Effect of diesel fuel injection parameters on performances and efficiency of a turbocharged dual-fuel compression ignition engine operating on propane

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Abstract. The paper presents results of investigation on a turbocharged dual-fuel engine operating on propane. The obtained results are presented in form of adjustment characteristics of the injection timing of diesel fuel pilot dose for a few chosen values of the boost pressure as well as injection timing of the main dose. The principal objective of this research was to observe the effect of diesel fuel injection parameters on thermal, mechanical and overall efficiencies of the investigated engine. Diesel fuel was delivered divided in two doses. Both, ratio between the doses and their injection timing were varied. Injection timing of the first dose varied in a broad range and depended on the boost pressure. Injection timing of the second dose varied in a narrower range, mainly due to considerable changes in the combustion process. The investigation were carried out for three values of the first dose preserving, at the same time, a constant energy quantity delivered with diesel fuel. The energy share of propane at each measuring point was equal to ca. 70%. The investigation were carried out for three values of the boost pressure, i.e. 200, 400 and 600 [mbar] but also for the naturally aspirated version. The obtained results answered a number of questions regarding the strategy of selection of diesel fuel injection parameters taking into consideration engine performances as well as thermal, mechanical and overall efficiencies at a high share of the gaseous fuel.

1. Introduction

For many years in the Department of Automobiles and Internal Combustion Engines of Kazimierz Pułaski University of Technology and Humanities in Radom there are carried out investigations on dual-fuel compression ignition engine. Recently, such operating mode is more and more frequently applied because it enables combustion of various fuels that, until now, were not applied for compression ignition engines. These fuel may be renewable or non-renewable – obtained from fossil fuels (e.g. propane and butane mixture). LPG mixture is of interest considering an adaptation of compression ignition engines due to its competitive price and well organized distribution network [2]. Analysis of literature reports regarding this subject indicate that the dual-fuel combustion strategy is analysed and developed in many scientific centres in Poland and abroad [1, 4÷9]. Considering the fact that turbocharging is a distinctive feature of contemporary engines, investigation over the range described with the title of this paper should be carried out.

2. The investigation object and the applied measuring equipment

The investigation object was an AVL 5402 single-cylinder test engine. Its technical data are presented in Table 1.

Table 1. Technical data of the AVL 5402 research engine

Number of cylinders	1
Bore	85,01 mm
Stroke	90,00 mm
Displacement	511,00 cm^3
Ignition type	compression ignition
Valves per cylinder	4
Compression ratio	17,5
Fuelling system	(common rail)
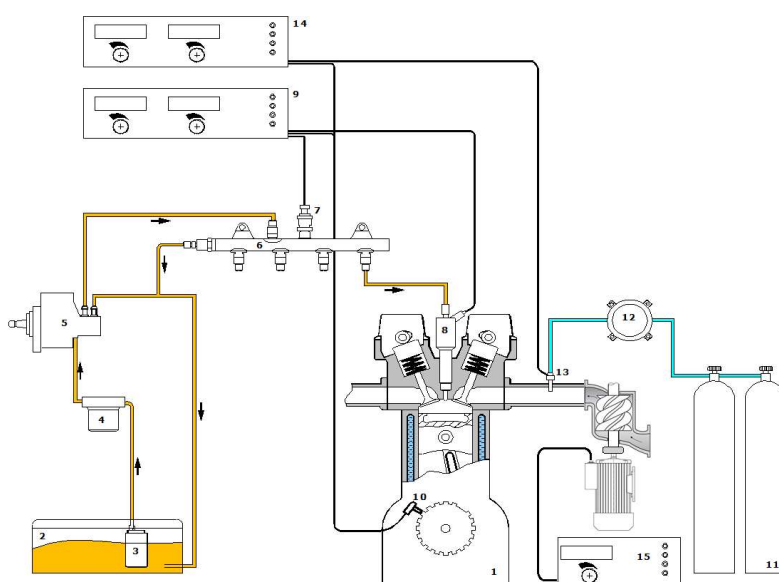
Figure 1. Scheme of the dual fuelling system of the CI engine: 1) dual-fuel engine, 2) diesel fuel tank, 3) low pressure fuel pump, 4) fuel filter, 5) high-pressure fuel pump, 6) container, 7) fuel pressure sensor, 8) diesel fuel injector, 9) common rail controller, 10) crankshaft position and speed sensor, 11) gas tank, 12) gas pressure redactor, 13) gas injector, 14) gas supply controller, 15) boost control system

A view of the test bed is presented in Fig. 2.
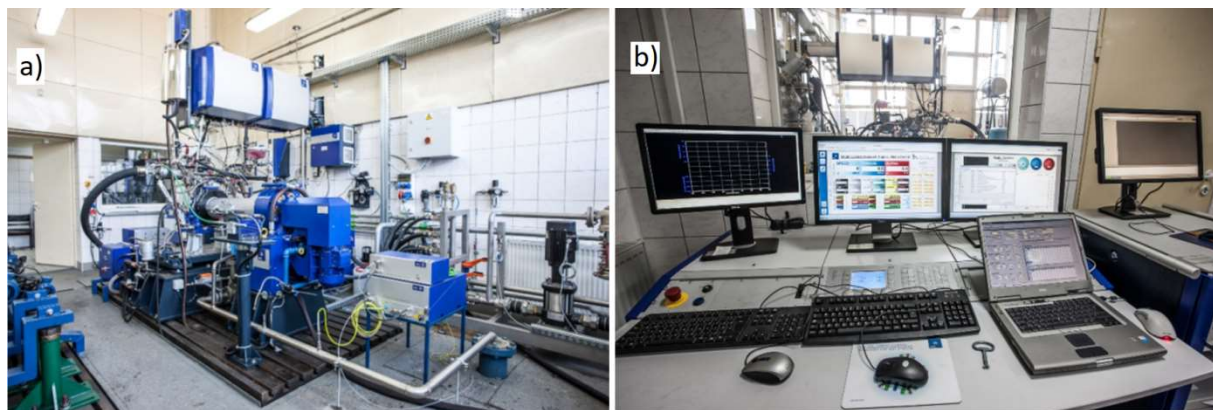
Figure 2. AVL test bed: (a) general view of the test bed, (b) view of the control room

The applied equipment enabled to do the following measurements:
- mass consumption of both fuels,
- engine torque,
- cylinder pressure

and to calculate such quantities as:
- mean indicated pressure,
- mean effective pressure,
- thermal efficiency,
- mechanical efficiency,
- overall efficiency.

The test engine described earlier was adapted by the Author to dual fuelling. Propane in the gas phase was delivered, via the injector, into the intake manifold near the intake valve. The injector opening time was synchronized with the cylinder filling time. Such way of delivery enable to reduce fuel losses during the valve overlap period and, thus, to obtain higher efficiency and lower hydrocarbon emission from the investigated engine. Using a fuel from the same batch during the whole investigation enabled to avoid false results arising from different physic-chemical properties of fuels taken from various batches

3. Investigation programme

As it was revealed in earlier investigations [5, 7, 10], the nature of the combustion course characterized by rapid and substantial pressure rise, much higher than in the case of conventional engine operation on diesel fuel, is the main limitation to use high shares of propane in the fuel charge. Increasing the engine load only by a gradual increase of propane share preserving, at the same time, injection parameters typical for conventional engine operation one may observe a visible increase of maximum rates of pressure rise. Increase of diesel fuel auto-ignition delay time is mainly responsible for this behaviour. Addition of propane, affecting physico-chemical properties of the compressed mixture, causes reduction of its pressure and temperature. In result, ignition initiated by the pilot dose is delayed in comparison with conventional engine operation where only air is compressed. This phenomenon is strongly related to the rate of pressure rise and thus to the combustion course. Typical combustion features, such as start of combustion, maximum combustion pressure and mass fraction burn rate are also changed.

The carried out investigation revealed that both changing of diesel fuel injection parameters and turbocharging give possibility to affect dual fuel combustion in such way to obtain its proper course and maintain its measures comparable to those typical for conventional engine operation.

The investigated engine, equipped with the common rail system, enabled to adjust, in a wide range, both quantity and injection timing of maximum four fuel doses in one working cycle. Earlier investigations showed that division of the diesel fuel dose into two ones, i.e. the pilot and the main, effectively reduces

the maximum rate of pressure rise. However, to render this possible, maintaining at the same time proper combustion and high efficiency of the dual-fuel engine, it is necessary to adjust both quantity and injection timing of both doses [11, 12]. To obtain this, it was decided to apply three quantities of the pilot dose: 2; 2.25 and 2.5 mg. The first quantity was established as the smallest dose causing clear changes in the combustion process.

The carried out investigation enabled to prepare the following characteristics:
- brake mean effective pressure BMEP [bar],
- overall efficiency η_o [%],
- thermal efficiency η_{th} [%]
- mechanical efficiency η_m [%],

versus pilot diesel fuel injection parameters.

Moreover, combustion pressure versus crank angle $p = f(\alpha)$ was registered in order to calculate the overall efficiency.

The following assumptions were made:
- constant engine speed n = 2400 rpm
- three boost pressure values

p_1=600 [mbar]

p_2=400 [mbar]

p_3=200 [mbar]

and the naturally aspirated version

p_4=0 [mbar]
- constant air excess ratio at each measuring point $\lambda \cong 1.3$
- constant index of the energy share of propane

$$\frac{E_{PROPANE}}{E_{PROPANE}+E_{DF}} \cong 70\% \tag{1}$$

- constant energy value of the propane charge in 1 working cycle (for the same boost pressure)

$$\frac{E_{PROPANE}}{1_{cycle}} \cong const. \tag{2}$$

- constant energy value of the total charge (propane + DF) in 1 working cycle (for the same boost pressure)

$$\frac{E_{PROPANE}+E_{DF}}{1_{cycle}} \cong const. \tag{3}$$

The diesel fuel charge was divided into two doses, i.e. the pilot QI and the main QII. Three QI values were applied in the investigation (2; 2,25; 2,5 mg/cycle). Injection timing αI of the QI dose varied over a wide range. Investigations were repeated for three αII values of the QII dose.

4. Results and discussion

4.1. Investigation on the effect of the diesel fuel injection parameters on the brake mean effective pressure

The investigation consisted in preparation of adjustment characteristics according to the assumptions described in the paragraph 3. The obtained results, in form of diagrams, are presented in Fig. 3.
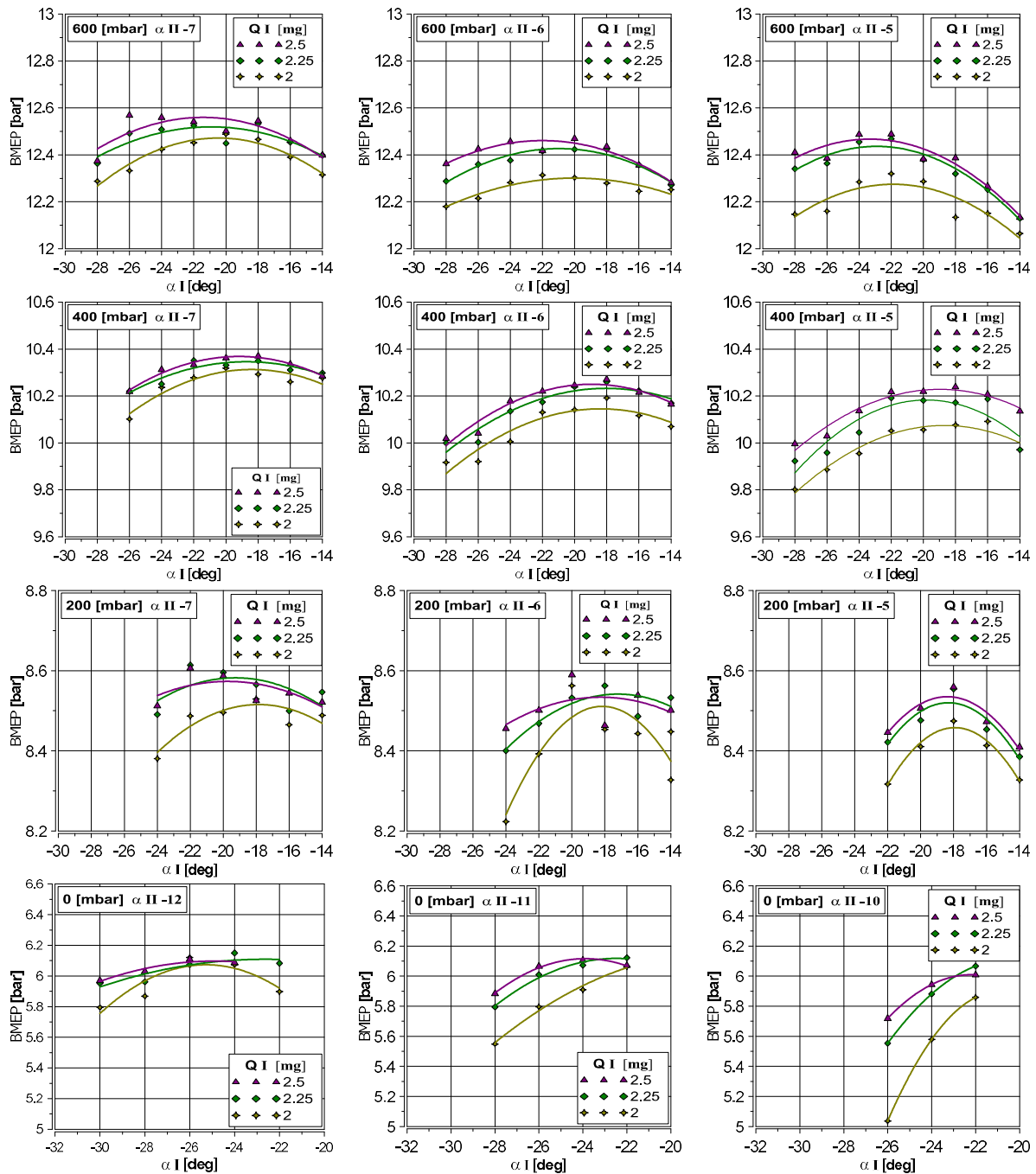
Figure 3. Brake mean effective pressure BMEP versus diesel fuel injection parameters

Analysis of characteristics put together in Fig. 3 indicates that the pilot dose quantity affects the brake mean effective pressure BMEP. There is revealed a clear dependence of BMEP increase with the pilot dose Q1 quantity increase. That trend is observed for almost all measuring points, regardless of the boost pressure. It should be stressed that further increase of the pilot dose quantity would result in BMEP increase, unfortunately leading to the increase of the maximum rate of pressure rise and in consequence its limit established at 1 MPa/deg would be exceeded. For the highest boost pressure 600 mbar, the

maximum BMEP value is obtained when the pilot dose injection takes place at 22° BTDC. Adjusting of the pilot dose injection timing, both acceleration and retardation, results in BMEP decrease. This means that, for given engine operating conditions (boost pressure, both fuel ratios, air excess ratio and crankshaft rotational speed) the pilot dose injection should take place at 22° BTDC taking into consideration the possibility to obtain the highest BMEP value. Injection timing of the main dose which clearly initiates the combustion and controls its dynamics, was adjusted over a much narrower range. During investigation on the turbocharged engine version the QII dose injection timing was adjusted three times by 1° CA starting from 7° BTDC. Injection timing of the main dose has a great influence on how the energy of the compressed mixture is released. Adjusting of the QII dose injection timing only by 1° gives a clear result in the form of BMEP change. Comparison of BMEP for the same engine operating conditions and only for various QII dose injection timing one can see that BMEP decreases with retardation of QII dose injection timing. Taking into consideration increase of the effective power one should strive to obtain possibly high BMEP values what may be achieved by further increase of the QII dose injection timing. However, this method is limited mainly because of the increase of the rate of pressure rise $(dp/d\alpha)_{max}$. Due to this fact, in the investigated turbocharged engine version the QII dose injection timing set at 7° BTDC was critical. In the case of the naturally aspirated engine version there was a need to adjust injection timing of both the pilot and the main doses. Lower temperatures of the medium at the end of the compression stroke, resulting from natural aspiration and from increase of the specific heat of the compressed gas - air mixture, led to a significant increase of the auto ignition delay time. Maintaining of diesel fuel injection parameters typical for the turbocharged version resulted in visible retardation of combustion thus leading to visible combustion unrepeatability and even misfires. To make possible engine operation in a dual-fuel mode when thermodynamic parameters (temperature and pressure) of the medium in the moment of the pilot diesel injection are lower in comparison to parameters obtained in the turbocharged version, it is necessary to adjust the injection timing, i.e. to accelerate it. Such adjustment may wipe out effects resulting from the increase of the auto ignition delay time.

4.2. Investigation on the effect of the diesel fuel injection parameters on the overall, thermal and mechanical efficiencies

To make possible a deeper analysis of the observed relationships, necessary measurements that enabled preparation of characteristics of overall, thermal and mechanical efficiencies. The overall efficiency was calculated on the basis of measurements of energy consumption of both applied fuels (propane and diesel fuel) and also on the basis of the registered engine torque. The registered combustion pressure courses were used to calculate the indicated power of the cycle what enabled to calculate the thermal efficiency. On the same basis, the mechanical efficiency was also calculated. Regulation characteristics of the overall efficiency are put together in Fig. 4.
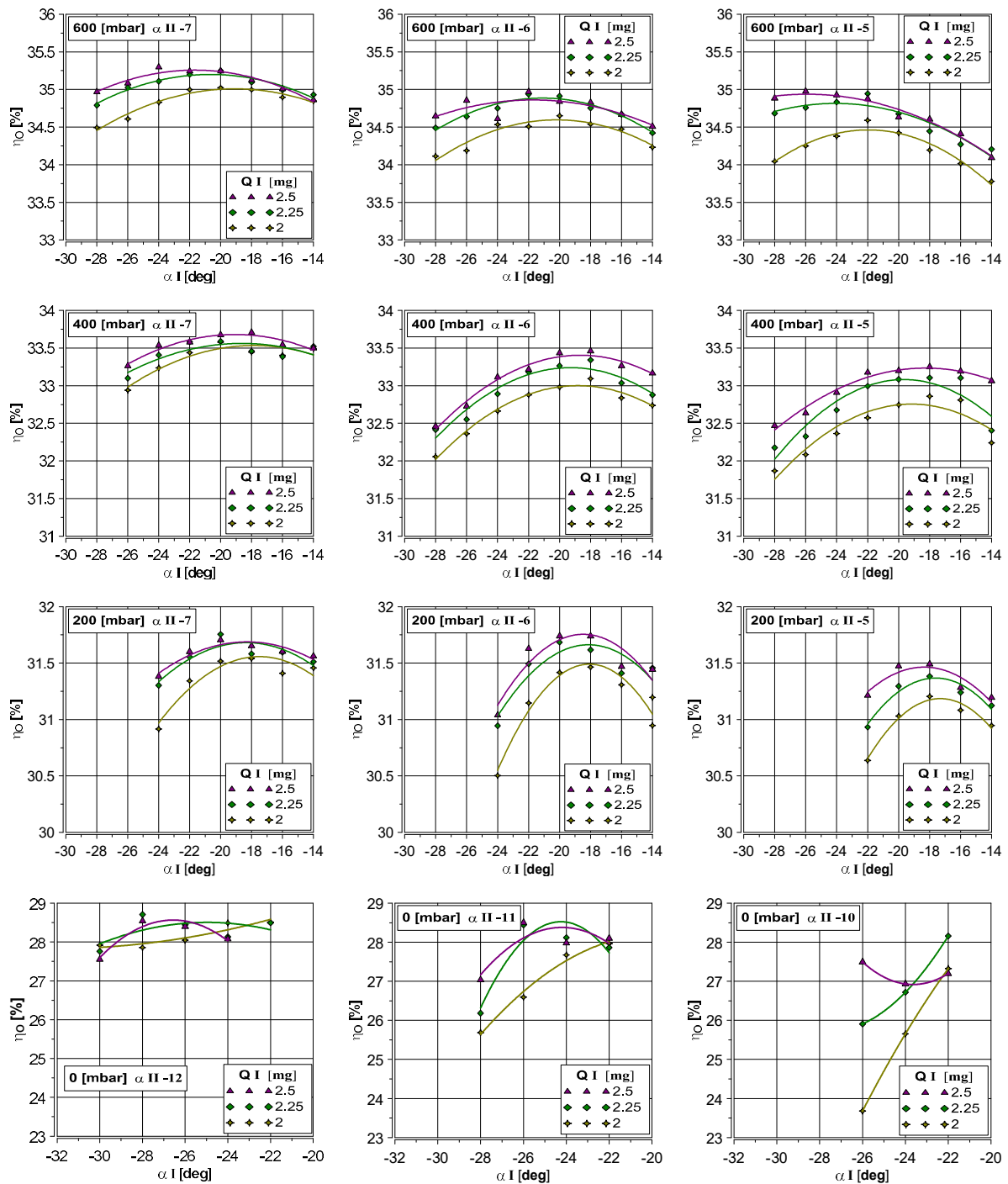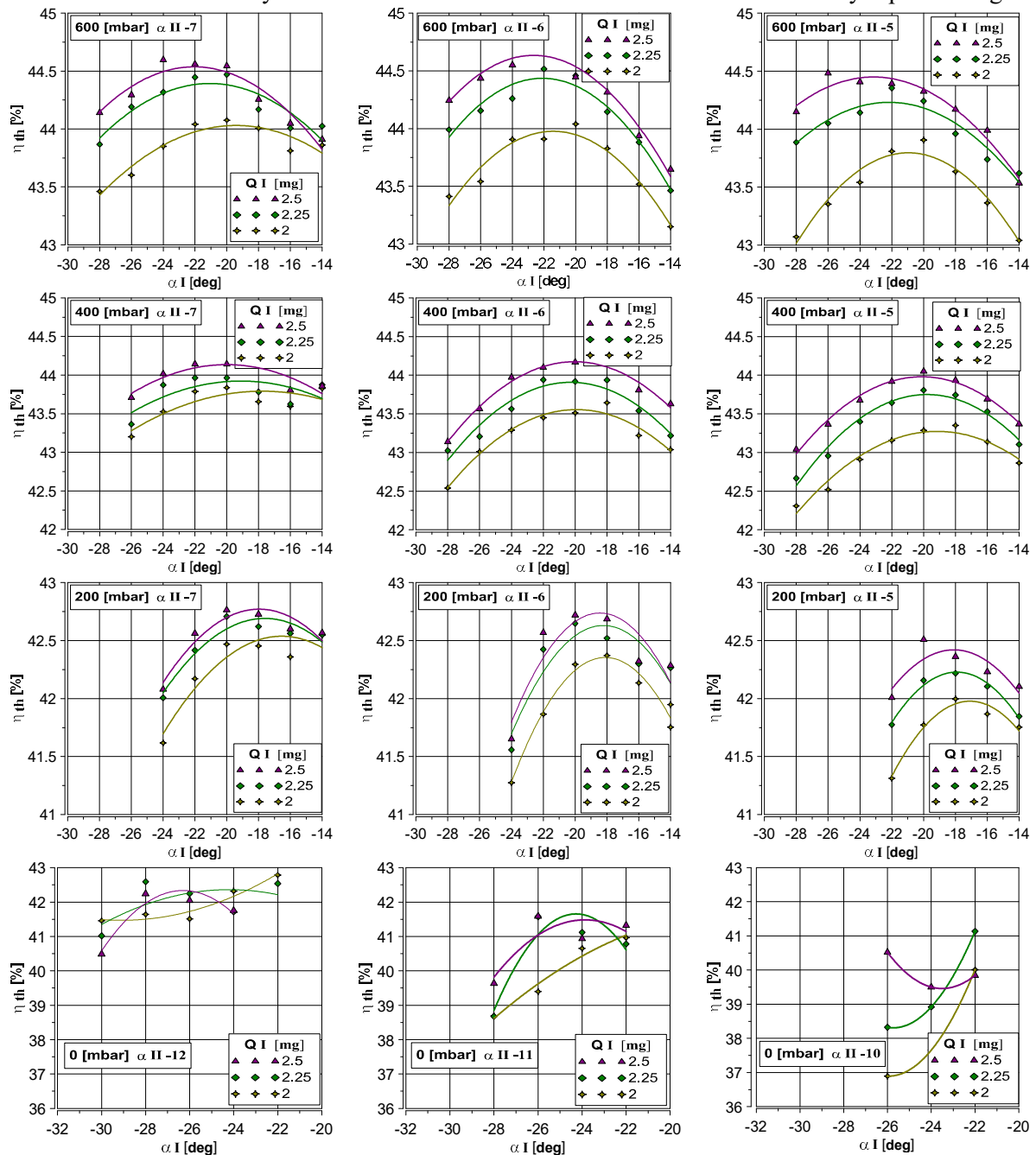
Figure 4. Regulation characteristics of the overall efficiency η$_O$ versus diesel fuel injection parameters

Analysis of the characteristics put together in Fig. 4. leads to the following conclusions:
- quantity of the pilot diesel fuel QI dose unequivocally affects the overall efficiency. For all boost pressure values, the overall efficiency of dual-fuel engine increases with this dose quantity,

- the QI dose injection timing also affects the overall efficiency of dual-fuel engine. In the turbocharged engine version one may observe maximum values of the overall efficiency at the QI dose injection timing from the range αI =18÷22° BTDC,
- the main diesel fuel dose injection timing, over the established adjustment range, slightly affects the overall efficiency. This influence is more visible in the case of the naturally aspirated engine.

Figure 5. Regulation characteristics of the thermal efficiency η_{th} versus diesel fuel injection parameters

A comparative analysis of characteristics presented in Figs. 4 and 5 indicates that the nature of the courses of overall and thermal efficiencies is very similar. Thus, one may conclude that changes in the overall efficiency result from changes in the thermal efficiency. To confirm this conclusion, the mechanical efficiency was calculated. Regulation characteristics of the mechanical efficiency are put together in Fig. 6.
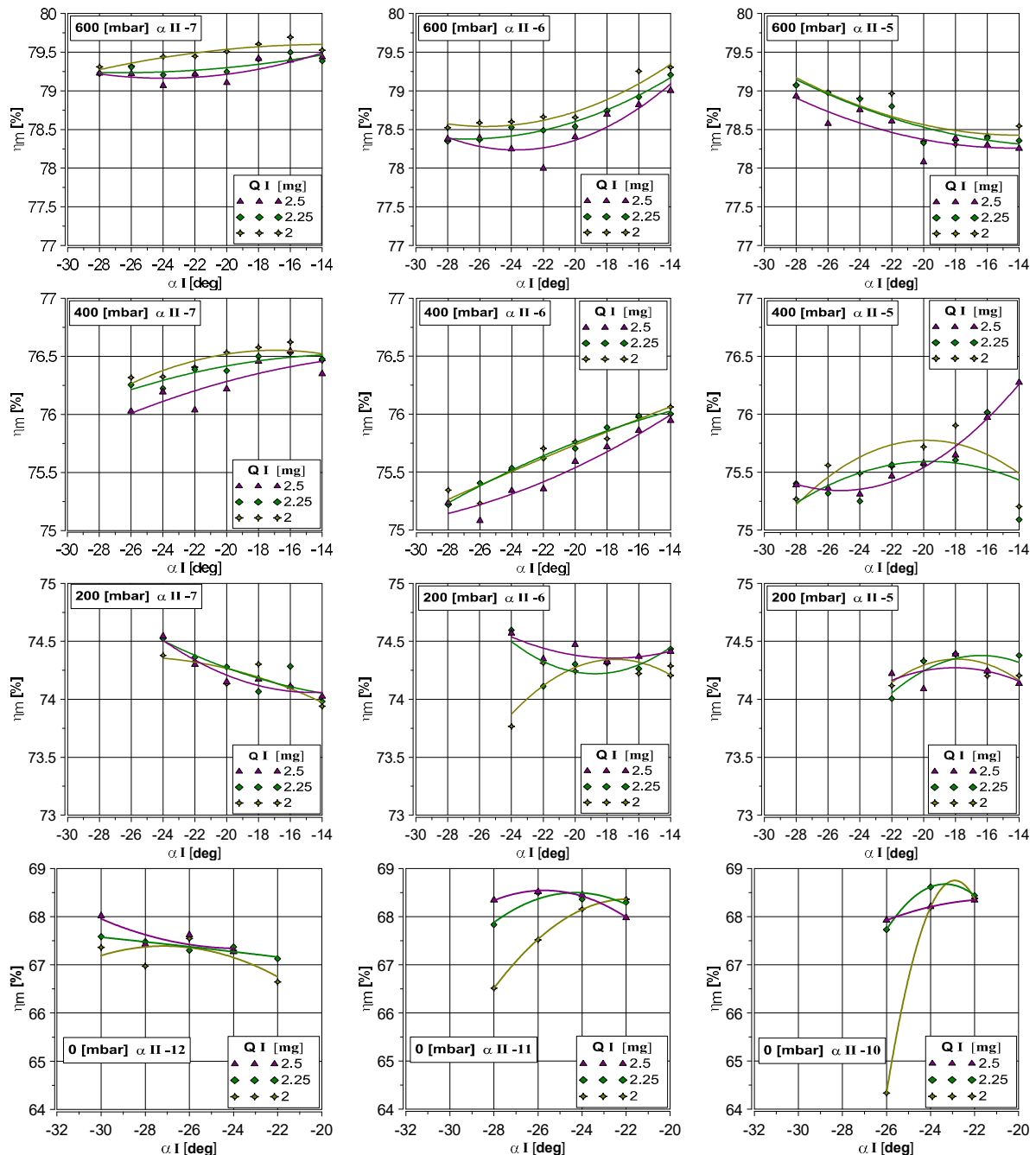
Figure 6. Regulation characteristics of the mechanical efficiency η_m versus diesel fuel injection parameters

Analysis of the presented characteristics demonstrates that the mechanical efficiency of dual-fuel engine for the established working conditions during investigations, slightly depends on the diesel fuel injection parameters in the case of the turbocharged engine version. A certain influence of the pilot dose QI quantity on the mechanical efficiency is observed in the case of the naturally aspirated engine version. In the last version, a proper selection of the injection timing is of essential importance.

Summarising this part of investigation, one may state that changes of the overall efficiency of dual-fuel engine result mainly from changes of the thermal efficiency because of slight changes of the mechanical efficiency.

Summary

- The reached brake mean effective pressure of a dual-fuel engine operating on propane depends on the quantity of the pre-injection diesel fuel dose (QI) that initiates ignition. The brake mean effective pressure increases with the QI quantity. This relationship is obligatory for all boost pressure values but also for the naturally aspirated engine version.
- The brake mean effective pressure depends also on the pilot diesel fuel dose (QI) injection timing. Maximum of the BMEP for the turbocharged engine is observed for the injection timing from the range 18÷22° BTDC.
- Analysis of the characteristics of brake and indicated mean effective pressures leads to the conclusion that a value of the reached brake mean effective pressure corresponds to a value of the indicated mean effective pressure.
- Value of the overall efficiency depends mainly on the value of the thermal efficiency of a dual-fuel engine. A nature of the courses of the overall efficiency clearly depends on thermal efficiency courses. The mechanical efficiency is marginally affected by diesel fuel injection parameters.

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