

Thermal Efficiency Enhancement of a Gasoline Engine

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ABSTRACT

The goal of this research was to improve thermal efficiency under conditions of stoichiometric air-fuel ratio and 91 RON (Research Octane Number) gasoline fuel. Increasing compression ratio and dilution are effective means to increase the thermal efficiency of gasoline engines. Increased compression ratio is associated with issues such as slow combustion, increased cooling loss, and engine knocking.

Against these challenges, a higher stroke-bore ratio (S/B ratio) and a lower effective compression ratio were tried as countermeasures. With respect to increased dilution, combustion of a high-EGR (Exhaust Gas Recirculation) was tried. High-energy ignition and optimized combustion chamber shape with high tumble port were tried as countermeasures against slow combustion and reduced ignitability due to a higher EGR rate. As a result of this study on single cylinder engine, a brake thermal efficiency of 45% was achieved at an engine speed of 2000 rpm with a S/B ratio of 1.5, a compression ratio of 17, an effective compression ratio of 12.5, and an EGR rate above 30%.

Application to a four-cylinder engine was investigated, taking into account factors such as an engine height, effects between cylinders and the impact of a supercharger on the intake and exhaust systems.

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INTRODUCTION

In recent years, automotive fuel efficiency improvements and reductions in emissions have been pursued in the face of ever-stricter regulations to protect the environment by reducing the CO₂ emissions considered to cause global warming. Electric technologies such as EV (Electric Vehicles) have been increasing in response, but for the time being, conventional vehicles running solely on internal combustion engines and hybrid vehicles which combine conventional and electric motors is likely to continue to be the mainstream, which means improvements in the fuel consumption of internal combustion engines will remain essential to the future. There are technologies which improve vehicles fuel consumption by improving partial thermal efficiency. Typical engine technologies include the downsized turbocharged engine configuration, Variable Cylinder Management (1), etc. On the other hand, there are technologies which improve overall engine thermal efficiency. For this purpose, it is necessary to improve the maximum thermal efficiency with a higher compression ratio and a higher EGR rate. This study focused improvement of the maximum thermal efficiency by these methods. The target value of the maximum thermal efficiency was set to the 45%, a 5 % improvement over the current 40%. In particular, the S/B ratio had a large effect. A higher S/B ratio makes Surface-Volume ratio (S/V ratio) of combustion chamber at TDC lower, therefore cooling loss is reduced(2). In this study, S/B ratio was varied from 1.2 to 2.0.

IMPROVING THERMAL EFFICIENCY

In pursuit of improvement in maximum thermal efficiency, stoichiometric air-fuel ratio, 91 RON gasoline fuel, and an engine speed of 2000 rpm were set as operating conditions. To estimate thermal efficiency, the engine specifications and efficiency were determined using a one-dimensional simulation. Using performance data on existing engines, thermal efficiency was estimated under MBT (Minimum advance for the Best Torque) condition in relation to compression ratio and EGR rate. Figure 1 shows boost pressure (vertical axis) and EGR rate (horizontal axis) in relation to brake thermal efficiency when the compression ratio is 15 (a) and 17 (b). When MBT operation is possible at a compression ratio of 17, EGR rate of about 30%, and boost pressures above 250kPa, 45% brake thermal efficiency can be achieved.

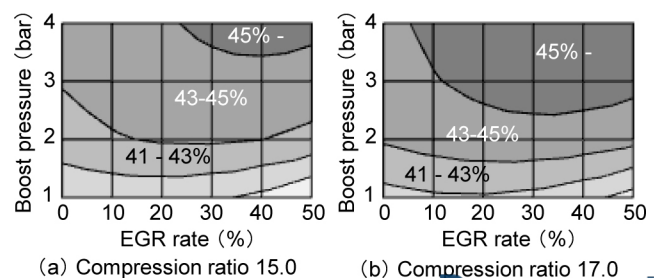


Figure 1. Estimated result of brake thermal efficiency at engine speed = 2000rpm, MBT

Experimental Methodology

In order to verify the improved thermal efficiency, engine specifications were tested using a single-cylinder engine. Table 1 lists the single-cylinder engine specifications. Various experiments were carried out by changing stroke, compression ratio, and effective compression ratio. Because bore was held constant while the stroke changed, displacement also changed. Effective compression ratio was changed by intake valve close (IVC) timing. A supercharger and low-pressure loop EGR system were used for air and EGR supply.

Table 1. Single-cylinder engine specifications

Displacement	499 , 626 , 835cc
Stroke	96.9 , 121.5 , 162mm
Bore	81mm
Stroke-bore ratio	1.2 , 1.35, 1.5 , 1.6, 2.0
Compression ratio	13.5 , 15 , 17 , 18 , 20
Number of Valves	4
Inlet Valve Open	-15° BTDC @ 1.0 mm lift
Inlet Valve Close	40,54,64,74,84° ABDC @ 1.0 mm lift
Air/EGR Supply	Supercharged/Low-pressure Loop
Fuel Supply	Port Injection/Direct Injection

Stroke-Bore Ratio

The combustion chamber shape flattens as the compression ratio increases. The surface-volume ratio (S/V ratio) of the combustion chamber at top dead center (TDC) also becomes high simultaneously. Figure 2 shows the relationship between the compression ratio and S/V ratio when the S/B ratio is 1.2 and 1.5. By increasing the S/B ratio from 1.2 to 1.5, it is possible to increase the compression ratio by 3 at the same S/V ratio. That is, increasing the S/B ratio seems to produce improvement with respect to slow combustion and increased cooling loss due to the flatter shape of the combustion chamber, which are issues accompanying a higher compression ratio(3).

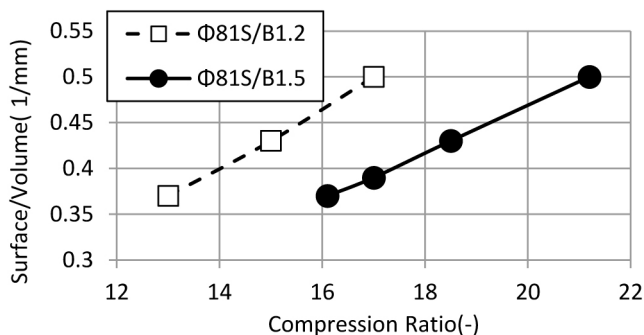


Figure 2. Effect of S/B ratio on surface-volume ratio

Figure 3 shows the brake thermal efficiency and degree of constant volume in relation to the compression ratio of the single-cylinder engine when the S/B ratio is 1.2 and 1.5. The brake thermal efficiency calculation for the single-cylinder engine assumed mechanical friction equivalent to a four-cylinder engine. Degree of constant volume is an index that evaluates time loss. Degree of constant volume is defined by the graph and equation of Figure 4. And Figure 3 also shows unburned loss at S/B ratio 1.2 and MBF50%-90% at S/B ratio 1.5. At an S/B ratio of 1.2, the maximum brake thermal efficiency is shown when the compression ratio is 15. On the other hand, at an S/B ratio of 1.5, thermal efficiency increases with the compression ratio, reaching a maximum at a compression ratio of 18. There is a common feature shown below in the condition of the limit of these compression ratios. The limit of the compression ratio is determined by the increase of time losses. Unburned HC and MBF 50-90% have great influence of the shape of the combustion chamber. If the average combustion chamber height at TDC is defined as the division of the cylinder volume at TDC by the cylinder cross-sectional area, these compression ratios coincide with the condition which average combustion chamber height is about 7mm. S/V ratio of the compression ratio 15 at an S/B ratio 1.2 and S/V ratio of the compression ratio 18 at an S/B ratio 1.5 are almost same from figure 2.

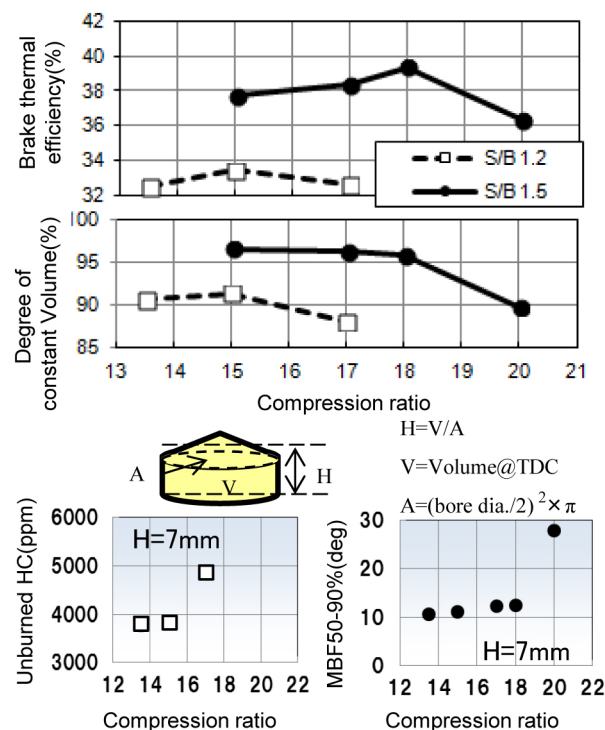


Figure 3. Effect of S/B ratio and compression ratio on combustion at engine speed= 2000 rpm, IMEP= 540 kPa, MBT

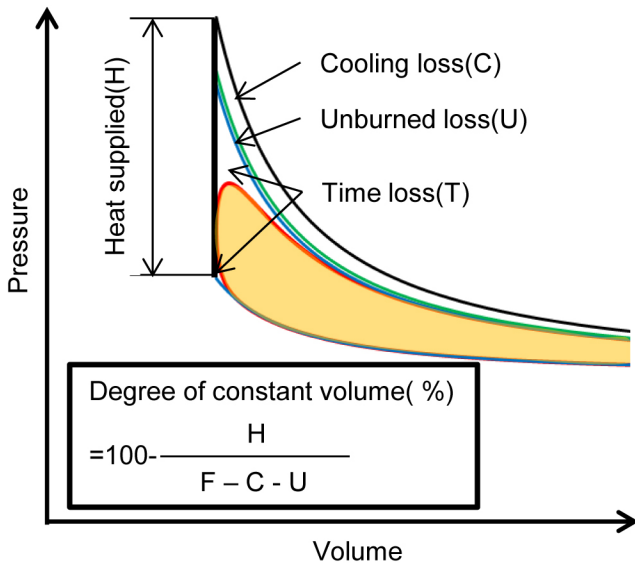


Figure 4. Definition of degree of constant volume

Figure 5 shows thermal efficiency, cooling loss, and pumping loss in relation to S/B ratio when the compression ratio of the single-cylinder engine $\epsilon = 13.5$. Cooling loss (middle) decreases (improves) with increase in S/B ratio, but does not change above 1.5. On the other hand, pumping loss (bottom) increases monotonically with the S/B ratio. Based on a balance between the two, the optimum S/B ratio at which thermal efficiency is maximized was 1.5.

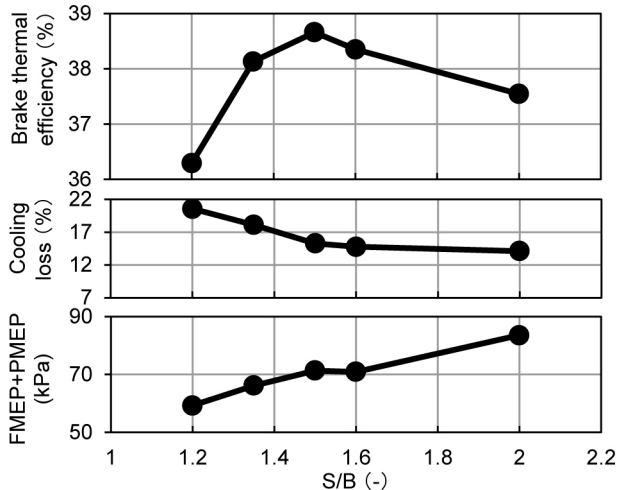


Figure 5. Brake thermal efficiency trend and work balance with variation of S/B ratio at engine speed=2000 rpm, IMEP=720 kPa, MBT

Effective Compression Ratio

As a countermeasure against knocking due to the increased compression ratio, the effective compression ratio was reduced by late IVC timing with the same compression ratio (expansion ratio). Figure 6 shows the influence of the compression ratio (ϵ) and the effective compression ratio on crank angle when the mass burn fraction (MBF) is 50% (MBF 50% CA) and on thermal efficiency. The horizontal axis is BMEP (Brake Mean Effective Pressure). The

S/B ratio was 1.5. As shown in Figure 6, in an Otto cycle with a compression ratio ϵ of 17, the ignition timing must be retarded due to knocking at high BMEP, and thermal efficiency is reduced. In contrast, by late IVC and reducing the effective compression ratio to 12.5, it is possible to maintain the compression ratio (expansion ratio) at 17 and the maximum thermal efficiency improves. Under these conditions, MBT operation is possible up to loads BMEP 750kPa close to a 13.5 compression ratio Otto cycle, as shown at the bottom of Figure 5.

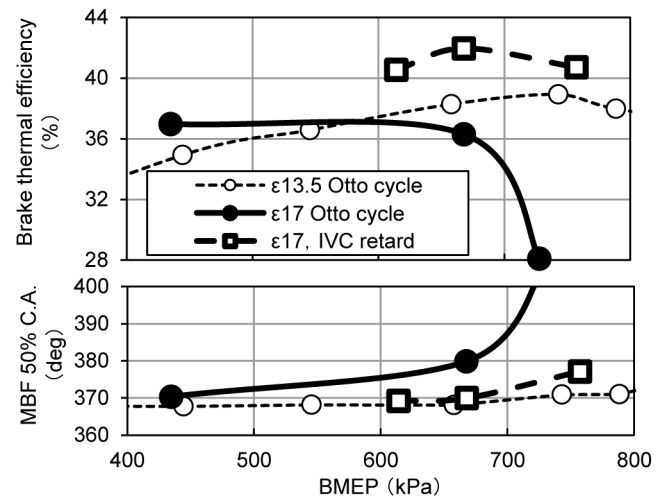


Figure 6. Influence of effective compression ratio at engine speed=2000 rpm, EGR=20%

High EGR-Ratio Combustion

Introduction of EGR is an effective way to reduce cooling loss and control knocking. However, EGR is associated with decreased ignition performance and increase of time loss due to the decreased speed of flame propagation. In order to operate at an EGR rate over 30%, burning velocity was improved using improved combustion chamber shape and enhanced in-cylinder flow; and ignitability was improved using high-energy ignition.

Since the combustion chamber volume becomes small due to the increased compression ratio, securing the volume around the ignition plug is a challenge (4). Increasing the S/B ratio made securing the volume around the ignition plug easier. However, since the compression ratio was set to 17, which is much higher than that of normal gasoline engines, an impact on combustion performance due to the volume around the ignition plug was likely to be observed. Figure 7 shows the impact on the limit EGR rate of changes in the volume around the spark plug by the shape of the piston. V1 represents the volume around the ignition plug based on a virtual sphere centered on the plug electrode gap and touching the cylinder head or piston at top dead center. The limit EGR rate rises until V1/V2 reaches 2%, and then is unchanged above 2%. In order to make V1/V2%, the piston combustion chamber was given a bowl shape.