ANALYSIS OF COMBUSTION PROCESS IN A DUAL-FUEL COMPRESSION IGNITION ENGINE FUELLED WITH LPG IN THE LIQUID PHASE

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Abstract

Investigation on fuelling a dual-fuel compression ignition engine with various fuels, that are unconventional for this type of engine, was carried out for many years in the Department of Internal Combustion Engines and Automobiles in Technical University of Radom. Such fuels as methanol, ethanol and natural gas were applied in the investigation. Recently, the investigation regards application of LPG – a fuel that is very popular in Poland. Within the project No. 4T12D02226 of the Committee of Scientific Research, it was tested, among others, an engine equipped with injection system for diesel fuel pilot dose – a common rail type. As a result of the former investigation, load characteristics of specific energy consumption as well as CO, CO_2, NO_x, HC and smoke emissions data were obtained [1]. In order to analyze variability of fundamental combustion process parameters, histories of the pressure inside combustion chamber have been registered during investigation. Investigation on changes of these parameters in the described engine version is particularly important due to possibility of knocking combustion occurrence that leads to the failure of such engine parts as piston or valves. Changes of these parameters versus engine load for various injection timing of diesel fuel pilot dose were analysed.

Keywords: *dual-fuel compression ignition engine, LPG*

1. Introduction

Investigation on dual-fuel compression ignition engine was carried out for many years in the Department of Internal Combustion Engines and Automobiles in Technical University of Radom.

The standard fuel injection system of a compression ignition engine was modified to deliver second fuel into the engine intake manifold. During the inlet and compression strokes, this fuel forms a homogenous mixture with air. Ignition of this mixture is initiated by the injected dose of diesel fuel.

Such combustion system solution is close to the HCCI (homogeneous-charge compression ignition) system that is considered to be the best future solution [2]. It is worth to mention that the described fuelling conception has many advantages, such as:

- easiness of compression ignition engine adaptation to combustion fuels having high octane and low cetane ratings;
- easiness of engine starting (using diesel fuel);
- improvement of engine overall efficiency;
- lower harmful emissions;
- possibility of application of various fuels (gasoline, alcohols, LPG, natural gas etc.) that until now were applied to spark ignition engines,
- easy way of adjustment and control of combustion process beginning.

Pertinence of this approach seems to be reasonable and confirmed by many publications that present results of investigations carried out in Poland and abroad [3-7].

Basic investigation was carried out using a stationary one-cylinder 1HC102 engine having cubic capacity $V_s = 0{,}98\ dm^3$, with direct injection to the combustion chamber located in the piston, compression ratio $\varepsilon = 17$, power rating N = 11 kW at the engine speed n = 2200 rpm. Till now, the effect of several fuels on basic engine operating parameters and emissions was analysed in investigation. The following fuels were applied:

- methanol evaporated in an evaporator and delivered in the gas phase into the intake manifold,
- methanol injected into the intake manifold in the liquid phase,
- ethanol injected into the intake manifold in the liquid phase,
- propane-butane mixture (LPG) evaporated in an evaporator and delivered in the gas phase into the intake manifold,
- propane-butane mixture (LPG) injected into the intake manifold in the liquid phase.

The following is to be said for the last of the above mentioned LPG fuelling system idea:

- expected improvement of filling the cylinder as a result of cooling the air charge in the process of LPG fuel evaporation,
- expected lowering of combustion temperature that favours lower NO_x emission and higher engine overall efficiency,
- precision of controlling the quantity of LPG dose as well as possibility of synchronisation between the LPG injection process and stages of the inlet valve opening,
- expected prevention of self-ignitions occurrence and knocking combustion of LPG – air mixture (as a result of lower circulation temperature).

The paper presents results of investigation on a dual-fuel engine, obtained during preparaton of load characteristics. In the initial investigation phase, characteristics of specific energy consumption versus the engine load were obtained. These characteristics allowed comparison of achieved engine torque as well as overall efficiency of the dual-fuel engine for various injection timing of diesel fuel pilot dose with the values obtained for the engine conventionally fuelled with diesel fuel. During preparation of these characteristics, pressure courses in the combustion chamber versus crankshaft angle were registered.

Registration of 100 succeeding cycles, after the averaging procedure, allowed carrying out the necessary analysis to determine variations of such parameters as: maximum combustion pressure $P_{max} = f(T)$, mean rate of pressure rise $(dP/d\alpha)_{av} = f(T)$ and maximum rate of pressure rise $(dP/d\alpha)_{max} = f(T)$. The knowledge of variations in the values of these parameters versus the engine load for various injection timing of diesel fuel pilot dose allows proper selection of the dual-fuel engine adjustment to prevent knocking combustion.

Knocking combustion, which occurs in a dual-fuel engine, determines the value of maximum torque that may be permanently kept by the engine. Therefore, this phenomenon limits the achieved engine torque (and in result – engine power) although the value of coefficient of excess air $\lambda \cong 1.4$, would indicated possibility of further fuel dose increase for engine load increase.

2. Description of the system applied in fuelling with LPG in the liquid phase

The scheme of LPG fuelling system is presented in Fig. 1. LPG fuel is injected into the intake manifold in the liquid phase with the use of injector, whose opening time and injection beginning are set by an electronic controller. Changing the opening time allows selection of LPG dose quantity. Choice of the moment of injection beginning gives opportunity to synchronize LPG fuel injection with opening time of the inlet valve.

In the described version of the fuelling system, power is regulated by changes of LPG – air mixture composition. This is accompanied by significant variations of LPG – air mixture composition – from very lean at medium loads, characterised by air excess ratio $\lambda > 10$, up to

$\lambda = 2,5\text{-}3,5$ at nominal engine load, depending on the quantity of diesel fuel injection dose. It is worth to mention, that at loads close to the nominal ones, LPG – air mixture is relatively lean ($\lambda = 2,5\text{-}3,5$), what is very important because this averts the occurrence of premature injections and phenomenon of knocking combustion of this mixture after initiation of diesel fuel combustion.

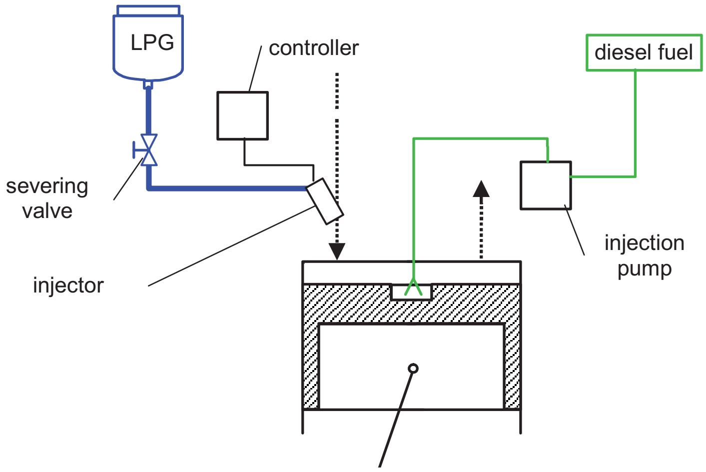

Fig. 1. Scheme of dual-fuel system of CI engine with injection system of LPG supply to the suction manifold in the liquid phase with CR system of diesel fuel injection

3. Investigation results regarding engine performance

Investigation on the engine was carried out by load characteristics registration for the engine speed n = 1800 rpm. To compare results, load characteristics of specific energy consumption were obtained with regard to different heating values of applied fuels (DF and LPG). The results are put together in Fig. 2.

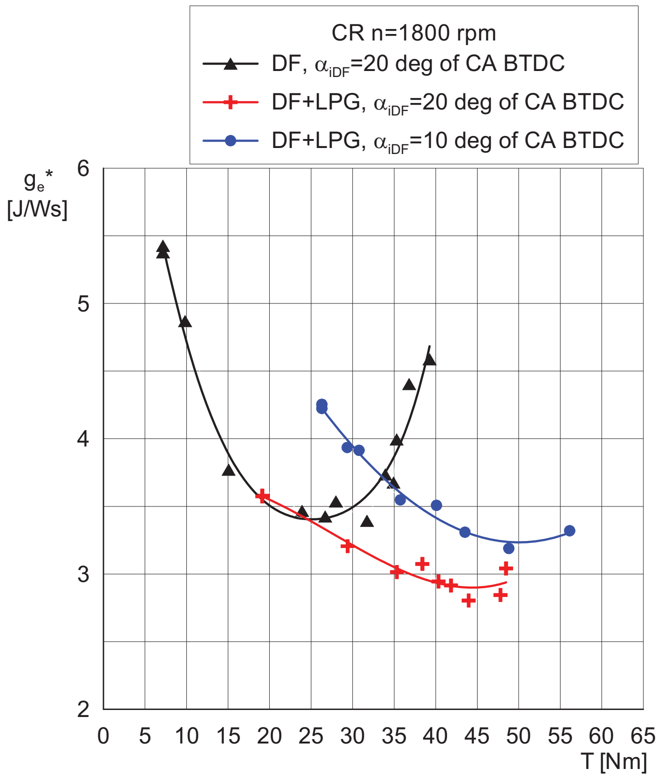

Fig. 2. Load characteristics of specific energy consumption for dual-fuel engine fuelled with diesel fuel with common rail system. Engine speed n =1800 rpm

Characteristics put together in Fig. 2 indicate that a dual-fuel engine may achieve maximum torque higher than in the case of an engine conventionally fuelled, at simultaneous improvement of overall efficiency (specific energy consumption decrease). Both these parameters are significantly influenced by the injection timing of diesel fuel pilot dose.

The dependence of specific energy consumption g_e* course on the established injection timing of diesel fuel pilot dose can be clearly seen for both versions of diesel fuel injection system.

Introduction of profitable adjustment of this parameter (for the engine speed n = 1800 rpm, close to the maximum speed for the investigated 1HC102 engine) results in overall efficiency improvement (specific energy consumption decrease). At the same time, at the load close to the maximum one, engine roughness is observed with high values of the maximum combustion pressure (Figs 3 and 5) as well as of mean and maximum rates of pressure rise (Figs 4, 6 and 7). This effect leads to limitation of maximum torque to the value equal ca. 50 Nm in comparison with values equal ca. 55÷60 Nm for later injection timing of diesel fuel pilot dose α_{iON} = 10° BTDC. However, it should be noticed that for both regulation of injection timing of the pilot dose, significant decrease of specific energy consumption (engine overall efficiency increase) for dual-fuel engine can be observed.

4. Investigation results regarding variability of fundamental parameters of the combustion process

During the load characteristics preparation, pressure courses in the combustion chamber versus crankshaft angle, for various engine load T [Nm], were registered. The courses, registered and averaged from 100 succeeding cycles, are presented in Fig. 3. These plots were used for calculation and preparation of other characteristics.

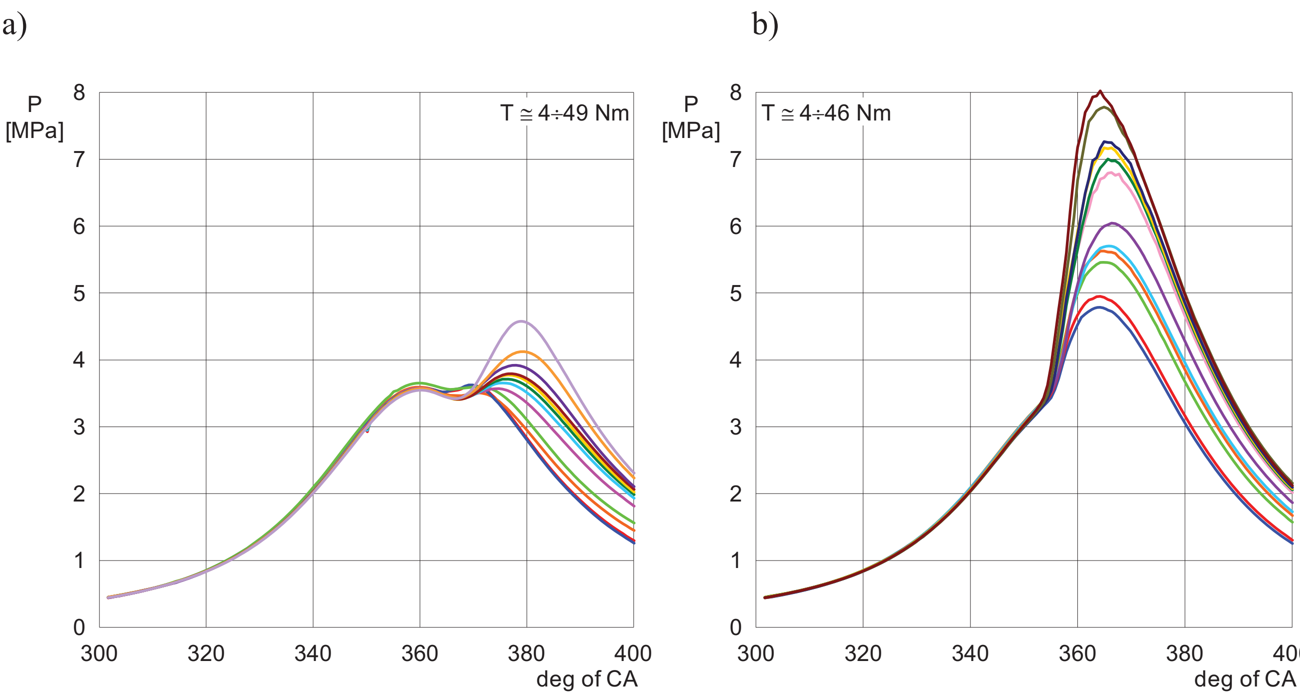

Fig. 3. The histories of the pressure P [MPa] in the combustion chamber as the function of CA position for different load T [Nm] of the engine. Engine speed n = 1800 rpm, a) injection timing α_i =10 deg of CA BTDC, b) injection timing α_i =20 deg of CA BTDC [8]

Just preliminary visual analysis of pressure courses versus crankshaft angle indicates that values of such parameters as maximum combustion pressure and rate of pressure rise strongly depend on the established injection timing of diesel fuel pilot dose. “Earlier” injection timing, $\alpha_i = 20^o$ BTDC results in distinct increase of both maximum combustion pressure P_{max} and inclination of the pressure rise curve what leads to the increase of both mean and maximum rates of pressure rise. “Retarded” injection timing, $\alpha_i = 10^o$ BTDC, distinctly results in decrease of maximum pressure and mean and maximum rate of pressure rise. This shifts the combustion process towards the exhaust stroke. This also leads to the reduction of pressure level and increase of exhaust loss. This is accompanied by a positive phenomenon – shifting the limit of knocking combustion towards higher engine load and in result – preventing higher engine torque T [Nm] achievement. However, this decreases engine overall efficiency (specific energy consumption g_e* [J/Ws] – Fig.2).

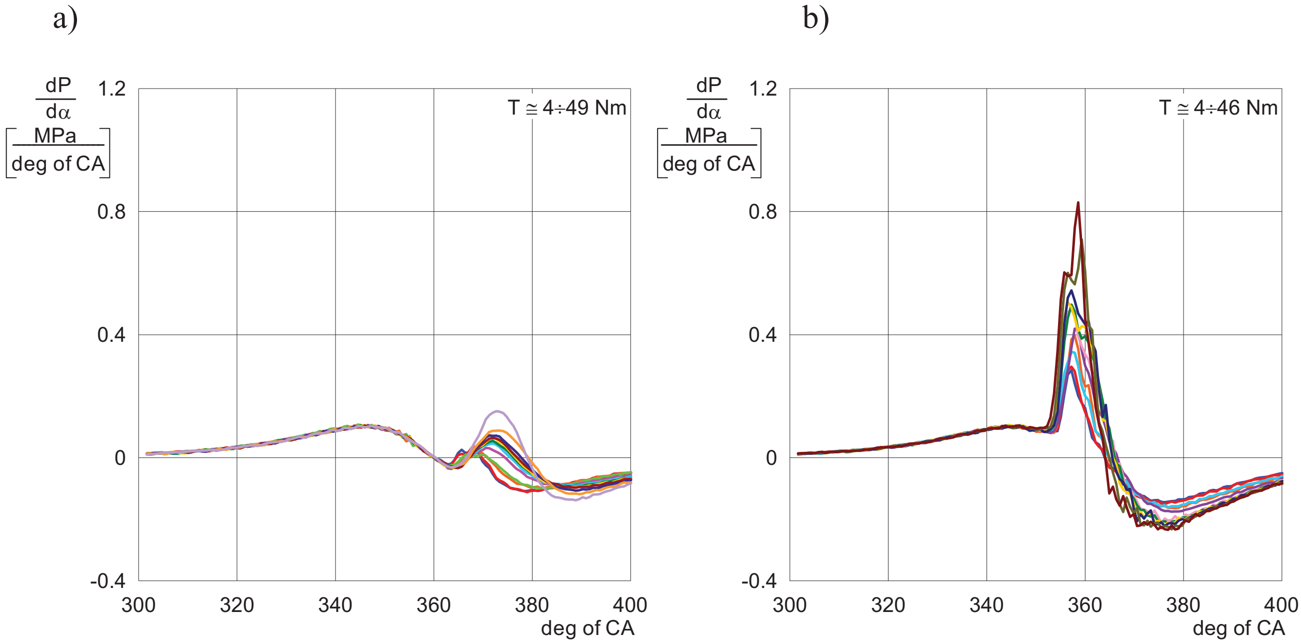

Fig. 4. The histories of the pressure rise dP/dα [MPa/deg of CA] as the function of CA position for different load T [Nm] of the engine. Engine speed n = 1800 rpm, a) injection timing α_i =10 deg of CA BTDC, b) injection timing α_I =20 deg of CA BTDC [8]

In order to estimate the values of maximum rate of pressure rise $(dp/d\alpha)_{max}$, differential of coefficient of pressure variability function $p = f(\alpha)$ was calculated. The results are put together in Fig. 4.

Observation of the course of $(dp/d\alpha)= f(\alpha)$ function confirms the relationships observed earlier. The basic dependence is that of maximum rate of pressure rise on the injection timing of diesel fuel pilot dose. Distinct increase of maximum rate of pressure rise with an injection timing increase in observed.

It should also be mentioned that values of the analysed combustion process parameters (maximum combustion pressure and mean and maximum rates of pressure rise) distinctly depend on the engine load T [Nm]. Therefore, variability characteristics of this parameters versus the engine load were prepared.

Variability of maximum combustion pressure P_{max} versus the engine load is presented in Fig. 5. It results from the presented characteristics that maximum combustion pressure level distinctly depends on the injection timing of diesel fuel pilot dose (what confirms observations done during pressure courses analysis – Fig. 3).

Dependencies of mean rate of pressure rise $(\Delta p/\Delta\alpha)_{av}$ [MPa/deg of CA] on the engine load are put together in Fig. 6.

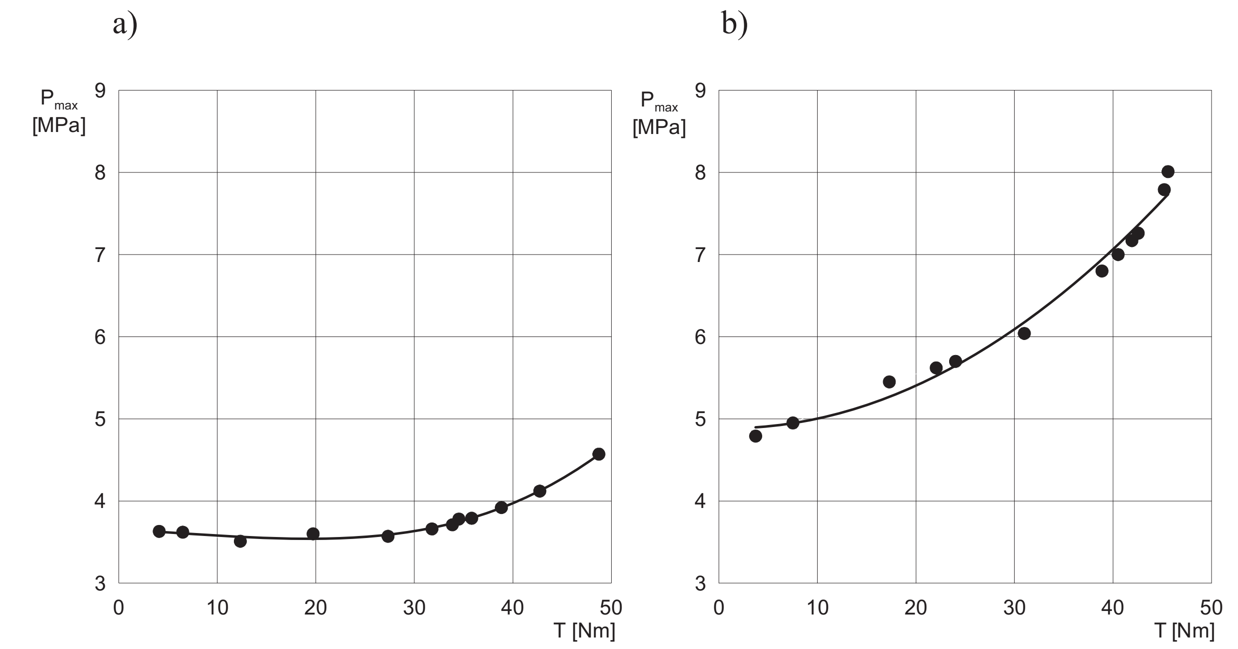

Fig. 5. The histories of the maximum combustion pressure P_{max} [MPa] as the function of the engine load T [Nm]. Engine speed n = 1800 rpm, a) injection timing α_i =10 deg of CA BTDC, b) injection timing α_i =20 deg of CA BTDC [8]

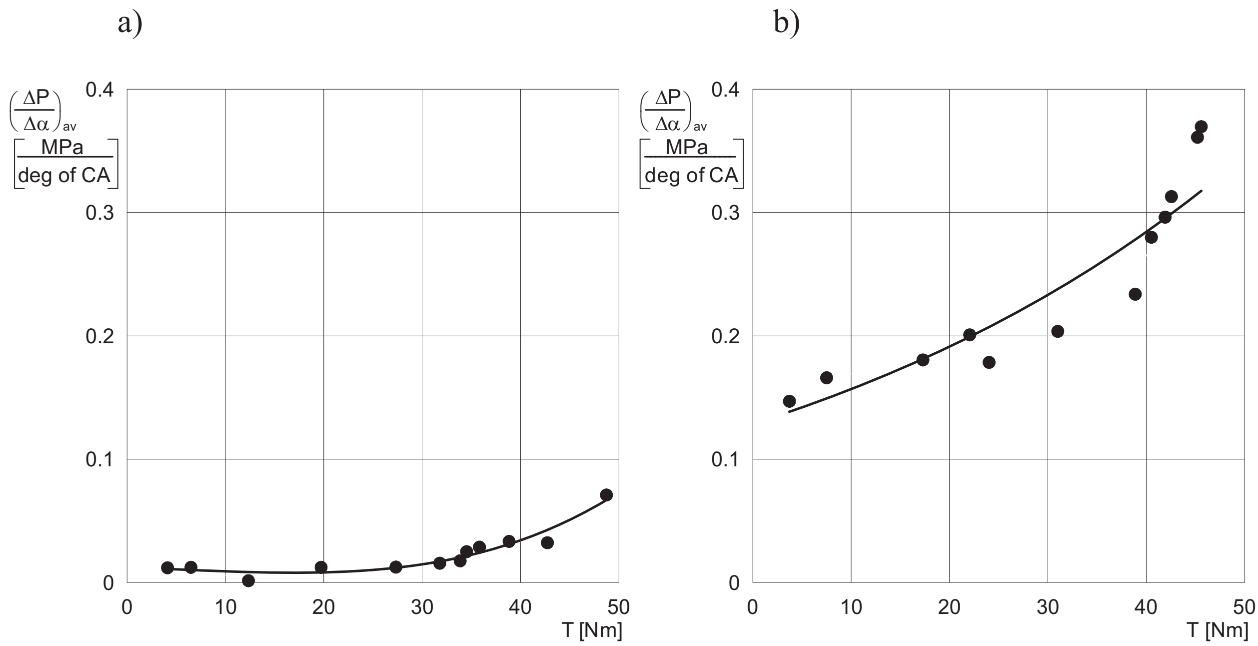

Fig. 6. The histories of average rate of pressure rise $(\Delta P/\Delta\alpha)_{av}$ [MPa/deg of CA] as the function of the engine load T [Nm]. Engine speed n = 1800 rpm, a) injection timing α_i =10 deg of CA BTDC, b) injection timing α_i =20 deg of CA BTDC [8]

Dependencies of maximum rate of pressure rise $(dP/d\alpha)_{max}$ [MPa/deg of CA] on the engine load are put together in Fig. 7.

In both cases, it can be seen that the levels of mean and maximum rates of pressure rise are influenced significantly also by the diesel fuel pilot dose injection advance angle.

It is obvious that values of the analysed parameters strongly depend on the engine load. Generally, the engine load increase is accompanied by an increase of maximum combustion pressure and mean and maximum rates of pressure rise.

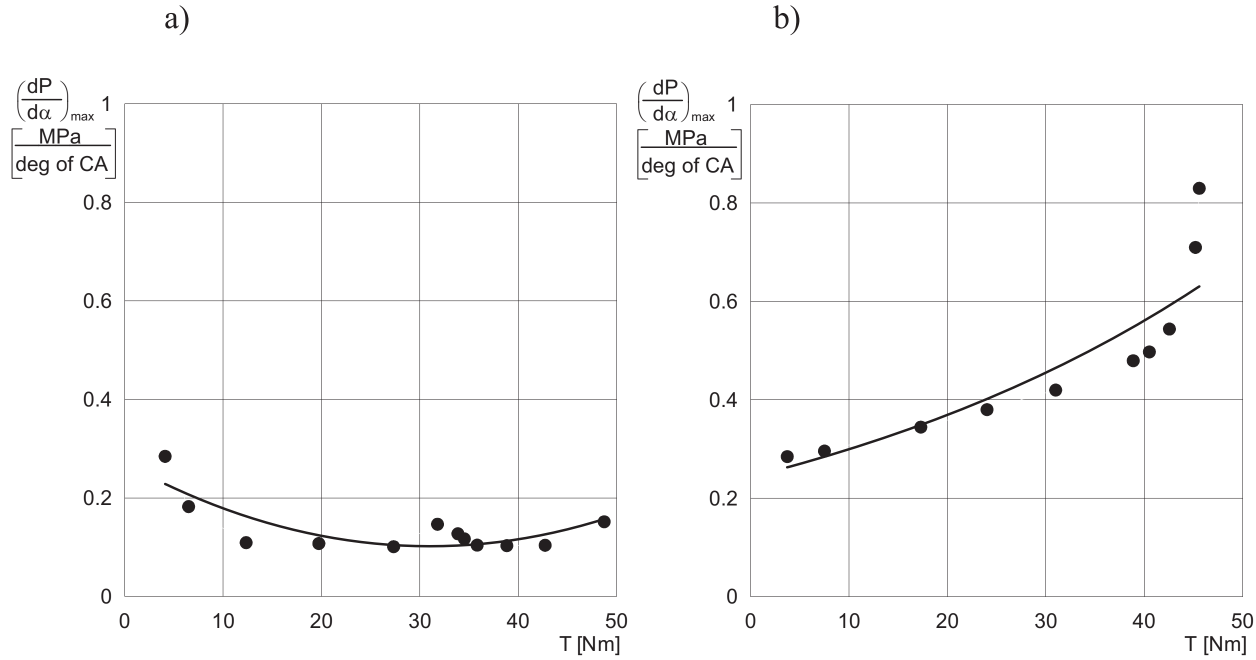

Fig. 7. The histories of maximum rate of pressure rise $(dP/d\alpha)_{max}$ [MPa/deg of CA] as the function of the engine load T [Nm]. Engine speed n = 1800 rpm, a) injection timing α_i =10 deg of CA BTDC, b) injection timing α_i =20 deg of CA BTDC [8]

5. Conclusions

- Value of maximum torque of a dual-fuel engine is limited by the occurrence of knocking combustion. The torque value at which knocking combustion occurs depends on the established injection timing of diesel fuel pilot dose.
- Increase of the diesel fuel pilot dose injection advance angle leads to the increase of maximum combustion pressure and mean and maximum rates of pressure rise what, in result, increases the dual-fuel engine overall efficiency.
- Increase of the diesel fuel pilot dose injection advance angle leads to knocking combustion occurrence what, in turn, limits the maximum torque that the engine may achieve.

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