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RESEARCH ON THE EFFECT OF DIESEL FUEL INJECTION PARAMETERS ON THE COMBUSTION PROCESS IN THE TURBOCHARGED CI ENGINE OPERATING ON PROPANE

Tomasz Skrzek

University of Technology and Humanities
Malczewskiego Street 29, 26-600 Radom, Poland
tel.: +48 48 361 76 42, fax: +48 48 361 76 44
e-mail: t.skrzek@uthrad.pl

Abstract

Results presented in the article regard the research on a turbocharged dual-fuel CI engine operating on propane. The research indicated that such engine might operate even if 70% of the standard fuel energy is replaced by propane. The research indicated that at such high share of the gaseous fuel, there is necessary to adjust diesel fuel injection parameters but it is important that there is no need to change the engine structure. Injection parameters may be adjusted in a wide range due to the modern fuelling system of the common rail type. The investigated engine was equipped with such system. Adjustments regarding the fuel charge division, fuel charge quantities, and injection timing enabled to influence combustion in such way to obtain its specific parameters, i.e. maximum combustion pressure, rate of pressure rise, maximum pressure, and the burn out ratio similar to those obtained for diesel fuel operation. The obtained results were 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 investigations were carried out for three values of the boost pressure, i.e. 200; 400 and 600 [mbar] but also for the naturally aspirated version. 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 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 combustion at a high share of the gaseous fuel.

Keywords: *combustion engines, dual fuel, propane, control of injection parameters*

1. Introduction

A concept of CI engine operation in a dual-fuel mode seems to be still attractive, what may be confirmed by a great number of scientific articles published in scientific journals dedicated to engines [1-12]. Compared to conventional engine operation on diesel fuel, dual-fuel engines enable to obtain better results regarding both ecological and economic aspects.

However, to render this possible, it is necessary to know phenomena and relations that accompany such processes as cylinder filling, charge creation, release of energy in the compressed mixture and in the pilot diesel fuel charge. Investigation on dual fuelling carried out by many world scientific and academic centres as well as by the Author showed that the above-mentioned processes differ significantly from those observed in conventional engine operation. A concept of the carried out investigation consists in affecting the combustion process in such way to utilize energy of both fuels in the best possible mode preserving, at the same time, such combustion parameters that provide high engine durability and reliability. Moreover, a share of the conventional fuel should be as low as possible what comes out from the main concept of dual-fuelling [2, 9, 10].

Previous investigation carried out in the Department of Automobiles and Internal Combustion Engines concerned mainly the naturally aspirated operation. Considering the fact that turbocharging [1, 5, 7, 8] is a distinctive feature of contemporary engines, it was decided to carry out investigation over the range described with the title of this article.

To analyse more profoundly relationships described in this article, concerning the effect of diesel fuel injection parameters on basic operating parameters (break mean effective pressure, overall efficiency) it was also decided to analyse the nature of changes of basic combustion parameters.

Registered courses of combustion pressure versus crank angle enabled to calculate the relationship between start of combustion (SOC), maximum rate of pressure rise $(dp/d\alpha)_{max}$, crank angle for 50 percent of mass fraction burned (MBF_{50}), maximum combustion pressure (p_{max}) and the pilot diesel fuel injection parameters. It was recognized that these parameters affect the course of combustion pressure and in consequence the thermal efficiency and in result – overall efficiency as well as the break mean effective pressure. It was also recognized that a proper selection of pilot diesel fuel injection parameters, due to its effect on combustion parameters, would enable to obtain higher values of both the break mean effective pressure and the overall efficiency of a dual-fuel engine.

2. The investigation object and the applied measuring equipment

The investigations were carried out on an AVL test bed equipped with a single cylinder AVL 5402 compression ignition engine adapted to dual-fuel operation. Propane in the gas phase was delivered, via an injector placed in the intake manifold. Both, the injector position and injection parameters were chosen in such way to reduce maximally fuel losses during the valve overlap period. Injection parameters were established in previous investigation [10].

An overall scheme of dual fuelling system is presented in Fig. 1.

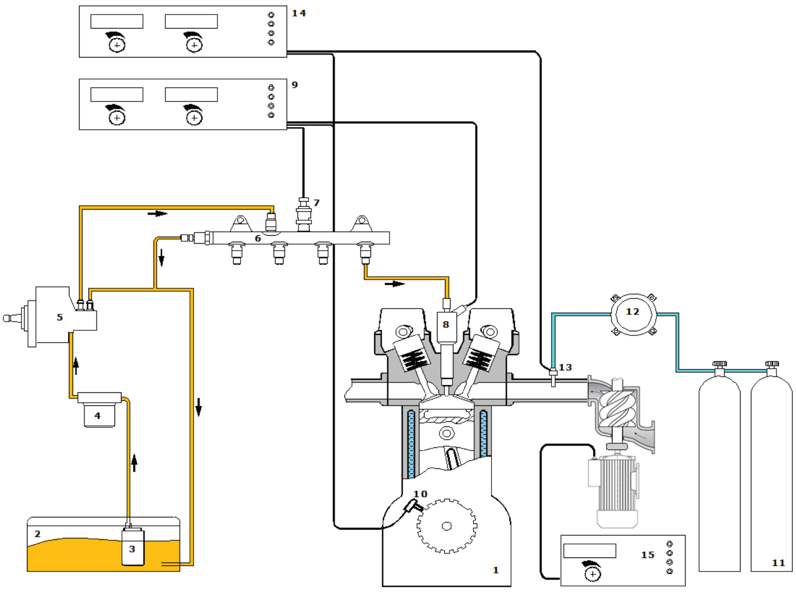

Fig. 1. Scheme of the dual fuelling system of the CI engine: 1 – dual-fuel engine, 2 – diesel fuel tank, 3 – low pressure fuel pump, 4 – fuel filter, 5 – high-pressure fuel pump, 6 – container, 7 – fuel pressure sensor, 8 – diesel fuel injector 9 – common rail controller, 10 – crankshaft position and speed sensor, 11 – gas tank, 12 – gas pressure redactor 13 – gas injector, 14 – gas supply controller, 15 – boost control system

Moreover, the test bed was equipped with the following measurement systems:
- electrorotational brake,
- indicating software (IndiCom),
- boost system (AVL boost – electric powered compressor),
- system for the exhaust gas analysis (SESAM and 60),
- system for the measurement of particulate matter mass concentration (Micro Soot Sensor),
- system for the measurement of hourly diesel consumption with temperature conditioning,

– system for the measurement of hourly propane consumption (mini CORI-FLOW).

An overall scheme of the test bed is presented in Fig. 2.

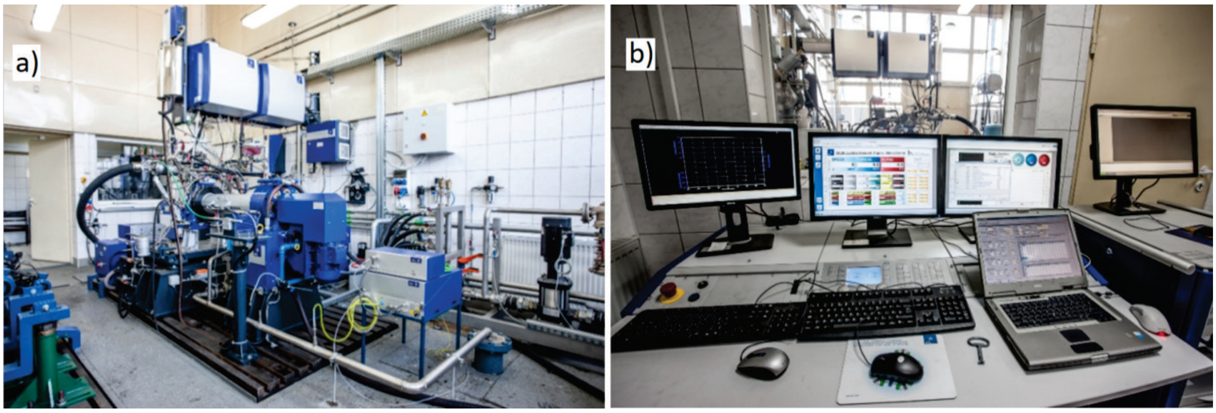

Fig. 2. AVL test bed: a) general view of the test bed, b) view of the control room

Fuel used for investigation was from the same batch what enabled to avoid false results arising from different physic-chemical properties of fuels taken from various batches.

3. Investigation programme – assumptions and range

It was decided to carry out the investigation in the following conditions:

- engine speed n = 2400 rpm,
- determine three values of the pilot diesel fuel dose: QI (2, 2.25, 2.5 mg),
- determine a broad range of injection timing changes of the pilot diesel fuel dose αI (14-30º BTDC),
- determine three values of the main diesel fuel dose α II (5º, 6º, 7º BTDC),
- determine three values of the boost pressure p (600, 400 and 200 mbar) and to investigate the naturally aspirated engine version (maximum applied boost pressure was limited by the maximum permissible combustion pressure; remaining parameters were determined arbitrarily),
- take assumption about a constant energy share of propane at the level of 70% of total energy delivered to the engine,
- determine a constant value of the air excess ratio for all measuring points of $\lambda = 1.3$,
- determine a constant energy quantity delivered with diesel fuel equal to 30% of total energy delivered to the engine (what means that variations of the pilot diesel quantity did not affect the total energy delivered with diesel fuel).

During the investigation, the combustion pressure versus crank angle was registered. Appropriate calculations enabled to determine the following values:

- angle of the start of combustion (SOC BTDC),
- maximum rate of pressure rise dP/dα (bar/deg) ,
- crank angle for 50 percent of mass fraction burned MBF_{50} (CA ATDC),
- maximum combustion pressure p_{max} versus the pilot dose injection timing α I for various dose quantities and for various injection timings of the main diesel fuel dose α II.

4. Investigation results

4.1. Maximum rate of pressure rise

As it was mentioned above, one of distinctive combustion features that clearly depend on the way of energy release is the maximum rate of pressure rise. This feature determines strategy of choice of diesel fuel injection parameters at dual-fuel operation and for that reason, results

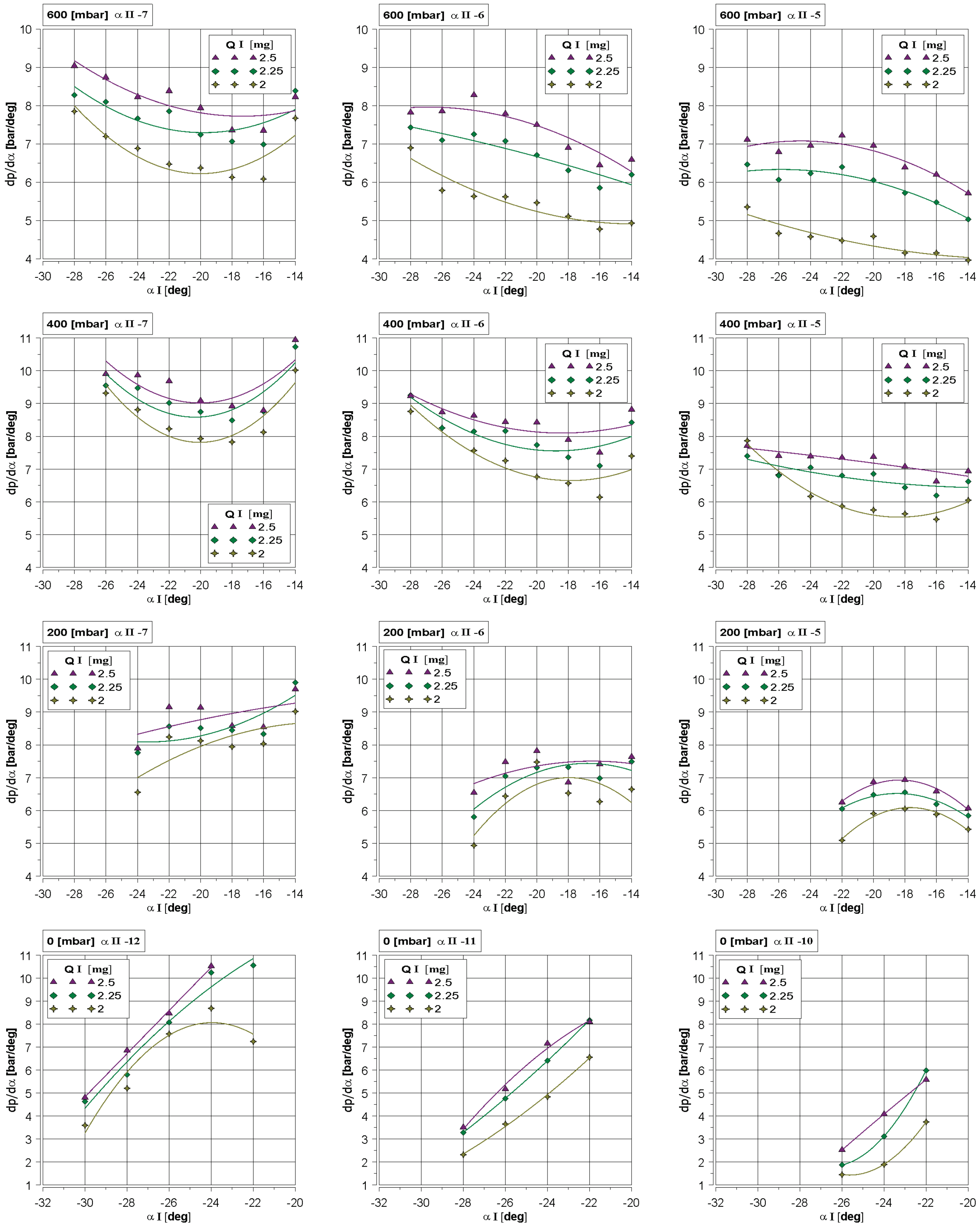

Fig. 3. Maximum rate of pressure rise $(dp/d\alpha)_{max}$ versus diesel fuel injection parameters

regarding the maximum rate of pressure rise will be discussed firstly. The rate clearly increases with the propane share what was showed in previous investigation [10]. Thus, it is a factor determining the maximum share of additional fuel. Usually, a maximum value of this factor at conventional engine operation does not exceed 1 MPa per C.A. and one of basic concepts in the investigation procedure of dual-fuel engines is not exceeding this value. As the investigation results indicate [10, 12], both injection timings of both diesel fuel doses and quantity of the pilot dose considerably determines the maximum rate of pressure rise. To reduce a value of this factor during dual-fuel operation a quantity of the pilot dose should be limited and injection timing of the main dose should be delayed. Delaying the injection timing of the pilot dose may also result in lowering of this factor. The limit is determined by the break-up time between the pilot and main doses. The break-up time decreases when the injection timing is delayed. Energy released from both fuels is concentrated near TDC what generates a visible increase of the maximum rate of pressure rise. When the break-up time is very short, the pilot fuel dose does not show any effect in order to limit the maximum rate of pressure rise. Thus, it is advantageous to inject the pilot dose at the moment when the temperature is high enough to initiate combustion and at the same time when the break-up time before the main dose injection is long enough to result in the stepwise energy release. This means that the energy released through the pilot dose should have a precisely described starting time and quantity. It should be stressed that the energy release caused by the pilot dose depends also on the content of the additional fuel in the compressed mixture. In the discussed case when the energy share of propane was equal to 70% of total energy delivered to the engine, the gas – air mixture was beyond flammability limits. Thus, in effect of the pilot dose delivery only a part of propane included in the fuel spray area will be combusted. The remaining part of energy will be released at the moment of the main diesel fuel dose injection. This dose injected into the area with higher temperature starts to combust almost immediately. A nature of that phenomenon may slightly differ in turbocharged and naturally aspirated engines. In the turbocharged engine (mainly 600, 400 mbar) there is observed a downward trend of the maximum rate of pressure rise with a delay the of the pilot dose injection timing. In the naturally aspirated engine, this phenomenon has different character. The maximum rate of pressure rise has the lowest values when the pilot dose injection timing is the earliest. The pilot dose does not initiate combustion. Thus, it does not affect thermodynamic parameters. Combustion initiated by the main dose starts very late, near TDC (Fig. 4) and the maximum pressure rise occurs during the compression stroke, C.A. 20º ATDC.

Taking into consideration the overall efficiency, such way of affecting combustion is advantageous. The pilot dose injected a few crank angles later contributes to rapid increase of the maximum rate of pressure rise. In-cylinder pressure variations resulting from the pilot dose injection timing changes are not noticeable between pilot and main doses injections but they visibly affect combustion initiated by the main dose. This means that the pilot dose injected a few crank angles later strongly affects thermodynamic parameters what results in shorter auto-ignition delay time of the main dose. Thus, delayed injection of the pilot dose within the range from 30º to 22º BTDC results in a visible increase of the maximum rate of pressure rise. This parameter may be lowered by delaying the main dose injection what, unfortunately, leads to decrease of thermal efficiency and, in consequence, the overall efficiency.

4.2. Start of combustion

Analysing an effect of diesel fuel injection parameters on combustion in a dual-fuel engine it is worth to trace such typical parameter as the start of combustion because it depends on the pilot dose quantity, its injection timing and the boost pressure. Moreover, it depends also on thermodynamic properties of the medium in which combustion is initiated.

Analysis of characteristics put together in Fig. 4 leads to the conclusion that an increase of the pilot dose quantity causes an earlier start of combustion for each boost pressure value but also in the case of naturally aspirated engine operation. This means that the QI fuel dose starts burning and, in consequence, the QII fuel dose is being injected into the medium that has higher temperature. In the case of the highest boost pressure and early injection timings of the pilot fuel dose, an injection of the main dose occurs when combustion takes place. Thus, the main dose ignites immediately, without the self-ignition delay time. When the boost pressure decreases, the

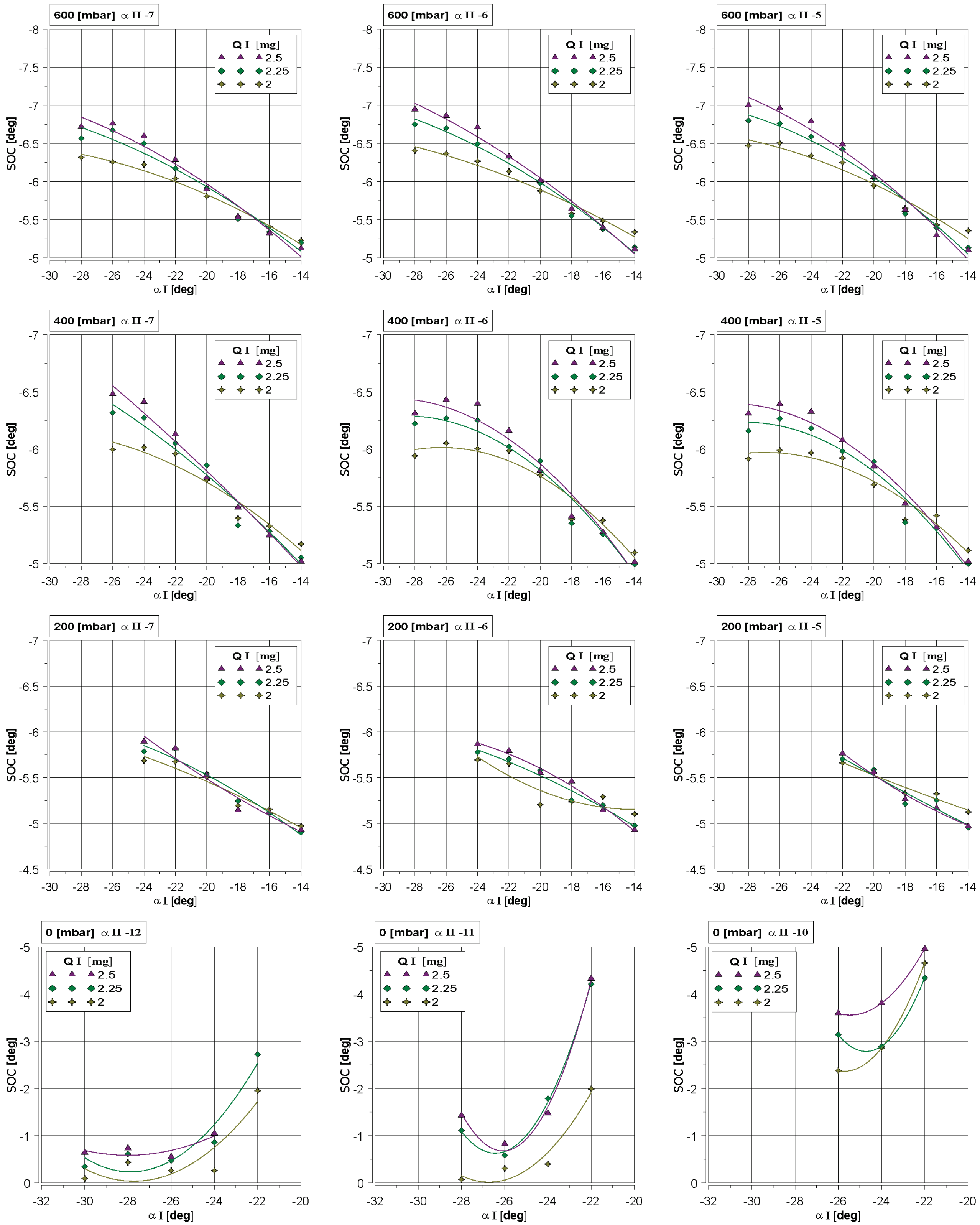

Fig. 4. Start of combustion (SOC) versus diesel fuel injection parameters

main fuel dose self-ignition delay time increases and combustion shifts towards the expansion stroke. For the turbocharged engine, a relationship between the pilot fuel dose injection timing, over the investigated range, and the start of combustion is obvious. Slightly different character of this phenomenon is observed for naturally aspirated engine operation. The earliest recorded start of combustion occurs when the injection timing of the QI dose is equal to 22º BTDC. Further decrease of the crank angle delays this process. This means that the effect of the pilot dose attenuates. It happens this way because temperature of the medium into which the pilot dose is being injected is too low to initiate combustion. This effect is more visible for a dual-fuel engine because specific heat of the compressed medium increases with the quantity of gaseous fuel delivered during the intake stroke what results in temperature decrease of the compressed mixture.

4.3. Burn out ratio

Analysis of the crank angle for 50 percent of mass fraction burned (MBF_{50}) is a very important issue. Previous investigation carried out by the Author and other researchers [3, 4, 6] indicate that value of this parameter significantly affects the engine overall efficiency. This angle, corresponding to the maximum intensity of heat release, determines the indicated work per cycle, thus the thermal efficiency and in consequence the overall engine efficiency. Previous investigation indicates that, concerning possibility to reach high overall efficiency, MBF50 should be C.A. 10º ATDC [10]. The discussed characteristics are put together in Fig. 5.

Analysis of the above presented results shows that an increase of the QI pilot dose quantity is accompanied by shorter burn out period of 50% fuel. This tendency concerns both turbocharged and naturally aspirated engines. This is a result of release of great portion of energy, which is a sum of energy derived from diesel fuel delivered in QI dose and energy derived from a share of propane, which will be combusted in result of QI dose injection. Therefore, release of high portion of energy before the TDC will result in shortening of the burn out time.

It is obvious that this parameter depends on the QII dose injection timing and the boost pressure. The discussed runs have minimum MBF_{50} value for the turbocharged engine version. Advantageous value of this parameter (CA 10º ATDC), concerning possibility to reach high overall efficiency, at the QI dose injection timing equal to C.A. 20-22º is possible to reach at the boost pressure 600 and 400 mbar as well as – bigger quantities of the dose QI = 2.5 mg. For lower boost pressures, MBF_{50} shifts towards the crankshaft position 13-14º ATDC while in the case of naturally aspirated operation it strongly depends on the QII dose injection timing. Therefore, selection of such important combustion parameter as 50% of mass fraction burned clearly depends on pilot diesel dose injection parameters. However, it should be noticed that even if it is possible to influence the combustion process controlling diesel fuel injection parameters to obtain advantageous regarding the thermal and in consequence overall engine efficiency MBF_{50} value, this may not be possible due to an excess of the maximum rate of pressure rise.

4.4. Combustion pressure courses

During investigation, at each measuring point determined by the boost pressure, the pilot diesel fuel injection timing α I and the main diesel fuel injection timing α II, there were registered cylinder pressure courses versus the crankshaft angle. Fig. 6 presents cylinder pressure courses for three boost pressure values and for naturally aspirated engine operation.

Among the registered 243 cylinder pressure courses there were chosen 12. There were presented only those courses for which the engine overall efficiency was high. Courses for the turbocharged engine were registered for the following diesel fuel injection parameters: the pilot dose injection timing α I 22º and the main dose injection timing αII 7º BTDC. For naturally aspirated engine operation, these parameters were equal to 28º and 12º BTDC respectively.

Analysis of the results presented in Fig. 6 reveals that for constant injection timings of both diesel fuel doses, despite their constant total energy content, increase of the QI energy results in a visible combustion pressure increase. Increase of the boost pressure results in shortening of the auto ignition delay time leading to an earlier start of combustion. This results in clearly visible changes in cylinder pressure courses. Therefore, it affects the indicated work area, the break mean effective pressure and the overall engine efficiency. This is an expected effect because an increase of the pilot dose quantity as well as an increase of the boost pressure results in an increase of the medium temperature during the pilot dose injection. This favours shortening of the auto ignition delay time as well as proper and faster combustion of the pilot dose. For better understanding of the combustion process in a turbocharged compression ignition dual-fuel engine operating on propane, there were prepared another characteristics regarding maximum combustion pressure.

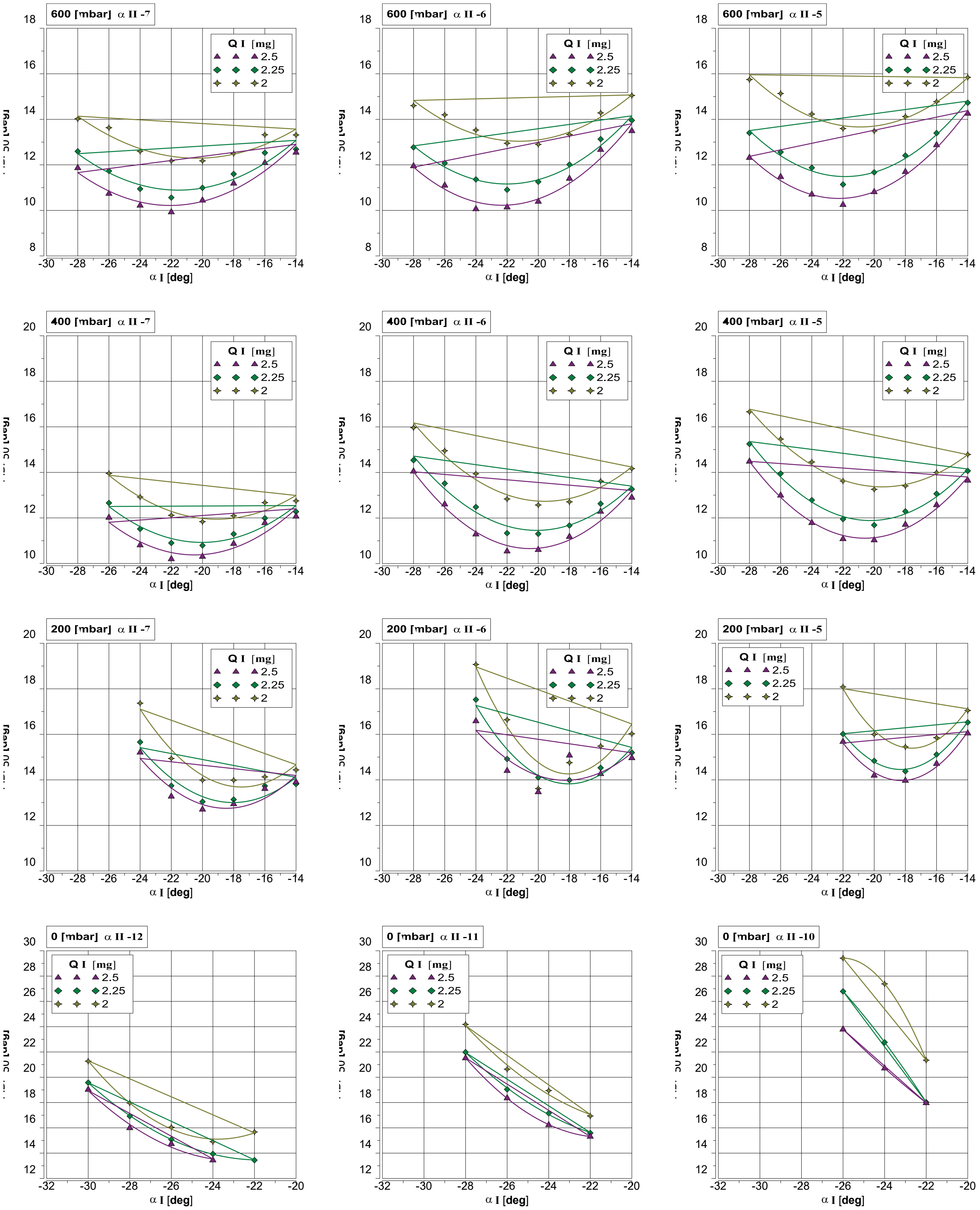

Fig. 5. Crank angle for 50 percent of mass fraction burned (MBF_{50}) versus diesel fuel injection parameters

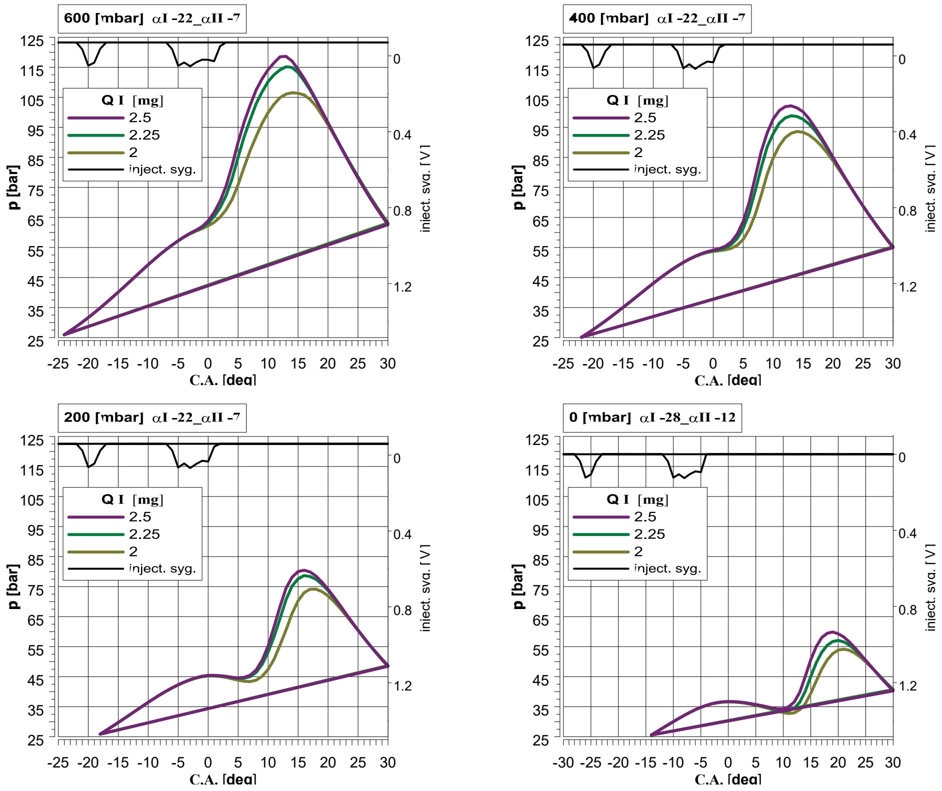

Fig. 6. Registered cylinder pressure courses for three pilot diesel fuel dose values QI (2, 2.25, 2.5 mg) and for four boost pressure values (600, 400, 200 and 0 mbar)

The results presented below were selected from among those in which there was obtained high engine overall efficiency, similarly as presented in Fig. 6.

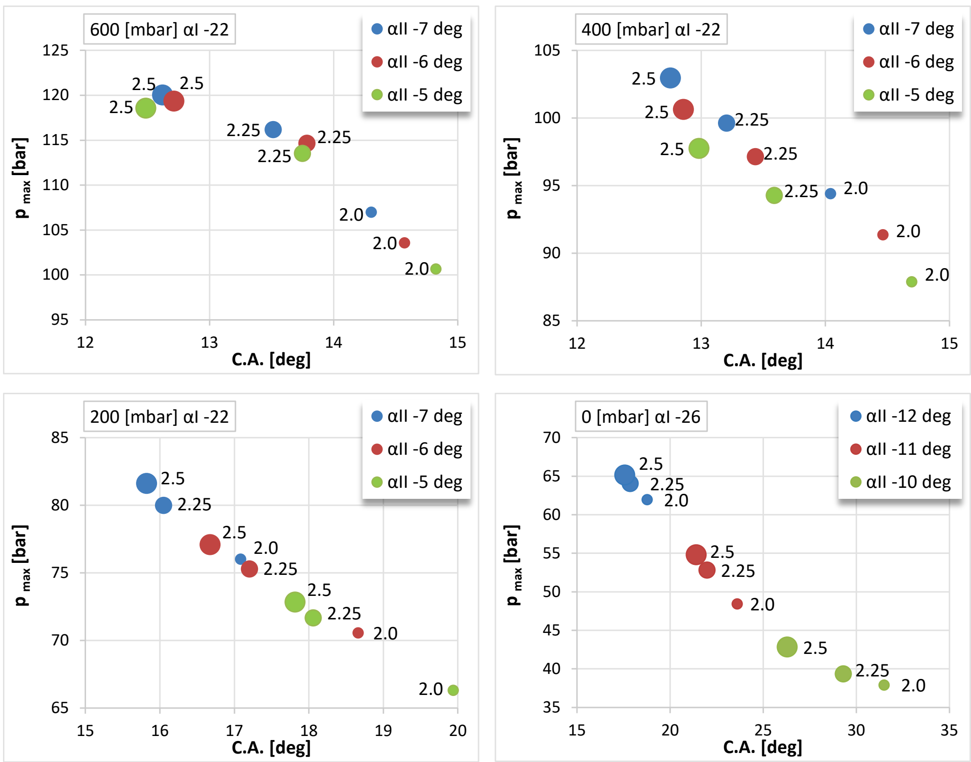

Fig. 7. Maximum combustion pressure for three pilot diesel fuel dose values QI (2, 2.25, 2.5 mg) and for four-boost pressure values (600, 400, 200 and 0 mbar)

They allow to state quite unequivocally that, in a dual-fuel engine, slight change of the QI dose quantity affects very clearly both position and value of maximum combustion pressure. The most visible difference concerns the engine turbocharged to the highest pressure (600 mbar). The greatest QI dose (2.5 mg) injected at 22º BTDC, when the QII dose was injected at 7º BTDC, enabled to obtain the highest combustion pressure at the level of 12 MPa. Reduction of the QI dose by only 0.5 mg resulted in decrease of the combustion pressure by C.A. 1.3 MPa. Change of the QI dose quantity resulted also in a peak pressure shift by C.A. 2º to later values. This means that the pilot dose quantity, particularly in a dual-fuel engine, has an essential influence on a number of parameters describing combustion. Explanation of such clear changes, that occur during combustion in effect of the pilot dose quantity changes, is the same as that presented in the section IV.1.

5. Summary

As it results from the present and previous investigations on dual-fuel engine operation, there are objective benefits resulting from an introduction of additional energy source such as propane or propane-butane mixture in the CI engine. The main benefit would be reduction of operating costs what gives the incentive to develop such idea. Because increase of additional fuel share results in better economy, it seems that limitation of the standard fuel will be a natural trend. This is associated with significant changes of the combustion process, which may be controlled, to a large extent, by adjustment of diesel fuel injection parameters. To obtain the expected effect via an adjustment of diesel fuel injection parameters (i.e. fuel dose division, pilot and main dose quantities and their injection timings) it is necessary to correlate them with a number of factors, such as share of the additional fuel, boost pressure, engine load and speed). This requires registration of a number of adjustment characteristics at such engine operation, taking into account the above-mentioned parameters. Obtained results indicate that there is a need of compromise when selecting the criterion of the change of injection parameters. Injection parameters advantageous for maximum thermal efficiency differ from those advantageous, for instance, for the lowest exhaust emission. However, capabilities of contemporary fuelling systems of the common rail type and possibility to affect a number of adjustment engine parameters allows to hope that there is a chance to limit effectively the unfavourable effects resulting from dual-fuel operation.

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