal parts injected in different time. The first dose injected with ignition advance angle, the same as in case of operation on diesel oil only, had its task to initiate combustion process. The second dose, injected with changing delay when, as assumed, phase of combustion process is already in progress, had its task to sustain process of combustion of gaseous mixture. Control of combustion process was attained by changes of ignition delay angle of additional dose.

Division of pilot dose, according to assumption, should lead to change of heat release rate, what was confirmed by performed tests, see Fig. 2.

In the Fig. 2 is distinctly seen a change of heat release run for ignition generated by divided pilot dose. Additional dose of diesel oil effects in generation of the second maximum on the heat release curve, with its value considerably higher than the first maximum. It can prove about growth of active combustion rate of gaseous mixture. Simultaneously, maximal values of heat release rate are smaller than the ones present during combustion of charge with single dose. It augurs well for process of NOx generation, especially in case of turbocharged engines.

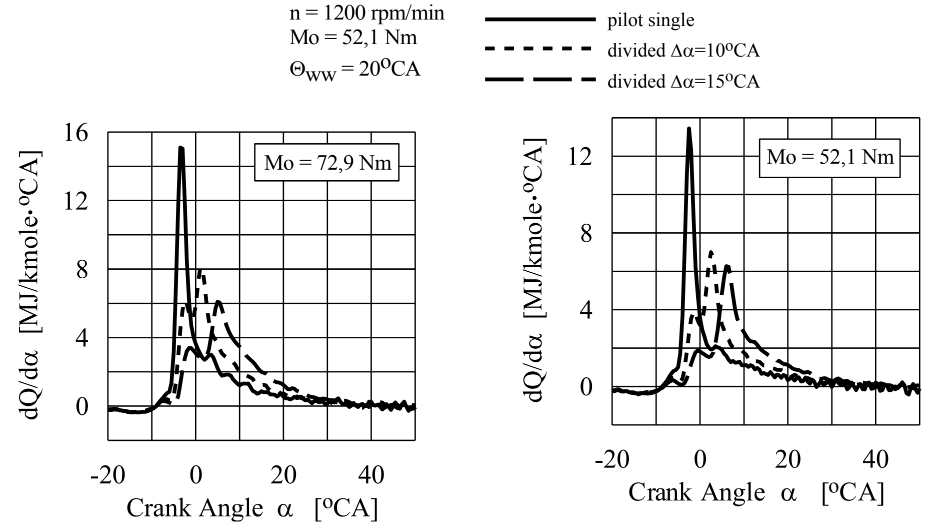

Fig. 2. Comparison of heat release rate in the dual fuel engine with single and divided pilot dose

In the present paper is discussed an effect of division of pilot dose on a selected parameters of dual fuel engine.

2. Test stand

The tests were performed on single cylinder, compression ignited engine of SB3.1 type. Technical data of the engine are specified in the Table 1, while view of the test stand is shown in the Fig. 3. Detailed description of the test stand and modifications made in the engine can be found in earlier publications [1,2].

Table 1. Technical data of the SB3.1 engine

Cylinder number	1
Bore	127 mm
Stroke	146 mm
Displacement volume	1848 cm^3
Compression ratio	15,8
Effective output power	22,8 kW
Rotational speed	2200 rpm/min
Combustion chamber	Direct injection to chamber in piston crown
Injection system of DO	Common Rail f-my Bosch
Injector of DO Bosch	0986435 004 090
Injection system of CNG	IC
Gas injector Bosch	F465 151 72
Presser of gas injection	1 MPa

Fig. 3. Engine test bend

In course of performed tests one used constant ignition advance angle of 20°CA before TDC, the same like in case of run on diesel oil only. Division of the dose was accomplished by split of injector's opening time in Common Rail system, τ_{ow}, according to the following rule: opening time of the injector for pilot dose $\tau_{ow1} = 0{,}5\tau_{ow}$, for additional dose $\tau_{ow2} = 0{,}5\tau_{ow}$. Performed earlier tests have revealed, that characteristic of injector output is exactly linear, while size of injected dose is proportional to opening time of the injector. It has enabled to assume equity of pilot and additional doses; $q_1 = q_2 = 0{,}5q_{on}$. Implemented controller has enabled recalculation of beginning of injection into angular values with respect to the TDC, what enables to maintain required values of injection advance angle of pilot dose Θ_{ww}. Ignition delay of additional dose was also measured as angular value $\Delta\alpha$, calculated from beginning of injection of the first dose. It should be underlined, that at small values of the dwell, $\Delta\alpha$, electromagnetic injector can be not fully closed, what can have such effect that preset delay of the additional dose effects in modulation of intensity of injected fuel only. This assumption was confirmed by the tests performed on a test stand without engine. The modulation has an effect on course of engine operation, what was confirmed during testing on engine dynamometer and in results of numerical analysis of combustion parameters.

Analysis of combustion parameters was performed on base of thermal calculations based on recorded indicator diagrams. In course of the calculations one made use of author’s computer program developed in the Department of Internal Combustion Engines, University of Bielsko-Biala. Description of the program and methodology of the calculations can be found in the work [7, 8].

3. Analysis of the test results

In the Fig. 4 are presented runs of heat release rate in range of active combustion, from beginning of the process up to 50°CA after TDC. Runs for two rotational speeds 1200 and 1400 rpm (near point of maximal torque) and for two engine loads (maximal: when gas-air mixture is the richest, and minimal: with maximal leaning of gaseous mixture) were analyzed.

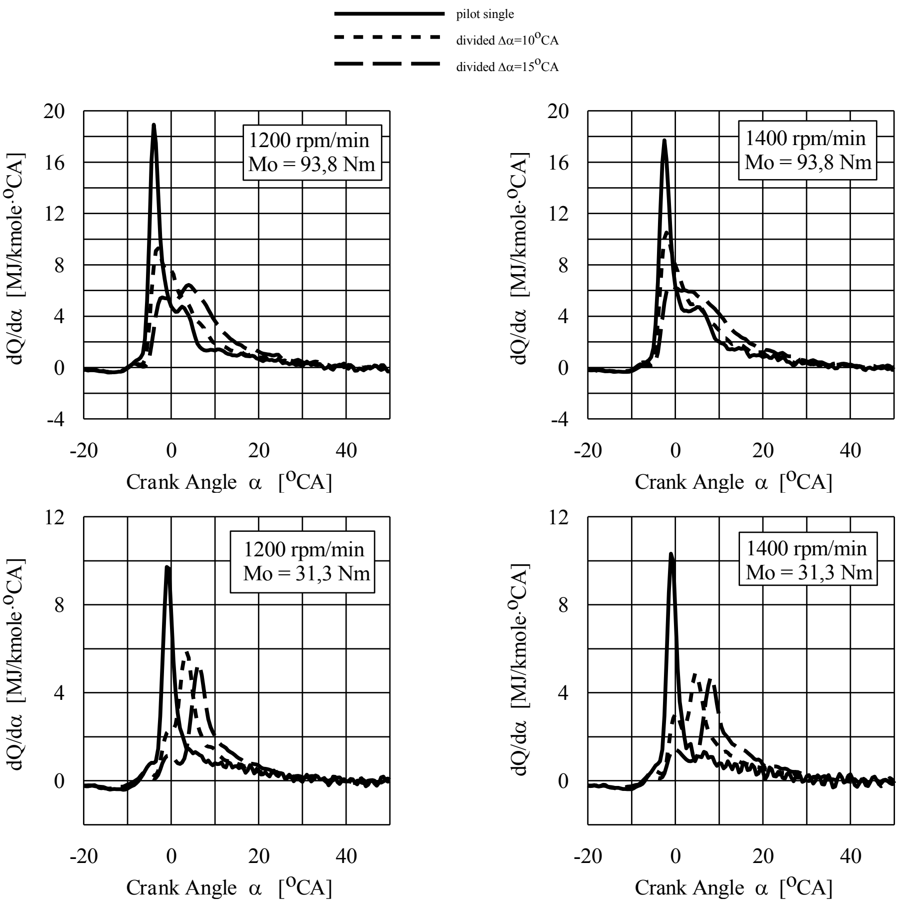

Fig. 4. Comparison of heat release rate in dual fuel engine with single and divided pilot dose

Analysis of the runs presented in the Fig. 4 is pointing at explicit changes in run of heat release depending on method of fuelling. In case of single fuel dose used, a single maximum is present. It results from rapid combustion of diesel oil in kinetic phase of combustion, evaporated during later self-ignition. After implementation of divided dosage, maximal value of heat release rate is nearly two-fold lower, and additionally shifted in direction of more late phases of combustion. In range of maximal engine load, rich gaseous mixture with high combustion rate, shift of maximum heat release is small, especially for delay of additional dose with $\Delta\alpha=10^{o}$CA. This delay is growing with leaning of gaseous mixture (partial loads) and increasing of injection delay angle of additional dose. At partial engine loads, on the $dQ/d\alpha$ curve are distinctly present two maxima, what confirms assumption about combustion of the dosages in different time. In spite of equal sizes of injected doses, maximal dynamics of heat release distinctly decreases together with growth of injection delay angle of additional dose.

Usage of divided pilot dose effects in reduction of maximal combustion pressures as injection delay of additional dose of diesel oil grows, Fig. 5. Simultaneously, pressure's run during initial phase of combustion is delayed comparing to the run with not divided dose. In consequence, point of maximal pressure is shifted in direction of more late angles after TDC. Character of described here pressure changes is present in whole range of engine load change. It should be underlined, however, that at partial engine loads, effect of the division and delay angle on initial phase of combustion is more distinct, what reveals a distinct inflexion of pressure line.

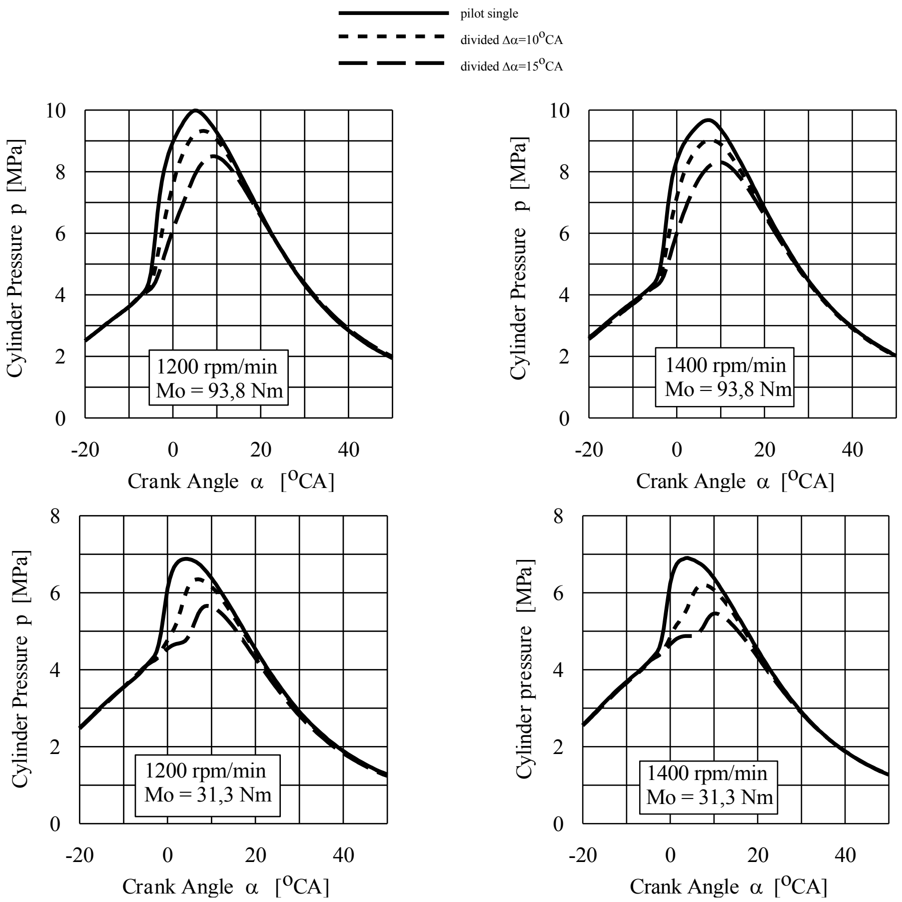

Fig. 5. Comparison of cylinder pressure in dual fuel engine with single and divided pilot dose

Maximal values of the pressure and heat release rate during combustion in function of engine load are presented in the Fig. 6. Values of the both analyzed parameters, when the pilot dose is divided, are smaller. Especially brings our attention a significant reduction of maximal value of the heat release rate, $(dQ/d\alpha)_{max}$. In range of maximal engine load, the reduction is 2,0÷2,5 fold, while at minimal loads with 25÷40%. It is also worth to underline, that in case of division of pilot dose, the same engine loads are developed at a lower maximal pressures, what can have effect on growth of durability of crankshaft system, especially bearings.

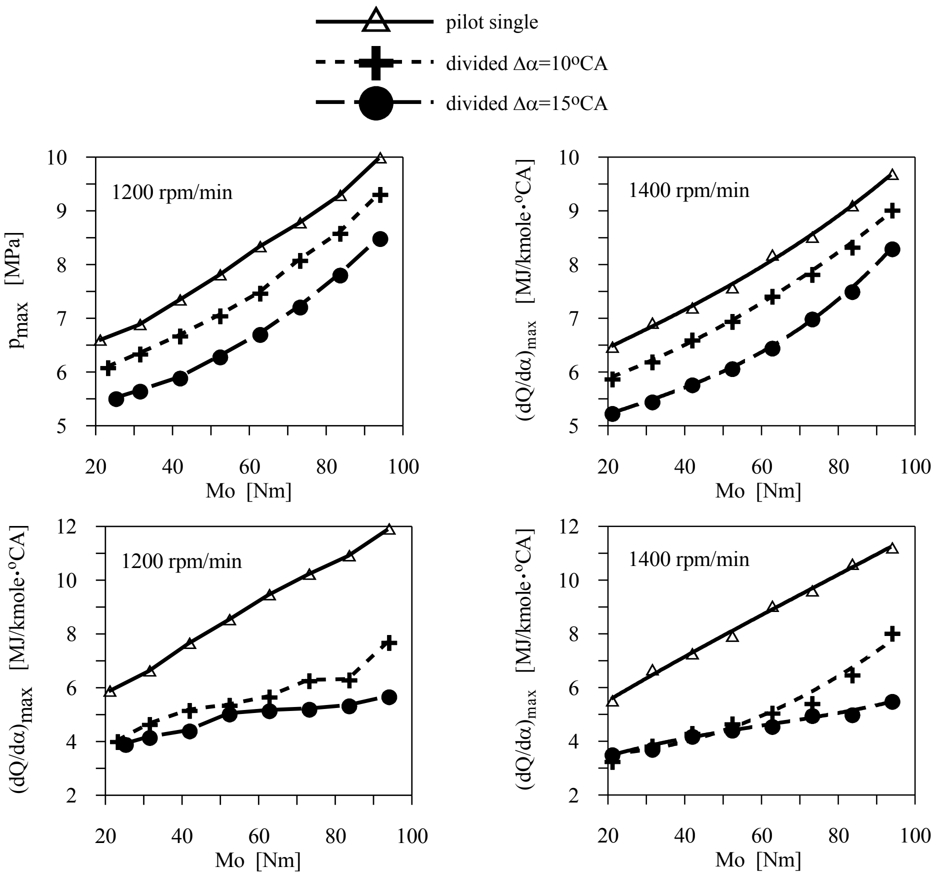

Fig. 6. Comparison of maximal combustion parameters in dual fuel engine SB3.1 with single and divided pilot dose: p_{max} – maximal value of cylinder pressure, $(dQ/d\alpha)_{max}$ – maximal value of heat release rater

Division of pilot dose results in growth of engine efficiency with 1,0÷3,5% of absolute units. More advantageous results were obtained at smaller injection delay angle of additional dose. Differences in analyzed values of the efficiency are also dependant on rotational speed. Increase of injection delay angle of additional dose effects adversely on efficiency of the engine, reducing differences between values of the efficiency for non split dose and divided dose. However, it is worth to underline, that for the both tested angles of injection delay, 10 and 15^{o}CA, the engine operated with a higher efficiency than in case observed with not split pilot dose. Absolute increase of engine efficiency with 1,0÷3,5% is pointing at distinct relative differences of the efficiency. They amount to 10÷15% for engine speed of 1200 rpm and 8÷10% for engine speed of 1400 rpm. Such meaningful growth can prove about considerable reduction of energy consumption by the engine operating at changing conditions of load.

Division of pilot dose, resulted in described earlier change of combustion run, advantageously effects on concentration of NOx in exhaust gases, decreasing considerably as injection of additional dose is delayed, Fig. 8. It results from two main reasons, reduction of maximal temperatures in zones of oxidation of liquid fuel, and reduction of oxidation rate in zones with a higher concentrations of carbon dioxide (additional dose undergoes oxidation in conditions of increased EGR).

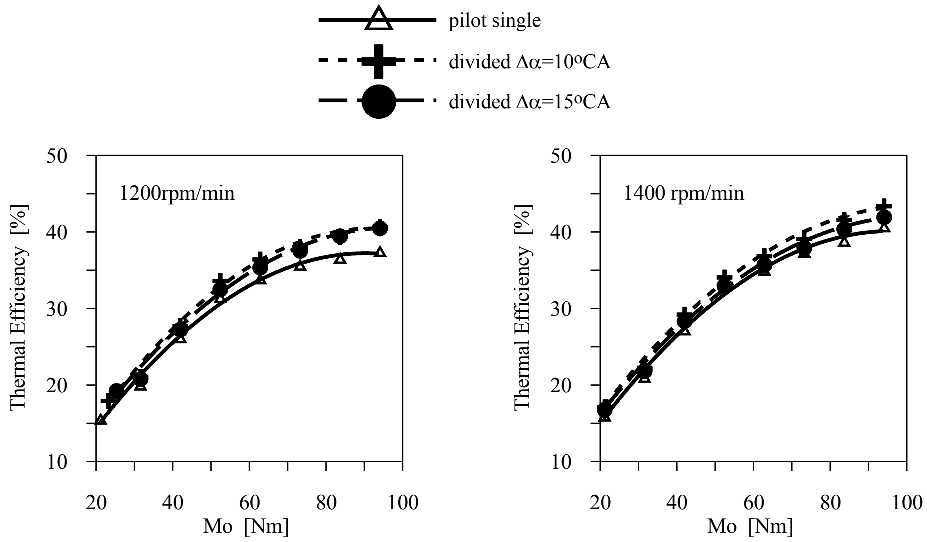

Fig. 7. Comparison of thermal efficiency in dual fuel engine with single and divided pilot dose

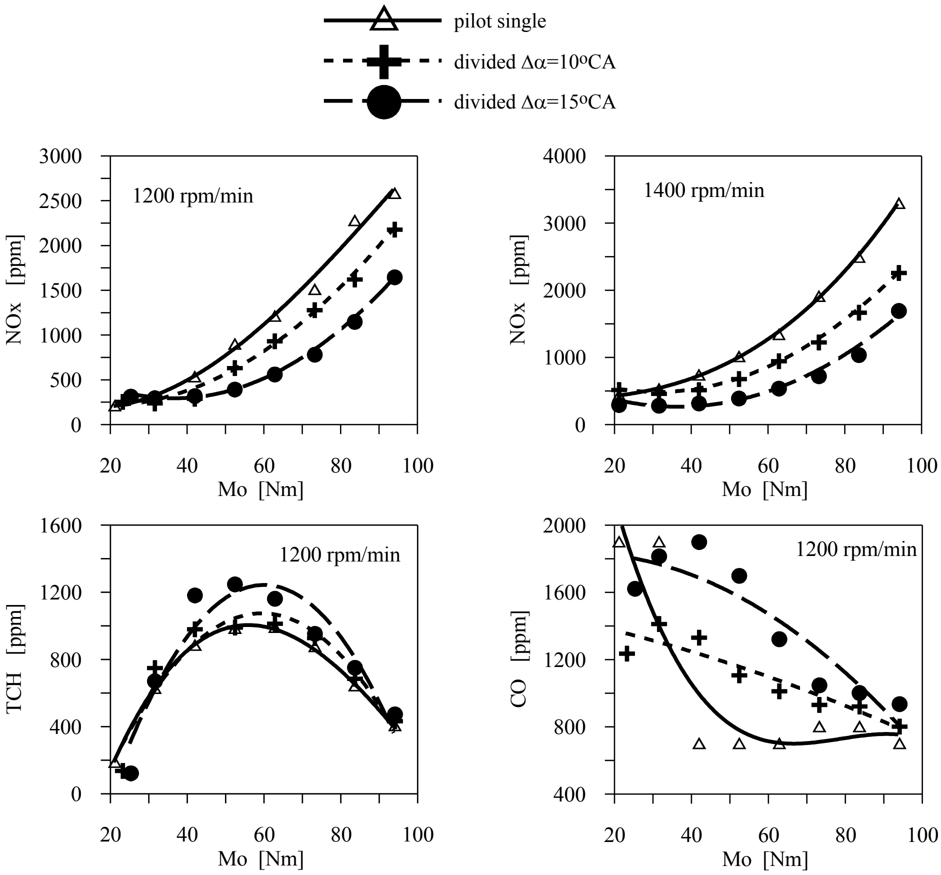

Fig. 8. Comparison of concentration of toxic exhaust components the dual fuelled engine SB3.1 with single and divided pilot dose

Reduction of oxygen concentration in zones of the reaction, caused by partial burn-out of the fuel, can also have additional effect. Observed changes in concentration of NOx suggest, that condition of oxidation of liquid fuel can have significant effect on emission of nitrogen oxides in dual fuel engines. Simultaneously, obtained results in range of NOx concentrations confirm that division of the pilot dose and correctly selected injection angle of additional dose can serve as a substantial tool to reduction of nitrogen oxides emission in highly supercharged dual fuel engines. It should be emphasized in this point, that reduction of NOx concentration was obtained together with simultaneous growth of overall efficiency of the engine, what – as seen from previous tests – is not possible with single pilot dose.

Delay in injection of diesel oil slightly increases concentrations of carbon oxide, CO, and total amount of hydrocarbons, TCH, (Fig. 8). It results from worsening of conditions of liquid fuel oxidation in more late phases of combustion. It is distinctly confirmed by differences in concentration of CO and THC for delay angles of 10 and 15^{o}CA. Slight growth of concentrations of CO and TCH does not create a problem in contemporary engines due to high conversion efficiency of oxidation catalysts. Moreover, concentrations of CO downstream the exhaust valve (before the catalyst) are smaller, with order of magnitude, from concentration of CO in case of gaseous engines with spark ignition.

4. Conclusions

Based on performed tests it is possible to formulate the following general conclusions:

- Division of pilot dose and changes in parameters of the doses are nowadays easy to be accomplished in compression ignition engines due to high pressure Common Rail injection systems, commonly used in the engines.
- The tests have shown that division of diesel oil dose in dual fuel engines leads to changes in combustion course of gaseous mixture. It is especially visible at partial engine loads, when the gas-air mixture is excessively leaned.
- Division of pilot dose can be accomplished only in dual fuel engines operated at a bigger energetic share of diesel oil. It is connected with possibilities of injection of very small doses of liquid fuel. Division at small portions of diesel oil requires incorporation of additional injector for pilot doses, what increases cost of engine adaptation to dual fuel feeding.
- To advantageous phenomena connected with division of the dose belong: absolute growth of overall efficiency of the engine with 1,0÷3,5% (8÷15% of relative growth), reduction of NOx emission in exhaust gases and more quiet and less noisy engine operation. Among adverse phenomena can be counted: a slight growth of CO and TCH emissions and when inappropriate injection parameters of additional dose were selected, possibility of growth of engine's thermal load.

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