SOME ASPECTS OF DUAL FUELLING OF THE MIDDLE CLASS MODERN CI ENGINES

Zdzisław Stelmasiak

Technical University of Bielsko-Biala
Internal Combustion Engines and Automobiles Branch
Willowa 2, 43-309 Bielsko-Biała, Poland

Abstract

The paper presents results of studies on the dual fuel engine equipped with the Common Rail high pressure injection system and low pressure natural gas injection into the inlet collector. Impact of some regulation parameters of the feed system on the engine performance parameters was examined. Research of the pilot dose selection showed that the minimal size of the dose was limited to ca 12÷13% of the nominal dose. It is a result of some troubles of the electromagnetic injector operation at short times of control. The effect of that is a notable deterioration of smoothness of the engine operation. However, electronic control of the injector opening timing enables to reduce the pilot dose size as the engine load is reduced. The research showed advantageous impact of the decreasing dose on the engine efficiency and exhaust gas toxicity at partial loads of the engine. The tests reconfirmed full usefulness of the system to combustion process optimization. A delay of the injection start at high engine loads enables to reduce nearly twice the NO_x concentration in exhaust gas with insignificant decreasing, some 1÷1.5%, of its efficiency. The used systems showed their high suitability to control charge quality in dual fuel engines, in traction applications in particular.

Keywords: *dual fuel, natural gas, gas injection, common rail, combustion process.*

1. Introduction

Application of modern feed systems, the Common Rail and gas injection system, to modern compression ignition engines, provides great capacities in respect of proper selection of charge quality in variable operating conditions of the engine. It is particularly important in traction applications of the engine, where the range of variation of operation parameters is very wide, and the alterations follow up rapidly. The previous mechanical systems of the dual fuel engine control did not allow for quick alteration of engine adjustment, and adjustment accuracy was also unsatisfactory [1, 3, 6, 7].

In a dual fuel engine, composition of the combustion mixture depends on both the Diesel oil pilot dose size and quantity of gas fed to the engine [2, 5, 9, 12]. Difficulties related to mechanical control of these parameters caused that a fixed pilot dose size was used generally, being set up for the nominal conditions of engine operation [12, 13]. The alteration of the engine load was effected by an alteration of the gas amount. It had an unfavourable impact on composition of the gas-air mixture, that was too lean at partial loads of the engine. The effect of such a way of the engine control was both lowering of the engine efficiency and significant increase of engine exhaust gas toxicity [4, 8, 11, 14] . Often, whilst at a partial load, in spite of gas use, the above mentioned parameters were worse than the ones of engines fed traditionally [6, 7, 14].

Modern feed systems, due to their electronic control applications, allow for free forming of the following adjustment parameters:

- size and pressure of the pilot dose injection,
- size of the gas dose and the injection timing,
- angle of pilot dose injection advance, conditioned by various optimisation criteria.

These parameters can be variable according to engine rotational speed and load, or adopted optimisation criterion as well.

The paper presents results of studies on dual fuel engine equipped with the high pressure Common Rail injection system and low pressure natural gas injection into the inlet collector. Impact of some feed system adjustment parameters on engine operation parameters were examined as well.

2. Experimental setup

The tests were made on a single cylinder compression ignition, direct injection engine SB3.1. The specifications for the test engine are presented in Table 1.

Tab. 1. Test Engine Specification

Cylinder number	1
Bore	127 mm
Stroke	146 mm
Displacement Volume	1848 cm^3
Compression Ratio	15.8:1
Brake power	22.8 kW
Engine speed	2200 rpm
Chamber Type	DI
Injection Timing	28 deg. btdc
Injector system for pilot dose of Diesel oil	Common Rail Bosch
Diesel oil injector	0986435 004 090 Bosch
Injection system of CNG	IC
Gas injector	F465 151 72 Bosch
Gas injection pressure	1 MPa

The induction system of the engine was provided with a two Bosch gas injector type F465 151 72. The volume of gas was regulated by a changing time opening of gas injector.

The engine load was regulated by means of variable gas volume for a constant initial dose quantity of the diesel oil. Four different initial doses were applied in the tests: 15, 20, 30, 40 mm^3/cycle.

The concentration of toxic components was measured by *Pierburg AG* exhaust-gas analysers: the CO by the infrared, TCH by flame ionisation, and NO_x by chemo- luminescent analyser. The exhaust smoke was measured by a smoke meter AVL type 409.

The combustion parameters were calculated based on the average indicator diagram, with 128 subsequent combustion cycles. Indicator diagrams were registered by means of the AVL INDIMETER system, type 619; and the AVL crank angle transmitter, type 3016. The pressure value in the cylinder was registered every 0.5 deg.CA for the whole working cycle, i.e. for the high-pressure part and for the charge exchange loop.

The overall engine setup is shown in Fig. 1.

During the tests, the angle of the gas injection start was constant, and set up that start of the gas injection process commenced upon closing of the outlet valve. The total gas injection angle was dependent on quantity of the gas fed, and was related to the size of the pilot dose and to the engine load. The angle of pilot dose injection advance was variable depending on engine operation parameters and optimisation criterion adopted.

Fig. 1. View of the research setup SB3.1 engine

3. Results and discussion

In the previous designs of the dual fuel engines, minimisation of the pilot dose was endeavoured [1, 2, 7, 10, 11, 16]. It was related to a notable difference between fuel prices, and endeavours to improve the engine operation economy. It seems that as far as dual fuel traction engines are concerned, the condition can be softened, and the both fuels can be considered equally. Assuming so, the size of the pilot dose should be set up basing on engine optimal efficiency and required minimal toxicity, or engine operation durability and reliability.

Assuming the above criteria, various pilot doses ranging q=12.5 - 39.3 mm^3/cycle were used in the tests, and that provided a power share of gas at nominal conditions within a 88 - 66% range.

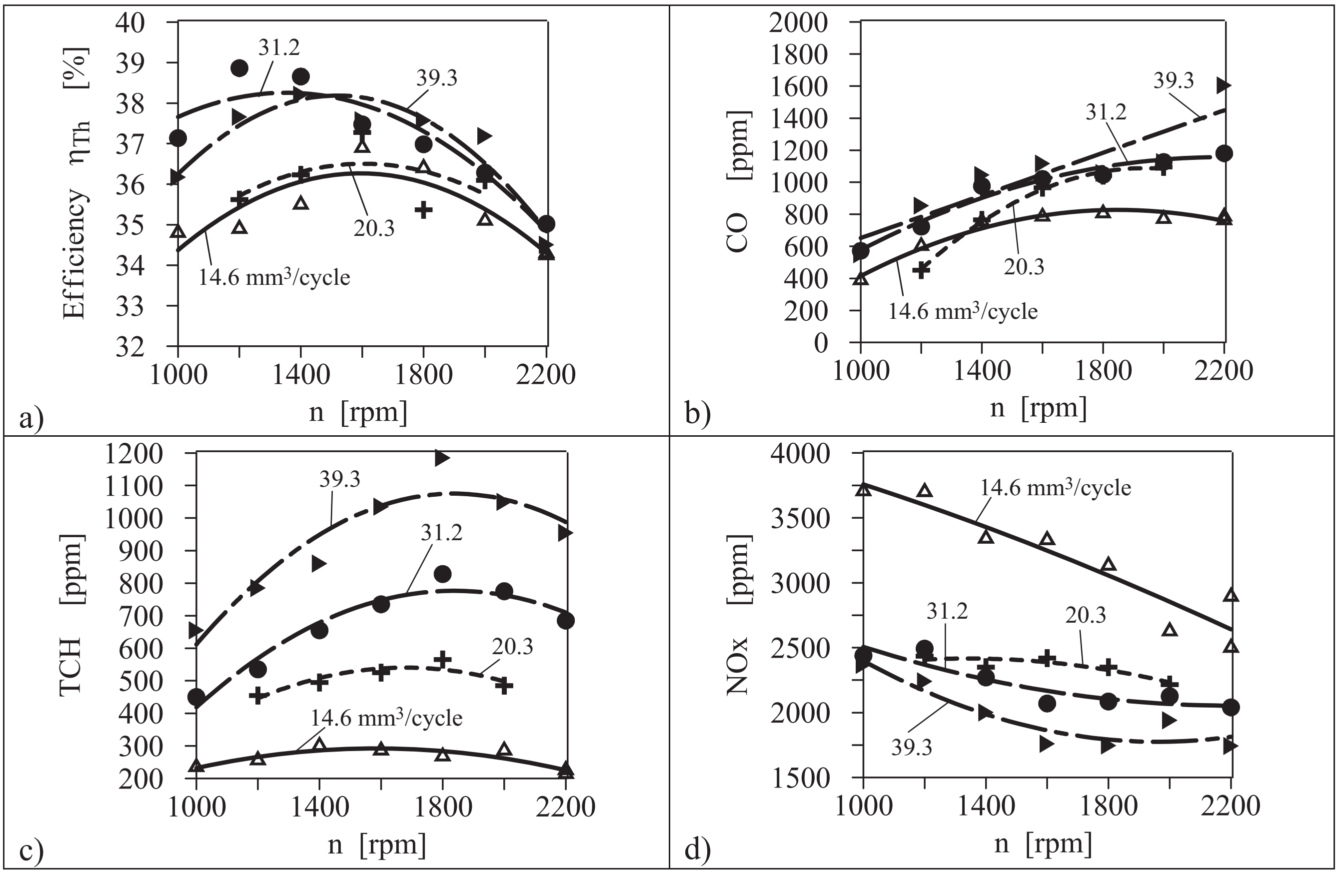

Fig. 2. Comparison of thermal efficiency and concentration of CO, THC and NO_x for various pilot dose quantities

Comparison of efficiency presented in the Figure 2a shows that at the maximal engine load the lowest efficiency was achieved at the minimal pilot dose of 14.6 mm^3/cycle. Increasing the pilot dose resulted in an increase of engine efficiency within the full range of its rotational speed. A notable increase of the efficiency was noted for greater doses of 31.2 and 39.3 mm^3/cycle amounting to 1.2 - 3.4%. Greater changes of engine efficiency were noted whilst lower rotational speeds, and as the rotational speed increases an impact of the dose size on engine efficiency is smaller. It seems that at lower rotational speeds, thus at a lower temperature of the combustion chamber, greater sizes of pilot doses burnt during longer periods provide greater portions of energy at the beginning of the combustion process, accelerating burning of the gas mixture. A greater space range of the liquid fuel stream also could matter favourably in the process.

However, increasing the pilot dose size effects an increase of the carbon monoxide CO and the total hydrocarbons THC concentration in exhaust gas (Figure 2b and 2c). Concentration of nitric oxides NO_x (Figure 2d) lowers as pilot dose size increases. It results from reduction of combustion speed of a lean gas-air mixture. The phenomenon refers mostly to zones outside the injected liquid fuel stream [12]. It effects a decrease of maximal temperature in the zone of the flame front and zones just behind the front, where the main amount of the nitric oxide NO is generated.

Alteration of the pilot dose size can improve also the gas-air mixture composition at partial loads of the engine. Reducing the pilot dose size, as the load is reduced, effects that the gas-air mixture has to be enriched in order the engine receives a sufficient quantity of energy. It causes an increase of the combustion speed, that soften somehow effects of prolonged combustion of lean gas mixtures. However, it has to be emphasized that, as the pilot dose is reduced, the range of the liquid fuel is lowered and quantity of energy - in the beginning phase of combustion when the flame front in the gas mixture is formed – is reduced either. Changes in the engine operation parameters are a resultant of the both above described interactions.

Impact of a variable pilot dose on the engine operation parameters is shown in the Figure 3.

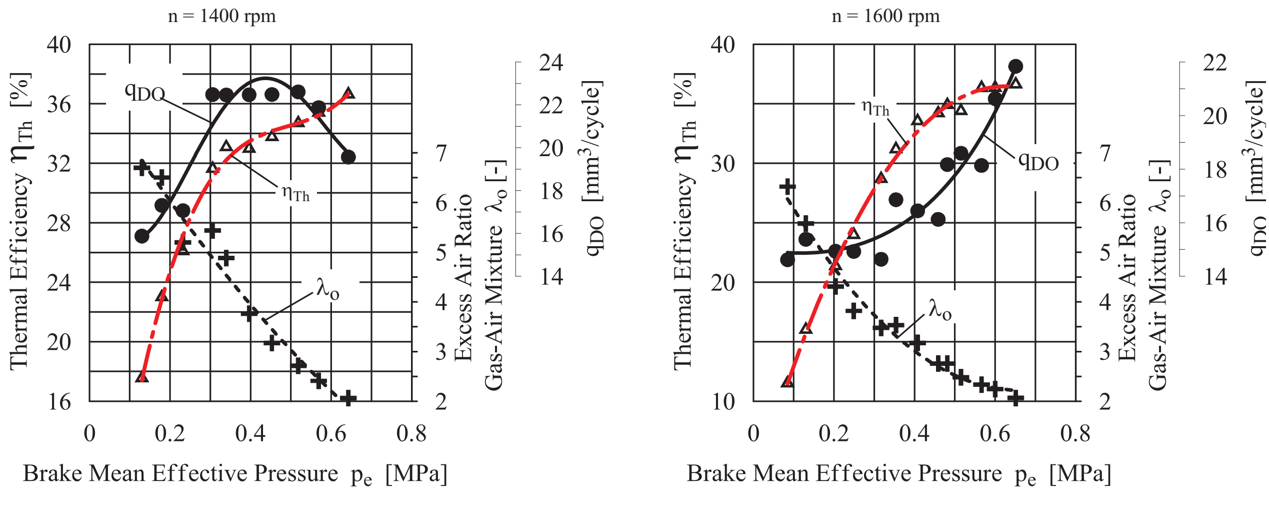

Fig. 3. The changes of thermal efficiency η_o, excess air ratio of gas-air mixture λ_o in function of engine load: injection timing 22°CA b. TDC; variable pilot dose quantity

Size of the dose has been reduced through change of injection's opening time as engine load decreases. The tests proved that although a high pressure fuel injection is applied, the size of the pilot dose should not be arbitrary reduced. The minimal doses, that we were able to get, were 12.52 - 13.0 mm^3/cycle. Another decreasing of the pilot dose size effected in non-uniform operation of the engine. Probably the cause of the phenomenon could be unstable fuel injection at very small times of electromagnetic injector opening of the Common Rail system [15]. The times were much shorter than the times while engine idle running. Disturbance in flame development at the beginning of the combustion process, deteriorating engine smoothness from one cycle to another, is of some significance as well. For fear of injector overheating, smaller pilot doses than the above were not applied.

Reduction of the initial dose's size has restricted leaning of the gaseous mixture in a small extent only. At minimal engine loads, excess air ratio of the gaseous mixture was still high and has amounted to λ_o = 6.02 - 6.8 for engine speed of 1400 rpm, and λ_o = 5.02 - 6.2 for rotational speed of 1600 rpm.

The Figure 4 shows comparison of dual fuel engine parameters operating on constant initial dose, independently on the load, and with the dose decreasing together with reduction of load. Comparison of overall efficiency of the engine shows that reduction of the initial dose advantageously impacts on overall engine's efficiency in range of average and maximal engine loads (Figure 4a). For low engine loads, p_e<0,2 MPa, the efficiencies for the both adjustments were similar in spite of significant differences in size of the initial doses. That fact is rather unexpected, because obtaining a similar engine load at smaller initial dose requires enrichment of the gaseous mixture, what should have an impact on course of its combustion.

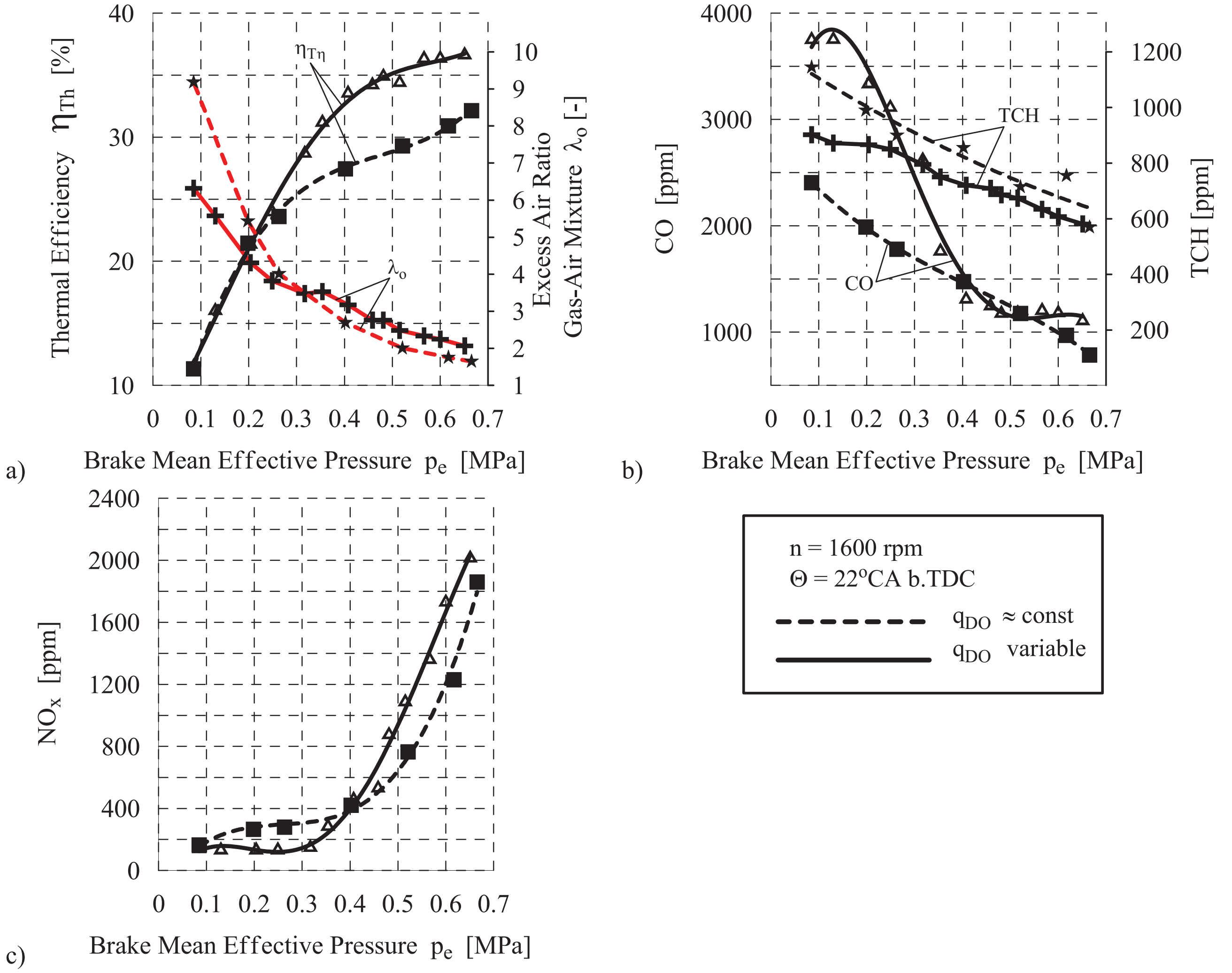

Fig. 4. Comparison of thermal efficiency η_o, CO, TCH and NO_x concentration in exhaust gas in engine dual fuel fuelled with constant and variable pilot dose quantity

Usage of reduced initial doses has resulted in growth of CO concentration in scope of low engine loads as illustrated in the Figure 4b. Simultaneously, however, in the entire range of change of the load concentrations of TCH hydrocarbons were smaller. It seems that change of combustion rate of the gaseous mixture, enriched during reduction of the initial dose, impacts on reduction of TCH concentration. Explanation for growth of CO concentration can be then suspected in reduced range of the stream and its energetic impact on the gaseous mixture. With reducing size of the initial dose the range of fuel stream also decreases, time of its combustion undergoes reduction and energetic effect resulted from combustion of diesel oil also decreases. Those factors can impact on quantity of generated CO and cause a growth of its concentration at partial engine loads. Simultaneously, however, combustion rate of the gaseous mixture enriched with use of a smaller dose grows as well. Results of the research do not show, however, any positive impact of growth of gas combustion rate on quantity of generated CO. It seems, however, that to such conclusion one should refer with a great care, because other factors not taken into consideration during the research can impact on quantities of the generated CO.

Concentration of nitrogen oxides in range of average and maximal engine loads has grown in result of usage of variable dosage, whereas in range of small loads, $p_e < 0.4$ MPa, has been reduced (Figure 4c). Changes in NO_x concentrations are connected, at tested sizes of the initial doses, with combustion rate of the gaseous mixture and result from change of excess air ratio λ_o. Growth of NO_x concentration in range of higher loads results from reduction of the excess air ratio λ_o and growth of combustion rate of the gaseous mixture. In area of low engine loads quantity of generated NO_x can be also affected by decreasing range of the stream at decreasing initial dose. That effect can result in reduction of generated quantity of NO_x.

Optimal size of the initial dose in full operating range of the engine is shown in the Figure 5. Making selection of the dose one has followed criterion of smooth engine operation with minimal size of the initial dose and partial engine loads, and proper cooling of injector in case of definition of the dose for maximal loads.

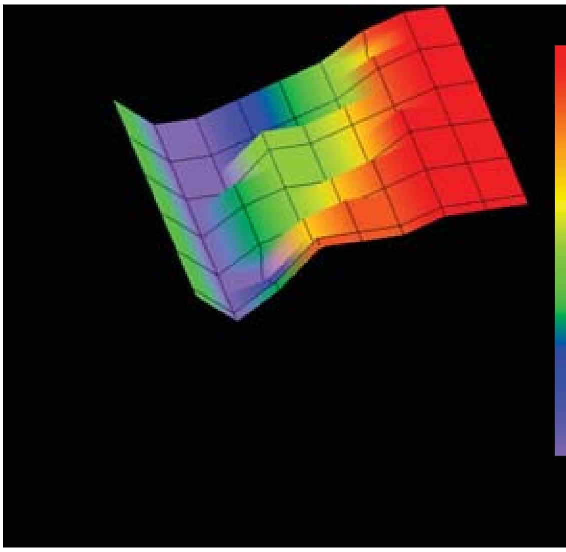

Fig. 5. Changes of pilot dose quantity in function engine load and engine revolution for optimal engine thermal efficiency

Great repeatability of injection of the Common Rail system and electronic control of injection start, provide free forming of the combustion process beginning in the dual fuel engine. It allows for determination of the optimal pilot dose injection start according to the engine speed and load. However, the tests showed that optimal combustion start depends on assumed criterion of optimisation, for instance efficiency or NO_x emission. Applying such criteria, there occur differences, especially whilst engine loads are close to maximum. Behaviour of the NO_x<1000 ppm concentration in the whole field of engine operation required a delay of pilot dose injection at maximal loads of the engine within $2 \div 4^o$CA. It resulted, as a rule, in reduction of general efficiency of the engine by 1-1.5%.

Implementation of modern electronic feeding systems offers a possibility of easy control of fuel injection parameters. Possibility of change of initial dose injection timing in function of engine speed, load and gas-air mixture composition is especially crucial in case of dual fuel engine. In course of the research described here one has performed optimization of the injection timing within entire range of rotational speeds and engine loads. Because of fears concerning overheating of the injector, complete optimization tests of the injection advance angle of the initial dose were carried out for size of the dose of about 20 mm^3/cycle, what constitutes about 15% of nominal dose at traditional fuelling.

Selection of the optimal injection timing was performed at constant engine speed and constant settings of initial dose and natural gas dose. Changes in engine parameters have resulted solely from changes of injection advance angle. The procedure was repeated for various engine speeds and different loads in order to cover by tests all possible conditions of engine operation.

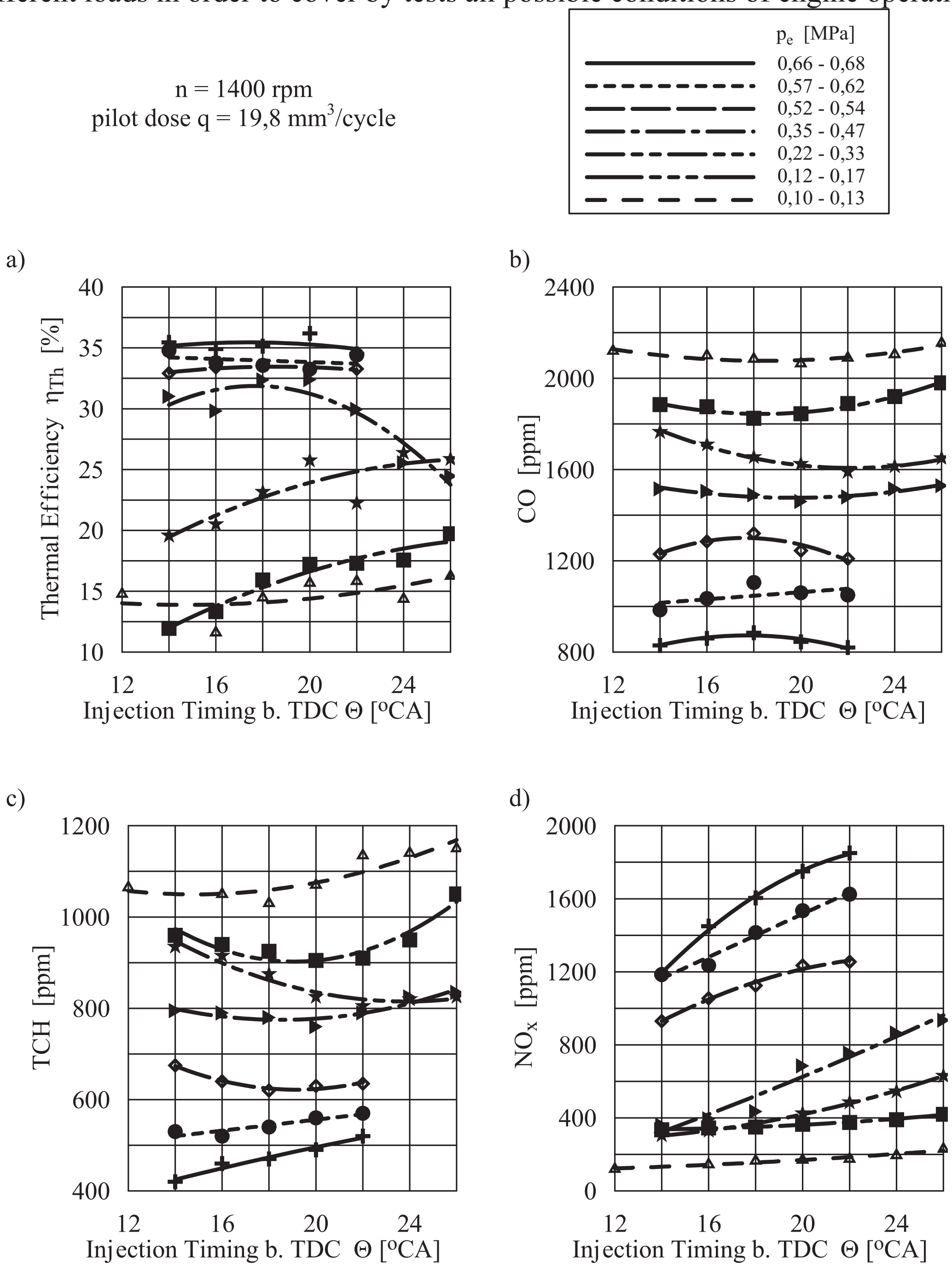

Fig. 6. The impact of the pilot dose injection timing on the thermal efficiency η_{Th} and on the concentration of CO, THC, NO_x in engine SB3.1 dual fuelled for various engine load

In the Figure 4, there is shown impact of the angle of advance of pilot dose injection on some parameters of engine operation. Working out characteristics, the pilot dose and gas dose sizes were constant, and the only one parameter being variable was the angle of advance of pilot dose injection. From the presented characteristics is seen that the maximal overall efficiencies are changing in function of the injection advance angle within interval of 33-35% for all tested measurement points (Figure 6a). Changes of the efficiency are relatively small for the highest engine load, whereas for partial loads a distinct impact of the injection advance angle on the run of analyzed efficiencies can be seen.

In result of the performed research, none distinct influence of injection advance angle of the initial dose on concentration of carbon oxide, CO, especially for lower engine loads, has been confirmed (Figure 6b). Such influence is more visible for highest engine loads, where concentration of the CO decreases together with growth of the injection advance angle. Similar characters of the changes occur for emission of total hydrocarbons THC (Figure 6c).

In case of the NO_x emission, the changes have more distinct character, where together with increase of the injection advance angle emission of the NO_x distinctly increases, Figure 6d. Depending on engine rotational speed and injection advance angle, quantity of the emission of nitric oxide is changing in range of 150÷300%.

In the Figures 7 and 8, there are shown the optimal angles of advance of pilot dose injection for the criterion of maximal efficiency of the engine (Figure 7) and NO_x<1000 ppm concentration (Figure 8). Only at maximal loads of the engine, behaviour of limited nitric oxide concentration required a delay of the injection start. While there are partial loads, the angles were kept the same as for the criterion of the maximal efficiency.

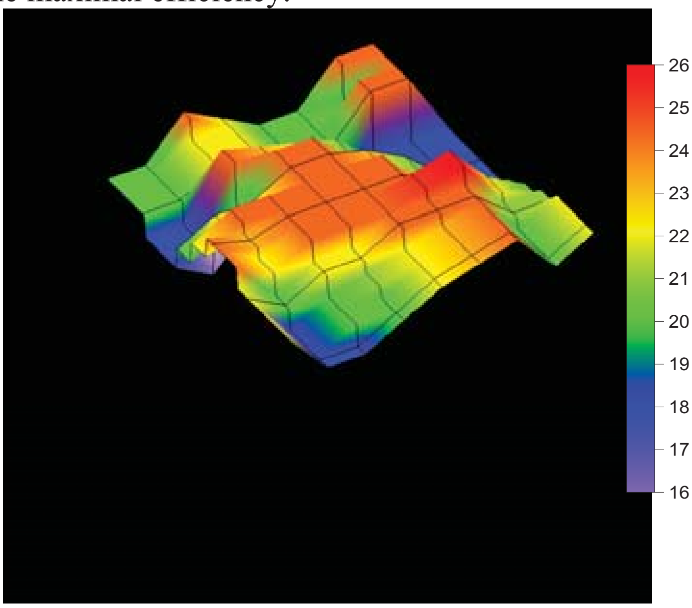

Fig. 12. Optimum injection timing for maximum thermal efficiency and non knock work SB3.1 engine dual fuelled

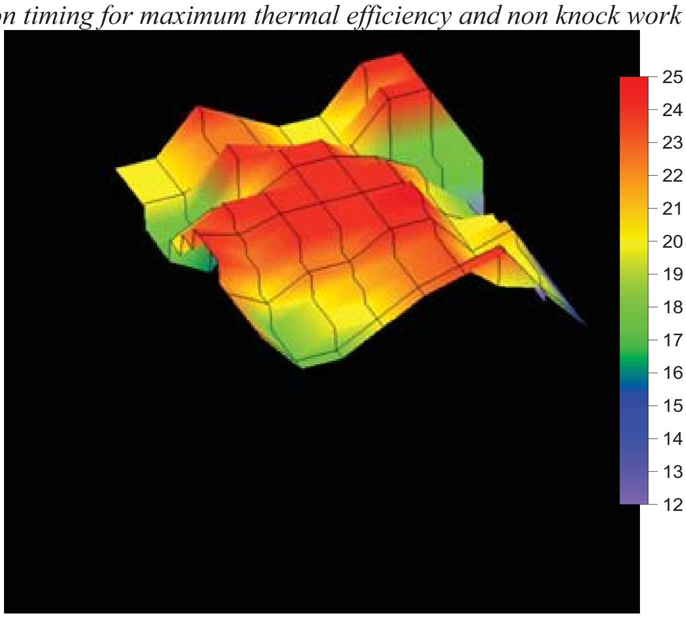

Fig. 13. Optimum injection timing for NO_x concentration lower than 1000 ppm in SB3.1 engine dual fuelled

4. Conclusions

The performed tests and examination showed that application of the Common Rail system to the pilot dose injection and low pressure gas injection into the inlet collector allows for accurate control of quality of the charge burnt in the dual fuel engine. It is a result of a high repeatability of injection of the both fuels and of electronic control of injection parameters. Such quality allow to get the following effects:

- nearly 90% energetic replacement of the Diesel oil for the natural gas,
- possibilities of active change of the pilot dose size, as the engine load is reduced, and that effects increase of the engine efficiency and reduction of exhaust gas toxicity,
- active change of the angle of the pilot dose injection advance, making optimisation of the combustion process according to a selected criterion possible,
- the Common Rail system enables a smooth transit on the running engine from dual fuel fuelling to Diesel oil fuelling, and injection of a nominal size of Diesel oil dose with no noticeable engine trouble.

In spite of electronic control of timing of the liquid fuel injector opening process, reduction of the pilot dose size is limited to the dose of 13-14 mm^3/cycle being 12-13% of the nominal dose. It is a result of injector operation troubles related to its not-complete opening at short control times. It causes an increase of irregularity in engine operation. Considering piezo-quartz injectors of smaller inertia, it seems that the phenomenon appears not so clearly.

The minimal size of the pilot dose at nominal conditions should be set up on a basis of durability tests, because possibilities of injector overheating at high engine loads have to be taken into account.

References

[1] Alla, G. H. A., Soliman, H. A., Badr, O. A., Rabbo, M. F. A., *Effect of pilot fuel quantity on the performance of dual fuel engine,* Energy Conversion & Management 41 (2000) pp. 559-572, 2000.

[2] Badr, O., Karim, G. A., Liu, B., *An examination of the flame spread limits in a dual fuel engine,* Applied Thermal Engineering 19 (1999) 1071-1080, 1999.

[3] Clark, N. N., Atkinson, Chr., Goto, S., *Saturn Dual Fuel Engine Optimization,* http:www.cemr.wvu.edu, 2002.

[4] Daisho,Y., Yaeo, T., *Controlling combustion and exhaust emission in a direct-injection diesel engine dual fuelled with natural gas,* SAE Paper 952436, 1995.

[5] Elsenbruch, T., *Highest Gas Engine Efficiency Requires High-tech Control,* VI Międzynarodowa Konferencja Gazowa “SILNIKI GAZOWE 2003”, Częstochowa 2003.

[6] Friedemann, Z., *Gasmotoren,* Vogel Buchverlag Wurzburg, 2001.

[7] Gebert, K., Beck, J., Barkhimer, R. L., Wong, H. Ch., *Strategies to Improve Combustion and Emission Characteristics of Dual Fuel Pilot Ignited Natural Gas Engines,* SAE Paper 971712, 1997.

[8] Kusaka, J., Okamoto, T., Daisho, Y., Kihara, R., Saito, T., *Combustion and exhaust gas emission characteristics of a diesel engine dual-fuelled with natural gas,* JSAE Review 21 (2000) 489-496, 2000.

[9] Ogawa, H., Mijamoto, N., Li, Ch., Nokazawa, S., Akao, K., *Low Emission and Knock-Free Combustion with Rich and Lean Biform Mixture In a Dual-Fuel CI Engine with Inducted LPG as the Main Fuel,* SAE Paper No. 2001-01-3502, 2001.

[10] Olsson, J. O., Tunestal, P., Haraldsson, G., Johansson, B., *A Turbo Charged Dual Fuel HCCI Engine,* SAE Paper 2001-01-1896, 2001.

[11] Stelmasiak, Z., *Analysis of Combustion Phenomena in Dual Fuel Engine Fed With Natural gas (CNG),* Fisita 2002 World Automotive Congress, paper No. F02 V030, 2002.

[12] Stelmasiak, Z., *Studium procesu spalania gazu w dwupaliwowym silniku o zapłonie samoczynnym zasilanym gazem ziemnym i olejem napędowym,* Wydawnictwo ATH, Rozprawy naukowe nr 5, 2003.
[13] Stelmasiak, Z., *Some Problems of Heat Release Rate and Regulation of a Dual Fuel Engine Fuelled with Natural Gas CNG,* Fisita 2004 World Automotive Congress, Paper No. F2004V180, 2004.
[14] Stelmasiak, Z., *Analiza emisji toksycznych składników spalin silnika o zapłonie samoczynnym zasilanego tradycyjnie i dwupaliwowo głównie CNG*, Międzynarodowa Konferencja Motoryzacyjna „KONMOT-AUTOPROGRES" Bezpieczeństwo i Ekologia Pojazdów, Zakopane 23-26 września 2004.
[15] Stelmasiak, Z., Knefel, T., Larisch, J., *The influence of the Time Break of the Fuel Divided Dose on the Work Parameters of the Injector Common Rail System,* PTNSS KONGRES 2007, Paper P07-C009, 2007.
[16] Sutkowski, M., *20V34SG-high-efficiency lean-burn gas engine for the most efficient Waertsila gas power plants,* PTNSS KONGRES 2007, Paper P07-C015, 2007.