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ATTEMPT TO COMPARE BASIC COMBUSTION PARAMETERS OF A DUAL-FUEL COMPRESSION IGNITION ENGINE FOR VARIOUS MAIN FUELS AND THEIR DELIVERY MODES

PRÓBA PORÓWNANIA PARAMETRÓW SPALANIA ZASADNICZEGO DWUPALIWOWEGO SILNIKA WYSOKOPRĘŻNEGO DLA RÓŻNYCH PALIW GŁÓWNYCH I SPOSOBÓW ICH ZASILANIA

A b s t r a c t

The paper presents results of investigation on a dual-fuel engine fuelled with various fuels (methanol, propane-butane mixture). In all cases, ignition of the main fuel was initiated by a diesel oil pilot dose injected into the combustion chamber. Engine power was controlled by changes of the main fuel charge (methanol or LPG). The paper presents comparison of engine performances, efficiency and variability of basic combustion parameters with reference to a standard engine fuelled with diesel oil only.

Keywords: *dual-fuel engine*, *LPG*, *methanol*, *exhaust emission*, *pilot dose*

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań dwupaliwowego silnika o zapłonie samoczynnym zasilanego różnymi paliwami (metanolem, propanem-butanem). W każdym przypadku zapłon paliwa głównego inicjowany był dawką oleju wtryskiwaną do komory spalania. Regulacja mocy silnika odbywała się poprzez zmianę wydatku paliwa w fazie gazowej (metanolu lub LPG). W artykule przedstawiono porównanie osiągów, sprawności oraz zmiany podstawowych parametrów procesu spalania w odniesieniu do silnika zasilanego standardowo tylko olejem napędowym.

Słowa kluczowe: *silnik dwupaliwowy*, *LPG*, *metanol*, *emisja spalin*

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1. Introduction

Nowadays, compression ignition engine becomes the main power source of automotive vehicles due to its economic (high overall efficiency) and ecological (lower harmful emission) advantages. It is used in almost all buses and trucks and is more and more popular in passenger cars.

In view of global crude oil shortage [1] and environmental regulations, the fuelling system of compression ignition engine undergoes various modifications in order to enable combustion of non-standard fuels. It can be observed an increased interest in dual-fuel technology where diesel oil dose is utilised only to ignite the main fuel that usually has low cetane number [2–8]. The overall scheme illustrating such fuelling system is presented in Fig. 1.

The most important concern regarding dual-fuel technology is a proper selection of diesel oil pilot dose quantity and its injection timing because both these values essentially influence engine performances, overall efficiency and emission levels. In most cases, engine power is controlled by changes of the main fuel charge what changes the composition of air-fuel mixture with engine load changes.

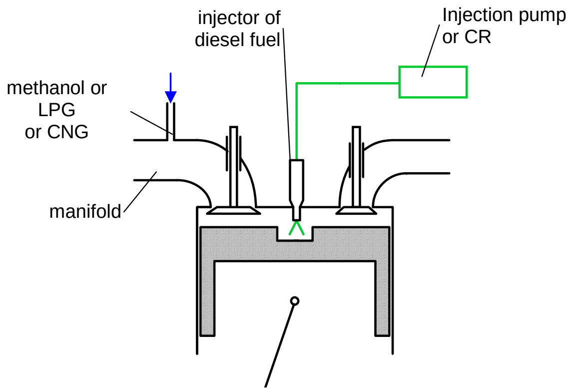

Fig. 1. Overall scheme of dual fuelling of a compression ignition engine where the main fuel is methanol or LPG

Rys. 1. Ogólny schemat dwupaliwowego systemu zasilania silnika o zapłonie samoczynnym, w którym głównymi paliwami są metanol lub LPG

It seems that the following favourable effects speak for the choice of such idea:

- possibility to achieve performances comparable with the standard engine (conventionally fuelled with diesel oil). Such thesis seems to be confirmed by comparable heating values of diesel oil – air stoichiometric mixture and stoichiometric mixtures of such fuels as: methanol, LPG or natural gas which can be considered as main fuels in the proposed fuelling system [5, 9, 11],
- possibility to achieve an increase in overall efficiency of a dual-fuel engine. In such engine, short-time combustion is possible at the most advantageous crankshaft position what enables achievement of possibly high indicated work of the cycle. It should be stressed that such combustion system is close to the intensively researched nowadays HCCI (homogeneous-charge compression ignition) system,

- certainty of precise control of the pilot fuel injection timing,
- easiness of the engine start-up because the engine can be started using diesel oil only,
- possibility to reduce harmful emissions because the main fuel (natural gas, LPG in the gaseous phase or methanol vapour) is very good mixed with air, during the intake and compression strokes, forming homogeneous air – fuel mixture that is advantageous from the point of view of exhaust gas composition,
- slight modification of the engine consisting in addition of a system enabling the main fuel delivery into the intake manifold, without basic design changes.

However, some disadvantages exist regarding dual-fuelling of a compression ignition engine. They are as follows:

- possibility that uncontrolled ignitions of the main fuel – air mixture occur at the end of the compression stroke, especially at higher engine loads, when the mixture being compressed becomes more rich. A way to eliminate this phenomenon is decreasing the main fuel share (leaning the main fuel – air mixture),
- possibility of knocking combustion of the main fuel – air mixture, beyond the zone of diesel oil dose combustion, resulting from rapid pressure increase after combustion start of the pilot dose and a part of the main fuel – air mixture that is comprised by the pilot dose. A way to prevent occurrence of this phenomenon is its detection with the use of a knock sensor and delaying injection of the pilot fuel.

Investigation on the above described dual-fuel compression ignition engine was carried out for many years in the Department of Internal Combustion Engines and Automobiles in Radom Technical University. During this investigation, various main fuels were applied. In all cases, ignition was initiated by a diesel oil pilot dose.

The present paper makes an attempt to compare and generalise results regarding engine performances, efficiency, harmful exhaust emissions and combustion variability for various main fuels and their various delivery modes into the intake manifold.

Results of investigation on the following fuelling modes of a dual-fuel compression ignition engine were compared:

a) fuelling with evaporated methanol using a mixer in the intake manifold (diesel oil injection realised with the use of classic in-line injection pump),
b) fuelling with evaporated LPG fuel using a mixer in the intake manifold (diesel oil injection realised with the use of classic in-line injection pump),
c) injection fuelling with LPG fuel in the liquid phase with an injector placed in the intake manifold (diesel oil injection realised with the use of classic in-line injection pump).

In all the above described cases, investigation was carried out using a stationary one--cylinder 1HC102 compression ignition engine. Details of this investigation are presented in monographs [9, 11, 12].

2. Results of investigation on the dual-fuel engine overall efficiency

During the investigation, load characteristics were obtained. The results are presented in form of specific energy consumption characteristics due to different heating values of the applied fuels.

Figure 2 presents characteristics obtained at similar engine speed for all investigated engine versions. These characteristics were obtained for properly chosen values of injection timing of the diesel oil pilot dose and its quantity from the point of view of engine performances, overall efficiency and harmful exhaust emissions. It should be added that the described operational engine parameters were individually chosen for the applied fuels and fuelling systems (the above described modes: a), b) and c)).

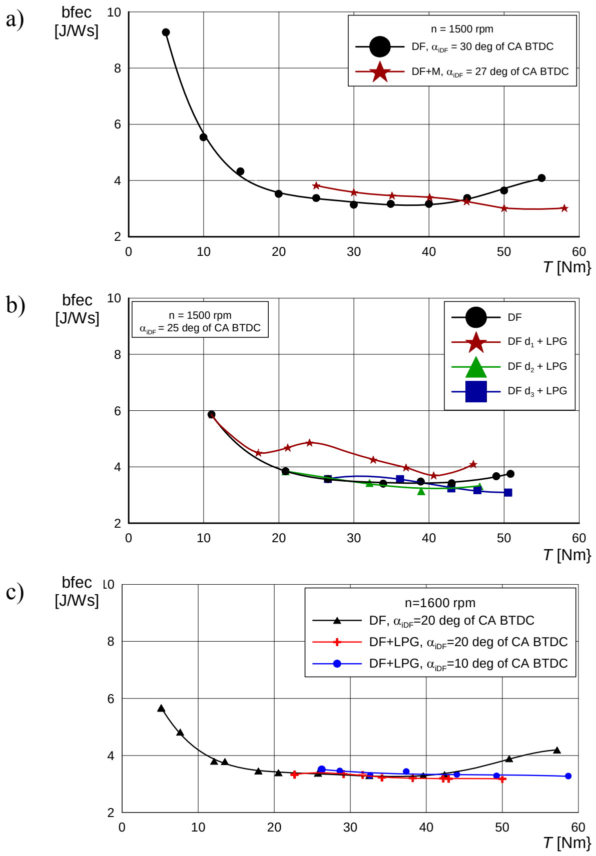

Fig. 2. Comparison of load characteristics of specific energy consumption for fuelling modes: a), b), and c) (described in chapter 1)
Rys. 2. Porównanie charakterystyk obciążeniowych jednostkowego zużycia energii dla przypadków a), b), c) (opis jak w rozdz. 1)

Careful analysis of characteristics presented in Fig. 2 leads to the following remarks:

- In all the above described fuelling modes (a), b) and c) – chapter 1) it is possible to achieve maximum torque values comparable or higher than those achieved by the standard engine fuelled with diesel oil only. These values clearly depend on injection timing of the diesel oil pilot dose and its quantity. Their proper settings depend on the applied fuelling system and the main fuel type.
- All dual-fuel engine versions may be characterised by increased overall efficiency (decreased specific fuel consumption) in the range of full loads (at significant share of

the main fuel). Possibility to achieve an improvement of the engine overall efficiency depends also on the established pilot dose injection timing and its quantity.

– For all dual-fuel engine versions exists possibility to establish such injection timing of the pilot dose and its quantity to achieve an improvement of both the maximum engine torque and overall efficiency compared to the standard version.

3. Results of investigation on exhaust gas composition

During preparation of load characteristics of specific energy consumption, measurements of exhaust emissions (CO, HC and NO_x) and smoke level were carried out. The established injection timing of the pilot dose and its quantity were the same as in the case of preparation of specific energy consumption characteristics.

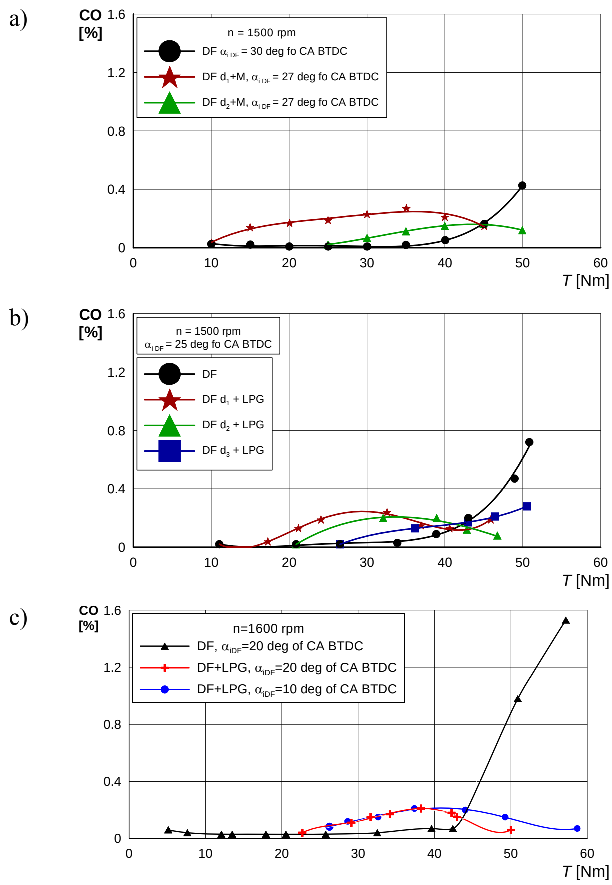

Fig. 3. Comparison of CO emissions for fuelling modes: a), b) and c) (described in chapter 1)

Rys. 3. Porównanie zawartości CO w spalinach dla przypadków a), b), c) (opis jak w rozdz. 1)

3.1. Comparison of CO emissions for investigated versions of the fuelling system

Analysis of the characteristics presented in Fig. 3 indicates that, in all of the investigated fuelling modes, concentration of CO in exhaust gas increases over the range of partial loads and decreases over the range of loads close to maximum, compared to the standard version of fuelling. It should be added that CO concentration in exhaust gas of the dual-fuel engine clearly also depends on the pilot dose quantity and its established injection timing.

3.2. Comparison of HC emissions for investigated versions of the fuelling system

Figure 4 presents HC emissions versus engine load for investigated versions of the fuelling system.

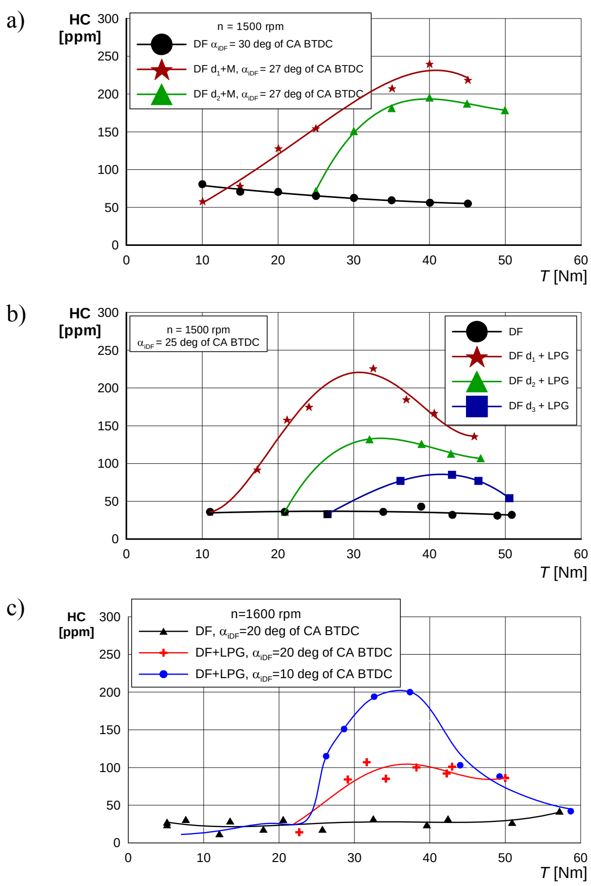

Fig. 4. Comparison of HC emissions for fuelling modes: a), b) and c)
(described in chapter 1)
Rys. 4. Porównanie zawartości HC w spalinach dla przypadków a), b), c)
(opis jak w rozdz. 1)

Analysis of the characteristics presented in Fig. 4 indicates that, in all of the investigated fuelling modes, concentration of HC in exhaust gas is higher for dual-fuel engine than for the standard engine fuelled with diesel oil only. At the same time, HC emission decreases and approaches the level as in the case of standard fuelling, with increase of engine load close to maximum values. It should also be noticed strong relationship between HC emission and the pilot dose quantity and its injection timing.

3.3. Comparison of NO_x emissions for investigated versions of the fuelling system

NO_x emissions versus engine load are presented in Fig. 5.

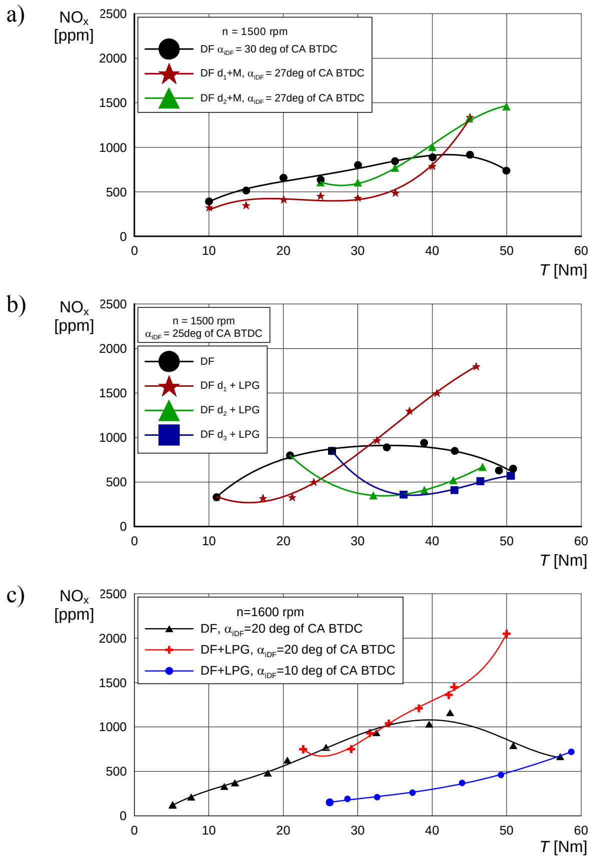

Fig. 5. Comparison of NO_x emissions for fuelling modes: a), b) and c)
(described in chapter 1)
Rys. 5. Porównanie zawartości NO_x w spalinach dla przypadków a), b), c)
(opis jak w rozdz. 1)

Analysis of the characteristics presented in Fig. 5 indicates that, over the range of partial loads, NO_x emission is lower for dual-fuel engine than for the standard version and increases with the engine load. Comparing these characteristics with the ones of the standard engine fuelled with diesel oil only, one can see that for most injection timings of pilot fuel and pilot fuel quantities, NO_x concentration in exhaust gas of the dual-fuel engine is lower over the range of partial loads and increases over the range of loads close to maximum. It should be added that NO_x emission of the dual-fuel engine strongly depends on the pilot dose quantity and its injection timing.

3.4. Comparison of smoke level for investigated versions of the fuelling system

The obtained smoke level characteristics are presented in Fig. 6.

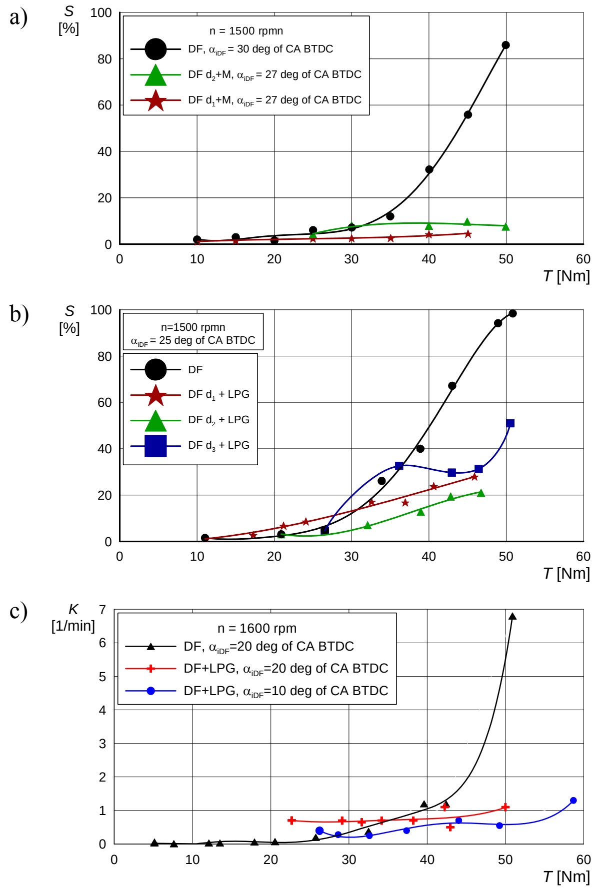

Fig. 6. Comparison of smoke level characteristics for fuelling modes: a), b) and c) (described in chapter 1)

Rys. 6. Porównanie charakterystyki zadymienia spalin dla przypadków a), b), c) (opis jak w rozdz. 1).

All characteristics presented in Fig. 6 indicate that over the range of low loads, smoke level in exhaust gas of the dual-fuel engine is comparable with that of the standard engine. In case of dual fuelling, significant smoke level decrease can be observed as the engine load approaches values close to maximum.

4. Analysis of basic combustion process parameters

Considering possibility that certain described earlier undesirable combustion related phenomena (uncontrolled ignitions of the compressed main fuel – air mixture and knocking combustion of this mixture) may occur in a dual-fuel engine, analysis of variability of two

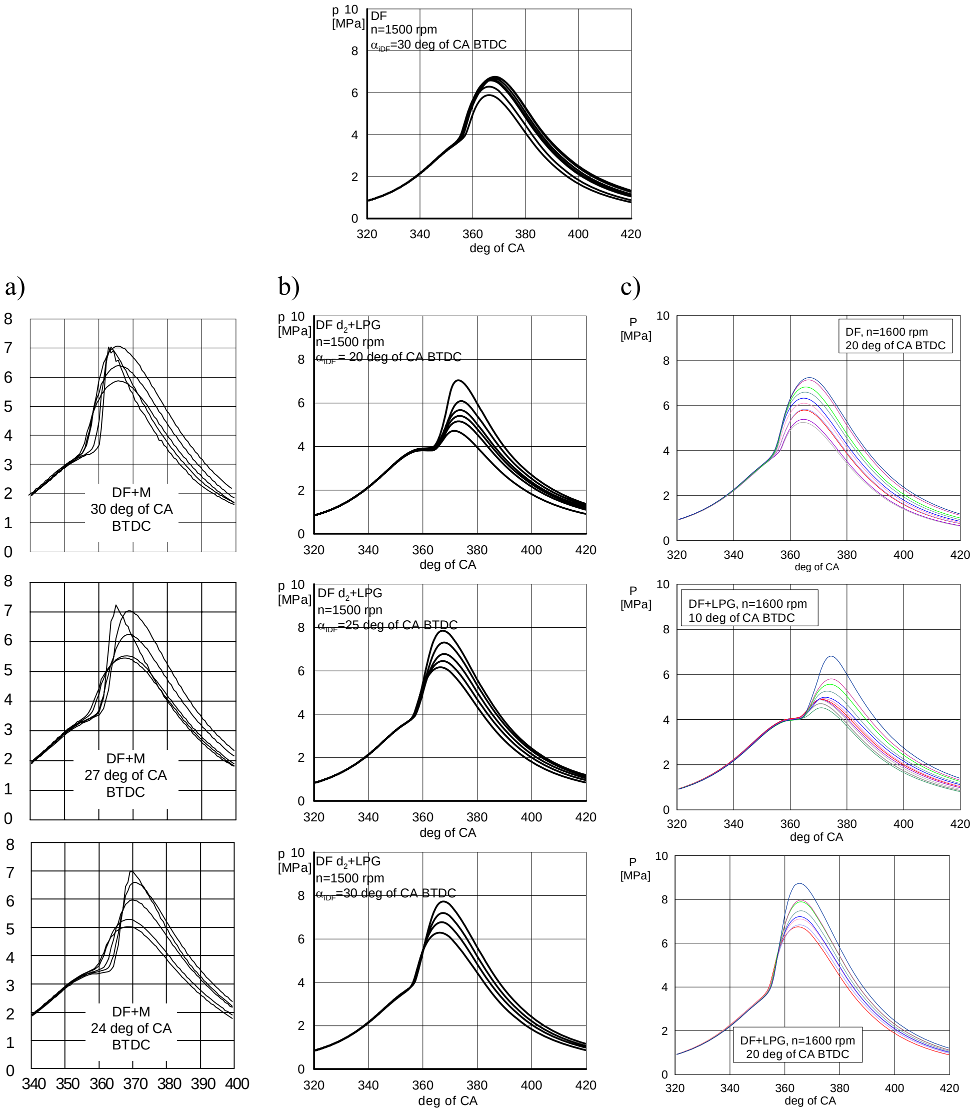

Fig. 7. Combustion pressure versus crankshaft angle $P = f(\alpha)$ for the standard fuelling (with diesel oil only) and for fuelling modes: a), b) and c) (described in chapter 1)
Rys. 7. Przebiegi ciśnienia spalania w funkcji kąta obrotu wału korbowego $P = f(\alpha)$ dla silnika zasilanego standardowo olejem napędowym oraz dla opisanych przypadków zasilania a), b), c) (opis jak w rozdz. 1).

basic combustion process parameters that induce such phenomena was carried out. Thus, variability of maximum combustion pressure and average rate of pressure rise was analysed. To this end, combustion pressure characteristics, averaged from 100 succeeding cycles, versus crankshaft angle, for various loads were prepared. The runs are presented in Fig. 7.

Preliminary visual analysis of the presented characteristics indicates that pressure runs in the dual-fuel engine differ distinctly from those in the standard engine. In the case of dual fuelling, higher maximum combustion pressures can be observed. Their values strongly depend on the established pilot dose injection timing and its quantity. To carry out necessary comparisons, graphs presented in Fig. 7 underwent analysis which enabled preparation of variability characteristics of maximum pressure P_{max} and average rate of pressure rise $(\Delta P/\Delta\alpha)_{av}$ versus engine load M.

4.1. Variability characteristics of maximum combustion pressure $P_{max} = f(M)$

As it was mentioned earlier, the carried out combustion pressure measurements enabled to determine maximum combustion pressures and obtain their variability characteristics versus engine load.

a)
b)
c)

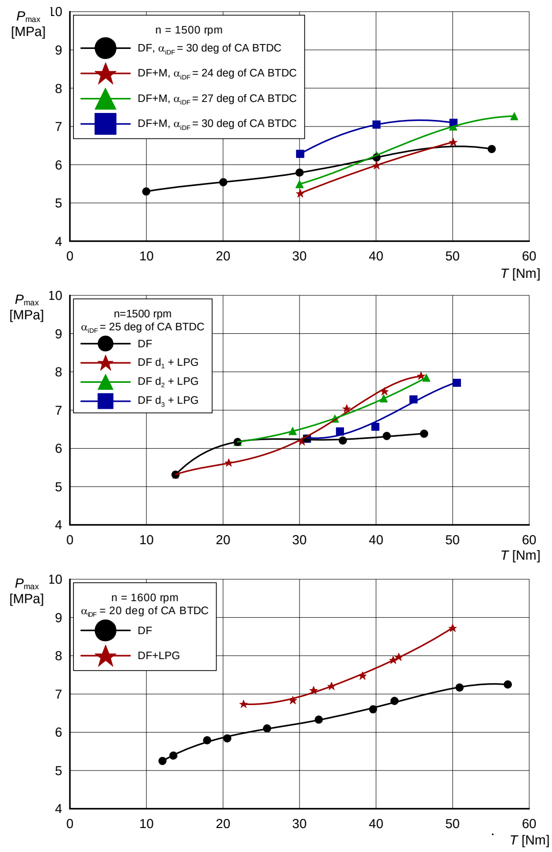

Fig. 8. Variability characteristics of maximum combustion pressure $P_{max} = f(M)$ for various injection timings of the pilot fuel and for fuelling modes: a), b) and c) (described in chapter 1)

Rys. 8. Charakterystyki zmienności wartości maksymalnego ciśnienia spalania w funkcji obciążenia $P_{max} = f(M)$ dla różnych wartości kątów wyprzedzenia wtrysku inicjującej zapłon dawki oleju napędowego i różnych przypadków zasilania a), b), c) (opis jak w rozdz. 1)

Characteristics presented in Fig. 8 show clearly that maximum combustion pressures at dual fuelling are definitely higher than at standard fuelling. This tendency is observed for various diesel oil pilot dose quantities and its injection timings. It can also be observed that delaying injection timing results in maximum combustion pressure decrease (it is especially seen in the case „c”).

Considering that increase of maximum pressures induces many undesirable effects (increase of mechanical loads and NO_x emission and sometimes – decrease of overall efficiency) the above mentioned injection timing should be established very carefully.

4.2. Variability characteristics of the average rate of pressure rise $(\Delta P/\Delta\alpha)_{av}$

The next parameter, essential from the point of view of thermal and mechanical loads of the crankshaft-piston assembly is the average rate of pressure rise. Pressure courses presented in Fig. 7 enabled to prepare variability characteristics of the average rate of pressure rise versus engine load. These characteristics are presented in Fig. 9.

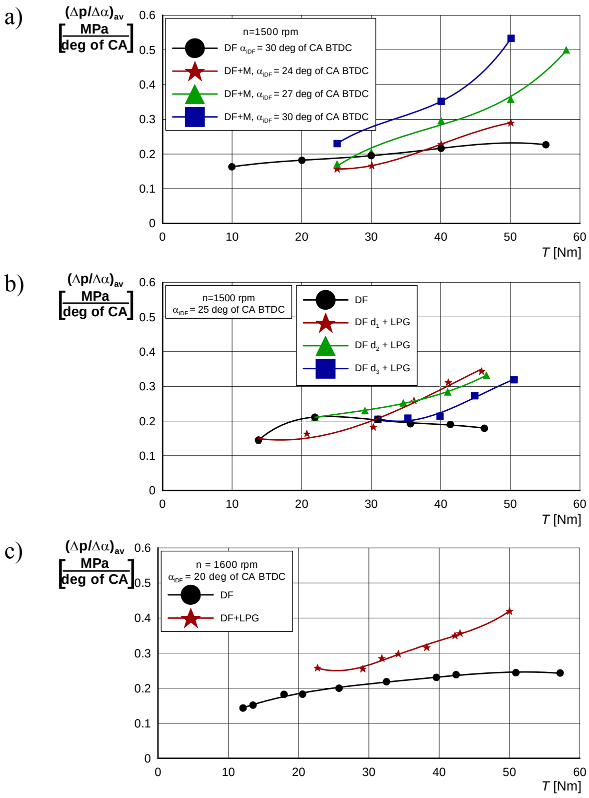

Fig. 9. Variability characteristics of average rate of pressure rise $(\Delta P/\Delta\alpha)_{av}$ for various injection timings of the pilot fuel and for fuelling modes: a), b) and c) (described in chapter 1)

Rys. 9. Charakterystyki zmienności wartości średniej szybkości narastania ciśnienia $(\Delta P/\Delta\alpha)_{śr}$ dla różnych wartości kątów wyprzedzenia wtrysku inicjującej zapłon dawki oleju napędowego i różnych przypadków zasilania a), b), c) (opis jak w rozdz. 1)

In comparison to the standard engine, combustion in a dual-fuel engine is characterised by higher dynamics of the process resulting from higher values of pressure rise rates. In result, maximum pressures are higher. This is an effect of volume combustion of the main fuel – air mixture in the zone covered by the stream of pilot fuel being combusted.

5. Conclusions

- Dual-fuel engine (regardless of the fuelling mode) may achieve higher torque output in comparison to the standard engine. It should be added that the main criterion regarding possibility to achieve maximum engine torque was the increase of smoke level. Clear tendency of smoke limit in a dual-fuel engine to be shifted towards higher loads in comparison with a standard engine enables to achieve higher maximum engine torque in this engine version.
- Dual-fuel engine is characterised by increase of overall efficiency over the range of loads close to maximum and decrease of this parameter at partial loads (it resulted from analysis of specific fuel energy consumption characteristics, Fig. 2). It should be noticed that overall efficiency of a dual-fuel engine strongly depends on the pilot dose quantity. Decrease of overall efficiency in case of applying small pilot fuel quantities results, according to the author, from incomplete combustion of the main fuel – air mixture in the zone of combustion chamber which is beyond the zone of pilot dose combustion. In engines having combustion chamber located in the piston (as in the case of 1HC102 engine) extinguishing of combustion may occur in the zone between piston surface and cylinder head plane. Increase of engine overall efficiency at full engine load, observed especially for higher diesel oil pilot dose quantities, should be explained by increase of indicated efficiency. It results from a volume mode of combustion of the main fuel – air mixture what enables to conduct this process in shorter time and at favourable crankshaft position. It should be noticed that dual-fuel engine overall efficiency depends also on the established pilot dose injection timing.
- Decrease of CO emission from a dual-fuel engine, over the range of loads close to maximum, results from favourable combustion conditions over this range, when the main fuel – air mixture becomes relatively reach. This phenomenon is especially seen when higher pilot dose quantities are applied. Increase of CO emission from a dual-fuel engine over the range of partial loads results, according to the author, from incomplete combustion of a very lean mixture of the main fuel and air, especially beyond the zone of pilot dose combustion (the same explanation as in the case of overall efficiency decrease at partial loads).
- Increase of HC emission from a dual-fuel engine results from incomplete combustion of a very lean mixture of the main fuel and air – with the same explanation as in the case of overall efficiency decrease at partial loads. Additionally, over the range of loads close to maximum, incomplete and imperfect combustion of the pilot dose injected into relatively rich mixture of the main fuel and air occur. Diesel oil droplets have worse contact with oxygen then when fuel is being injected into air charge, as it is realised in a standard engine fuelled with diesel oil only.
- NO_x emission, generally lower from a dual-fuel engine over the range of low loads results, according to the author, from a decrease of combustion temperature caused by

incomplete and imperfect combustion of the main fuel. This is confirmed by the observed increase of CO and HC emissions over this range and decrease of engine overall efficiency. Combustion process improvement (decrease of CO and HC emissions) results in higher temperatures in a dual-fuel engine in comparison with a standard engine and, in consequence, increased NO_x emission.

– Decrease of smoke level from a dual-fuel engine over the range of loads close to maximum is a characteristic feature for these compression ignition engines in which, instead of diesel oil, gaseous fuels are applied (in the investigated case – methanol vapour or propane-butane mixture).
– To prevent uncontrolled ignitions of the main fuel – air mixture and knocking combustion it is necessary a very careful choice of the pilot fuel injection timing. In all of the described cases, it can be observed decrease of the average rate of pressure rise as well as decrease of maximum pressures with delaying injection of the pilot fuel. It should be mentioned that the proper choice of the pilot fuel injection timing is also essential due to maximum engine torque output, overall efficiency and emission levels.

Recapitulating, it should be remarked that the observed and described features of a dual-fuel engine are typical for the case when natural gas is applied as the main fuel [5, 13].

References

[1] Khandare S.S., Garg R.D., Gaur R.R., *Investigation on the use of solid fuels for diesel engine*, SAE Paper, 872094.

[2] Kusaka J., Daisho Y., Kihara R., Saito T., *Combustion and exhaust gas emission characteristics of a diesel engine dual-fuelled with natural gas*, The Fourth International Symposium COMODIA'98 Proceedings, Koyoto, Japan 1998.

[3] Jothi N.K.M., Nagarajan G., Renganarayanan S., *Experimental studies on homogeneous charge CI engine fuelled with LPG using DEE as an ignition enhancer*, Renewable Energy, Elsevier, Vol. 32 (2007), 1581-1593.

[4] Furutani M., Ohta Y., Kono M., Hasegawa M., *An ultra-lean premixed compression-ignition engine concept and its characteristics*, The Fourth International Symposium COMODIA'98 Proceedings, Koyoto, Japan 1998.

[5] Stelmasiak Z., *Effect of the magnitude of diesel fuel initial dose on the work parameters of dual-fuel engine fed with diesel fuel and natural gas*, Journal of Kones – Internal Combustion Engines, Vol. 8, No. 3–4, 2001.

[6] Clark N.N., Atkinson Chr.M., Atkinson R.J., *Optimized emission reduction strategies for dual fuel compression ignition engines running on natural gas and diesel*, www.cemr.wvu.edu/englab/projects/saturn.htlm, 2002.

[7] Gebert K., Beck N.J., Barkhimer R.L., *Strategies to improve combustion and emission characteristics of dual-fuel pilot-ignited natural gas engines*, SAE Paper 971712, 1997.

[8] Chen Z., Konno M., Goto S., *Study on homogeneous premixed charge CI engine fuelled with LPG*, JSAE, Elsevier, Vol. 22 (2001), 265-270.

[9] Luft S., *Studium silnika o zapłonie samoczynnym zasilanego alkoholem metylowym*, Monografia nr 29, Wydawnictwo Politechniki Radomskiej, 1997.

[10] Takatsuto R., Igarashi T., Iida N., *Auto ignition and combustion of DME and n-butane/air mixtures in homogeneous charge compression ignition engine*, The Fourth International Symposium COMODIA'98 Proceedings, Koyoto, Japan 1998.
[11] Luft S., *Dwupaliwowy silnik o zapłonie samoczynnym zasilany mieszaniną gazów propan-butan (LPG) i olejem napędowym*, Monografia, nr 54, Wydawnictwo Politechniki Radomskiej, 2002.
[12] Luft S., *Dwupaliwowy silnik o zapłonie samoczynnym z wtryskiem ciekłego LPG do kolektora dolotowego*, Monografia, nr 103, Wydawnictwo Politechniki Radomskiej, 2007.
[13] Stelmasiak Z., *Wpływ niektórych parametrów regulacyjnych na osiągi dwupaliwowego silnika o zapłonie samoczynnym zasilanego gazem ziemnym*, Zeszyty Naukowe Politechniki Częstochowskiej nr 155, Mechanika, nr 25, Częstochowa 2003.

W tekstach obcojęzycznych Redakcja dokonała tylko standardowej adiustacji, zachowując ich oryginalną wersję.