

Combustion Technology Development for a High Compression Ratio SI Engine

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ABSTRACT

Internal combustion engines still play a vital role in realizing the low carbon society. For spark ignition engines, further improvement in thermal efficiency can be achieved by increasing both compression and specific heat ratios. In the current work, the authors developed practical technologies to prevent output power loss due to knocking at full load, which is a critical issue for increasing compression ratio. These new technologies allowed to increase the compression ratio significantly and provide an equivalent torque level as a conventional engine. As a result, thermal efficiency has been improved at partial load.

INTRODUCTION

In recent years, development of hybrid and electrical vehicles has been accelerated, adopting electric devices for lower fuel consumption. It is expected, however, that internal combustion engines will still account for a high percentage of automobile powertrains even in 2020 [1]. Electric devices such as idle-stop [2] and regenerative braking will probably further gain popularity in the future due to further cost reduction from volume efficiency, but thermal efficiency of its base internal combustion engine is a key to achieve maximum effect of those devices, and high compression ratio and lean combustion are effective in improving the thermal efficiency of a SI engine. For the lean combustion engines, stratified combustion and homogeneous charge compression ignition (HCCI) combustion have been studied, but not yet widely introduced in the market due to many outstanding issues to resolve. Meanwhile, for the high compression ratio engines, torque loss due to engine knocking is a big challenge, and thus the engines currently available in the market have a compression ratio (CR) of only approx. 11.0 with the use of direct injection technology. In this study, combustion technologies that realize the high compression ratio SI engine have been developed, which utilize low-temperature oxidation reactions that take place before ignition in a high compression ratio engine and employ the new techniques to the conventional rapid

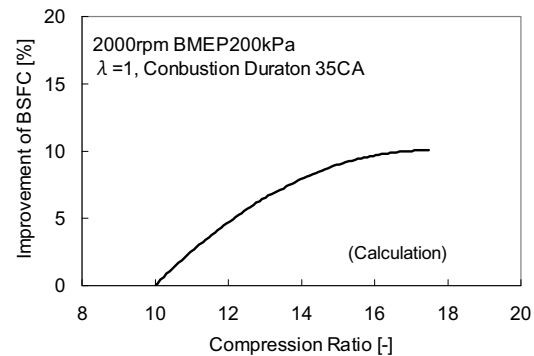


Fig. 1 Improvement of BSFC per compression ratio

combustion and air-fuel mixture cooling for knocking prevention.

INVESTIGATION OF MAJOR ISSUES WITH HIGH COMPRESSION RATIO ENGINES

A cycle simulation was used for the study and revealed that a reduction of exhaust loss and increment in cooling loss were balanced out if a CR was increased higher than 15, assuming an excess air factor (λ) of 1, Figure 1. This lowered the effect of a thermal efficiency improvement. Therefore, the level of torque loss due to knocking and improvement in fuel consumption were experimentally investigated with CRs varied from 11.2 to 15.0 in order to reacknowledge the issues with the high compression ratio engines.

EXPERIMENTAL METHODOLOGY

Table 1 shows the engine specifications used for the study. The CR of 11.2, pent roof combustion chamber and flat piston of the production-type direct injection engine were employed as the base features. In addition to these, other types of piston were created with their top faces raised (convex) as shown in Figure 2 to achieve higher CRs.

RESULTS OF EXPERIMENT

Torque at Full Load

Table 1 Engine specifications

Engine Type	In-line 4, DOHC
Bore X Stroke	87.5mm X 83.1mm
Displacement	1998.8cm ³
Compression Ratio	11.2, 13.0, 14.0, 15.0
Combustion Chamber	Pent-roof
Tumble Ratio	1.1 (SCV Open)
Swirl Ratio	3.7 (SCV Close)
Fuel System	Direct Injection
Injector Type	Swirl Injector
Fuel	Gasoline 96RON
Air Fuel Ratio	WOT 13.0, Partial Load 14.7

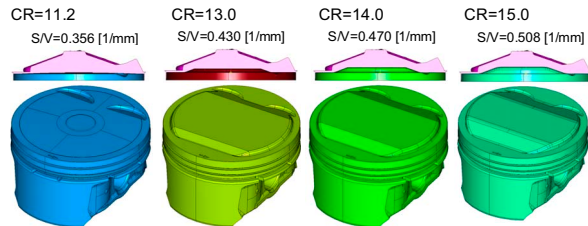


Fig. 2 Shape of piston top for each compression ratio

Figure 3 shows the Brake Mean Effective Pressures (BMEPs) relative to each CR at the knock limit ignition timing and the low engine speed of 1500 rpm WOT where knocking tends to occur. When the CR was increased from 11.2 to 13.0, the BMEP was lowered by approx. 12%, but in case of increasing the CR up to 15.0, almost no decrease in the BMEP was observed. Therefore, the BMEPs for each CR (11.2, 13.0 and 15.0) were checked, based on the same ignition timing. As shown in Figure 4, the BMEP was lowered when the CR was increased from 11.2 to 13.0, but it was increased in case of the CR of 15.0. For a comparison purpose, combustion states of each CR at 8 degrees After Top Dead Center (ATDC), which is the knock limit ignition timing of the CR of 15.0, are shown in Figure 5; (a) heat release rate and (b) P-V diagram. When increasing the CR from 11.2 to 13.0, the heat release rate slowed and its duration became longer, resulting in lower constant volume degree. As the combustion chamber was designed to a convex shape, conflicts of in-cylinder flow occurred during the compression stroke (Figure 6), which weakened the tumble, and flame right below the ignition plug hit the piston, which caused flame surface area being reduced and resulted in disturbance of flame propagation. Therefore this was thought to have slowed the initial combustion. In case of the CR of 15.0, however, heat due to low-temperature oxidation reactions was generated close to TDC before ignition, which accounted for approx. 4% of the gross heating value. Further, compared to the CR of 13.0, the combustion speed was much faster in the early stage and about the same after the intermediate stage of combustion. Given the influence of the combustion chamber design, the engine with the CR of 15.0 was thought to lead to a slow combustion, but in reality, the combustion duration was the same as the other engines with the CR of 13.0. This created an expectation that the low-temperature oxidation reactions could improve the combustion speed. As

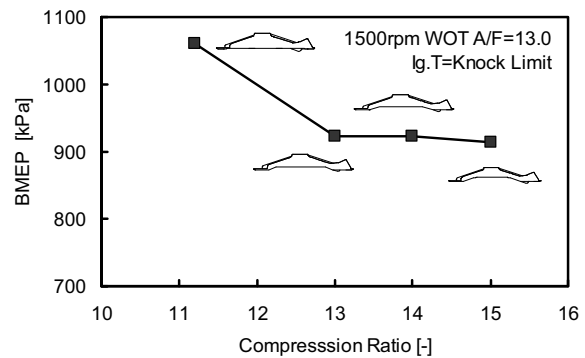


Fig. 3 Effect of compression ratio on BMEP

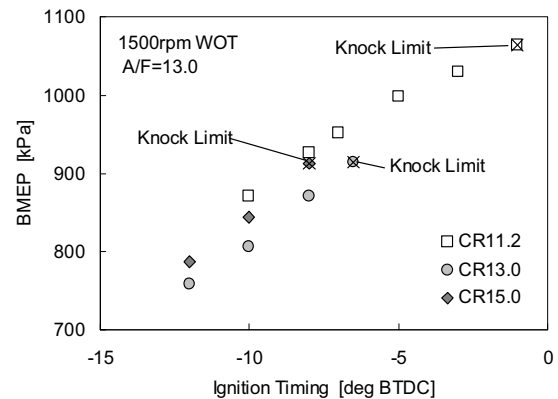
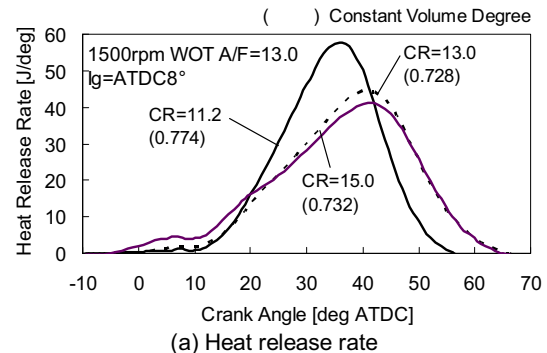
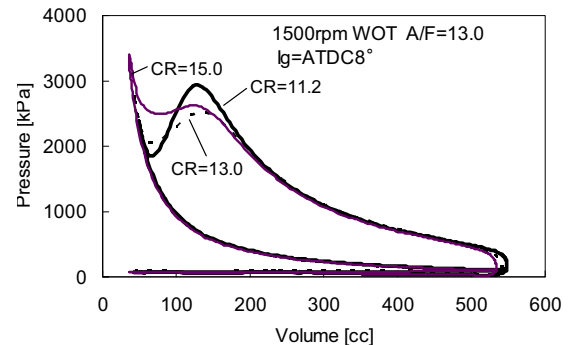


Fig. 4 Comparison of BMEP between 11.2, 13.0 and 15.0



(a) Heat release rate



(b) PV diagram

Fig. 5 Effect of compression ratio on combustion speed

shown in Figure 7, full-load torque over the low engine speed was only around 12% lower in the CR of 15.0 than the CR of 11.2, though the original prediction was that this could be more than 30%. The finding of this phenomenon that the torque did not decrease as

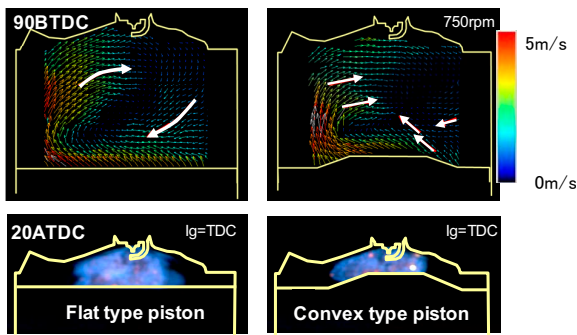


Fig. 6 Effect of tumble and flame in cylinder of transparent engine

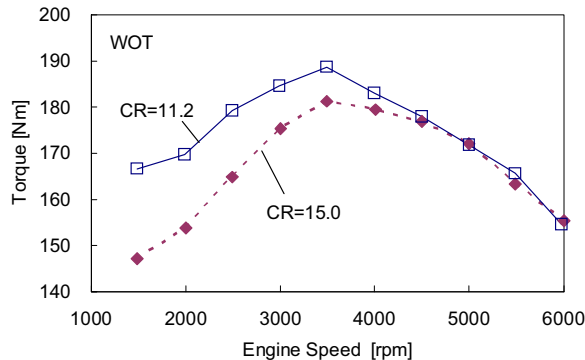


Fig. 7 Comparison of power between CR11.2 and 15.0

expected even if the CR was increased higher than 13.0 led to accelerating the technology development of a high compression ratio SI engine. Nevertheless, the torque with the CR of 15.0 was still lower than the conventional engines, and therefore further improvement was needed for a practical use.

Fuel Consumption at Partial Load

Contrary to the expectation, the fuel consumption did not improve further when increasing a CR. Figure 8 shows the improvement of fuel consumption of each CR relative to the CR of 10.0, indicating the weighted average values of representative fuel consumption points of actual vehicles. It shows that the fuel consumption did not improve in case of CRs higher than 13.0. The cause of this was the lowered constant volume degree due to slow combustion, Figure 9, which was also described in "Torque at Full Load" above. In addition to this, as shown in Figure 10, the increase in the indicated work did not increase as much as expected due to the rise in combustion gas

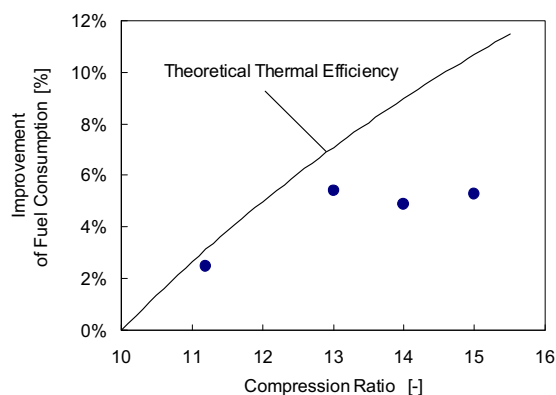


Fig. 8 Relation between compression ratio and fuel consumption

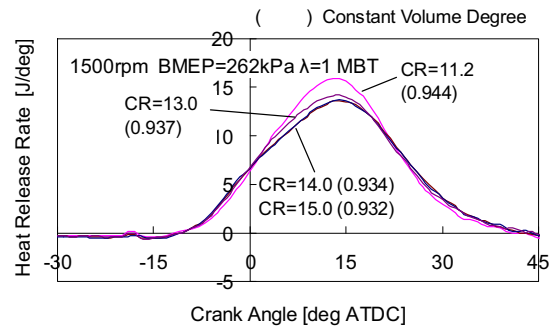


Fig. 9 Effect of compression ratio on heat release rate at partial load

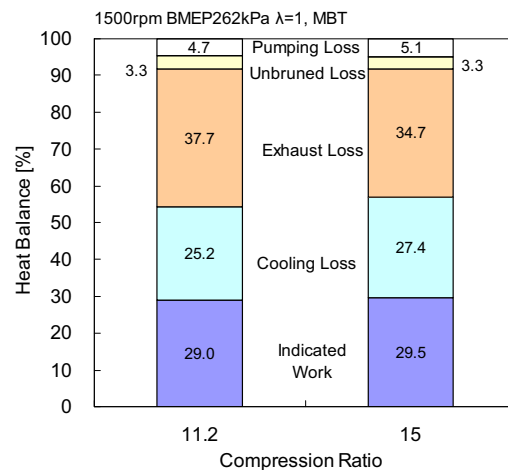


Fig. 10 Comparison of heat balance between CR11.2 and 15.0

temperature associated with a higher CR and the increase in cooling loss due to larger ratio of S/V (surface area of combustion chamber) to V (volume of combustion chamber). It was therefore essential to control the decrease in the constant volume degree and increase in cooling loss in order to achieve the improvement of fuel consumption expected in case of a high compression ratio engine.

Through these studies to realize a high compression ratio engine, it became important to understand and utilize a mechanism to control the torque loss by the low-temperature oxidation reactions and prevent knocking by further reduction of the combustion duration and air-fuel mixture cooling so that a torque higher than that of the conventional engine could be ensured at the full load. For the improvement of fuel consumption at the partial load, shorter combustion duration and reduction of cooling loss were required.

IMPROVEMENT IN FULL-LOAD TORQUE

ANALYSIS ON EFFECT OF SUPPRESSING TORQUE LOSS BY LOW-TEMPERATURE OXIDATION REACTIONS

A numerical analysis was conducted to see the effects of low-temperature oxidation reactions on combustion. Firstly, in order to comprehend the condition inside the combustion chamber, three-dimensional calculations on chemical reactions were made using the calculation code with CHEMKIN-II incorporated.