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COMPUTATIONAL INVESTIGATION OF COMPRESSION RATIO AND BORE DIAMETER INFLUENCE ON ENGINE PERFORMANCE AND KNOCK INTENSITY

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Abstract

Processes of the combustion in combustion engines depend on cylinder bore and compression ratio. Compression ratio is a ratio of in-cylinder volume when piston is in bottom dead centre to volume when piston is in top dead centre. Theoretical engine efficiency is increasing together with compression ratio. However, in the real engine there are also other phenomena affecting the efficiency of the engine, which could results in lower performance of engine with higher compression ratio. This study presents knock intensity and performance gain in engine speed function of the 0D-1D engine model with different pistons set. Knock intensity is founded by implementing in combustion process knock sub-model based on Douaud and Eyzat induction time correlation using different pistons geometry. Examined engine model is air restricted Formula Student motorcycle engine. Mounted in intake system, air restrictor decreases knock intensity. Therefore, compression ratio could be increased. It was noticed that bigger bore diameter could reduce knock intensity. Researches realized that bigger bore size could cause performance drop at high rpm when flow is chocked. With changing of compression ratio, performance characteristic changes. Growing compression ratio decrease torque on low engine speed and increase on high engine speed. Further characteristic of the engine could be tuned by matching pistons with modified bore size and compression ratio.

Keywords: *simulation, combustion engines, compression ratio, motorsport, engine performance, knocks*

1. Introduction

Compression ratio in combustion engines is a ratio of largest to smallest capacity of cylinder. In piston engine, it is ratio of combustion chamber and cylinder volume when piston is in bottom dead centre to combustion chamber volume when piston is in top dead centre. It could be described by equation:

$$\varepsilon = \frac{V_S + V_k}{V_k}, \tag{1}$$

where according to Fig. 1:
V_s – displacement volume,
V_k – clearence volume.

There are two main factors that have influence on engine power and torque. Displacement and break mean effective pressure, what is described by formula [7]:

$$N_e = p_e V_{ss} \frac{n}{30\tau}, \tag{2}$$

where:
p_e – break mean effective pressure (BMEP),
V_{ss} – engine displacement,
n – engine speed,
τ – engine stroke number coefficient.

From construction, point of view break mean effective pressure depends on volumetric efficiency and general engine efficiency, which is described by equation [7]:

$$p_e = \frac{\eta_t \eta_i \eta_m \eta_v W_u p_o}{MR L_p T_o}, \tag{3}$$

where:
η_t – theoretical efficiency,
η_i – indicated efficiency,
η_m – mechanical efficiency,
η_v – volumetric efficiency,
W_u – calorific value of fuel,
p_o – ambient pressure,
MR – gas constant,
L_p – amount of air necessary to burn 1 kg of fuel,
T_o – ambient temperature.

Theoretical efficiency is defined by formula [5]:

$$\eta_t = 1 - \frac{1}{\varepsilon^{k-1}} \frac{\alpha\beta^k - 1}{(\alpha - 1) + k\alpha(\beta - 1)}, \tag{4}$$

where:
$\alpha = \frac{p_3}{p_2} = \frac{p_{max}}{p_2}$ – degree of pressure increase during heat supply,
$\beta = \frac{V_4}{V_2} = \frac{V_4}{V_k}$ – indicated efficiency,
k – mechanical efficiency.

Since theoretical engine efficiency increases with increasing compression ratio, it can be assumed that the increase in the compression ratio increases the power. However, in the real engine there are also other phenomena affecting the efficiency of the engine, which also depend on the compression ratio such as burning rate, heat conduction, and friction. Their relative effect on the engine's parameters is dependent on the speed and load. Although the geometric compression ratio is strictly, defined but dynamic compression and expansion process also depends on the valve timing. Mechanical efficiency decreases with a high compression ratio. It has been proven that the exhaust gas temperature decreases when the efficiency and compression ratio increases. It has also been proven that the heat loss through the cylinder walls is lower when the compression ratio is greater.

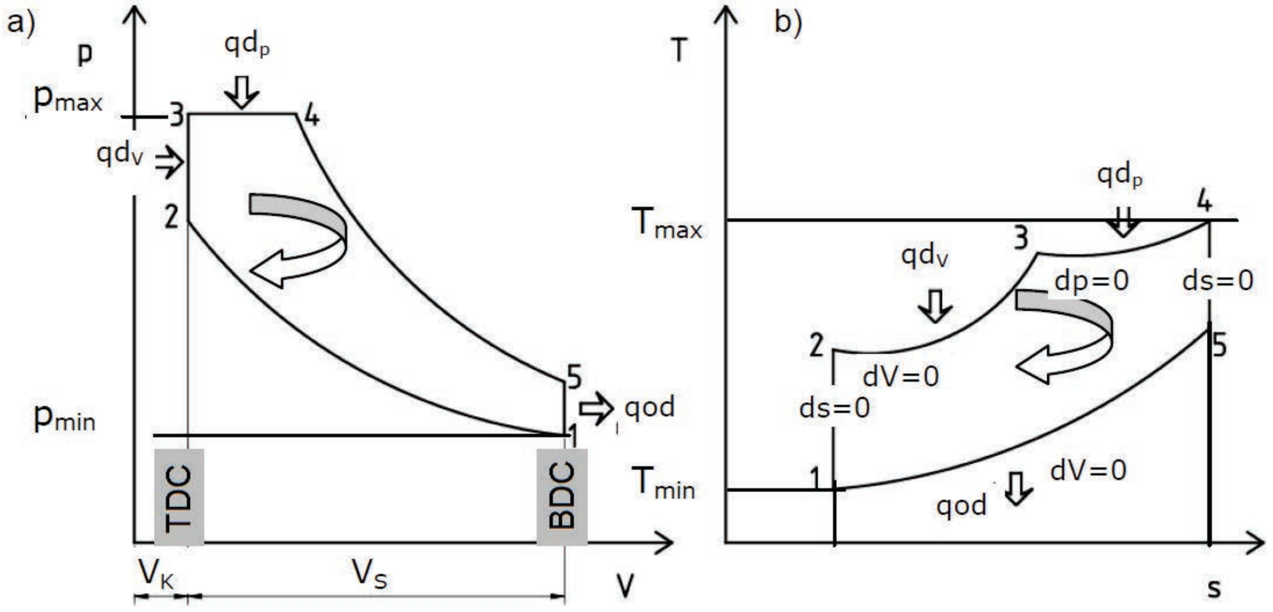

Fig. 1. Sabathe cycle in p-V (a) and T-s (b) coordinates [4]

The maximum value of the compression ratio is also limited by the phenomenon of knocking, depending on the fuel octane number [3].

Some experimental studies so far prove that the efficiency of fuel combustion with full open throttle increases with compression ratio up to value of CR = 14. However, due to the fuels, the usually used compression ratio values are below 12 [3, 4].

Caris and Nelson's tests showed that the engine has the highest efficiency with a compression ratio of 16:1, and the highest power with a compression ratio of up to 17:1 [1].

Muranaka studies have shown that the optimum compression ratio value decreases with a reduction in engine displacement. He stated that in a combustion engine with a cylinder size of 250 cm^3, the compression ratio should be 11, and for engine with cylinder size 500 cm^3 it should be 15 [6]. Because there is no strict answer, on that how compression ratio affect engine performance in this article was done numerical analysis in 0D-1D engine model.

2. Model

To find influence of compression ratio and bore diameter on knock intensity and engine performance was used validated 0D-1D engine model. Engine model is based on Honda CBR600RR engine adapted to Formula Student rules. Engine bore & stroke is 67 mm × 42.5 mm, which is giving displacement of 599 ccm. Compression ratio of stock engine is 12.2:1. Because of Formula Student rules in intake system is mounted air restrictor with 20 mm diameter.

There are aftermarket piston kits that could increase compression ratio to 13.5:1 and increase bore diameter to 68 mm or 69 mm which is giving respectively 618 cm^3 and 636. Additionally, higher compression ratio was also tested.

Simple knock sub-model based on the Douaud and Eyzat induction time correlation was applied to 1D engine model [2]. Induction time is calculated based on following formula:

$$\tau = \frac{0{,}01869}{A_p}\left(\frac{ON}{100}\right)^{3{,}4107} p^{-1{,}7} e^{\frac{3800}{A_t T}}, \tag{5}$$

where:
A_p – pre-expotential multiplier,
ON – fuel octane number,
p – cylinder pressure [kgf/cm^2],
A_t – activation temperature multiplier,
T – unburned gas temperature [K].

Induction time is decreasing together with increasing of unburned gas temperature and pressure. Knocks occurs when induction time is less than flame arrival time. In model, it is happening when:

$$\int_{t_0}^{t_i} \frac{d\tau}{\tau} = 1, \tag{6}$$

where:
t_0 – start of end-gas compression,
t_i – time of auto-ignition,
τ – induction time, defined above.

Model should have coefficients values calibrated to knock occurrence on the dynamometer. The values provided (Tab. 1) are for comparison purpose only and do not provide real values.

Tab. 1. Comparison of influence of emissions of different types of transport

A_p – pre-expotential multiplier	1.5
ON – fuel octane number	95
A_t – activation temperature multiplier	1.5
Post-knock burn scale multiplier	1.5

3. Results of simulation

Important fact is that air restrictor is decreasing total amount of air, which is provided to the cylinder. That is decreasing maximum cylinder pressure and it is connected with that knock intensity. Due to that fact, it is possible to increase CR ratio without danger of knock occurrence.

Dotted lines on Fig. 2 shows knock intensity for CBR600RR engine with stock and replaced pistons without air restrictor. It is assumed that those are limits of knock intensity to examined engine. Knock intensity of restricted engine is shown by not dotted curves, which are mainly below curve of not restricted engine. Curves with 13.5:1 and 14.0:1 are more or less in assumed safety region. 14.5:1 pistons are giving higher knock intensity up to 10,000 rpm. It is assumed that 14.5:1 pistons are out of the safety region. Irregularity of curves is connected with engine torque characteristic.

Worth to notice it is fact that increased cylinder bore was lowering maximum cylinder pressure and was connected with that knock intensity.

Performance gain curves for different sets of pistons are shown on Fig. 3. Pistons with higher CR makes engine more high rev with torque gain from 10,500 rpm and torque loss below that engine speed. It is clearly visible that engine with bigger displacement gives even 15% of improvement in lower part of engine speed. 68 mm piston bore is giving 8% max torque gain in compare to standard 67 mm, CR: 12.2:1 pistons.

In high range of engine speed torque is not increased because airflow through air restrictor was already chocked. Performance is even lowered because with greater bore friction is growing.

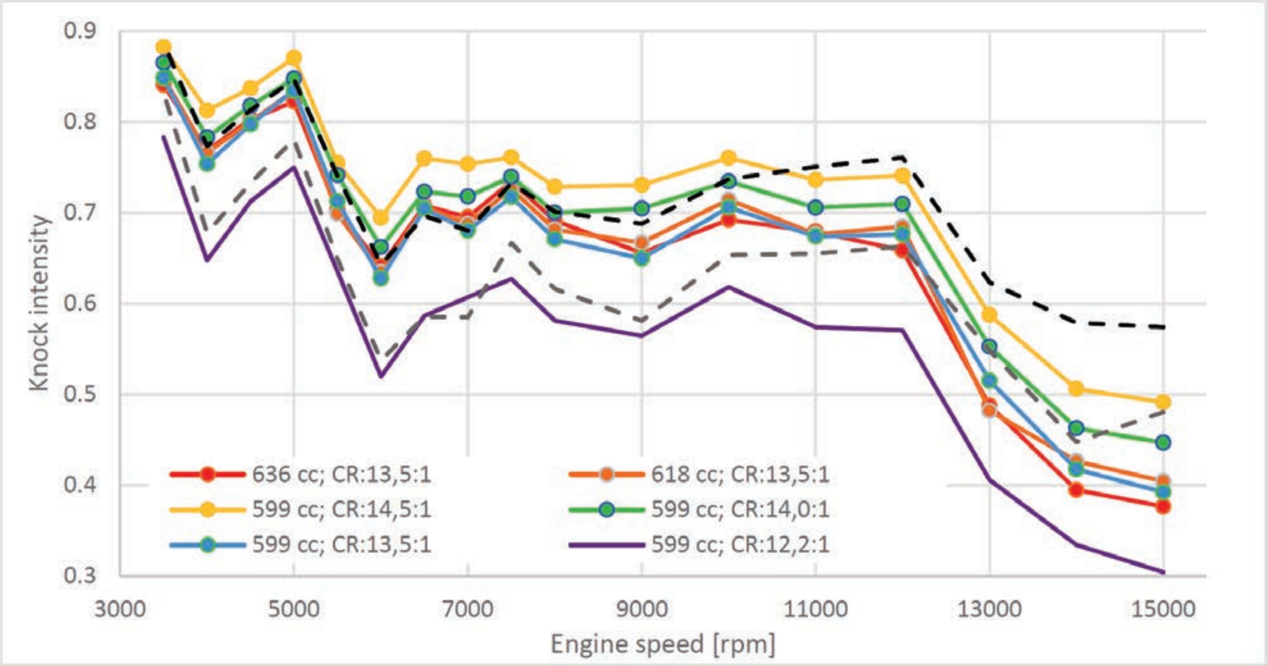

Fig. 2. Knock intensity with couple piston design

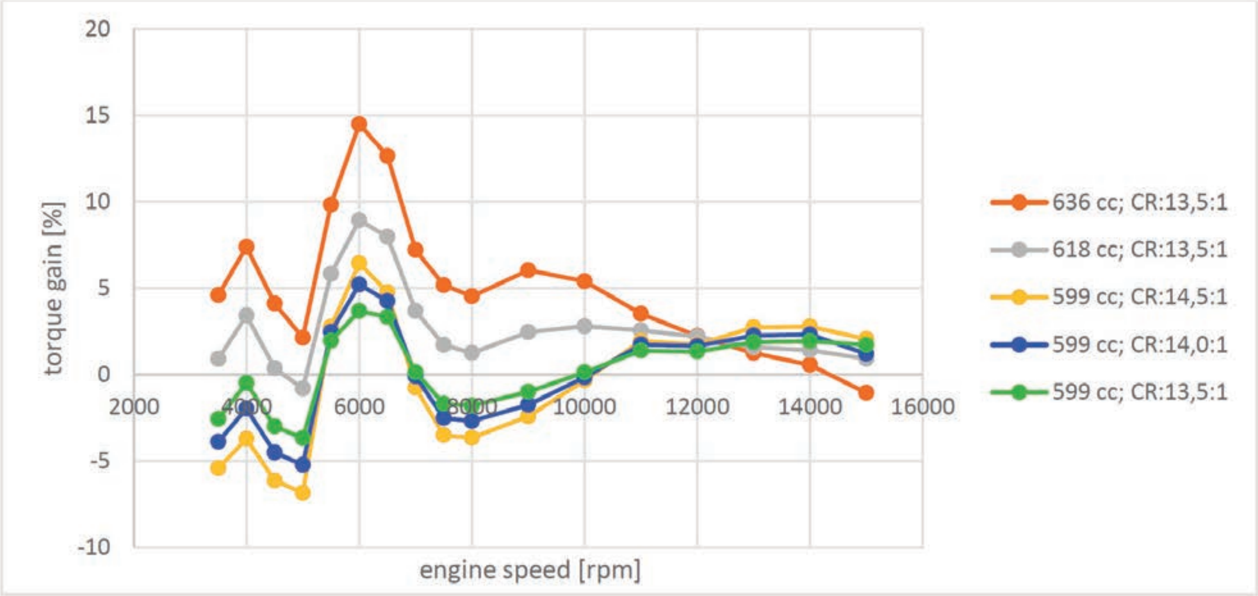

Fig. 3. Torque gain characteristic with couple piston design

4. Summary

In air, restricted engine compression ratio could be safely increased. Increased compression ratio is changing torque characteristic. On low engine speed, performance is lowered while on high engine speed is increased. On the other hand, greater bore is increasing torque on lower engine speed to the point when airflow is chocked. Big bore also decreases knock intensity both modification could be combined and matched with each other. Further characteristic of the engine could be adjusted by different intake/exhaust geometry and valve timing.

References

[1] Carris, D., Nelson, E., *A new look at High Compression Engines*, SAE Technical Paper 590015, 195.

[2] Douaud, A. M., Eyzat, P., *Four-octane-number method for predicting the anti-knock behavior of fuels and engines*, SAE Paper 780080, 1978.

[3] Heywood, J. B., *Internal Combustion Engines Fundamentals*, McGraw-Hill, Inc., 1988.

[4] Olczyk, A., *Analiza możliwości zwiększania mocy tłokowych silników*, Cieplne Maszyny Przepływowe, No. 141, Lodz 2012.

[5] Ricardo *WAVE 2015.2 Help System*.

[6] Stone, R., *Introduction to internal combustion engines – 4th edition*, SAE International, Warrendale, Pensylwania, USA 2012.

[7] Wajand, J., A., Wajand, J. T., *Tłokowe silniki spalinowe średnio- i szybkoobrotowe*, WNT, Warszawa 2005.

[8] Jankowski, A., *Heat transfer in combustion chamber of piston engines,* Journal of KONES 2010 Powertrain and Transport, Vol. 17, No. 1, pp. 351-358, Warsaw 2010.

[9] Jankowski, A., *Laser research of fuel atomization and combustion processes in the aspect of exhaust gases emission,* Journal of KONES 2008 Powertrain and Transport, Vol. 15, No. 1, pp. 119-126, Warsaw 2008.

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