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Michal PUŠKÁR[1], Melichar KOPAS[2], Dušan PUŠKÁR[3]

INFLUENCE ANALYSIS OF DETONATIONS RELATED TO OUTPUT CHARACTERISTICS AND TO DAMAGE LEVEL OF ENGINE PARTS IN ORDER TO ELIMINATE POTENTIAL RISKS AND ENSURE RELIABILITY OF THE HCCI TECHNOLOGY

Summary. The engine output characteristic offers very important information during the real application of the HCCI technology. This kind of combustion process significantly influences the wearing degree of the main engine components or even the engine damage. The principle of the HCCI combustion is basically beneficial, however, it can also be destructive. Described in this article are measurements of the engine output characteristics in the case of an experimental piston combustion engine. These measurements were performed by means of a data recording system, whereby the detonation combustion was evaluated using a quantitative method. The real values of atmospheric conditions and fuel mixture composition were added to the measured values. The resulting values were visually compared with a degree of the engine piston damage caused by the detonations. The final result is a limit value, which represents a maximal

[1] Faculty of Mechanical Engineering, Technical University of Košice, Letná 9, 04001 Košice, Slovakia. Email: michal.puskar@tuke.sk
[2] Faculty of Mechanical Engineering, Technical University of Košice, Letná 9, 04001 Košice, Slovakia. Email: melichar.kopas@tuke.sk
[3] Faculty of Mechanical Engineering, Technical University of Košice, Letná 9, 04001 Košice, Slovakia. Email: dusan.puskar@tuke.sk

number of the detonation units that are permissible in order to ensure reliable operation of the HCCI engine.
Keywords: analysis, detonation, reliability, HCCI technology

1. INTRODUCTION

A normal combustion is a regulated one of a mixture of fuel and air in a combustion chamber. It is stable combustion, which develops at a spark plug and continues in a combustion chamber in a three-dimensional way.

A detonation is a phenomenon, which is classified as an abnormal combustion. It is an auto-ignition of a residual mixture of fuel and air in a combustion chamber. It occurs after a normal combustion. At an initial phase, there is normal mixture combustion, then under the influence of high pressure and heat, there are the spontaneous ignitions, hence, detonation combustion [1].

Detonations induce high pressure in a combustion chamber. This pressure is very short time. In a combustion chamber, the pressure behaviour seems to be normal with increasing development and then the pressure increases evidently. The rapid increase of pressure is indicated as the excesses in comparison with a normal one. These excesses intensify the pressure which causes detonation combustion. Also, the rapid increase of pressure amplifies the forces in a combustion chamber which induces the resonances in the engine design. These resonances are characterised for detonation combustion. The noise or vibrations present the phenomenon, which is recorded with a detonation counter [2-10].

It is important to know that detonation need not be necessarily destructive. Many engines work with a certain number of detonations. Some engines can stand strong detonations for a very long time without destruction. The control detonation combustion is useful because it increases engine output performance. The aim of this contribution is the measurement of output characteristics of a high-speed racing engine, which was performed by means of a data-recording system and the detonation combustion was evaluated using a quantitative method. Next aim was to find a limit where an examined engine produces the highest performance but which the detonation combustion does not damage its design components. Furthermore, there is the consideration of the influence of detonation combustion on maximum values of an output performance and torque as well as their behaviours depending on the engine speed.

2. EXPERIMENTAL MODEL AND MEASURING DEVICES

The detonations are influenced by the design of the combustion chamber (a shape, a size, geometry, a replacement of spark plug), compression ratio, proportion of air and fuel in a combustion mixture, shape of the ignition curve, atmospheric conditions and the octane number of the fuel [11]. If the surface of a piston or the combustion space is damaged or destroyed, detonation combustion may start also in such conditions, which are not critical, but this damage effects directly as an initiator of detonation combustion. The engines, which are exposed over time to detonation combustion, tend to overheat themselves which initiates an avalanche effect. The higher the temperature, the faster the detonation combustion and consequently, the faster the destruction. The piston absorbs a great deal of heat, on four sides causing dilatation which can induce destruction [12]. The combustion temperatures are very high in the moment of detonation ignition which causes the melting down of the piston and combustion space materials [13,14].

For this reason, it is difficult to determine theoretically the limit for detonation combustion and then prove its authenticity for a petrol engine. Although there is a software for modelling of the processes operating inside a cylinder and an exhaust system during combustion, the real results are seriously performed [15,16].

This is the reason the experiment was used to achieve the main aim. It is necessary to choose the experimental model for experimental measurements. The development was realised with this experimental model. Furthermore, there is the need to choose the measurement devices (to provide feedback; to give information about a real output proposition for a concrete change in detonation combustion).

The petrol combustion engine with capacity 125 cm^3 was used as the experimental model. Two testing and measuring devices were developed for the need of the experimental measurements.

2.1. Engine Watch and Control System (EW&C)

This is a data-recording system, that is, a device which scans and stores information during a motorcycle ride (in real conditions, in real loading). This device makes it possible to diagnose the parameters of a combustion engine: an output performance, a torque and their behaviours, the temperature of the exhaust system and its behaviour and other characteristics.

A number and a kind of scanned parameters are related to the types and the number of sensors, which are installed on the combustion engine.

In Figure 1 there is the block diagram for data measurement, operating and evaluation. The engine activity record is dependent on time as a result of this system. The principle of the EW&C system consists of the measurement of instantaneous engine revolutions; an instantaneous temperature of the exhaust system and a reading of an active speed gear or throttle position in the carburettor.

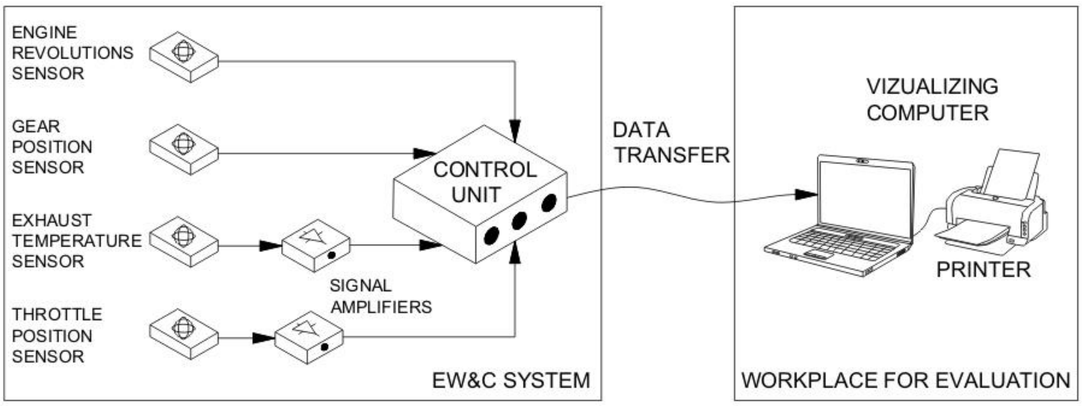

Fig. 1. Block diagram of the EW&C system

The system does a functional record of the engine activity on the basis of scanned and entered data (a wheel circumference, gear ratios of individual speed gears, a curve of air resistance and a motorcycle weight). This record is stored in the memory of the EW&C system. After concluding the measurement, it is possible to copy the record into a PC.

2.2. Detonation Counter

For the measurement of detonations, the detonation counter was used. The detonation counter sensor picks up irregular combustion, therefore, the detonation of the engine and provides a number of detonation units. In Figure 2, there is the block diagram for detonation measurement, operating and evaluation. As shown in Figure 2, in Range A, detonation occurs at a high load (throttle opening 50% to 100%), and in Range B, detonation occurs at a light load (throttle opening close to 50%).

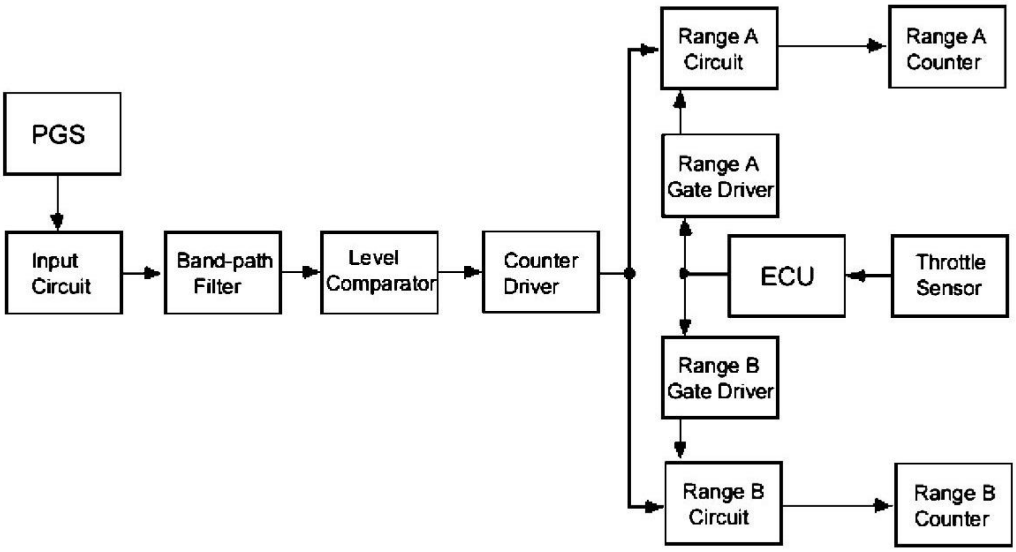

Fig. 2. Block diagram of detonation counter

The PGS (plug gasket sensor) is a pressure sensor which is made from a piezoelectric element and outputs an electric charge according to pressure.

3. RESULTS AND DISCUSSION

The performed measurements are intent on the analysis of the detonation combustion influence with an output characteristic in consideration of the defined aim.

The aim of the consecutive measurements was determined by the limit, expressed in a number of detonation units per an overridden kilometre, where the combustion is beneficial and helps to increase the output performance and does not cause destruction in the design components of the engine.

In the experimental model, these were applied the diagnostic devices, described in the above-mentioned paragraph. The measurements were performed for a racing circuit. The obtained results, which are presented in this paragraph, were verified with multiple consecutive measurements to prevent any potential random error.

In the introduction of the previous paragraph which described the factors which influence detonation combustion. These factors are the design of a combustion chamber (a shape, a size, geometry, a replacement of spark plug), compression ratio, the proportion of air and fuel in a combustion mixture, shape of the ignition curve, the atmospheric conditions and the octane number of the fuel.

Paragraph 2 describes in detail the used shape of an ignition curve and the design shape of a combustion space. These shapes are equal for all measurements. Unleaded petrol with the octane number 100 was applied as the fuel. In Table 1 are the scheduled atmospheric conditions for each of the four measurements and as well as the used compression ratios. In Table 2, there are recorded numerical presentations of the fuel maps.

Tab. 1

Input Conditions

No.	Atmospheric Conditions			Compression Ratio
	Temperature [°C]	Pressure [Pa]	Humidity [%]	
1	27	$97{,}3 \cdot 10^3$	37	14.46
2	21.2	$98{,}2 \cdot 10^3$	36	14.43
3	17	$97{,}5 \cdot 10^3$	65	14.67
4	18.8	$97{,}2 \cdot 10^3$	44	14.71

Tab. 2

Fuel Maps

No.	Throttle Position [%]								
	0÷20	30	40	50	60	70	80	90	100
1	106	106	132	160	188	215	240	265	289
2	106	106	132	160	188	215	240	265	289
3	98	92	130	160	188	215	242	267	292
4	106	109	137	165	193	219	244	269	293

Table 2 contains four fuel maps. In the upper row are the given percentage positions of the throttle. In the left column there is the consecutive number of measurement, so every row represents one map. The numerical value, given for the concrete position of the throttle, represents a flow space. Through this flow space, the fuel flows into the diffusor of the carburettor. Subsequently, in the diffuser, there is an in-flow of fuel mixed with air. These values help in the comparison of various alternatives for fuel maps. If a value is higher then it represents a more overrich alternative for the concrete injection setup and on the other hand, if a value is lower then the mixture is weakened. The fuel maps for the measurements No.1 and No.2 are equal. In the case of the map No.3, it is the mixture weaker at the throttle position up to 40%. At the throttle position over 80%, it is the mixture more overrich than for the maps No.1 and No.2. The map No.4 is fuel overrich in the whole range of the opening with the throttle position from 30%. The fuel volume at the complete opening of throttle position is regulated by means of the main jet, which was 3% smaller at the measurements No.3 and No.4 than it was at the first two.

The measurement No.1 was done during the first testing day in the racing circuit. In Table 1, there are scheduled the input conditions of the measurement and the fuel maps is given in Table 2. In Figure 3, it is illustrated in the record of the EW&C system.

In Figure 3, it is shown in the record of engine activity and the behaviour of engine performance is dependent on the time axis. The time axis is represented in the bottom part of the figure. The engine activity record is represented with an upper curve (saw-tooth type).

On the left axis is the engine speed (revolutions), which makes it easy to define the range of operating speed which the engine operates in. The axis of temperature in the exhaust system is on the right side. The temperature behaviour is represented in the curve given in the lower section of the figure. In this case, the illustrated curve is almost a line because the relevant sensor was inactive.

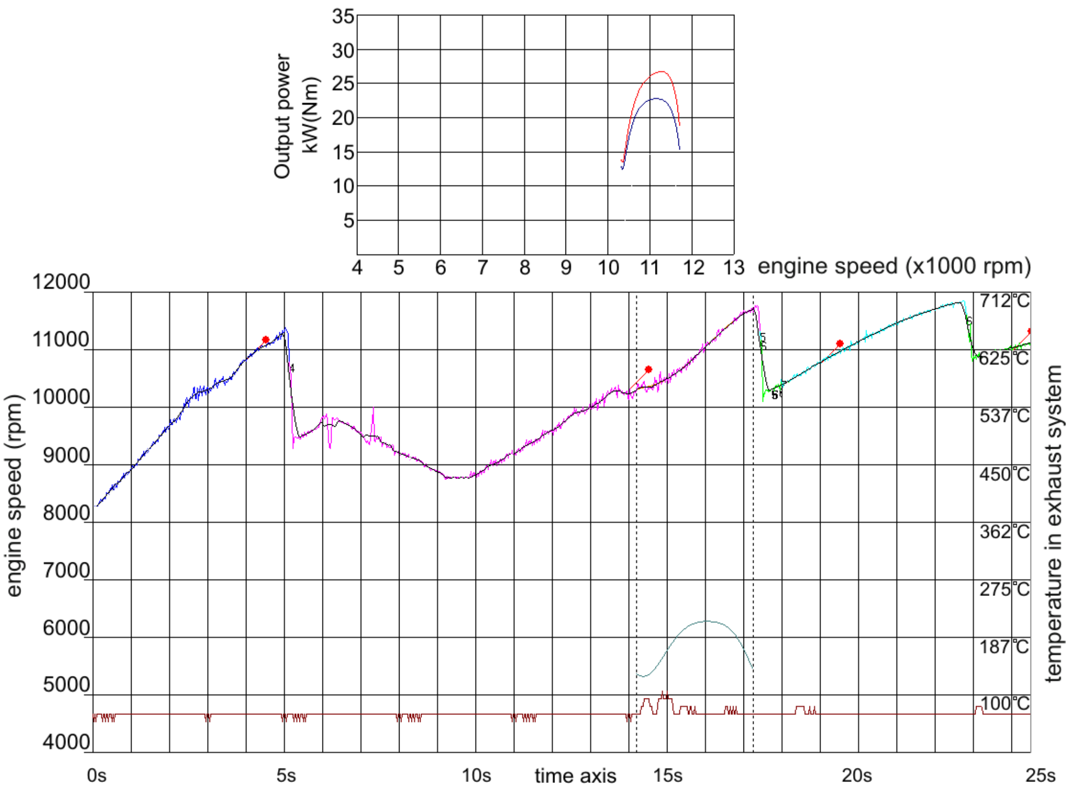

Fig. 3. Activity Record and Output Behaviour of Engine at Measurement No.1

The concrete extent of activity engine record was selected. This extent was terminated on both sides (with dash vertical lines) and then analysed with regards to the output performance. This analysis is illustrated by the graph on top of this figure. The horizontal axis belongs to the engine speed (revolutions) and the vertical axis is for the output performance.

The output performance analysis was done for all measurements at the fourth speed gear. From experience, it is this speed gear that has the highest output performance.

In the display of the detonation counter, it is shown the number of detonation units after the measurement number 1. The number 1545 indicates a total number of detonation units during the whole ride. It is necessary to calculate the total number per one overridden kilometre. In Table 3, there is a re-calculated number of detonation units per an overridden kilometre for all four measurements. Analysis of the output data from the EW&C system and the detonation counter depicted in Table 3 was built up, where the input of the stated number of detonation units per overridden kilometre as well as all the measured output values therein. For the measurement, No.1 maximum output performance was 27 kW and maximum torque 23 N·m.

Fig. 4. Undamaged Piston

The number of detonation units is 8 per one overridden kilometre. After the complete analysis, it is evident that the detonation combustion is out of the limit at this measurement. This fact is also obvious in Figure 4 in which a piston is displayed. This piston has not got any mark of damage or any black deposition. The output characteristics were stable.

On the next testing day which was done on measurement No.2 in the same racing circuit. The conditions for the measurement No.2 are referred in Table 1 and Table 2. In Figure 5 was the engine activity record. Maximum output performance was 29.5 kW and maximum torque 27 N·m. The number of detonation units is 30 per one overridden kilometre. Other measured data are in Table 3. The output parameters were stable which means that they did not decrease during the testing ride.

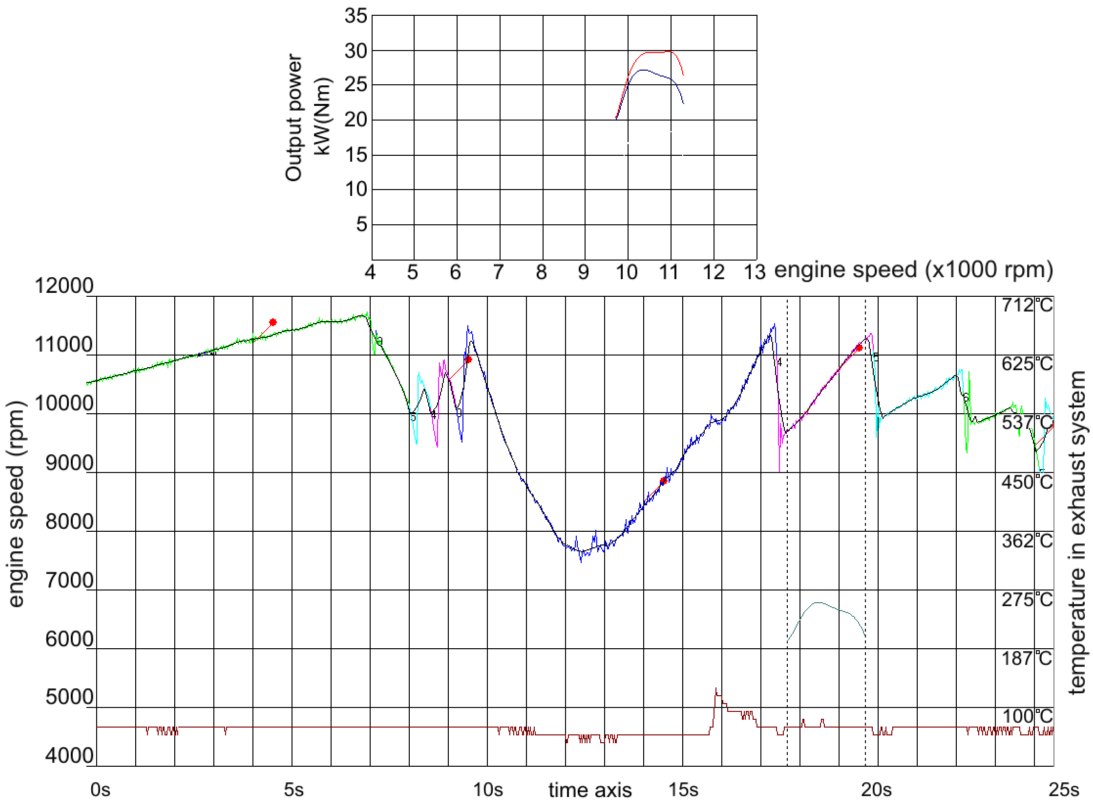

Fig. 5. Activity Record and Output Behaviour of Engine at Measurement No.2

This setup was characterised by the large range of exploitable speed. The engine was set much better than No.1, which is documented with higher maximum output performance and torque and their ranges as well. After disassembling there was evidently no significant damage of the piston, Figure 6.

Fig. 6. Piston with Black Deposition

The following measurement No.3 was performed with an effort to determine whether it is possible to load the engine with an even greater rate of detonation combustion and the extent of influence on the engine output parameters as well as potential damage.

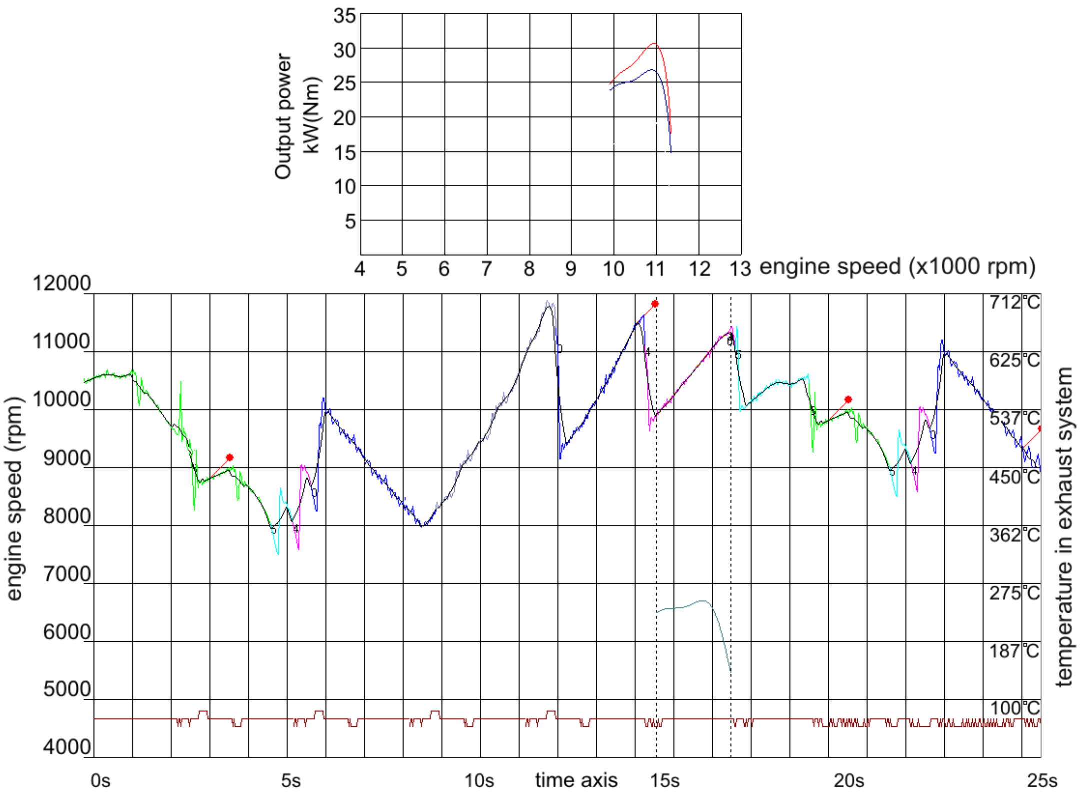

Fig. 7. Activity Record and Output Behaviour of Engine at Measurement No.3

Likewise, the testing circuit was the same and the input conditions, as well as the shape of the fuel map, are stated in Table 1 and Table 2.

In Figure 7 is the engine activity record. Maximum output performance was 32 kW and maximum torque 27 N·m. The number of detonation units is 44 per one overridden kilometre. Other measured data are in Table 3. Maximum output performance increased in comparison with the previous measurement which was caused by abnormal detonation combustion. It is important to know that this performance is transient and the engine reached it only at the beginning of the measurement. During the next kilometres, there were engine overheating with small damage of the piston (Figure 8) and the loss of output performance. Moreover, the range of exploitable speed decreased significantly.

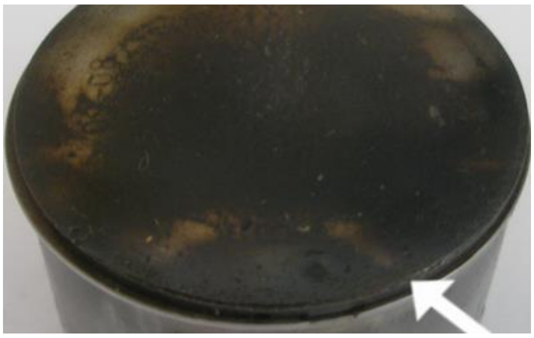

Fig. 8. Piston with Moderate Damage

In Figure 8 there is the black deposition of the piston similar to one shown in Figure 6. But the moderate abrasive wear is evident at the edge of the piston, where a pointer shows. This wear indicates that the detonation combustion has definitely assumed a destructive character.

During the measurement No.4, the engine was exposed to extreme detonation combustion. This measurement was performed in the same racing circuit. In Table 1 are the conditions for performance of the measurement No.4, while in Table 2 is the fuel map. In Figure 9 there is the record from the EW&C system.

Maximum output performance was 29.5 kW and maximum torque 26 N·m. The number of detonation units is 56 per one overridden kilometre. Other measured data are in Table 3. The range of exploitable speed was very short. The engine reached these values only at the initial phases of the testing ride before significant overheating and expressive destruction occurred. The output performance was transient in maximum extent.

Tab. 3.

Measurement results.

No.	Number of Detonation Units (NDU) [NDU/km]	Maximum Output /Engine Speed [kW/rpm]	Range of Speed for Output over 25kW [rpm]	Maximum Torque/Engine Speed [N·m/rpm]	Range of Speed for Torque over 20 N·m [rpm]
1	8	27 / 11 200	700	23 / 11 100	900
2	30	29,5 / 10 800	1 300	27 / 10 300	1 600
3	44	32 / 10 900	1 200	27 / 10 800	1 300
4	56	29,5 / 11 100	500	26 / 11 050	900

In Figure 10 as illustrated is a piston which is considerably damaged with detonation combustion. The black deposition is throughout the surface of the piston bottom. The pointer shows the spot with great damage where the material was melted down with detonation combustion. Similarly, the combustion space and an upper section of the cylinder are also damaged. The damaged design components are not applied in practice anymore.

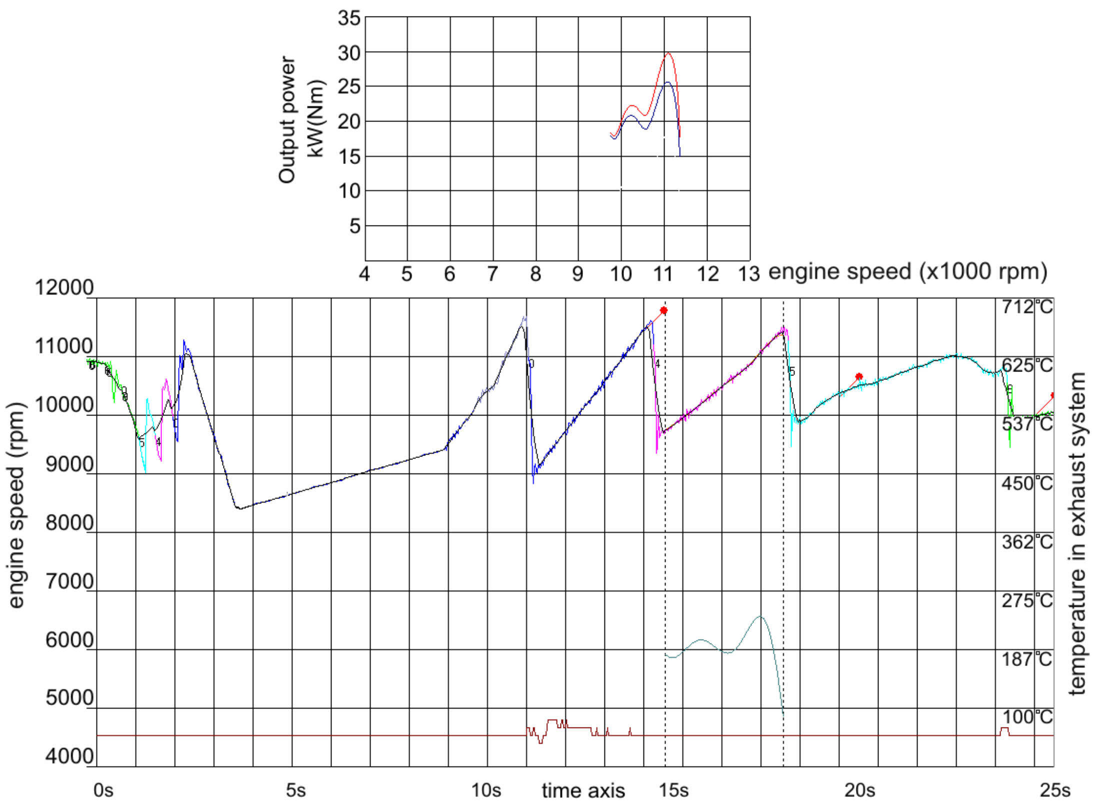

Fig. 9. Activity Record and Output Behaviour of Engine at Measurement No.4

Fig. 10. Piston with great damage

4. CONCLUSIONS

The measurements and intent on detonation combustion have brought many interesting observations.

It is possible to theoretically assume that the higher extent of detonation combustion provides even greater output performance at least in the initial phase of the testing. However, the results indicate that neither the output performance nor the torque was increased.

On the contrary, these values were decreased in comparison with measurement No.3 where detonation combustion was weaker. This phenomenon is caused by the fact that much energy is consumed for negative work. This work is spent on a breaking down of resistances such as a high compression ratio. Figure 10 is a piston, which is significantly damaged with detonation combustion. Throughout the whole surface of the piston bottom is saturate black deposition. The pointer shows the spot with great damage caused by detonation combustion. Similarly, the combustion space and an upper section of the cylinder are already inapplicable.

Resulting from data of the measurements, it is necessary to keep detonation combustion at a certain level. According to these results, there are 30 detonation units per overridden kilometre. This value is possible to reach in various ways and the combinations of elements have influence on the detonation combustion.

At this value, the engine permanently reached high output performance, the large range of exploitable speed and detonation combustion did not cause engine destruction. The utilisation of detonation combustion for the increase of output performance is consider hazardous. Therefore, the measurements show that through means of a change of atmospheric conditions that combustion can occur. However, the combustion will be destructive. Detonation combustion has got great significance which is also evident from the difference between the measurement No.1 and No. 2 (Table 3). By means of detonation combustion for the measurement No.2, the maximum output performance and torque in principle is higher than for the measurement No.1.

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