COMBUSTION WITH LOW NO_X AND SMOKELESS IN A DUAL FUEL DIESEL ENGINE FUELLED WITH NATURAL GAS AS THE MAIN FUEL

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Abstract

The present paper shows results of comparative tests of a single cylinder, direct injected engine type 1CA90, fed traditionally and in a dual fuel system on compressed natural gas. Performed experiments have shown significant differentiation of heat release run in the dual fuel engine comparing with an engine fed traditionally. Run of the gas combustion outside stream of liquid fuel and change of maximal dynamics of the gas combustion together with change of gas concentration in the mixture are the reason of the differentiation. Reduction of gas concentration in the mixture results in shifted location of maximal dynamics of the gas combustion in direction of more and more bigger angles of crankshaft rotations after TDC. It constitutes one of reasons of the thermal efficiency reduction of dual fuel engine operating at partial load [5-7]. Because of this, maximal leaning of the gaseous mixture has been limited to excess air ratio of λ_o<4,0. It has enabled restriction of a harmful phenomena connected with combustion of lean gas-air mixtures at partial load of the dual fuel engine.

It has been ascertained that use of the natural gas enables to significantly reduce emission of NO_x and smoke in exhaust gases. Reduction of NO_x at maximal engine load amounted to 35-55% with respect to emission of an engine fed traditionally. Even bigger differences were found at partial load where reduction of NO_x emission was nearly threefold. The biggest differences in the smoke of exhaust gases were present at maximal load of the dual fuel engine, where more than fourfold reduction of the smoke has been observed. Dual fuel engine, however, has shown increased emission of CO and non-burnt THC hydrocarbons. The growth was nearly twice at maximal engine load and was growing at partial load. Worsening of conditions of oxidation of the gas at partial load and increasing range of flame extinguishing near to cylinder walls are the reasons of increase of CO and THC emission.

Keywords: dual fuel, combustion, heat release rate, natural gas, low NO_x, smokeless.

1. Introduction

In naturally aspirated dual fuel engines operated at constant pilot dosages, partial loads are obtained via reduction of quantity of the gas flowing into the engine. It results in leaning of the gas-air mixture, and as a consequence in changed run of its combustion. Leaned mixtures are burnt effectively in the zones adjacent to streams of liquid fuel due to heat exchange between the stream and gaseous mixture during combustion of Diesel oil. At low pilot dosages, time of combustion of Diesel oil, anyhow, is short and due to it an impact of the stream of Diesel oil is limited. In effect, run of combustion of the gas-air mixture occurring after termination of combustion of pilot dosage is of fundamental meaning. In leaned mixtures the rate of flame propagation decreases, duration of combustion undergoes prolongation and thermal loss between the charge and the walls is growing. In a consequence, in zones remote from the stream of liquid fuel the rate of oxidation is small enough and the fuel cannot be oxidized completely. At bigger cylinder diameters decay of the flame near to the walls can occur, whereas extent of such phenomenon is growing as the air-gas mixture is leaned [1, 2, 5]. The phenomena discussed here result in reduction of general efficiency and increase of CO and CH emission, what constitutes a fundamental problem of dual fuel engines operated at partial loads.

2. Experimental setup

The experiments were carried out on a single cylinder compression ignition direct injection engine type 1CA90. The engine parameters are presented in the Table 1 below.

Natural gas was supplied to the induction system via mixer. Pilot dose of Diesel oil was injected directly to combustion chamber via typical injection system implemented in the engine. Engine load was adjusted by change of volume of gas flowing into engine at constant quantity of pilot dose.

Table 1. Test engine specifications

Cylinders	1
Bore x Stroke	90 x 90 mm
Displacement Volume	573 cm^3
Compression Ratio	16.8:1
Power/Speed	6.1 kW/3000 rpm
Chamber Type	DI
Injection Timing	28° BTDC
Inlet Valve Opens	18° BTDC
Inlet Valve Closes	52°30' ABDC
Exhaust Valve Opens	52°30' BBDC
Exhaust Valve Closes	18° ATDC

In the present analysis one made use of combustion parameters calculated on base of averaged indicator diagram from 128 successive cycles of single combustion. Indicator diagrams were recorded with use of the AVL INDIMETER type 619 system. Routine for calculation of combustion parameters is presented in the study [6]. The concentrations of exhaust toxic components has measured using Pierburg analysers: infrared CO, flame-ionisation THC, chemo-luminescence NO_x and exhaust gases smokiness with use of AVL smoke meter.

3. Results and discussion

Fig. 1 shows a comparison of pressures and heat release rates during combustion in the engine fed traditionally and in dual fuel system. The comparisons were performed for two engine speeds and two engine loads: the maximal and the minimal one. At low engine speeds and maximal loads, maximal pressures in the dual fuel engine are higher in range of 0.4-0.6 MPa comparing to the pressures present in traditional feeding. It is connected with relatively rapid combustion of gaseous mixtures. At higher engine speeds, differences in maximal pressures are decreasing and at high engine speeds the maximal pressures are similar for the both feeding systems.

Together with reduction of engine load maximal pressures in dual fuel engine are decreasing and at low engine speeds are similar to the pressures in an engine fed traditionally. At higher engine speed, pressures during combustion of the charge in dual fuel engine are significantly smaller than the pressures in traditional feeding. It results from reduced combustion rate of leaned gaseous mixture and from a growth of self-ignition delay angle, what is explicitly seen from more late beginning of combustion.

Maximal heat release rates in complete range of dual fuel engine operation are significantly smaller. In course of performed experiments it has been found that reduction of $(dQ/d\theta)_{max}$ value was in range of 45-65% with respect to the value in case of traditional feeding. The above fact means that temperatures in reaction zones in dual fuel engine are smaller, what results in reduction of quantity of generated NO_x. Simultaneously, however, rate of fuel oxidation decreases what results in growing quantity of generated CO and THC. That phenomenon can be observed especially distinctly at lean gaseous mixtures.

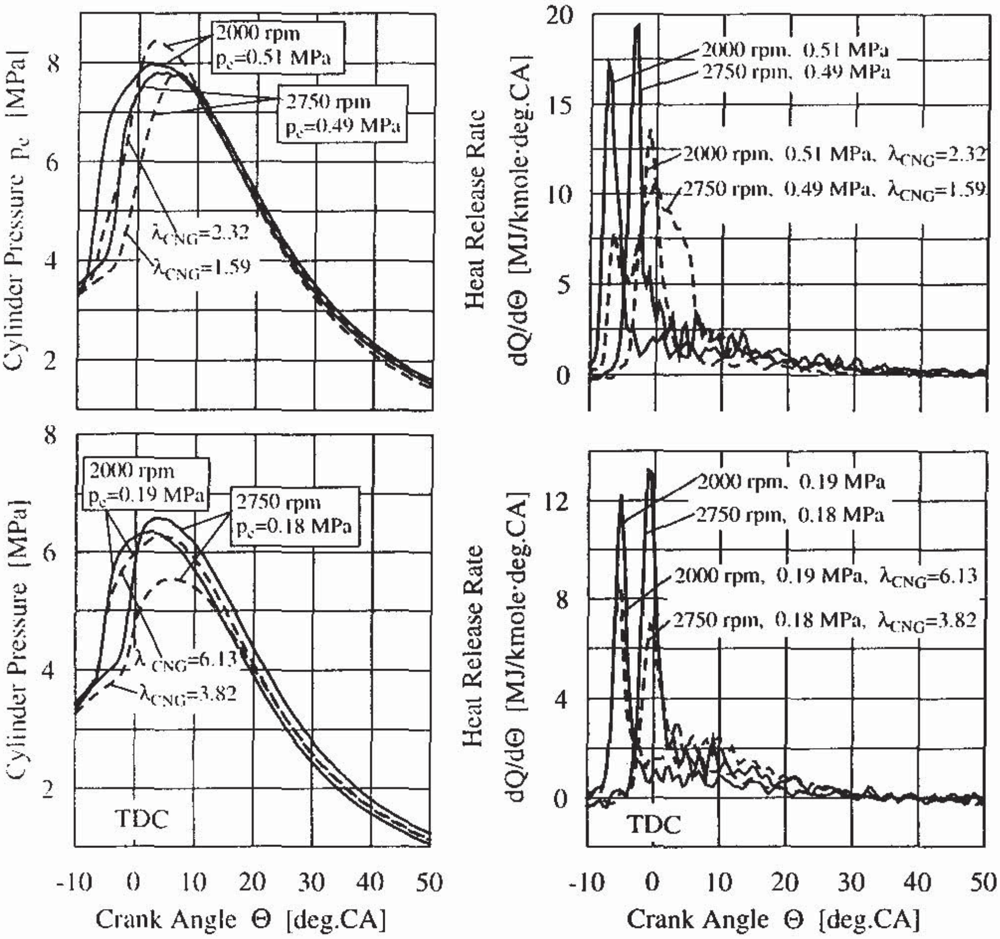

Fig. 1. Comparison of pressures and heat release rates during combustion in the test engine fed traditionally – solid lines, and fed in a dual fuel system – dashed lines

Growth of maximal pressures at maximal loads also results in a growth of average temperatures of the medium at beginning of the combustion, Fig. 2. Simultaneously, in further phases of the combustion temperatures of the working medium are similar to the ones at traditional fuelling. It results from relatively high combustion rate of the gaseous mixture and its smaller change in course of combustion process. In effect, time of completion of combustion process of gaseous mixtures is shorter than duration of combustion at traditional feeding. At partial loads, duration of combustion prolongs what could result in growth of average temperatures, which is maintained till opening of the exhaust valve. At higher engine speeds and low loads, smaller temperatures were observed at dual fuel feeding. It could be explained by growing share of non-burnt gas with respect to complete charge. In spite of change in the run of average temperatures none significant changes of exhaust gases temperature in exhaust system have been observed. In course of performed experiments only slight, in range of 15-25 K, increase of exhaust gases temperature, comparing to traditional feeding, has been confirmed.

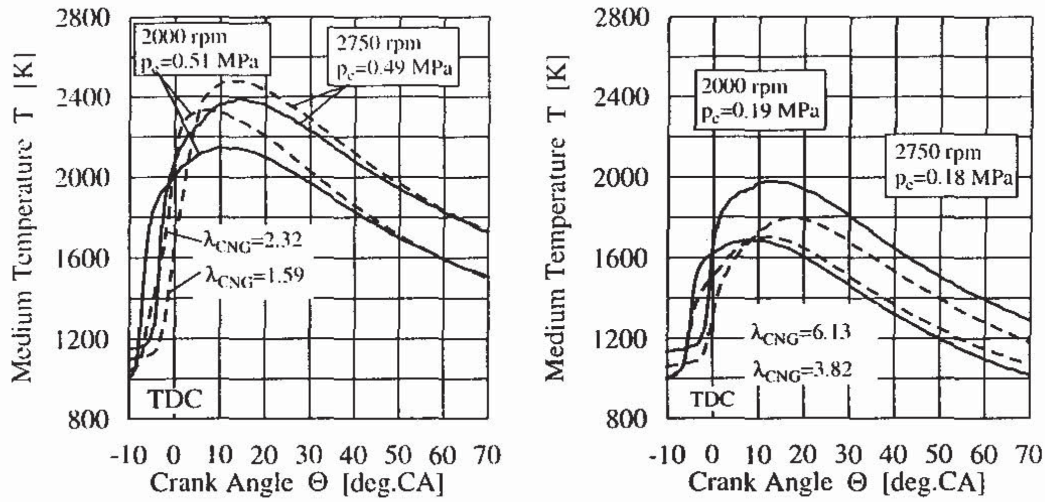

Fig. 2. Comparison of average temperatures of working medium during combustion in the test engine fed traditionally– solid lines and fed in a dual fuel system – dashed lines

The Fig. 3 shows changes of maximal heat release rate corresponding to combustion of pilot dose only $(dQ/d\theta)_{DOmax}$ and the gas only $(dQ/d\theta)_{CNGmax}$, as a function of gas-air mixture composition. Those parameters were obtained on base of valuation of the maximums present on heat release curve $dQ/d\theta$ calculated from indicator diagrams of the engine fed on gas-air mixtures with various concentrations of gas (changeable λ_{CNG}). The pilot dose quantity in the tests was approximately constant. From the presented changes is visible that maximal heat release rate of gas distinctly decreases together with reduction of natural gas concentration in the mixture. The biggest changes of $(dQ/d\theta)_{CNGmax}$ are present during changes of λ_{CNG}<4.0. For engine speed of 2000 rpm reduction of $(dQ/d\theta)_{CNGmax}$ amounts to: from 13.8 MJ/kmlole·deg.CA to the value of 2.15 MJ/kmlole·deg.CA what constitutes reduction of combustion dynamics of the mixture with 84.5%. Similarly, for engine speed of 2750 rpm the reduction amounts to: from 10.75 MJ/kmlole·deg.CA to 3.17 MJ/kmlole·deg.CA i.e. with 71.6%.

Changes of combustion dynamics of the gas generate only slight changes in combustion run of pilot dose. For low engine speeds, leaning of gaseous mixture initially increases values of $(dQ/d\theta)_{DOmax}$ however in course of further leaning the dynamics of combustion of Diesel oil decreases. At higher engine speeds dynamics of combustion of Diesel oil decreases together with reduction of gas concentration in the mixture. This phenomenon can be explained by impact of changeable concentration of oxygen in the gaseous mixture and influence of pre-flame reactions in the gas during compression and in phase of self-ignition delay of pilot dose. At low engine speeds in the initial stage of leaning, increase of oxygen concentration advantageously impacts on combustion of Diesel oil. In course of further leaning, however, decreasing impact of energy of pre-flame reactions begins to prevail and in effect combustion rate of Diesel oil decreases. Similar conclusions can be found in works [1, 7, 8]. At higher engine speeds, due to higher temperatures of the charge during compression, pre-flame reactions are of prevailing meaning. The pre-flame reactions rate decreases with leaning of gas-air mixture. In effect, combustion rate of Diesel oil decreases in complete range of change of the λ_{CNG}.

Leaning of gas-air mixture for compositions of λ_{CNG}>4.0 slightly influences combustion dynamics of the both fuels and the values of $(dQ/d\theta)_{CNGmax}$ and $(dQ/d\theta)_{DOmax}$. It results, however, in deterioration of operational parameters of dual fuel engine, especially its efficiency and toxicity of exhaust gases, what has been mentioned in previous studies [1,3,4,5].

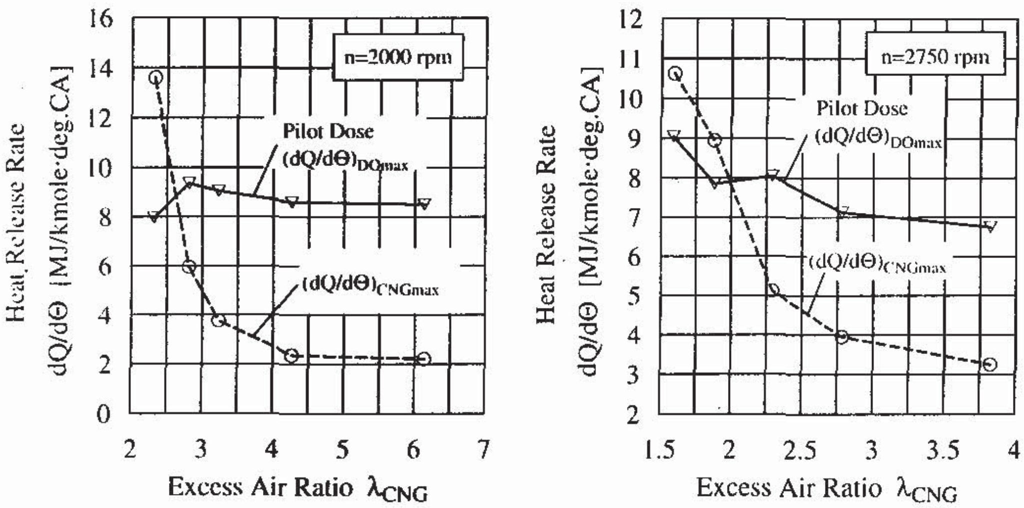

Fig. 3. Changes of maximal value the heat release rate from diesel oil combustion $(dQ/d\theta)_{DOmax}$ and from natural gas combustion $(dQ/d\theta)_{CNGmax}$ in function gas-air mixture composition λ_{CNG}

The NO_x concentration decreases together leaning of the gaseous mixture and in small extent depends on engine speed, Fig.4. Especially high reduction of NO_x concentration has been observed in rich mixtures, λ_{CNG}<3.0, where drop of NO_x concentration was nearly threefold. Further leaning of the mixture, λ_{CNG}>3.0, impacts on NO_x contents in a smaller extent. It is generally known, that rate of NO_x generation exhibits exponential dependency on the temperature. It is understandable; therefore, that reduction of CNG concentration in the mixture leading to reduction of the temperature of the medium in reaction zones leads to reduction of NO_x concentration. It should be underlined, that confirmed big reduction of the NO_x together with growth of λ_{CNG} enables to make assumption, that in the dual fuel engine there is a possibility of controlling of NO_x contents by usage of proper composition of the combustible mixture.

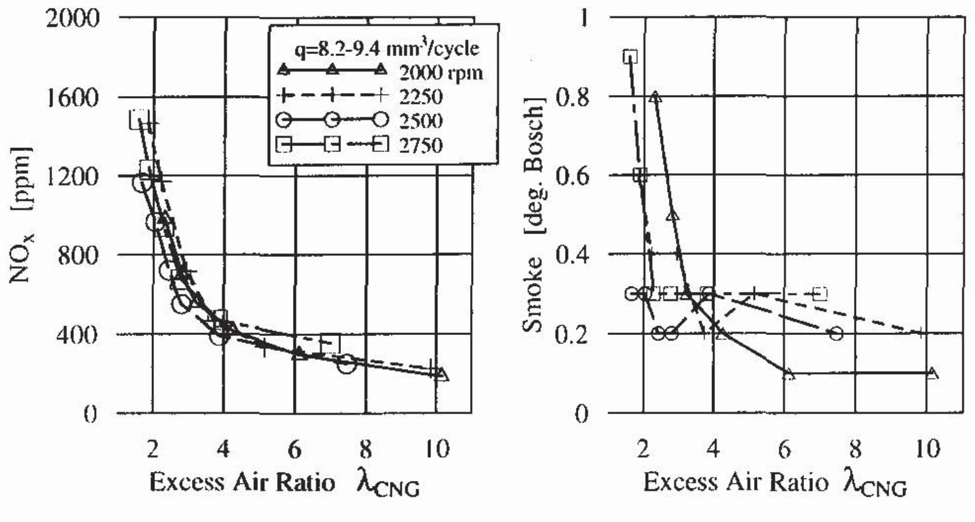

Fig. 4. Changes of NO_x concentration and smoke as a function of air excess ratio λ_{CNG} for various engine speed

Run of change of exhaust gases smoke as a function of λ_{CNG} shown in the Fig.4 indicates at significant reduction of the smoke during leaning of rich mixtures, in range of λ_{CNG}<3.0. There occurs then nearly fourfold reduction of the smoke. It testifies for the fact, that combusted gaseous fuel reducing quantity of oxygen in the charge significantly impacts on conditions of oxidation of liquid fuel, what constitutes the main source of exhaust gases smoke in the dual fuel engines.

Analysis of combustion curves described in the study [1, 4, 5, 8] as well as fact of worsening of dual fuel engine parameters at partial loads, resulted from excessive leaning of gaseous mixture have inclined to necessity of limitation of gas-air mixture composition to value of air excess ratio of λ_{CNG}<4.0. It enables to minimize a harmful phenomena connected with combustion of lean gaseous mixtures. In this connexion, further analyses were limited to mixture compositions of λ_{CNG}<4.0. It can be accomplished by partial throttling of the air and including skip-fire mode at minimal loads of dual fuel engine.

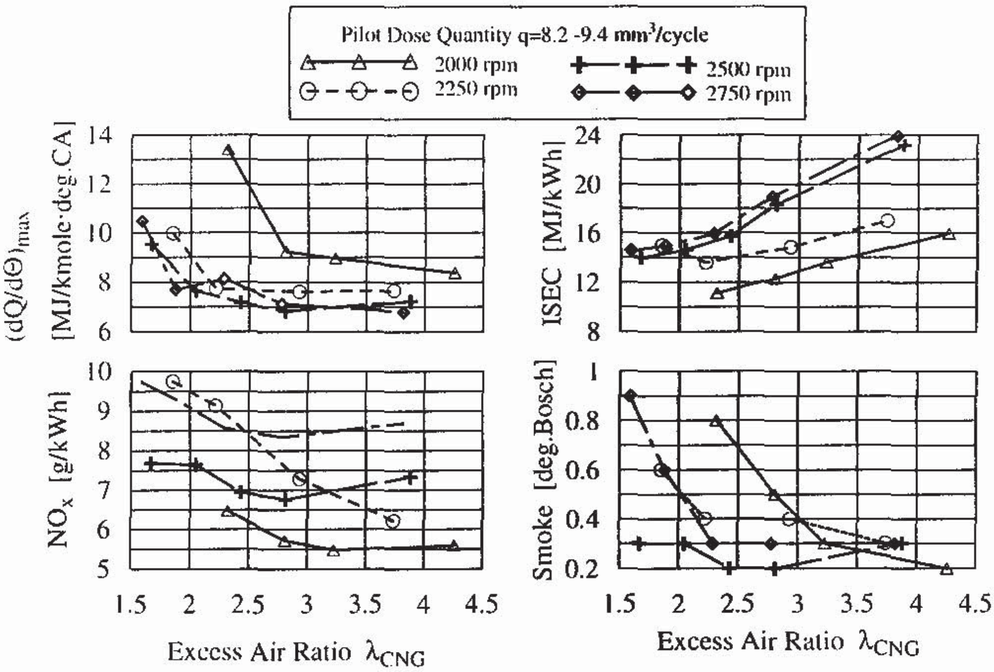

Fig. 5. Run of maximal values of heat release rate $(dQ/d\Theta)_{max}$, indicated specific energy consumption ISEC, NO_x concentration and exhaust gases smoke as a function of gaseous mixture composition λ_{CNG} for various engine speed

From the curves shown in the Fig 5 is evident that the biggest changes in total heat release rate $(dQ/d\Theta)_{max}$ in dual fuel engine are present at changes of gaseous mixture composition in range of λ_{CNG}=1.5-3.0. In the aforesaid range of mixture composition there also occur a significant changes in NO_x emission and smoke of the exhaust gases. It is worth to pay attention on fact of generally low NO_x emission in range of 5.5-9.5 g/kWh.

Comparison of exhaust gases emission in traditional and dual fuel feeding is shown in the Fig. 6. From the curves shown in the Fig. 6 is explicitly seen that usage of natural gas in naturally aspirated engine, with traditional system of engine adjustment results in growth of CO and THC emission as well as in distinct reduction of NO_x emission and smoke of exhaust gases with respect to the values observed in the engine fed on Diesel oil only. Similar statements can be found in [1, 3, 6, 7]. Differences in CO, THC and NO_x between dual fuel and traditional feeding are growing as engine load is reducing (what is accompanied by leaning of the gaseous mixture). It results from discussed earlier worsening of oxidation conditions of the gaseous fuel, what leads to increase of CO and THC emission, and simultaneously to reduction of quantities of generated NO_x. Only differences in the smoke of exhaust gases are reducing together reduction of engine load, what is connected with mentioned earlier improvement of conditions of combustion of initial dosage.

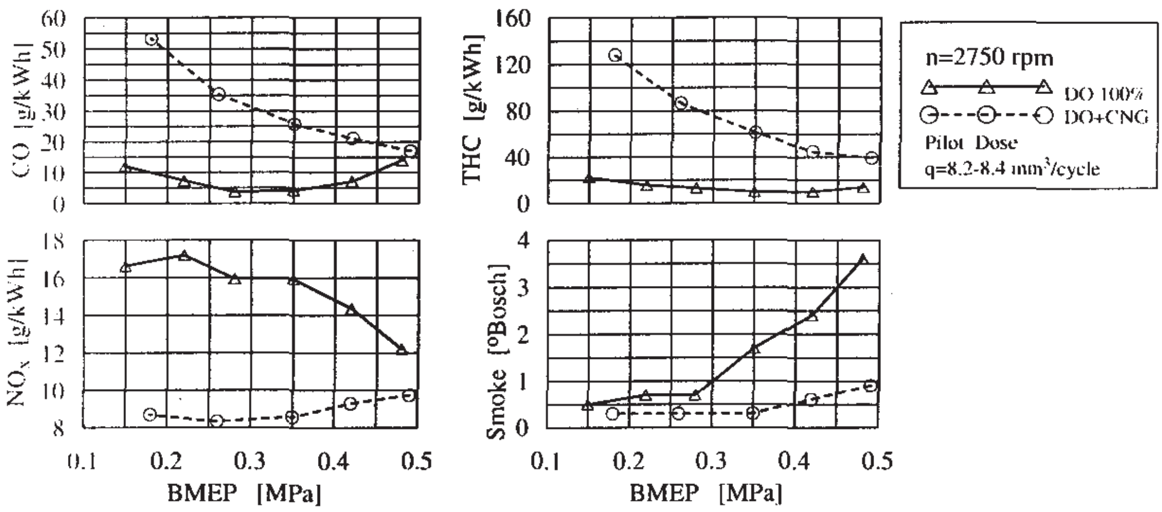

Fig. 6. Comparison of exhaust gases emission of the test dual fuel engine and the engine fed traditionally

In course of performed experiments it was fund that NO_x emission at maximal load of dual fuel engine is lower in a limits of 35÷55%, comparing with the engine fed traditionally. Even much more bigger differences are present during reduction of the load, where occurs 2÷3 fold reduction of NO_x emission. It is mainly connected with combustion of lean gaseous mixtures, what is accompanied by low heat release rates and lower temperatures in reaction zones.

Analysis of exhaust gases smoke curve shows that in majority of tested measuring points, at dual fuel feeding, more than forth fold reduction of the smoke is present. It means that even small share of the natural gas in entire energy supplied to the engine significantly reduces emission of solid particulates, what can be implemented in bus engines driven in downtown of a big cities.

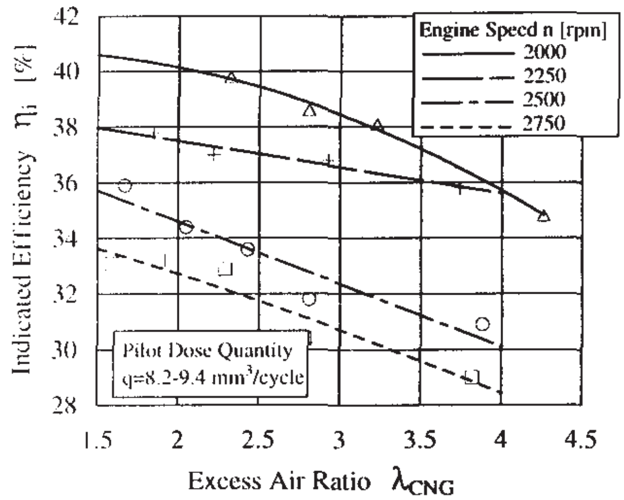

Fig. 7. Effect of gas air mixture composition on the indicated efficiency for various engine speed

Change of engine's indicated efficiency connected with leaning of gas-air mixture is shown in the Fig. 7. At constant pilot dose, indicated efficiency decreases together with reduction of gas concentration in gaseous mixture. In course of performed tests it has been found that change of mixture composition in range of λ_{CNG}=1.5-4.0 results in reduction of indicated efficiency with 5.9% at engine speed of 2000 rpm and 5.1% at 2750 rpm. Meaningful reduction of indicated efficiency shows, that one should enter into account a similar reduction of thermal efficiency of the engine operated at partial load. Concurrently, efficiency curves in the Fig. 7 show that it would be advantageous to still more reduce the maximal leaning of the mixture up to λ_{CNG}=3.0. Changes of indicated efficiency would not exceed then the value of 2.0-2.8%. Limitation of specified above leaning of gaseous mixture could be difficult to be accomplished in traction engines at very low engine load. In this case, improvement of engine efficiency could be obtained by partial throttling of the air, skip-fire mode or changing over to traditional fuelling.

4. Conclusions

Implementation of dual fuel system for feeding of gaseous engines is an effective method of reduction of NO_x emission and smoke in an compression ignition engines. In course of performed experiments it has been found that reduction of NO_x emission with respect to traditional fuelling is in the limits of 35-55% at maximal loads and 2-3 fold at minimal engine load. Quantities of generated NO_x depend mainly on composition of the gaseous mixture and undergo the biggest changes at change of the composition in range of $\lambda_{CNG}<3.0$. It gives a possibility to control generated NO_x via maintaining relevant composition of the gaseous mixture what can be used in turbocharged engines.

The tested engine at maximal load has shown more than fourfold lower smoke of the exhaust gases. At constant pilot dosage the smoke decreases together with reducing concentration of gas in the mixture. It testifies for non-advantageous impact of the gas on oxidation conditions of the Diesel oil.

Usage of the natural gas has caused more than twice growth of CO emission and non-burnt THC hydrocarbons. That growth increases together with reduction of engine load, what is connected with worsening of oxidation conditions of gaseous fuel and decay of flame near to cylinder walls. Restriction of the emission of those components in combustion process of dual fuel engine is very difficult, and the only rational method is to use oxidation catalysts.

Maximal leaning of the gas-air mixture at partial engine load of the dual fuel engine should be limited to composition of $\lambda_{CNG}<4.0$. It shall enable to restrict harmful phenomena connected with combustion of lean mixtures, leading to reduction of engine efficiency and growth of CO and THC emission.

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