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KNOCK COMBUSTION IN DUAL FUEL DIESEL ENGINE

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Abstract

This article presents the problem of the knock combustion in a dual fuel compression engine, in which additional fuel besides diesel oil was compressed natural gas (CNG). CNG was injected into the engine intake system and mixed with air supplying the engine. In this paper described the reasons of knock combustion, which occur with more intensity with the increase of methane content in engine fuel. The phenomenon of knock combustion in the dual fuel engine is difficult to eliminate, often impossible to avoid, and it forms a barrier limiting increase of methane share in the fuel. Also, this article contains the results of engine indicating and discussion on changes in the indicating diagrams caused by knock combustion. Carried out tests included engine indicating and numerical calculation of indicator diagrams with using spectral analysis and filtering cylinder pressure signals with high-pass filters. As a result of this calculation, several parameters describing intensity of knock combustion were determined. They allow to tell taking into account only cylinder pressure analysis if there is knock combustion inside engine combustion chamber or not. Knocking is an undesirable type of combustion in the engine, leading to excessive thermal and mechanical loading of the engine parts, causing premature wear of them. For this reason, this type of combustion should be eliminated from the engine operation and researchers of combustion processes must be provided with tools to detect and determine this kind of combustion.

Keywords: *road transport, IC engines, alternative fuels, combustion process in engine*

1. Introduction

Many researchers report that too much addition of methane to diesel oil may cause knocking in the dual fuel CI engine combustion. Knocking combustion relies on formation of uncontrolled outbreaks, where combustion as a result of uncontrolled self-ignitions of methane has detonation character, consisting of a many violent micro-explosions in areas near these sources of self-ignition.

In dual fuel CI engine with methane as an additional fuel combustion process should be organized as follows. The methane filling the combustion chamber should be ignited from the pilot dose of diesel oil injected into the combustion chamber. Diesel oil ignites spontaneously and the resulting flame burns the methane. The core of knock combustion in dual fuel diesel engine relies on fact that sources of self-ignition may occur not only at the border of the injected stream of diesel fuel and charge filling combustion chamber but also inside of the ambient compressed air-methane mixture. If the sources of self-ignition appear inside of the air-methane mixture, we are dealing with uncontrolled process of knock combustion, disturbing regular combustion required for proper CI engine operation.

The measure of the fuel resistance to knock combustion is the value of its octane number. Methane has relatively high octane number (RON>100) and therefore it is used in spark ignition engines with compression ratios of the order $\varepsilon\approx10$. In the CI engines, usually average value the compression ratio is $\varepsilon\approx17$, which makes that conditions existing in combustion chamber are far from optimal ones for the use of this fuel. For this reason, methane cannot be added in large quantities to a CI engine. The maximum methane content in engine fuel is limited by the engine resistance to knock combustion.

In the areas where knock combustion appear, flame front does not develop in a manner typical for the combustion process in reciprocating engines. In IC engines combustion rate is controlled by the intensity of turbulence of the charge contained inside cylinder. Knock combustion because of its explosive nature proceeds at much greater rates than normal combustion resulting shock wave. This wave is reflected by walls of the combustion chamber, and interferes with registered pressure, whereby pressure signal measured has a saw-tooth shape characteristic. When in an engine appears knock combustion we can hear characteristic sound similar to knocking. Knock combustion is a reason of the increased thermal and mechanical loading of the piston and crankshaft.

The risk of the knock combustion in dual fuel engine takes place during the occurrence of high temperatures in the combustion chamber, which promotes high values of compression ratio, high engine loading, high boosting and low cetane number of the fuel. Normally in spark ignition engines knock combustion occurs at lower engine speeds and higher loadings.

2. Tested engine

The tests were carried out on direct injection compression ignition engine taken from light duty truck. Its essential data are shown in Tab. 1. The engine was adapted to dual fuelling throughout injection of natural gas into its inlet pipe. The engine was indicated using AVL Indismart indicating system. Pressure transducer was installed in one cylinder in the whole where previously was installed glow plug.

Tab. 1. Essential data of the tested engine

Number of cylinder:	4
Capacity [cm^3]:	2637
Power output [kW]:	85
Rated power speed [rpm]:	3600
Maximal torque [Nm]:	250
Maximal torque speed [rpm]:	2000-2600

3. Engine testing

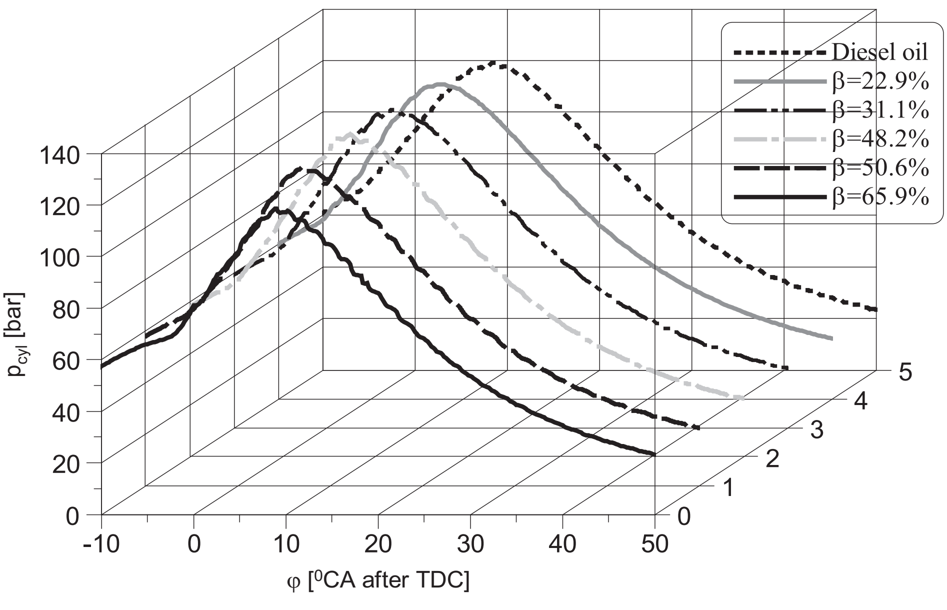

Fig. 1. Cylinder pressure as a function of crank angle for various share of methane in fuel (\b); n=1800 rpm, T=200 Nm

The addition of a methane to air entering into cylinder influences possibility of the ignition in the combustion chamber and fuel combustion. In a compression ignition, engine combustion process is initiated as a self-ignition of diesel fuel injected into combustion chamber. The higher fuel cetane number the easier its self-ignition. Methane injected to the engine fresh charge has high value of research octane number (RON) and low cetane number, thus it needs external source of ignition. This source is usually pilot dose of diesel fuel.

In a dual fuel engine with increase of natural gas, content in cylinder the share of diesel oil decreases. It leads to limitation of the number of places where self-ignition took place, and from where the flame spreads through air-fuel mixture filling the cylinder.

In Fig. 1 shown cylinder pressure in the engine operating in conditions close to rated speed. It can be noticed that the first symptoms of knock combustion in this engine appear when content of methane in fuel is greater than 50% ($\beta > 50\%$), wherein for the curve corresponding to β=50.6% are hardly noticeable waves on expansion curve, on a curve marked β=65.9% the symptoms of knock combustion are clearly visible in the form of a characteristic saw-tooth wave form.

In order to better investigation of the presence of knock combustion, in Fig. 2-4 shown the spectral analysis of cylinder pressure, made by using Fast Fourier Transform (FFT). On Fig. 2 shown the drawing at which the knock combustion does not occur because of too small engine loading. Whereas, on Fig. 3 and 4 we are dealing with knock combustion for curves marked by dashed line, corresponding to the maximal content of methane in the fuel. The accumulated experience indicates that the risk of knock combustion at condition of whole opening throttle (WOT) starts for the share of methane in the fuel $\beta > 50\%$. Analysing Fig. 2-4 we can see that for all tested speeds and regardless of the fuel actual composition, in the vicinity of frequency of 5.3 kHz on every characteristic appeared local maximum. The reason for the presence of this maximum is due to the acoustic phenomena caused by way of mounting piezoelectric pressure transducer in the combustion chamber. Because of the installing of the sensor in the glow plug seat the sensor diaphragm was not directly in the combustion chamber but it was recessed in a few millimetres long channel created by the glow plug whole. The frequency of the waves generated by the acoustic resonator in form of a glow plug channel may be calculated from the following formula [2]:

$$f = \frac{\sqrt{\kappa \, R \, T}}{2\,\pi} \sqrt{\frac{r^2 \pi}{V\, l}}\,, \tag{1}$$

where:
κ – polytrophic exponent;
R – gas constant [J/kg K];
T – gas temperature [K];
r – the radius of the channel connecting pressure sensor with combustion chamber [m];
l – length of the channel connecting pressure sensor with combustion chamber [m];
V – volume above the channel [m^3]:

According to formula (1) acoustic wave generated in the resonator is a higher frequency, the higher the temperature of the gas inside cylinder. Its frequency is variable during compression stroke and will be the largest when the gas temperature is the highest. The changes of temperature in the compression and expansion strokes may be a reason of observed increase of pressure amplitude on Fig. 2-4 in the frequency range 4000-5500 Hz. Generated acoustic wave interferes with the recorded pressure and consequently the pressure sensor registers a saw-tooth waveform with clearly imposed a constant frequency wave. For this reason, charts showing the pressure should always be filtered and smoothed before their placing in the final report.

4. Intensity of knock combustion

One of the possible ways of examination signs of knock combustion is a method of analysing of registered cylinder pressure by finding the characteristic frequency of saw-tooth wave imposed on

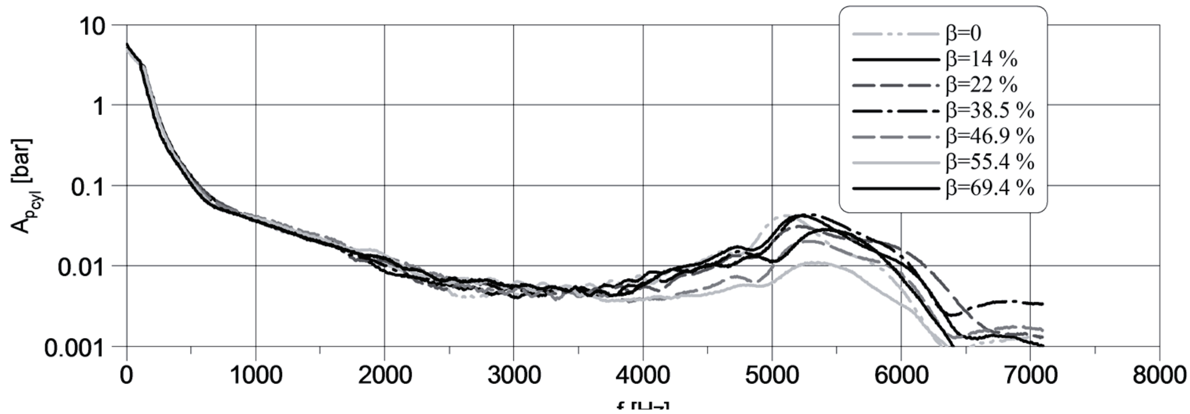

Fig. 2. FFT (Fast Fourier Transformate) spectral analysis of cylinder pressure for various share of methane in fuel (\b); n=1500 rpm, T=100 Nm

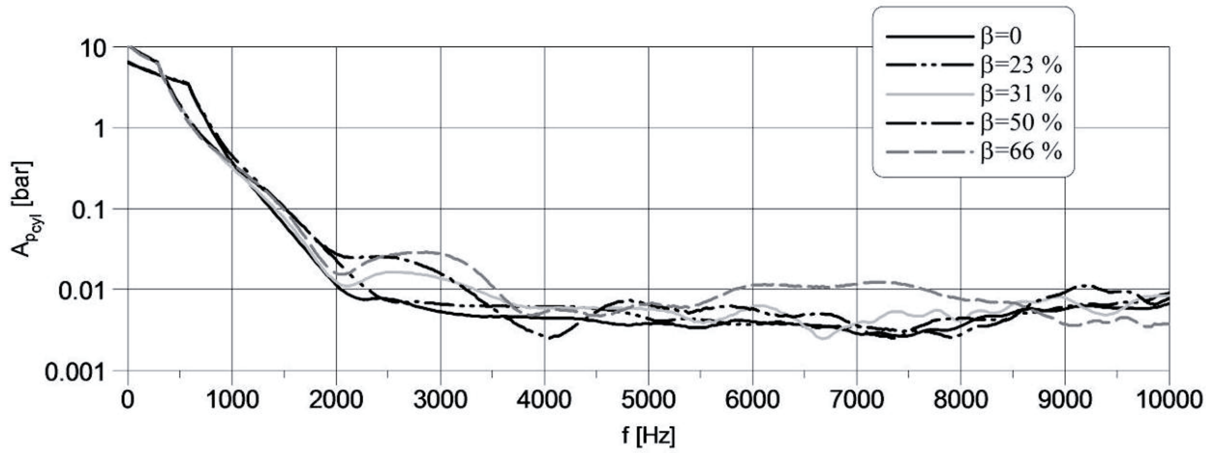

Fig. 3. FFT spectral analysis of cylinder pressure for various share of methane in fuel; n=1800 rpm, T=200 Nm

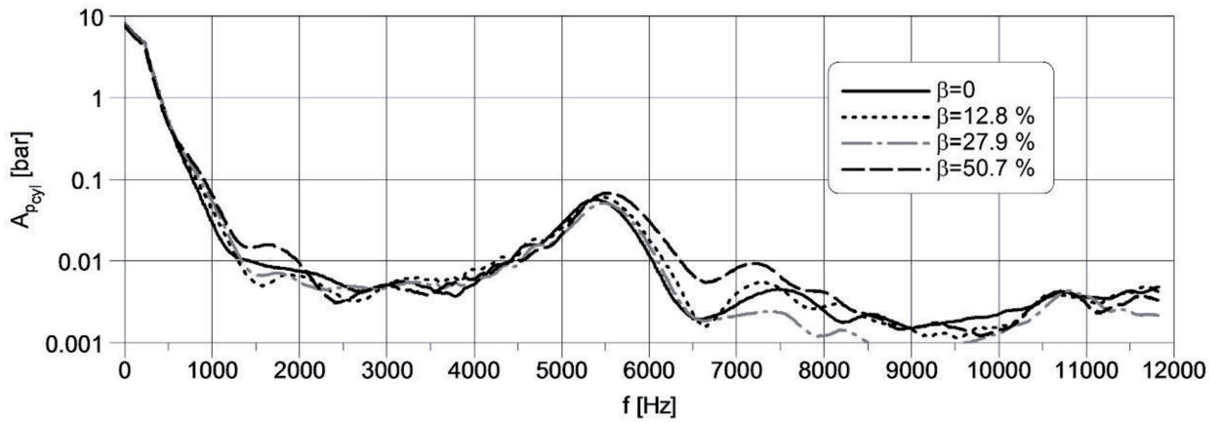

Fig. 4. FFT spectral analysis of cylinder pressure for various share of methane in fuel; n=2500 rpm, T=200 Nm

cylinder pressure. This can be done by filtering the pressure signal by using high-pas filter, which could cut off low frequency characteristic for the pressure changes in the cylinder being a result of regular combustion process. Remaining, separated pressure components are characteristic for knock combustion. On Fig. 5-7 shown the results of pressure filtered through a high-pass filter with cut-off frequency of 5.5, 6 and 6.5 kHz. The cut-off frequencies of the high-pass filter were changed in order to obtain the largest difference between the maximum amplitude of the pressure components. Average decrease of the pressure component amplitudes versus frequency range is about 50% for every 500 Hz.

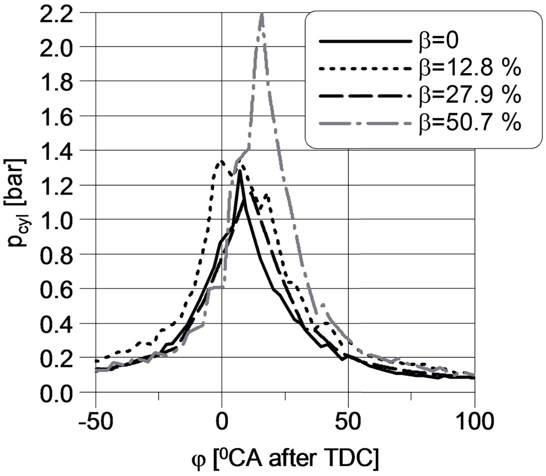

Fig. 5. Cylinder pressure filtered with high pass filter, cut off frequency 5.5 kHz; n=2500 rpm, T=200 Nm

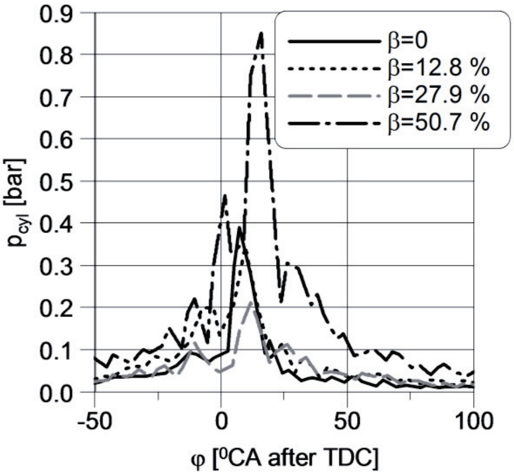

Fig. 6. Cylinder pressure filtered with high pass filter, cut off frequency 6 kHz; n=2500 rpm, T=200 Nm

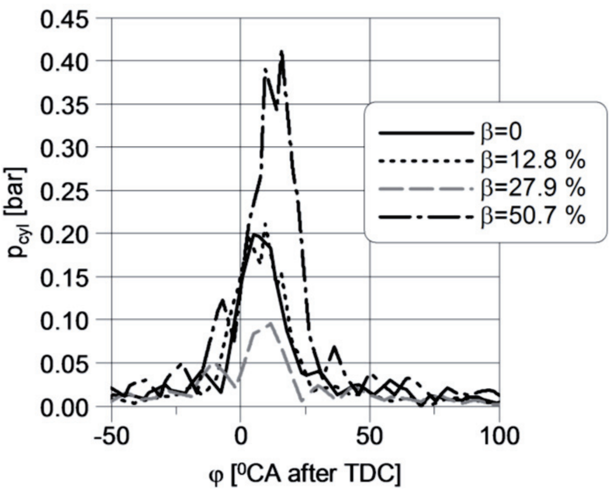

Fig. 7. Cylinder pressure filtered with high pass filter, cut off frequency 6.5 kHz; n=2500 rpm, T=200 Nm

Looking at pressure components on Fig. 5-7 we can see that regardless of the methane content in the fuel, these curves practically are coincided before the crankshaft angle equals to 10 °CA after TDC roughly. This position corresponds to the crankshaft angular position immediately after maximal cylinder pressure and occurs near the position of maximum temperature in the cylinder. From this position in the engine supplied with the fuel containing above 50% of methane ($\beta > 50\%$) there occur conditions causing knock combustion. Mathematical confirmation of this can be seen on Fig. 5-7 as a new pressure component with the natural frequency of more than 6.5 kHz. This component is caused by knock combustion.

Integrating the curves shown on Fig. 5-7 we can determinate the areas beneath these graphs, which can be identified with a measure of the knock combustion intensity. For better correctness of these calculations, the integration should be initiated immediately with the appearance of the knock combustion symptoms, for example at the time when the cylinder pressure reaches its maximum value. Integration should be completed at the end of heat release. For the case, show on Fig. 5-7 integration should be completed for the crankshaft position $\varphi \approx 40$ °CA after TDC. This position corresponds to the geometric point where the component amplitude graphs of cylinder pressure meet themselves at the same point for all tested mixtures of diesel oil and methane. On Fig. 8 shown the integrals of graphs shown on Fig. 6. Line corresponding to the share of methane in the fuel β=27.9% shows the area where there is no knock combustion. Line β=50.7% shows the area where knock combustion is already very clear, the hatched area on Fig. 8 corresponds to such methane contents in the fuel for which knock combustion develops still in a little noticeable way.

The graphs on Fig. 5-8 can be used to analyse the intensity of knock combustion. There are two possible methods to calculate it:

1. Determination of the maximum peak amplitude of the pressure component representing of the knock combustion (Fig. 5-7). The ratio of the amplitudes can be used as a measure of the knock combustion intensity.
2. Comparison of integrals of filtered pressure oscillations being induced by knock combustion and integrals of the curves where there is no knock combustion (Fig. 8).

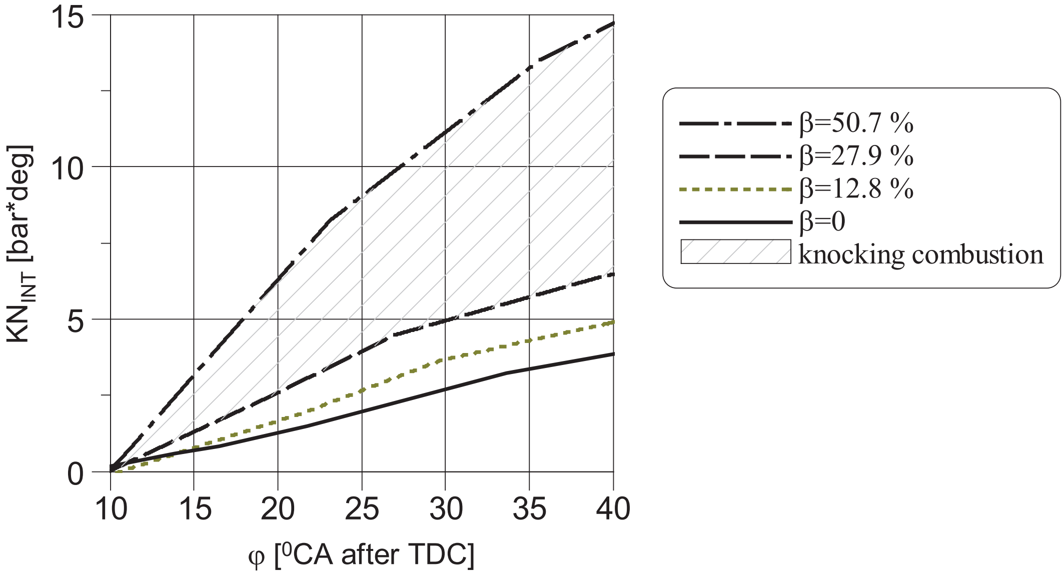

Fig. 8. Integral of pressure oscillations filtered by high-pass filter with a cut-off frequency of 6 kHz; n=2500 rev, T=200 Nm

It can be read (Fig. 5-7) that the ratio of maximum value of knock combustion component to background component exceeds a value of 2. According to [3] it can be assumed that criterial value for the knock combustion occurrence is two and more for the ratio of the peak amplitudes of the cylinder pressure components.

Similar criteria can be formulated for the integral method and it can be assumed that if the integral of the pressure oscillations at the end of combustion process is two times greater than the value of the integral of the pressure in a process in which there is no knock combustion, then we can talk about the occurrence of symptoms of the knock combustion. Fig. 5-8 shows that in the engine, where content of methane in fuel is about 50%, there occur symptoms of knock combustion.

Apart from the above analysis and determining the fact of presence of the knock combustion also should be take into account the frequency of engine cycles with this type of combustion. Fig. 9 shows the peak pressure oscillation amplitude recorded in successive 200 cycles of engine operation. From the Fig. 9 we can conclude that none of the peak amplitudes of the pressure oscillations in the combustion chamber (NK_{PK}) for the fuel with a methane content of 50.7% (dotted line) is not smaller than the mean amplitude of the other curve. It means that in the analysed range of cycles no knock combustion occurs. Analysing histogram shown on Fig. 10 it may be said that for content of 50.7% of methane in fuel, frequency of knock combustion presence in subsequent cycles (probability of knock combustion) is greater than 80%.

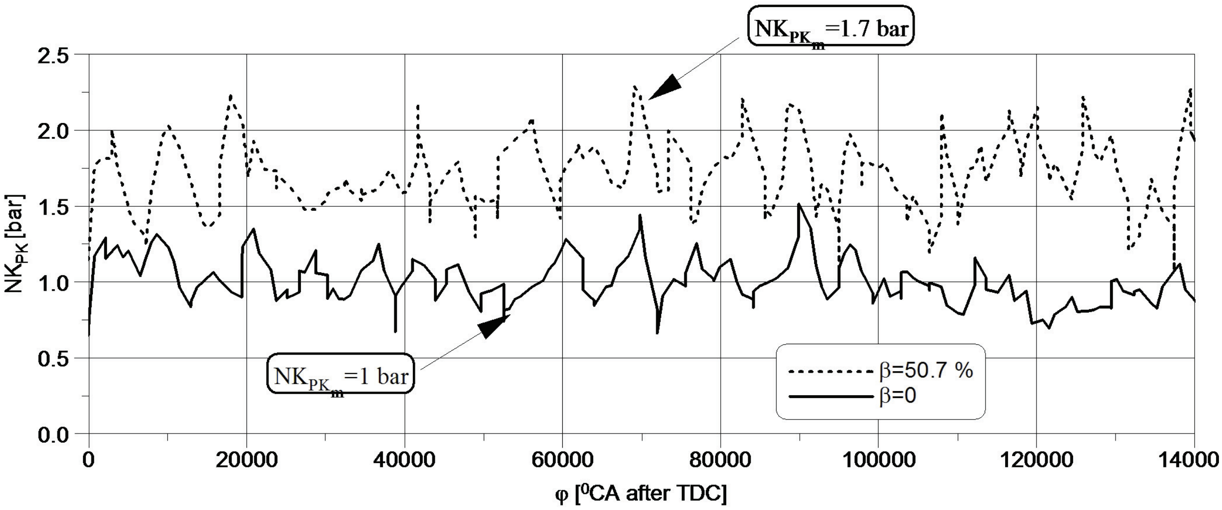

Fig. 9. Envelope of cylinder pressure filtered with high-pass filter, cut-off frequency 5.5 kHz; n=2500 rpm, T=200 Nm

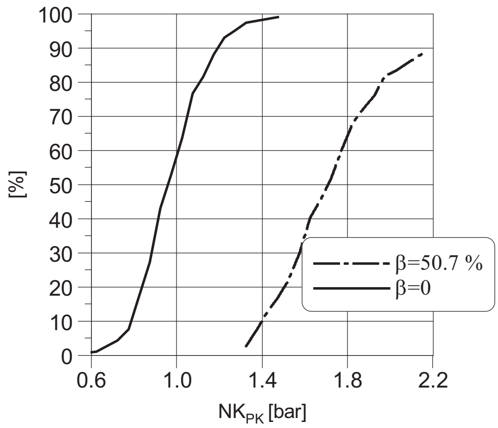

Fig. 10. Cumulative frequency versus knock peek

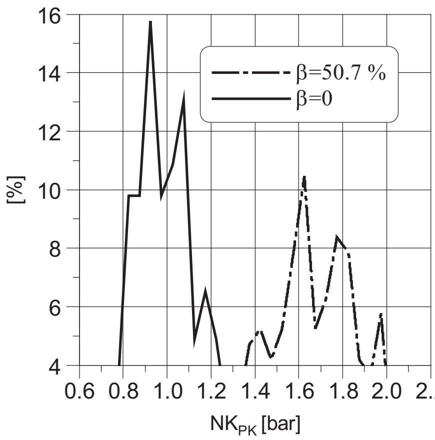

Fig. 11. Relative frequency versus knock peek

5. Conclusions

1. Knock combustion in dual fuel engine is a barrier limiting the possibility of any increasing the share of methane in the fuel.
2. In tested engine knock combustion occurred at the methane content in the fuel of 50%.
3. Analysing the cylinder pressure-indicatingindicating diagram) allows to calculate some indicators useful to determine intensity of knock combustion.

References

[1] Indicom Light version 1.6. Product Guide. October 2006, AT2237E.Rev.00.
[2] Pischinger, R., *Engine indicating*, AVL publishing, Graz 2002.
[3] Selim, M., *Sensitivity of dual fuel engine combustion and knocking limits to gaseous fuel composition*. Energy Conversion and Management 45, 411-425, 2004.
[4] Königsson, F., *Advancing the Limits of Dual Fuel Combustion*, Department of Machine Design, Royal Institute of Technology, Stockholm.
[5] Nwafor, O., *Knock characteristics of dual-fuel combustion in diesel engines using natural gas as primary fuel*, Sadhana Vol. 27, Part 3, pp. 375-382, 2002.