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Engine Output Increase of Two-stroke Combustion with Exhaust System Optimization

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In principle, an exhaust system influences the maximum output and characteristic of a two-stroke combustion engine. The first part of the contribution deals with the possibility of transformation in a maximum output and a range of exploitable speed values by means of the change of exhaust manifold length in exhaust pipe section. This knowledge covers an output curve variability of an engine operating speed range. The second part of this contribution deals with the combustion product's temperature influence in an exhaust system for a maximum engine output and a range of exploitable speed. By increasing the combustion product's temperature in an exhaust system, the maximum engine output is reduced overall. There is the transfer of engine output to higher engine speed because the exhaust manifold length is short theoretically. That is why it is necessary to provide the optimum value of combustion products temperature in an exhaust system and so achieve maximum values of outgoing parameters.

Povećanje izlazne snage motora s dvotaktnim izgaranjem optimizacijom ispušnog sustava

Izvornoznanstveni članak

Načelno, ispušni sustav utječe na maksimalnu izlaznu snagu i svojstva dvotaktnog motora s izgaranjem. Prvi dio rada obavlja pretvorbu s maksimalnom izlaznom snagom i opsegom iskoristivih vrijednosti brzine pomoću promjene duljine ispušne grane u dijelu ispušne cijevi. Ovaj prikaz pokriva raznolikost ispušne krivulje opsega brzine rada motora. Drugi dio ovog priloga razmatra utjecaj temperature proizvoda izgaranja u ispušnom sustavu za maksimalnu izlaznu snagu motora i raspon iskoristive brzine. Povećanjem temperature proizvoda izgaranja u ispušnom sustavu, maksimalni izlazna snaga motora se sveukupno smanjuje. Postoji prijenos izlazne snage motora na veću brzinu motora jer je duljina ispušne grane teorijski kratka. To je razlog zbog kojega je nužno osigurati optimalnu vrijednost temperature proizvoda izgaranja u ispušnom sustavu i na taj način dostići maksimalne vrijednosti izlaznih parametara.

Keywords
Engine output
Temperature of exhaust system combustion products

Ključne riječi
Izlazna snaga motora
Temperature proizvoda izgaranja ispušnog sustava

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1. Introduction and aims

An exhaust system is an important supplement of all engines. It has the determining influence on engine outgoing parameters for engines with a two-stroke operating cycle. Gas flow in an exhaust system is controlled by means of the difficult principles of non-stationary convection with very difficult calculation. Although the existing special software reached certain voluminous results, the main merits of the work are still in the verification of calculated values on a testing engine. In practice, in most motorcycle firms which are the leaders for development, there are several modifications of exhaust systems designed according to generally known rules. These modified systems are tested and consequently improved with output brake engine tests. One exhaust system is suitable theoretically only for one value of engine speed. It is rather a small speed range in practice. The final modification of an exhaust system is accommodated to the most using speed values considering the operation possibility in its other modes.

In a cylinder on a piston top edge, there is an impulse created by means of the opening of an exhaust outlet. It causes an overpressure wave which spreads into an exhaust manifold in the existing environment with the speed of sound. In an exhaust manifold, the sound speed is much higher than in the open air. Exhaust manifold gases are exposed to pressure wave influence step by step. In consequence of this fact the gases begin to move outwards from an engine. But there is a reflection back of a pressure wave from the opposite cone (Figure 1) which causes gas oscillation following a longitudinal axle of an exhaust stroke. The aim of the correct dimensioned exhaust system is to improve exhaust of gases from a cylinder and this way to improve the scavenging process. During scavenging of working space with overflowing streams, there is a certain mixing of combustion products and fresh fuel-air mixture. The part of fresh fuel-air mixture leaks out into an exhaust outlet. A fuel-air mixture and combustion products mixing continues there. Near, an engine the gas mixture contains rather few combustion products. That is why there is the effort dimensionally to dispose of the exhaust system so that the back movement occurs in the final phase. This back movement comes into existence by reason of the oscillation and again there is the return of off-take gases into the cylinder working space.

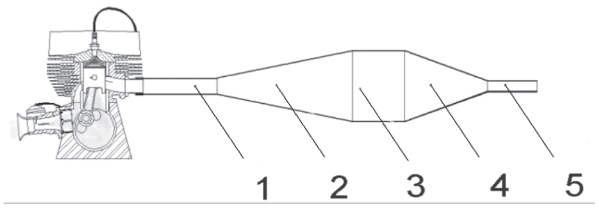

Figure 1. Parts of exhaust system: 1- exhaust pipe, 2- expansion cone, 3- rezonator, 4- opposite cone, 5- fishtail

Slika 1. Dijelovi ispusnog sustava: 1- ispušna cijev, 2- konus ekspanzije, 3- resonator, 4- suprotni konus, 5- izlazna cijev

The fuel-air mixture, which contains lower percentage of combustion products, can be used at combustion. In Fig.1 there is the design of an exhaust system with two-stroke engine in the section.

The aim of this article was established as a consequence of the described theoretical knowledge about combustion products oscillation in an exhaust system:

"to increase the output of two-stroke combustion engine by means of exhaust system optimization with keeping its main technical parameters (a diameter of diffuser in carburator, a shape of ignition curve, an origin mould of engine block and a compression ratio)"

The following steps are connected to this main aim:

- analysis of exhaust system length influence on a maximum engine output and a range of exploitable engine speed,
- analysis of combustion product temperature influence in an exhaust system on a maximum engine output and its position in engine speed range.

2. Experimental models and devices

It is very difficult to develop theoretically the individual components' and then to demonstrate the components influence on the output parameters and torque of a two-stroke petrol engine. Although there is software for modelling of the processes which operate inside a cylinder and an exhaust system during the combustion, the real results are performed seriously. That is why 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. Further there is a need to develop the measurement devices (to provide feedback, to give information about a real output proposition for concrete change in an exhaust system).

2.1. Experimental models

The motorcycle Aprilia RS 125 was used as the first experimental model. This single-track vehicle is equipped with the two-stroke engine ROTAX 122 (Figure 2). In Tab.1 there are the technical parameters of serial version for this engine (specified by manufacturer).

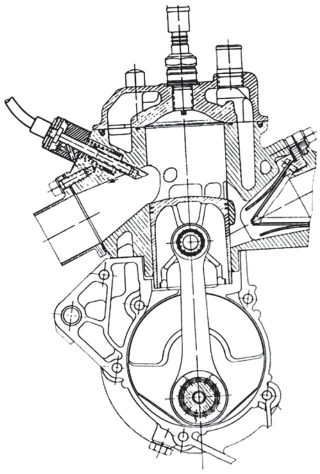

Figure 2. Engine ROTAX 122

Slika 2. Motor ROTAX 122

The motorcycle Honda RS 125R was used as the second experimental model. The second single-track vehicle is equipped with the engine Honda 125. The principle of filling and scavenging of this engine is similar to that for the engine ROTAX 122. The technical parameters of serial version of this motorcycle are also similar. Only the diameter of carburator diffuser (39 mm) in the shape of an ignition curve is different and that is why a maximum output is higher and reaches the value 44 hp at 12 250 rpm.

2.2. Experimental devices

Two testing and measuring devices were developed for the requirements of experimental measurements.

Table 1. Technical parameters of engine ROTAX 122

Tablica 1. Tehnički parametri motora ROTAX 122

Type / Tip	a single-cylinder, a two-stroke engine, liquid cooled, membrane filled, an electrically-controlled exhaust power valve / Jednocilindričan, dvotaktni motor, hlađen tekućinom, punjen u membranama, električno kontroliran ventil ispuha
Capacity / Kapacitet	124.8 cm^3
Bore x Stroke / Promjer x hod	54 x 54.5 mm
Compression ratio / Omjer kompresije	12.5 ± 0.5:1
Max. output / Max. izlazna snaga	29.3 hp -11 000 rpm
Max. torque / Maksimalni moment	1.95 kpm – 10 000 rpm
Carburator / Karburator	Dell'Orto PHBH 28 BD

Output engine brake

This is the starting dynamic brake (Figure 3). Its advantage is the possibility to obtain an output–moment characteristic during several seconds. A measurement is performed in place; this is why a testing ring is not needed. In Figure 4 there is the block diagram for data measurement, data operating and data evaluating. The principle consists in an accelerating of constant mass (balance-wheel) which has a constant moment of inertia. The sensor, which is set on the brake frame, scans every revolution of the balance-wheel and time when the revolution is done. The program determines an average of times from a certain number of revolutions. The time-lag between individual averages is proportional to an output increment. The operating period of one measurement is relatively short (circa several seconds). When the measurement is finished, the software calculates the functional relation among engine output, torque and engine revolutions (Figure 6).

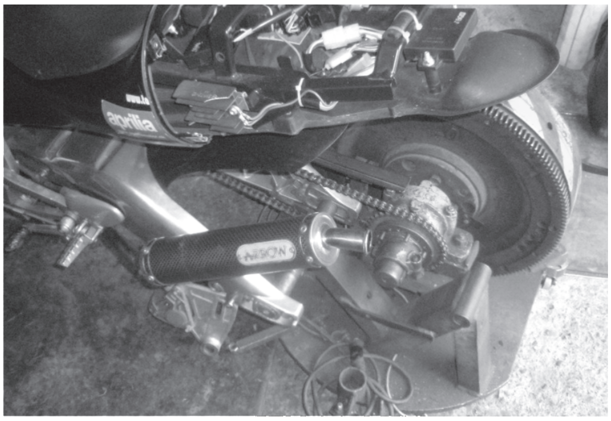

Figure 3. Output (engine) brake

Slika 3. Kočnica izlaza (motora)

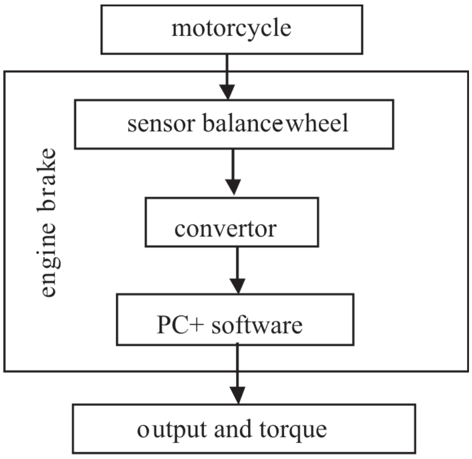

Figure 4. Block diagram of engine brake

Slika 4. Blok-dijagram kočnice motora

This is a data-recording system, i.e. a device which scans and stores information during a motorcycle ride (in real conditions, in real loading). This device makes it possible to diagnose parameters of a two-stroke combustion engine: an output, a torque and their behaviours, a temperature of exhaust system and its behaviour, detonating strokes and their number per time unit and other characteristics. A number and kind of scanned parameters are related to the types and a number of sensors which are installed on the two-stroke. The block diagram for data measurement, operating and evaluation is similar to an output engine brake but there is a difference in its output. The engine activity record depending on time is the result of this system.

The principle of EWaC system is in the measurement of the engine instantaneous speed, an instantaneous temperature of exhaust system and scanning of active speed gear or further parameters. The system does a functional record of engine activity on the base 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 EWaC system. After finishing measurement, it is possible to copy the record by mean of parallel port into PC (Figure 5). On PC display (Figure 10) there is the record of engine activity depending on a time axis, graphically presented (by means of the software which is a component of EWaC system). Every point of the record covers an instantaneous speed, detonating strokes, a temperature of exhaust system and an output at a crank shaft end.

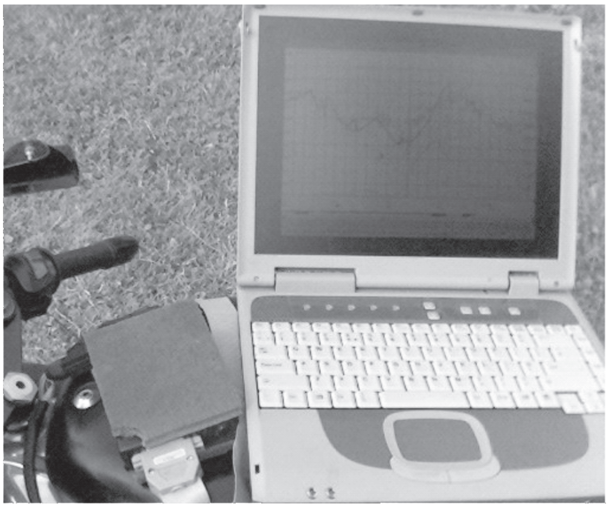

Figure 5. Engine watch and control system

Slika 5. Nadzorni i upravljački sustav motora

The notes for the figures:

axis:

x – axis revolutions per minute
y – axis (left) engine output [hp]
z – axis (right) torque [kpm]

Upper legend in the graphs:

MOTOR – engine
VYFUK – exhaust port
KARB. – carburator
ZAPAL. – ignition
Q.S.K. – capacity of combustion space
STRB. – distance between the piston and head
TLAK – pressure
TEPL – temperature
VLHK. – humidity
BENZ. – petrol
P_{max} = / rpm
Mk_{max} = / rpm

3. Experimental results

3.1. Analysis of exhaust system length influence on output characteristic

The performed measurements are intent on the analysis of an exhaust system length influence with an output characteristic in consideration of the defined aim. The motorcycle Aprilia RS 125 was used as an experimental model. Aprilia RS 125 is equipped with the engine ROTAX 122 (Figure 2).

A standard exhaust system, used in the motorcycle Aprilia RS 125, was applied for the first measurement APR1. The second measurement (APR2) was performed with the same exhaust system which had the 5-mm-trimmed exhaust pipe (Figure 1). For realisation of APR3 measurement there was the exhaust system again shortened. The system had the 10-mm-trimmed exhaust pipe.

The measurement device was used as the output engine brake (Figure 3). In Fig. 6, 7, 8 the measured dependences of output and torque on engine speed are illustrated graphically using various exhaust system variants. An upper curve represents the dependence an of output on revolutions; a bottom curve represents the behaviour of torque. In Figure 9 there is the comparison of these measurements.

The range of exploitable speed, i.e. revolutions in which the high value of instantaneous output (over 30 hp) and torque (over 2 kpm) are constantly kept, is the most important parameter in terms of practical application. In Table 2 are the measurement results and the individual ranges of exploitable engine speed displayed.

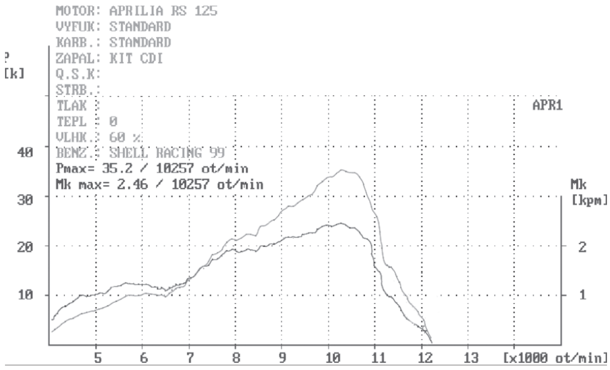

Figure 6. Output and torque behaviour with using of standard exhaust system

Slika 6. Ponašanje izlazne snage i momenta uporabom standardnog ispušnog sustava

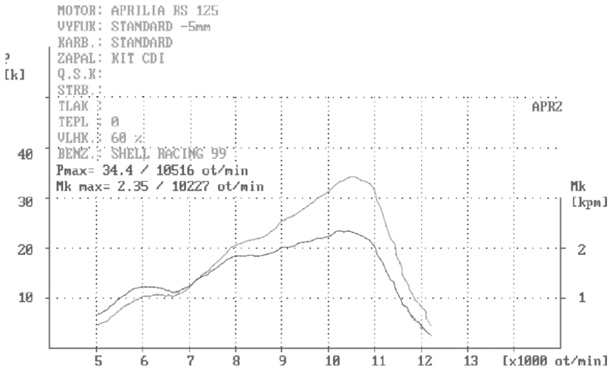

Figure 7. Output and torque behaviour using 5-mm-trimmed exhaust system

Slika 7. Ponašanje izlazne snage i momenta uporabom ispušnog sustava skraćenog za 5 milimetara

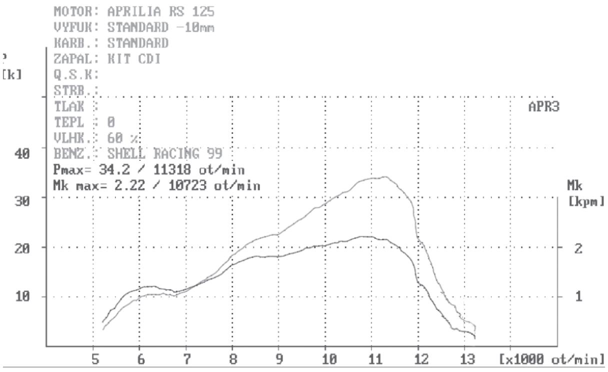

Figure 8. Output and torque behaviour using 10-mm-trimmed exhaust system

Slika 8. Ponašanje izlazne snage i momenta uporabom ispušnog sustava skraćenog za 10 milimetara

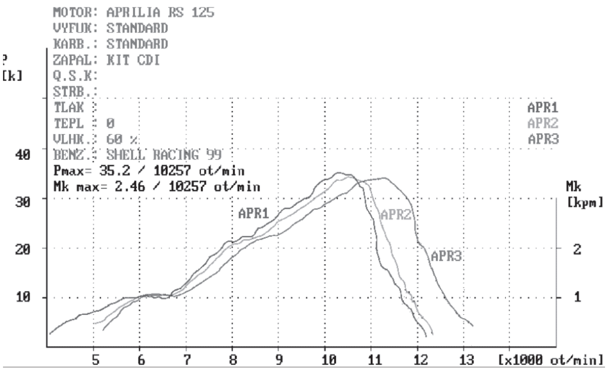

Figure 9. Comparison of output behaviours using all three exhaust systems

Slika 9. Usporedba ponašanja izlazne snage uporabom svih triju ispusnih sustava

Table 2. Measurement results

Tablica 2. Rezultati mjerenja

	Speed range with the output over / Raspon brzine s izlaznom snagom iznad 30 hp n [rpm]	Speed range with the torque over / Raspon brzine sa momentom iznad 2 kpm n [rpm]
Standard exhaust system / Standardni ispusni sustav	1200	2000
5-mm-trimmed standard exhaust system / standardni sustav skraćen za 5 mm	1250	2000
10-mm-trimmed standard exhaust system / standardni ispusni sustav skraćen za 105 mm	1500	2000

3.2. Analysis of combustion products temperature influence in exhaust system for output characteristic

When the exhaust system length is shortened the maximum output and the maximum torque are moved into higher operating speed of the two-stroke combustion engine. That is valid at a constant temperature and a constant pressure (section 3.1).

And, similarly, the sonic wave rate of spread depends on pressure and temperature (1) according to the undulatory theory:

$$C = \sqrt{K \times \frac{R \times T}{M}}\ , \qquad (1)$$

where: C – sonic waves rate of spread:

K = 1,4

R – gas constant

T – temperature

M – molar mass

A sonic wave rate of spread increases with an accumulative temperature in the exhaust system (1). A maximum and minimum temperature exists theoretically for every exhaust system, defined shape and dimensions. The output and torque behaviours increase the most effectively in this thermal interval because the scavenging of two-stroke engine cylinder is optimized by means of the exhaust system. With regard to above-mentioned assumption, the experimental measurements were performed on the base of this prediction and these measurements were intended to explain combustion products temperature in an exhaust system for an output characteristic of a two-stroke combustion engine. The measuring device was the Engine Watch and Control System (EWaC system) (Figure 5). The motorcycle Honda RS 125R was used as an experimental model (section 2.1).

The aim of measurements was defined for the optimal operating thermal interval to achieve a maximum output for a used exhaust system.

Three thermal states were used for the measurement in the exhaust system:

- Thermal interval from 440 to 540 °C (Figure 10)
- Thermal interval from 520 to 620 °C (Figure 11)
- Thermal interval from 600 to 720 °C (Figure 12)

The temperature values were measured at points where the temperature of exhaust system reaches the maximum, i.e. in the area of exhaust pipe, approximately 150 mm from the upper edge of exhaust port (Figure 1). In outputs from the EWaC system the record of engine activity depending on time is displayed. That is illustrated by means of an upper curve. The concrete section, delimited with both sides, is selected from this curve. In this section the output analysis (left smaller window) and temperature analysis of combustion products in an exhaust system (the curve in the middle of the picture) are performed.

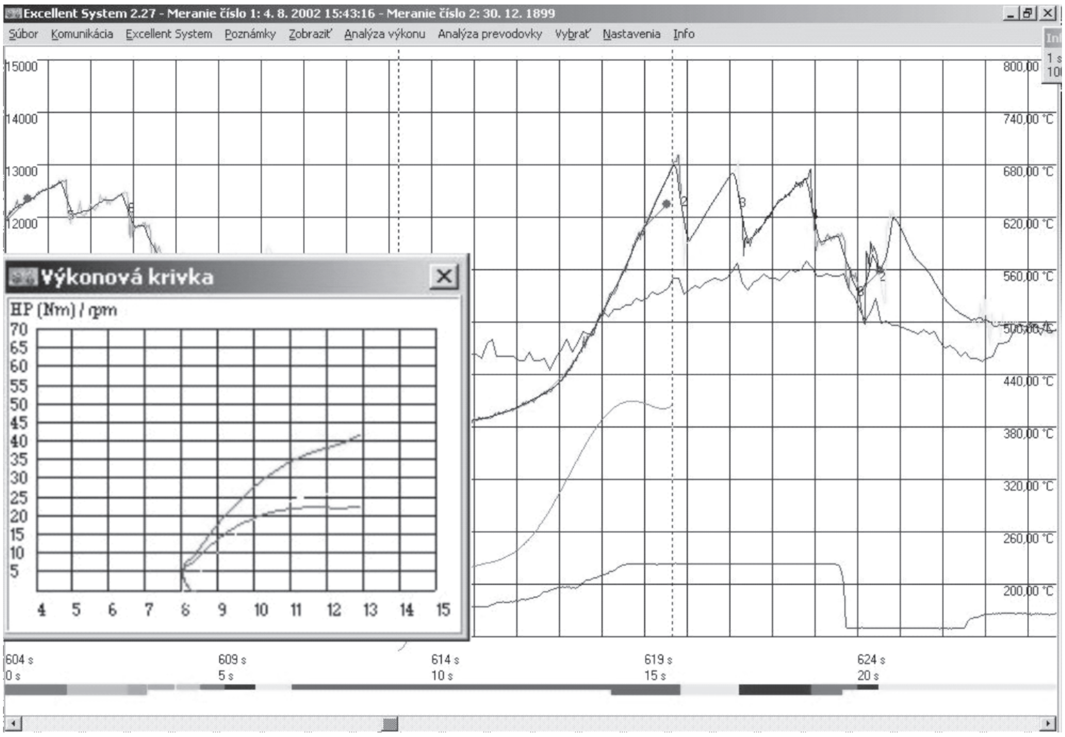

Figure 10. Activity record and output behaviour of two-stroke engine in 1st thermal state

Slika 10. Bilježenje aktivnosti i ponašanje izlazne snage dvotaktnog motora u 1. toplinskom stanju

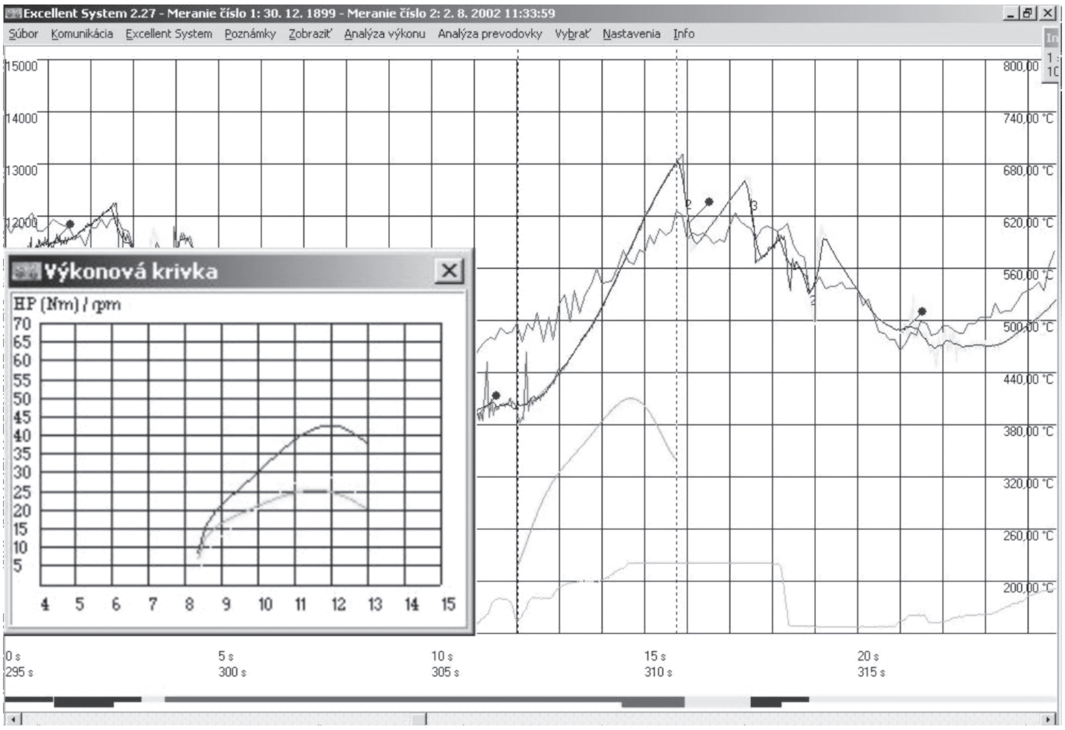

Figure 11. Activity record and output behaviour of two-stroke engine in 2nd thermal state

Slika 11. Bilježenje aktivnosti i ponašanje izlazne snage dvotaktnog motora u 2. toplinskom stanju

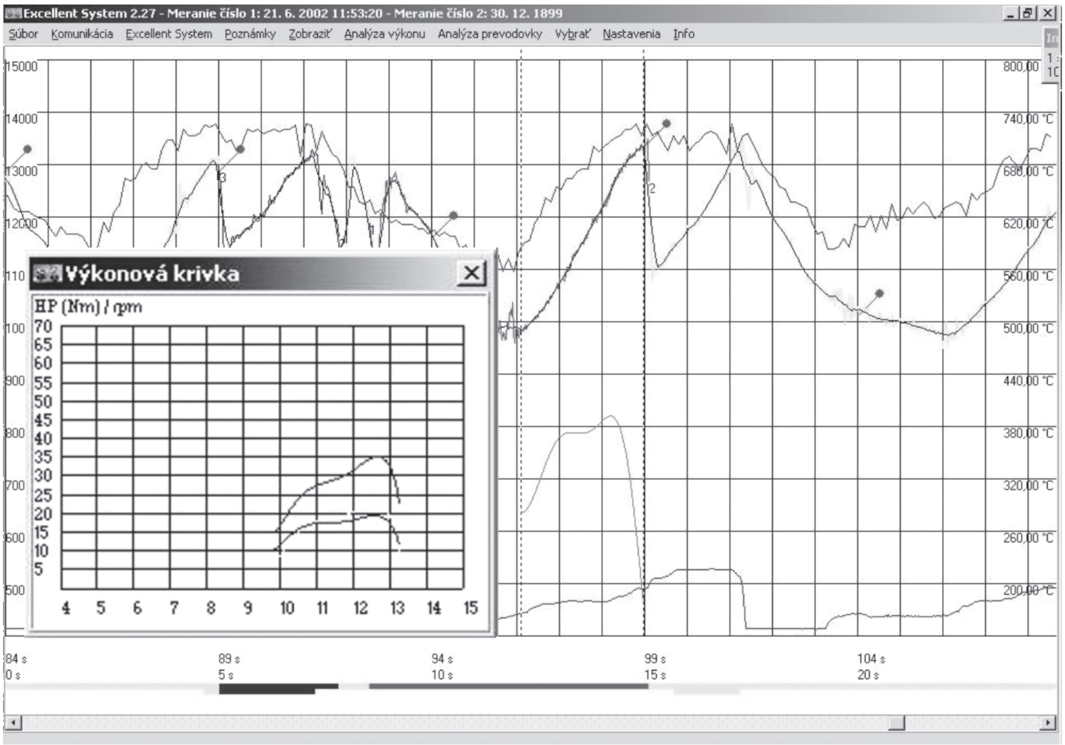

Figure 12. Activity record and output behaviour of two-stroke engine in 3rd thermal state

Slika 12. Bilježenje aktivnosti i ponašanje izlazne snage dvotaktnog motora u 3. toplinskom stanju

A sonic waves rate of spread increases with accumulative temperature (1). In the exhaust system, a back wave returns quicker and so the back scavenging process of a cylinder is accelerated. Theoretically, an exhaust system is shortened.

An exhaust system temperature has to rise with the increasing revolutions of an optimally adjusted engine; therefore, the exhaust system is theoretically shorter at a higher speed and theoretically longer (with lower temperature) at a lower engine speed.

The maximum output and range of exploitable speed, i.e. revolutions with high value of instantaneous output is constantly kept (over 30 hp), are important parameters for practical use.

In Table 3 are measurement results, maximum outputs and ranges of exploitable speed in individual thermal intervals.

Table 3. Measurement results

Tablica 3. Rezultati mjerenja

	Maximum output at the end of crank shaft / Maksimalna izlazna snaga na kraju radilice *P* [hp] / *n* [rpm]	Range of exploitable speed / Raspon iskoristive brzine *n* [rpm]
1. Thermal interval: from 440 to 540 °C / Toplinski interval: od 440 do 540 °C	42/13000	2700
2. Thermal interval: from 520 to 620 °C Toplinski interval: od 520 do 620 °C	43/12000	3000
3. Thermal interval: from 600 to 720 °C Toplinski interval: od 600 do 720 °C	35/12500	1100

4. Conclusions

According to the measurement results analysis in section 3.1 the shortening of exhaust system length in the area of exhaust pipe induces the transfer of a maximum output and a maximum torque to the higher operating speed of a two-stroke combustion engine. Simultaneously, the range of operating speed (i.e. revolutions, in which the engine reaches the constant high output, over 30 hp) is wider. The next contribution is the more fluent increase of an output and torque, which provides better steering control. This knowledge provides variability of the output curve according to the concrete necessity of a given single-track vehicle.

According to the measurement results analysis in section 3.2, the ⟨520; 620 °C⟩ is the optimal interval of operating temperatures in an exhaust system for this two-stroke combustion engine. The engine reaches the perfect output 43 hp at 12 000 rpm and the range of exploitable speed is 3000 rpm. However, the conditions are not so optimal in this interval of limited values 520 °C and 620 °C. The highest output is reached if the temperature converges in an exhaust system to the mean value of interval, i.e. 570 °C. The temperature in an exhaust system increases with an output, which is characteristic for optimal adjustment.

In a thermal interval ⟨440; 540 °C⟩ the maximum engine output was lower and the range of exploitable speed decreased as well. The exhaust system was overcooled, thus theoretically shorter. That is valid predominately for a temperature of 440 °C. The exhaust manifold is theoretically shortened toward an upper limit of interval and engine characteristics are improved significantly.

In the thermal interval ⟨600; 720 °C⟩ the maximum engine output was lowest and the range of exploitable speed was practically unavailable. That is valid, predominately for a temperature of 720 °C. In the lower limit of interval 600 °C there are good output characteristics. The output parameters are significantly worse with an increasing temperature. The system is overheated and, theoretically, the exhaust manifold is excessively shortened.

In the exhaust manifold, the low temperature means that there is an overrich mixture (fuel redundancy) and it follows an imperfect burning.

In the exhaust manifold, the high temperature means that there is a weak mixture; it smoulders out in the exhaust manifold and the combustion process takes more time (lack of fuel).

In the exhaust manifold, the optimal temperature means that the composition of mixture is optimal and heat is changed into mechanical energy with high efficiency.

It follows that temperature in an exhaust system has a cardinal influence on an engine output characteristic. That is why it is necessary to ensure its optimal interval. It will be important for this thermal interval, where the temperature increases proportionately with an operating engine speed and an engine load. It causes theoretically the lengthening (for lower operating engine speed) and theoretically the shortening (for higher operating engine speed) of an exhaust system. This effect provides a higher output in the whole regime of revolutions and decreases production of emission because there is more perfect combustion here. Now, the highest efficiency of two-stroke combustion engine will be provided.

The problem of an increase for output parameters of a two-stroke combustion engine is solved at the present time in the framework project VEGA 1/0146/08-material flows and logistics, innovation processes in construction of manipulation and transport devices as active logistic elements with the aim of increasing reliability.

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