RESEARCH OF COMBUSTION IN OLDER GENERATION SPARK-IGNITION ENGINES IN THE CONDITION OF USE LEADED AND UNLEADED PETROL

by

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This paper analyzes the potential problems in the exploitation of the older generation of spark-ignition engines with higher octane number of petrol (unleaded petrol BMB 95) than required (leaded petrol MB 86). Within the experimental tests on two different engines (STEYR-PUCH model 712 and GAZ 41) by applying piezoelectric pressure sensors integrated with the engine spark plugs, acceleration sensors and special electronic block connected with distributor, show that the cumulative first and second theoretical phase of combustion when petrol of higher octane number (BMB 95) is used lasts slightly longer than when the low-octane petrol MB 86 is used. For new petrol (BMB 95) higher optimal angles of pre-ignition have been determined by which better performances of the engine are achieved without a danger of the combustion with detonation (also called knocking).

Key words: *petrol, alkylate lead, deposits, octane, detonation, rate of combustion*

Introduction

Theoretically observed, the transition of the work of engines designed for using leaded petrol onto unleaded ones, does not affect the effective parameters of the engine, due to approximately equal values of the thermal power of petrol. Some experiences and facts indicate that some other problems might occur, too.

The common characteristic of the exploitation of the engine operating with both leaded and unleaded petrol is the formation of deposits in the combustion chamber, but the mechanisms of formation, the chemical structure, the stabilization period, the important values and the ultimate effect of these deposits on the engine operations in the two cases differ dramatically. The increase in the amounts of deposits in the combustion chamber lasts for a certain period of time, after which the equilibrium, defined by the equality of the speed of the formation and removal of deposits, is established [1]. Time necessary to establish this balance is the stabilization period, after which the amount (thickness) and composition of deposits, do not change any more. Some studies show that the stabilization period ranges from 5.000 to 8.000 km of a distance covered by a vehicle when leaded petrol is used, whereas it is about twice as long [1]

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when unleaded petrol is used. Simultaneously, 1/3 to 2/3 of the total amount accumulates at the head of the piston [1]. Deposits in the combustion chamber are not only formed from petrol, but also from the used engine oil.

Lead oxides in the deposits, as a kind of ceramics and heat insulators, reduce the effect of the convective heat transfer from the mixture to the chamber walls, reducing the level of the thermal load of the engine [1]. In this way, the working process also approaches the adiabatic process, which theoretically implies the better petrol economy of the engine. The part of the deposits accumulated on the valve seat and on the valve head has the role of a shock absorber, too, which is particularly important when the exhaust valves and their seats exposed to the high temperature of exhaust gases are concerned.

Deposits formed by the use of unleaded petrol types do not have any of the above mentioned positive features of deposits originating from petrol with the addition of lead alkylates. Due to their chemical composition, deposits provide high-values of convective heat exchange between the mixture and the elements which form the combustion chamber, and their deep black color considerably increases the heat transfer by means of radiation [1]. This means that, in comparison with the deposits in the use of leaded petrol, we have higher temperatures of the elements which surround the engine combustion chamber and the higher temperatures of the cooling medium. These deposits do not have significant lubricating properties, nor the effect of the shock absorber when the valve hits its seat. The damage of the valve seat of engines has shown not to appear in the normal everyday use of the vehicle. The case of the damage of the valve seat which lead to the engine failure was noticed only on the laboratory acceleration tests, when the engine worked under the constantly high operation load [2]. In such conditions, it has been shown that the valve was not considerably damaged. Also, the previous accumulation of lead deposits and an increased amount of burnt oil deposits on the valves and the valve seats in older engines, prevent the occurrence of micro-welds in the contact metal to metal.

On the other hand, the mechanism of overheating and damaging of the exhaust valves and pistons when unleaded petrol is used, could be related to the statement that the mixture of air and high-octane petrol combusts slowly. The increase of the percentage of carbohydrates resistant to detonation (aromatics) on the account of the percentage of carbohydrates apt to detonation (some paraphines and olephines) increases the resistance of the mixture to detonative combustion [3, 4], as well as the combustion speed [3]. On the other hand, carbohydrates with different structures and different number of the Carbone atoms have different vaporization characteristics, which can reflect on the differences of the homogeneity of mixture, which makes one of the major influences on the combustion speed.

The duration of each of the three theoretical combustion phases in the Otto engines depends on numerous factors and is explained in full detail in [5]; however, only the direct impact of the octane rating of the used petrol will be highlighted here. The induction period or the ignition delay period, is known to be directly dependent on the temperature of the aspirated mixture and the temperature of the mixture compressed in the cylinder is related to the increase in the pressure during the compression. In the Otto engines with a principally lower compression ratio, the temperature is lower too, since the suppressed air pressure is lower at the time when the spark plug starts the ignition of the petrol mixture. In using the petrol with the declared octane number, this temperature is sufficient to complete petrol vaporization and the pre-flame reactions. However, due to a different chemical composition, high-octane petrol could require higher temperatures for the regular process of the induction period. Because of that, the insufficiently high temperature of the compressed mixture could cause the extension of the Induction phase of combustion. The speed of chemical reactions is of primary importance for the duration of the main combustion phase. If the ratio of the excess air is fixed, the duration of this period depends on the chemical composition of the petrol. In the third phase of the combustion process, the petrol which was not burnt in the second phase burns down. These are the particles of the mixture by the cold walls, the elements of lean mixture and dissociated products of combustion. The potential elongation of first two periods would lead to a shifting of combustion periods deeper in the expansion stroke and, in this way, to higher temperatures of the combustion products and the remaining small amount of unburnt mixture. This would also increase the amount of heat delivered to the coolant through the combustion chamber elements and transferred to other engine parts. Based on the above analysis, we come to a conclusion that, when the engines of older design are concerned, the use of high-octane petrol types theoretically really leads to the overheating of the engine, which is partly due to the prolonged combustion process.

In order to check the hypothesis on the different combustion speed of the low-octane (MB 86) and the high-octane (BMB 95) petrol, this paper presents the original procedure of the laboratory measurement of pressure flow in one of the cylinders of the STEYR-PUCH model 712 and GAZ 41 engines as well as the temperatures of exhaust gases with both types of petrol. Additionally, an attempt was made for these, and similar engines to find the optimal pre-ignition angles suitable for the majority of the exploitation conditions with the fuels of higher octane values so that the best use of the potentials of the new, higher quality petrol is achieved in order to improve the general performance of the engine. This would also fulfill the author's main goal here, to give a modest contribution to researchers' current efforts to improve the energetic and ecological efficiency of internal combustion engines [10-13].

Object of examination

The comparative review of the basic technical characteristics of the tested STEYR-PUCH model 712 and GAZ 41 engines is given in tab. 1. The STEYR-PUCH model 712 engine was selected as a typical representative of the “Western School” in the design and manufacture of the engine (Austria), whereas the GAZ 41 engine was selected as the representative of the “Eastern School” (the Former Soviet Union). The GAZ 66, ZIL 130, ZIL 375, and ZIL 157 engines are very similar in construction to the GAZ 41 engine, with the unified key components and similar or identical compression ratios. This is indicative of the fact that it is possible to claim, and that with a great certainty, that these engines will work similarly to the GAZ 41 engine, when power petrol is changed. The ignition distributors on the engines of the “Soviet” program are equipped with the so-called octane (mechanical) corrector, *i. e.* a mecha-

Table 1. Comparative overview of the basic characteristics of the tested engines

Characteristic	STEYR-PUCH model 712 engine	GAZ 41 engine
Overall volume	2499 cm^3	5530 cm^3
Stroke of the engine	Four stroke engine	Four stroke engine
Compression ratio of the engine	7.5	6.7
Required static pre-ignition angle for petrol MB 86	From 0° to 1.4°	4°
Construction of the engine	L4	V8, 90 deg. angle
Maximum power at rpm	64 kW (87 hP), 4000 rpm	103 kW (140 hP), 3200 rpm
Maximum torque at rpm	176 Nm (18 kpm), 2000 rpm	353 Nm (36 kpm), 2000-2500 rpm
The order of ignition	1-2-4-3	1-5-4-2-6-3-7-8

nism with the angular division which, if necessary, can be used for manual correction of the static pre-ignition angle without using special tools or devices. The STEYR-PUCH 712 model engine is specific because its original version was designed for the exploitation with 93-octane petrol. Subsequently, the compression ratio was reduced from 7.8 to 7.5 so that driving with the the octane numbers ranging from 86 to 88 could be made possible.

Description of the used measuring equipment

The schematic diagram of the measuring equipment used for monitoring and the acquisition of the quickly variable parameters of the STEYR-PUCH model 712 and GAZ 41 engines in real-time is shown in fig. 1. For these experiments, the usual procedure [6, 7] was used, by having one of the spark plugs replaced by a special spark plug with an integrated piezoelectric pressure sensor, made by Kistler, together with the simultaneous use of the vibration sensors – accelerometers (type 4321 Bruel & Kjer). The location of these sensors on the engine GAZ 41 is shown in fig. 2, where the accelerometer is marked with number 1, and the special spark plug with number 2. Later, after the processing of the measurement results, the frequency spectra of the signal amplitudes of the vibrations were obtained by application of the fast Fourier transform (FFT).

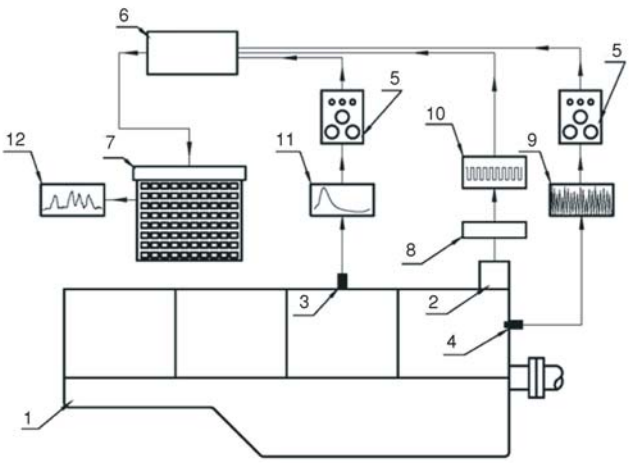

Figure 1. Schematic view of the measurement equipment used for the tracking and acquisition of quickly variable parameters in real time
1 – engine, 2 – distributor, 3 – piezoelectric pressure sensor integrated in the spark plug, 4 – acceleration sensor, 5 – amplifier of charge, 6 – NI USB 6210 device, 7 – computer with a developed LabView application for data acquisition, 8 – generator of the rectangular signal with distributor, 9 – signal from the accelerometer, 10 – rectangular signal from the distribution, 11 – signal from the piezoelectric pressure sensor, 12 – FFT diagram of the signal from the accelerometer

Figure 2. The arrows show the locations of the vibration sensors – the accelerometer (Bruel & Kjer type 4321) and the spark plugs with an integrated piezoelectric pressure sensor (Kistler) on the GAZ 41 engine

A particular problem was how to rely these parameters measured in real-time can be related to the working process of the engine. This problem was not solved by applying the incremental encoder of the position of the crankshaft [6-9]; a special electronic block was designed and made instead, and it was connected with the primary of the ignition circuit of the distributor, and it produced the rectangular impulses with the amplitudes of up to approximately 4 V. The ascending slope of the impulse was formed synchronously with the initial jumping of the sparks across the gaps of the spark plugs of the engine, *i. e.* when the first higher amplitude of the voltage with a damped oscillatory character was induced on the primary of the ignition circuit of the distributor (fig. 3). The principal scheme of this block is shown in fig. 4. A line of regular rectangular impulses of the same intervals (≈1.2 ms) synchronized with the jumping of the sparks across the spark plugs was obtained at the end of the block.

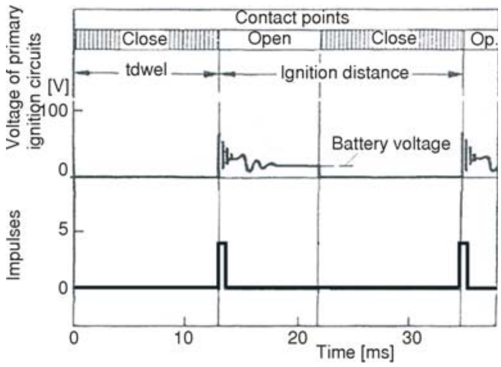

Figure 3. The voltage change of the primary of the ignition circuit of the distributor and the rectangular impulses generated in the electronic block

A very high sampling frequency of 60 kHz enabled the obtaining of the FFT diagram within the measurement range from 0 to 30 kHz. Since both engines were mostly tested at the minute number of the engine speed of 2500 rpm, the selected sample size number of 18000 enabled the recording of the data of the five, and in some cases six consecutive cycles per one measurement. There was no possibility nor the need, to perform the calibration of the signal from the accelerometer and to translate it into the appropriate acceleration unit [ms^{-2}], so that the original electrical measurement – voltage, and the appropriate measurement unit volt (V) were kept.

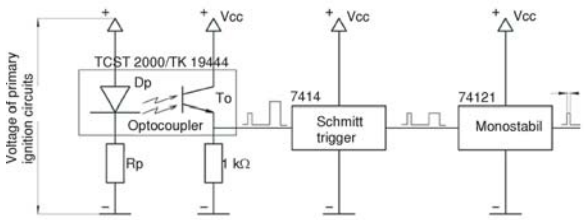

Figure 4. The principal scheme of the electronic block which produced the rectangular voltage signals synchronized with the sparks jumping on the spark plugs of engine

Figure 5 shows a typical example of measured "row" data during one measurement session on the GAZ 41 engine.

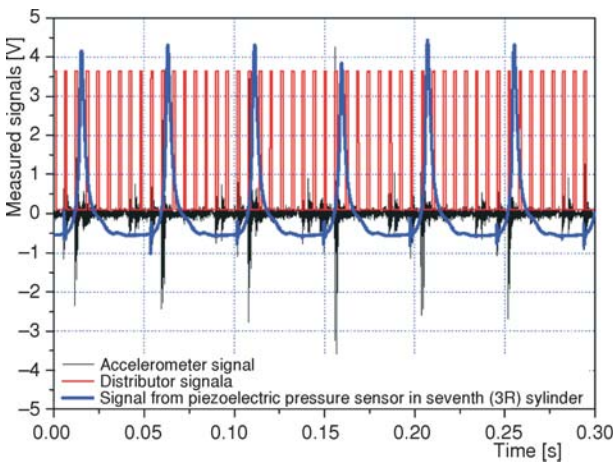

Figure 5. The typical diagram of the measured signals on the GAZ 41 engine recorded
(for color image see journal web site)

Information obtained from these measurements

The generated rectangular impulses from the distributor, synchronized with the moments of sparks jumping across the individual cylinders of the engine, enabled the "cutting out" of the parts specific for one cycle of the engine from the recorded databases (fig. 5) as well as generating a series of new diagrams (databases) which can be analyzed separately. Key information is contained in the first 0.01 second when the working processes were going on in the cylinders of the tested engines.

The first important information obtained from these diagrams (databases) is related to whether combustion in the observed cylinder was performed regularly or there was detonation. Figure 6 shows the pressure flow during five consecutive working cycles of this engine when the working process was followed by a series of detonative combustions, their mean value and the mean value of the accelerometer signal. Cycle variations of the pressure are evident. The increased amplitudes of the mean value of the accelerometer signal, which was partly without "the noise" in that way, correspond to the measured oscillations of the cylinder pressure in cylinder during the combustion process, even deeply in the expansion stroke, which, by itself represents a phenomenon that once more speaks for the high complexity of thermal and dynamic occurrences during detonation. The FFT analysis of the accelerometer signal during the five consecutive cycles, and their mean value helps us to clearly notice the higher level of the amplitudes at frequencies of around 7.5 kHz to 8.5 kHz. The frequency range of 7.5 kHz to 8.5 kHz is, therefore, the frequency range in which the higher level of the amplitude of accelerometer signal is indicative of the occurrence of detonation, with STEYR-PUCH 712 engine.

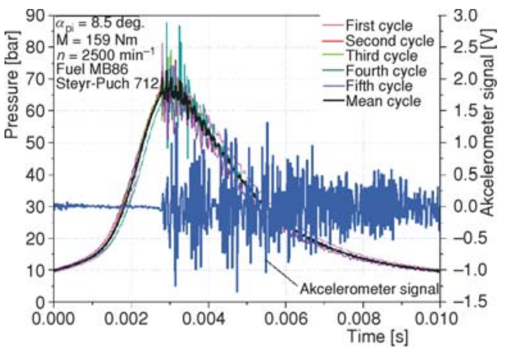

Figure 6. The flow of cylinder pressure and accelerometer mean signal of the accelerometer during five consecutive working cycles with detonative combustion in the STEYR-PUCH 712 engine at maximal load (α_{pi} = 8.5 deg., MB 86 fuel) (for color image see journal web site**)**

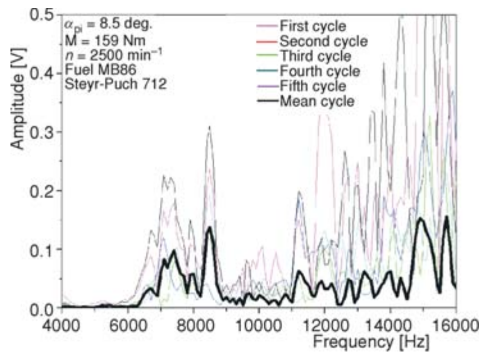

Figure 7. FFT analysis of accelerometer signals during five consecutive working cycles with detonative combustion in the STEYR-PUCH 712 engine at maximal load (α_{pi} = 8.5 deg., MB 86 fuel) (for color image see journal web site**)**

A similar analysis can be carried out for the GAZ 41 engine. Figure 8 shows the flow of the pressure and the signals from the accelerometer for three consecutive working cycles in the regime close to the maximum moment when using petrol BMB 95, with a static pre-ignition angle of 14 degrees. Detonation was not noticed in any of the cases. Using the petrol of a lower octane number (MB 86), in the same testing conditions, the detonation of different intensity was frequently registered on the engine. One such case, for three consecutive working cycles, is shown in fig. 9.

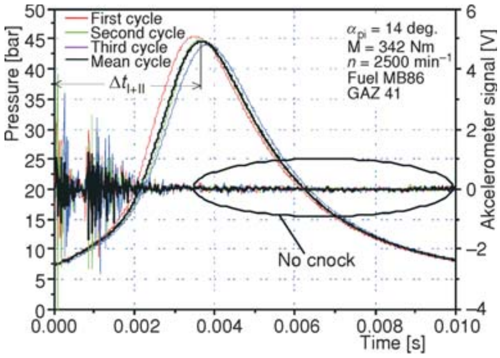

Figure 8. Flow of cylinder pressures and accelerometer signals during three working cycles of GAZ 41 engine without noticeable detonative combustion at maximal torque (α_{pi} = 14 deg., BMB 95 fuel)
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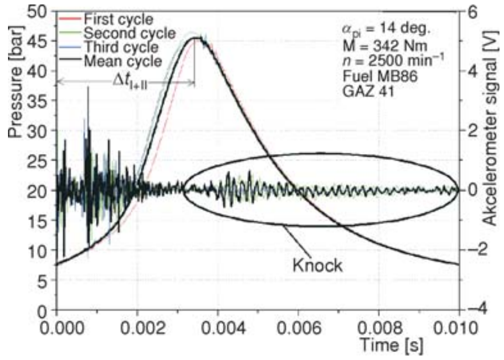

Figure 9. Flow of cylinder pressures and accelerometer signals during three working cycles of GAZ 41 engine with detonative combustion at maximal torque (α_{pi} = 14 deg., MB 86 fuel)
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Figure 10 shows the FFT diagrams of accelerometer signals showed in fig. 8, while fig. 11 shows the diagrams of accelerometer signals from fig. 9, when a detonative combustion occurred for certain. The increased level of the amplitudes in the segment of the diagram in fig. 11, which was about 5.6 kHz, indicates the occurrence of detonation. It can be noticed, similarly to STEYR-PUCH engine, model 712 (fig. 7), that by finding the mean value of the several signals recorded from the accelerometer, the "noise", as a systematic measurement error, is successfully eliminated, whereby the general level of the amplitudes on FFT diagram is considerably reduced.

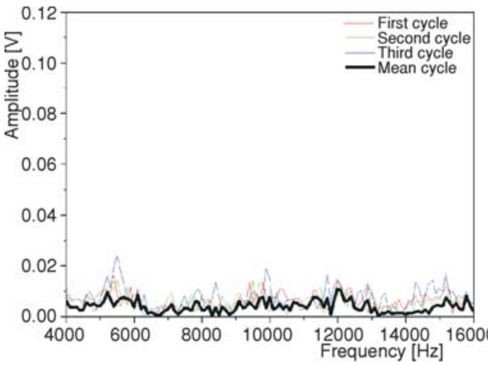

Figure 10. FFT analysis of accelerometer signals showed on fig. 8
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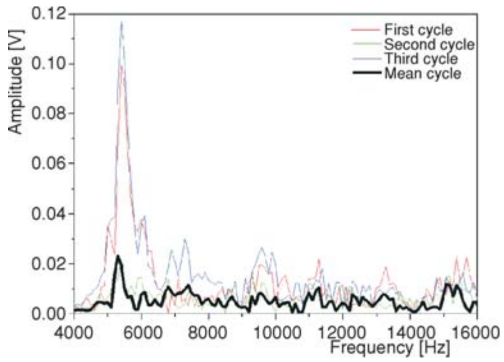

Figure 11. FFT analysis of accelerometer signals showed on fig. 9
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Figures 8 and 9 show that accelerometer signals for two cases (knock, no knock) behave to a great extent, as periodic functions at the same working conditions of testing (the same load and number of revolutions). Minor deviations are primarily the result of the stochastic characteristics of the working processes, as well as the inevitable measurement errors ("noise" in the first place). In both cases, the corresponding FFT diagrams can indicate the regularity of combustion. The crucial difference is noticed in the segments of those diagrams which correspond in the beginning of the last phase of the combustion process in the observed cylinder, and they are presented as eclipses in figs. 8 and 9 so that, even without FFT analysis of the recorded signals, with a little more experience in the analysis of the measurement results, it is possible to distinguish these two cases, and even estimate the intensity of the probable appearance of detonation.

The other important information which was sought for in this research is the answer to the question: are there any differences in the working processes of the engine, while using the fuels with different octane numbers, which clearly indicate to the different combustion speeds?

The principle setup of this study has enabled us to estimate the cumulative duration of the first and the second phases of combustion (the ignition delay period and the period of real combustion), and that value was marked with $\Delta t_{\mathrm{I+II}}$ in fig. 8 and 9. By means of the analysis of the measurement results, it was determined that detonation in the STEYR-PUCH model 712 engine begins during the second theoretical phase of combustion (fig. 6), and in the GAZ 41 engine – during the third phase (fig. 9). This fact made it impossible for us to determine the $\Delta t_{\mathrm{I+II}}$ size with the STEYR-PUCH model 712 engine at the time of detonation, so the focus of this analysis will be on the GAZ 41 engine, where it is possible to estimate the $\Delta t_{\mathrm{I+II}}$ value even when detonation occurs in the cylinders of that engine (fig. 9).

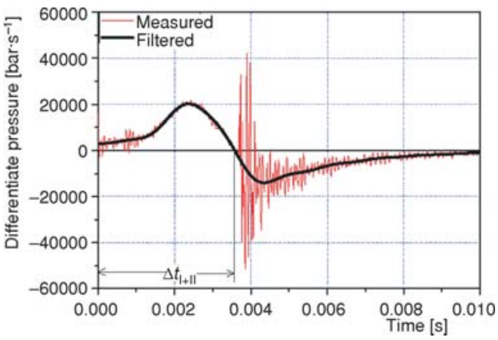

Figure 12. Typical diagram of the change of pressure differential (GAZ 41 engine)

The systematic errors of the measurement of pressure in the cylinders are best shown in the diagram of the derivative (a differential) with respect to time, as shown in fig. 12. It is obvious that the differential of the measured pressure contains a large number of high-frequency pulsations which (except in the case of detonation) cannot be the result of realistic physical and chemical reactions in the combustion chamber, but belong to the systematic measurement errors. By filtering of the pressure differentials, a relatively smooth curve was obtained and its shape is shown as the bold black line in the same figure. The most important thing about the presented filtering is the subsequent mathematical processing of the raw signal by application of the Fourier trigonometric polynomial, *i. e.* the analysis and the synthesis of the raw signal with a definite number of members of that polynomial. For these tests, the first 40 members of the Fourier polynomial were empirically selected. The first section of the pressure differential curve with the abscissa simultaneously helped us to accurately determine the $\Delta t_{\mathrm{I+II}}$ period, since the pressure reaches its maximum at that point.

On the basis of this research, it was not possible to estimate the duration of the third theoretical phase or the cumulative duration of all the three theoretical phases. Far more information could have been obtained if the incremental encoder of the crankshaft position had been included in the measuring chain, too, and if at least one measurement of the pressure changes had been done when combustion failed in the observed cylinder. In that case, by statistical processing, *i. e.* by means of finding the mean value (averaging), we would be able to estimate the duration of every theoretical combustion phase individually. However, even such statistically obtained mean value of the cumulative duration of the first two theoretical combustion phases is very useful and can be used to estimate the differences in the combustion speeds of these two types of fuel.

Test results

Engine STEYR-PUCH model 712

The STEYR-PUCH 712 model engine was being tested with the pre-ignition static angles of 5 degrees, 6.5 degrees, and 8.5 degrees, with both types of petrol, but when the static pre-ignition angle was 6.5 degrees, the engine was not indicated. Figure 13 shows the change in the maximum engine moment on the regime close to the regime of the maximum moment (at 2500 rpm) in the function of pre-ignition static angle for two different types of fuel (MB 86 and BMB 95). Obviously, by application of the petrol with the higher octane number (BMB 95), higher peak torques are achieved in comparison to the MB 86 petrol, and that refers to all the values of the set static pre-ignition angle. The greatest increase in the maximum torque, 5.88%, was obtained under the pre-ignition static angle of 5 degrees, when the largest increase in the nominal power of 3.95% was recorded. This primarily resulted from the fact that high-octane petrol BMB 95 has a higher resistance to detonation while increasing the angle of pre-ignition. Therefore, it was possible to obtain better performance by the increase of the pre- ignition angle.

This is best illustrated by fig. 14, which clearly shows that with the pre-ignition static angle of 5 degrees, in the regime close to the maximum torque, the use of BMB 95 petrol does not bring about detonation and it is possible to achieve the best engine performance. On the contrary, when MB 86 petrol is used, that zone of the pre-ignition static angle practically cannot be of any help, because the working process was not going on regularly in any of the recorded cycles regularly, but rather as a series of intense consecutive detonations in the engine cylinder (fig. 14 shows the most extreme case). With the static pre-ignition angle of 8.5 degrees, milder forms of detonation were also recorded with the BMB 95 petrol.

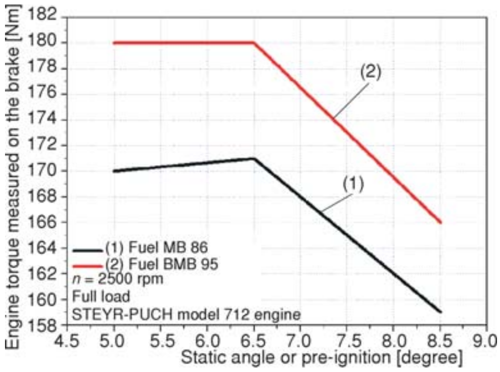

Figure 13. Change in maximum torque at 2500 rpm in the function of pre-ignition static angle for two different types of fuel (MB 86 and BMB 95)

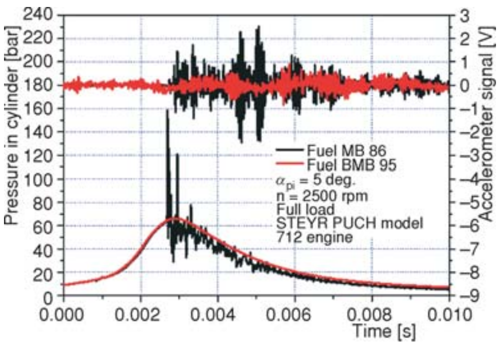

Figure 14. Comparative diagram of the change in pressure and accelerometer signal at 2500 rpm, maximum load and the pre-ignition static angle of 5 degrees with MB 86 and BMB 95 fuels (for color image see journal web site**)**

Engine GAZ 41

The GAZ 41 engine was tested at the pre-ignition static angles of of 4 degrees, 10 degrees, and 14 degrees, with both types of petrol (MB 86 and BMB 95). The angle of 4 degrees was recommended by the manufacturer for the initial regulation after engine overhaul. The angle value of 10 degrees was chosen under the assumption that the engine, tuned in such a way, would have optimal working characteristics, using BMB 95 petrol. The extremely large angle of 14 degrees was chosen for the purpose of testing the resistance of the engine to the occurrence of the detonation.

Figures 15 and 16, respectively, illustrate the effect of the static pre-ignition angle and the type of petrol (MB 86 and BMB 95) on the maximum torque and the torque at the nominal working regime. Obviously, the maximum torque (fig. 15) reaches its maximum value at the static pre-ignition angle of 10 degrees and with the both types of petrol, with the difference that, when using the BMB 95 petrol at that regulation, detonation is totally avoided, whereas the use of the MB 86 petrol occasionally brings about mild detonations. Intensive detonation at the regime of the maximum torque was recorded at the static pre-ignition angle of 14 degrees, with the use of 86 MB petrol, while with the use of BMB 95 petrol, no detonation was recorded even in that case. With the pre-ignition angle of 10 degrees, the maximum nominal power is obtained if unleaded BMB 95 petrol is used (fig. 16). Although these benefits are not great and, according to their values (1.46% and 1.66%) are close to the measurement error, there is a clear tendency for such a regulation in the GAZ 41 engine to represent the optimal regulation, when BMB 95 petrol is used.

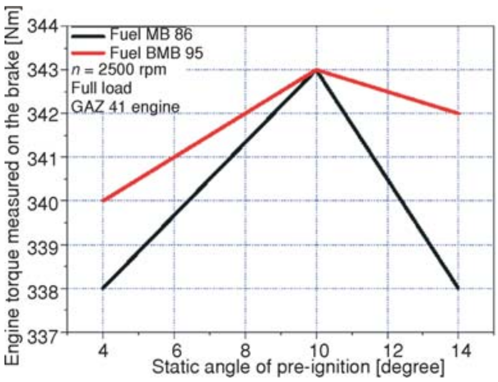

Figure 15. Dependence of the GAZ 41 engine maximal torque, measured on brake, on the set value of pre-ignition static angle for MB 86 and BMB 95 fuels

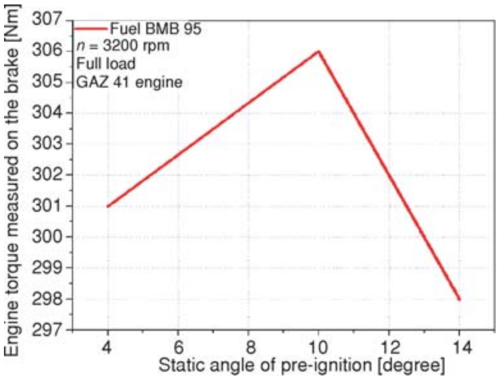

Figure 16. Dependence of the GAZ 41 engine maximal torque, measured on brake, on the set value of pre-ignition static angle for BMB 95 fuel at nominal regime (3200 rpm)

With the GAZ 41 engine, by establishing the mean value, from the measured, then processed and filtered diagrams of the pressure, the cumulative duration of the first and the second theoretical phase of combustion ($\Delta t_{\mathrm{I+II}}$) was estimated. Such estimation, at the regime of the maximum torque of the GAZ 41 engine in the function of the pre-ignition static angle when using MB 86 petrol and BMB 95 is shown in fig. 17. All the key points in this diagram were obtained by measuring and averaging about 50 working cycles, except for the point regarding the 95 MB petrol at the pre-ignition static angle of 14 degrees, which was obtained as the mean value of the nine working cycles altogether that could reasonably be "cut" so that we could recognize the beginning (the spark jump) and the end (the next spark jump). Namely, this "point" was obtained almost at the end of the measurement when the measuring devices had already been rather heated and oversaturated, so it happened that the key rectangular voltage signals from the ignition distributor were not always generated. Therefore, this segment of the diagram is represented by a broken line, and the accuracy of its assessment is disputable. This analysis shows that the average duration of the first two theoretical phases of combustion is significantly longer when BMB 95 unleaded petrol with the higher octane number is applied in relation to the MB 86 low-octane petrol.

A similar dependency is given in fig. 18 as well, with a difference in the fact that the average duration of the first two phases of combustion in the degrees of the crankshaft angle ($\Delta\alpha_{I+II}$) was estimated here. For the each "cut-off" cycle, this data was obtained through a clear proportion based on the total number of the measured points of the files related to the observed cycle and the ordinal number of the point at which the second theoretical phase of combustion was completed in that cycle, and then the averaging of all the related data (the same static angle of pre-ignition and the same petrol) was done. The fluctuations of the angle crankshaft speed could not be taken into consideration, which reduces the accuracy of this estimation, but the relatively small "error" is almost the same for all the estimated values. The disputable part of the diagram whose estimation is not sufficiently reliable is presented by the broken red line here, too. According to the calculations, the cumulative duration of the first two theoretical phases of combustion calculated by the crankshaft angle at the pre-ignition static angle of 4 degrees is about 1.94 degrees of the crankshaft higher when unleaded petrol BMB 95 is used, in comparison to 86 MB petrol, and the pre-ignition static angle of 10 degrees is by 1.81 degrees of the crankshaft higher.

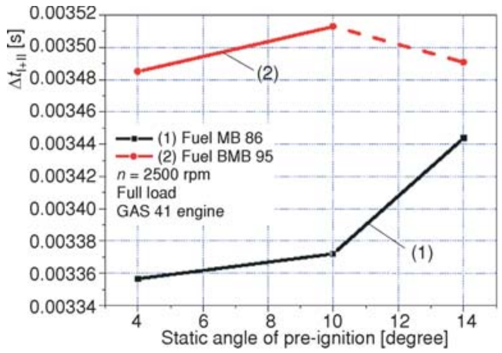

Figure 17. Distance between the moment of spark jump and reaching of the maximum pressure in the cylinder, in function of time, when using MB 86 and BMB 95 fuels

The obtained experimental data show that, for higher-octane fuel (BMB 95), one (perhaps even both) of the first two theoretical phases of combustion, lasts longer, in relation to MB 86 lower-octane fuel. Due to the mentioned conceptual limitations of this experiment, the contribution of each of these phases to the total longer duration of the combustion process could not be determined. As a consequence of a higher shift of the mean maximum value of the pressure in the GAZ 41 engine cylinder, and perhaps of longer duration of the third theoretical phase

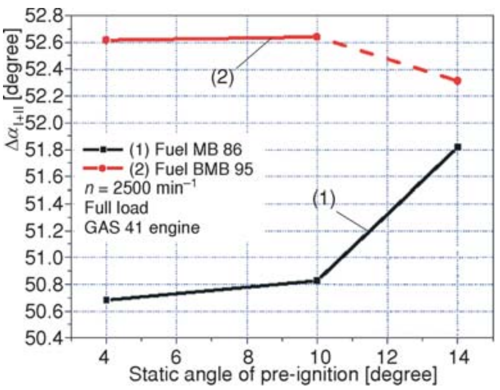

Figure 18. Distance between moments of spark jump and maximum pressure in the cylinder, estimated in the function of the crankshaft angle, when using MB 86 and BMB 95 fuels

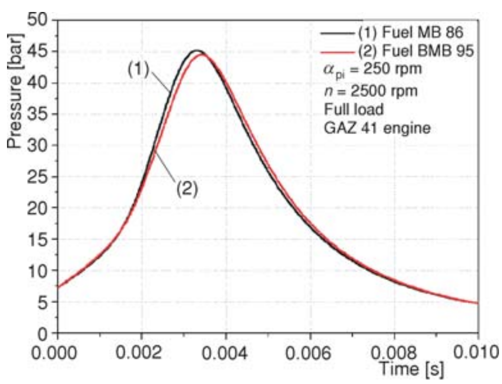

Figure 19. Mean cycles of pressure change in the same test conditions (α_{pi} = 4 deg., n = 2500 rpm, full load), but with different types of fuel (MB 86 and BMB 95)

of combustion, the curve of the expansion is generally shifted more to the right when BMB 95 petrol is used, as compared to 86 MB petrol, which is clearly shown in fig 19. The curves in fig. 19 represent the average values of the pressures measured in the cylinder under the same test conditions (α_{pi} = 4 deg., n = 2500 rpm, full load), but with different petrol types (MB 86 and BMB 95) and , at the same time, show the manner in which the initial points of the broken lines shown in fig. 17 were obtained. The comparison of the shapes of the curves is indicative of the fact that higher pressures during the expansion stroke can actually lead to higher temperatures of the combustion products, and therefore higher temperature of the exhaust gases of the GAZ 41 engine, which is exactly the same as the experimentally obtained data, illustrated by the diagrams presented in figs. 20 and 21. It can be noted that the value close to 10 degrees is imposed here, too, as the optimal static pre-ignition angle at which the temperatures of exhaust gases are the lowest when the high-octane petrol BMB 95 is used. The increase, in comparison to the case when MB 95 is used, is also the lowest furthermore, that is the value at which the best performances of the GAZ 41 engine at nominal working regimes were obtained (fig. 15 and 16).

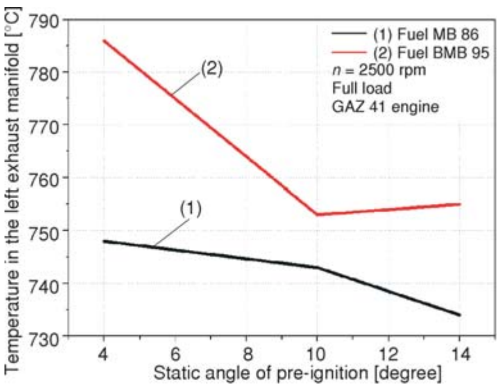

Figure 20. Dependence of exhaust gases temperature in the left exhaust manifol, on pre-ignition static angle and the type of the used petrol at maximal torque regime

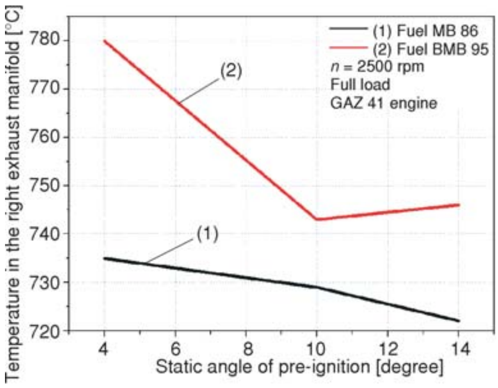

Figure 21. Dependence of exhaust gases temperature in the right exhaust manifold on pre-ignition static angle and type of used petrol at maximal torque regime

Cycle variations of the cumulative duration of the first and the second theoretical combustion phase and estimation of measurement error

Figure 22 presents the cycle variations of the time passed from the moment of the spark jumping, to the moment of reaching the maximum GAZ 41 engine pressure, *i. e.* the cumulative duration of the first and the second theoretical combustion phase (Δt_{I+II}), the measured data which helped us to obtain the mean values presented in fig. 19. Vertical columns in fig. 22 represent the number of cycles at which Δt_{I+II} exists at the time interval shown on the abscissa. For MB 86 petrol, the majority of the cycles whose Δt_{I+II} exists at the time interval from $33\cdot10^{-4}$ to $34\cdot10^{-4}$ seconds (16 of the total number of 53), where there is also the mean value, which is $33.5661\cdot10^{-4}$ s. This is not the case with the BMB 95 fuel. The mean value Δt_{I+II} in this case is $34.8501\cdot10^{-4}$ s, and it is in the same range of $34\cdot 10^{-4}$ to $35\cdot10^{-4}$ s as well as 8 of the 50 recorded cycles, but there are more recorded cycles in the next left and the next right range (11, *i. e.* 12).

Statistical data about the deviancies for these two cases are given in tab. 2. Almost identical situation is repeated with the static pre-ignition angles of 10 and 14 degrees.

This analysis clearly shows that the cycle variations of the values of the maximum pressure when using BMB 95 fuel are somewhat more intense in relation to MB 86 fuel. The cycle variations of the values of the maximum pressure were not analyzed out of two reasons: the first is that they were not important for this research, and the second is the fact that it is very difficult to estimate the real pressure flow in the cylinder based on the signal from the piezo-sensor, without the simultaneous application of the incremental sensor.

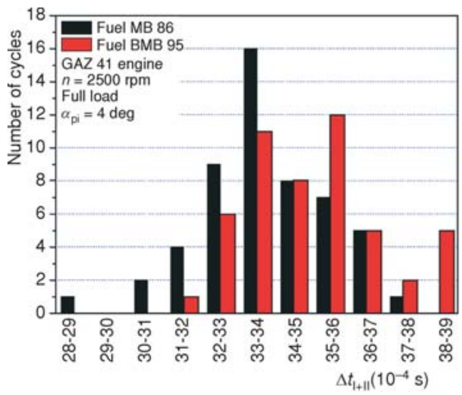

Figure 22. Cycle variations of the cumulative duration of the first and second theoretical combustion phase (Δt_{I+II}) of the GAZ 41 engine for α_{pi} = 4 degree when using MB 86 and BMB 95 fuels

Table 2. Statistical data on the deviation

Fuel	Standard deviation	Variation	Coefficient of variation	Mean absolute deviation	Median
MB 86	4.90	24.01	0.92	3.76	4.50
BMB 96	3.92	15.36	0.63	3.06	5.50

Table 3. Number of points (columns) in "cut off" files

Fuel	Ordinal number of measurement									
	1	2	3	4	5	6	7	8	9	10
MB 86	2890	2885	2859	2872	2876	2869	2883	2873	2886	2868
	2878	2884	2857	2876	2878	2872	2879	2870	2884	2866
	2876	2885	2855	2875	2879	2872	2880	2868	2884	2866
	2878	2888	2860	2874	2877	2874	2876	2869	2888	2867
	2878	2885	2860	2878	2874	2875	2879	2867	2888	2868
				2879	2880				2887	
BMB 95	2874	2883	2875	2886	2874	2868	2874	2876	2865	2868
	2877	2879	2875	2879	2878	2866	2878	2873	2886	2875
	2873	2881	2872	2885	2873	2868	2877	2874	2873	2886
	2876	2880	2875	2876	2875	2867	2874		2873	2869
	2875	2878	2862	2885	2875	2869	2885		2873	2875
	2878						2874			

The estimation of the measurement mistake of the Δt_{I+II} value is based on the number of points (rows) contained in the "cut off" databases during one measurement session, where the points are supposed to represent engine operating cycles, one by one. In tab. 3, the data for the databases are given on the basis of which mean pressure curves presented in fig. 19 were created. It is obvious that the databases have different lengths, which indicates that the systematic measuring errors are present. The length of the "cut off" databases depends on the sampling frequency, the actual engine revolution number and the spark jumping moment across the spark plugs of the engine. With the desirable revolution number of 2500 rpm and the sampling frequency of 60 kHz, every database would ideally have 2880 points. Deviation of the revolution number by ±10 rpm would bring about the deviation of the number of points by ±11.5 on average. If we analyze the values shown in tab. 3, it can be noticed that the variations of the lengths of the recorded databases in one row, *i. e*. one measurement session when the average revolution number was approximately constant were not so big, and resulted, in the first place, from the cycle variations of the moments of the spark jumping across the spark plug. These variations depend on the clearance in bearings of the driving shaft of the ignition distributor in the first place. The average number of points in the databases obtained in the research with MB 86 fuel was 2875.055, and with BMB 95 fuel it was 2874.843. Mean deviation from these mean values was, in the case of BMB 95 fuel, between –2.655 (–0.093%) and +2.645 (+0.092%) points and, in the case of BMB 95 fuel, it was between –4.043 (–0.104%) and +4.157 (+0.144%) points. This means that the mean values of the "length" of databases in relation to the mean value in the case of MBM 86 fuel are between $-4.425\cdot 10^{-5}$ s and $+4.408\cdot10^{-5}$ s, and, in the case of MBM 95 fuel, they are between $-6.738\cdot10^{-5}$ and $+6.928\cdot10^{-5}$ s. Extreme deviations for MB 86 fuel were –4 points (–0.139%) and +5 points (+0.173%), and for BMB 86 fuel –9 points (–0.313%) and +8 points (+0.278%). This means that the measured lengths of databases, in extreme cases varied between $-6.667\cdot10^{-5}$ s and $+8.333\cdot10^{-5}$ s with MB 86 fuel, and between $-1.5\cdot10^{-5}$ s and $+1.33\cdot 10^{-5}$ s with BMB 95 fuel. The "length" of $\Delta t_{\mathrm{I+II}}$ period is more than 12 times shorter than the "length" of the whole working cycle, and the number of points which make it is approximately proportionate to the total number of points during the whole cycle, so the measuring error is approximately proportionate to the total number of points during the whole cycle.

This means that the period $\Delta t_{\mathrm{I+II}}$ for the beginning points on the broken lines shown in fig. 17 is estimated with approximately the same percentage of the mean and maximum values of the measuring mistakes which were obtained in the estimation of the lengths of operating cycles.

Conclusions

This paper presents the results of the experimental tests of combustion process in the two gasoline engines of older generation, on two different engines (STEYR-PUCH model 712, and GAZ 41) in the conditions of changing from MB 86 petrol to the unleaded MB 95 petrol.

The following rather important conclusions can be highlighted here.

- Increasing the static pre-ignition angle by 5 degrees (STEYR-PUCH 712 model engine), and by 6 degrees (GAZ 41 engine) when petrol BMB 95 is used, makes it possible for the engines to work without detonation. Such a regulation of the pre-ignition angle in the case of STEYR-PUCH 712 model engine whose compression ratio is 7.5, enables an increase in the maximum torque by 5.88% and the nominal power by 3.95%. In the GAZ 41 engine, the percent of the increase in the maximum torque is 1.46% and 1.66% in the nominal power, because of the smaller compression ratio (6.7).
- The appearance of detonation was detected by the comparative analysis of the signals from the piezoelectric pressure sensors and the accelerometer signal. It was shown that the signal from the accelerometer behaves to a great extent as a repeatable, periodic function in approximately the same working conditions. It is also shown that that, by a comparative, and especially the FFT analysis of the signals we can clearly make difference between the cases of the regular combustion, and the combustion with detonation. The appearance of

detonation is characterized by an increased level of amplitudes in the FFT spectrum of these signals at frequencies of around 7.5 kHz, up to 8.5 kHz, for the STEYR-PUCH engine model 712, and 5.6 kHz, for the GAZ 41 engine.

- It was explicitly shown that, when the fuel of a high-octane number (BMB 95) is applied, the first two theoretical phases of combustion last longer, when compared with the MB 86 low-octane fuel. Expressed by the crankshaft angle: with the static pre-ignition angle of 4 degrees, that increase is by about 1.94 degrees of the crankshaft higher when petrol BMB 95 is used, as compared to the MB 86 petrol type, and with the static pre-ignition angle of 10 degrees, the cumulative duration is higher by 1.81 degrees of the crankshaft. As a consequence of a bigger shift of the mean maximum value of the pressure in the cylinder of the engine, and perhaps for the reason of a longer duration of the third theoretical phase of combustion too, the curve of the expansion is also generally rather shifted to the right when BMB 95 petrol type is used, comparing with the 86MB petrol type. Higher pressures during the expansion stroke reflect on the higher temperatures of combustion products, and therefore, on the higher temperatures of the elements of the combustion chamber and exhaust gases. With the regulation where the pre-ignition angle was 10 degrees, with the GAZ 41 engine and BMB 95 fuel, the least increase in the temperature of exhaust gases was obtained, so this regulation proved to be optimal even in that respect.
- Hypothesis on the greater thermal load of the engine working with the fuel with a higher octane number was not scientifically proved, because it implies an expensive, long- lasting research, but the results from this experiment indicate to that possibility.
- The cycle variations of the position of the pressure maximum in cylinder with the application of BMB 95 fuel are slightly more intense, in relation to the variations when MB 86 fuel is used.

Nomenclature

BMB 95 – petrol without lead alkylates 95 declared octane number
Dp – TCST 2000 photodiode
FFT – fast Fourier transformation
MB – 86 petrol with lead alkylates 86 declared octane number
Rp – TK 19444 resistor
To – phototransistor
$\Delta t_{\mathrm{I+II}}$ – cumulative duration of the first and second theoretical combustion phase
Vcc supply voltage (5 V)

Greek symbols

α_{pi} – pre-ignition static angle
$\Delta\alpha_{\mathrm{I+II}}$ – cumulative duration of the first and second theoretical combustion phase in function of crankshaft angle

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