

Combustion Development to Realize High Thermal Efficiency Engines

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ABSTRACT

Improving vehicle fuel economy is a central part of efforts toward achieving a sustainable society, and an effective way of accomplishing this aim is to enhance the engine thermal efficiency. Measures to mitigate knocking and reduce engine cooling heat loss are important aspects of enhancing the engine thermal efficiency. Cooled exhaust gas recirculation (EGR) is regarded as a key technology because it is capable of achieving both of these objectives. For this reason, it has been adopted in a wide range of both hybrid vehicles and conventional vehicles in recent years.

Cooled EGR has the potential to achieve further lower fuel consumption if the EGR ratio can be increased. Fast combustion is an important and effective way for expanding the EGR ratio. The engine combustion enhancement can be categorized into measures to improve ignition characteristics and methods to promote flame propagation. Ignition characteristics can be improved by increasing the length of the arc discharge or intensifying ignition energy when the air flow around the spark plug is increased. Measures to promote flame propagation include intensifying in-cylinder turbulence through flows such as swirl, squish, and tumble. Toyota has been introducing these technologies as ESTEC (Economy with Superior Thermal Efficient Combustion) in these years.

This paper describes how air flow and air turbulence contribute to enhancing combustion by using the results of several different engines and lead to enhance the engine thermal efficiency. Especially the merits of high tumble concept are mentioned.

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INTRODUCTION

Improving vehicle fuel economy remains a central part of measures to cope with issues such as energy security and climate change. Automakers have been developing a wide range of technologies to improve fuel economy through weight reduction, CVT (continuously variable transmission), hybrid systems in addition to the engine technologies. Hybrid vehicles (HVs) in particular have a large effect on improving fuel economy and have been widely accepted by customers. HVs lead to achieve this improvement by using motor drive to restrict engine operation in the low load condition where thermal efficiency is relatively low compared to high load conditions. For this reason, the fuel economy of HVs can be improved by enhancing the maximum thermal efficiency of the engine. [Figure 1](#) shows the historical and possible future trends of maximum engine thermal efficiency.

Currently, the highest maximum thermal efficiency of a gasoline engine is 40%. The maximum thermal efficiency of HV engines has been increased by adopting Atkinson cycle to mitigate knocking, an electric water pump, and low-friction technologies as well as cooled EGR (exhaust gas recirculation) [1-2]. These technologies have been applied to conventional vehicles as ESTEC [3, 4, 5].

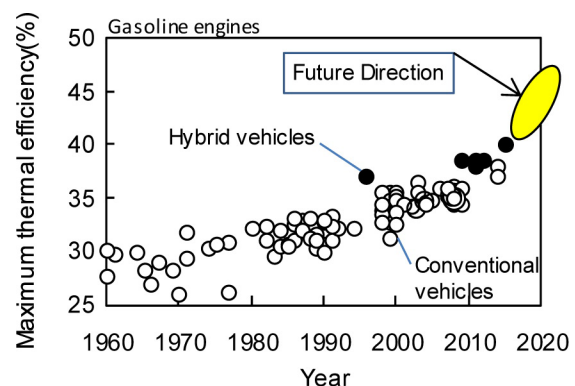


Figure 1. History and future direction of engine thermal efficiency

This paper focuses on combustion technologies such as high-tumble concept and discusses the relationship between combustion technologies and the engine thermal efficiency. It is considered that these technologies will be a mainstream for the engine development and widely spread all over the world.

ENGINE THERMAL EFFICIENCY IMPROVEMENT MEASURES AND FUTURE DIRECTION

As described above, increasing engine thermal efficiency plays a key role in improving fuel efficiency. The theoretical thermal efficiency in the Otto cycle is calculated as shown in Equation (1).

$$\eta_{th} = 1 - \left(\frac{1}{\varepsilon}\right)^{\kappa-1} \quad (1)$$

$$\kappa = \frac{c_p}{c_v} \quad (2)$$

Here, ε is the compression ratio or the expansion ratio, c_v and c_p are the specific heat at constant volume and pressure, respectively. According to this theory, increasing the engine compression ratio and the specific heat ratio are effective ways for improving thermal efficiency. The former one can be achieved by raising the mechanical compression ratio or by optimizing the opening timing of the exhaust valves. The latter one can be achieved by adopting lean burn combustion.

On the other hand, an actual engine thermal efficiency results from mechanical loss, pumping loss, cooling heat loss, exhaust loss, and unburned loss as shown in Figure 2.

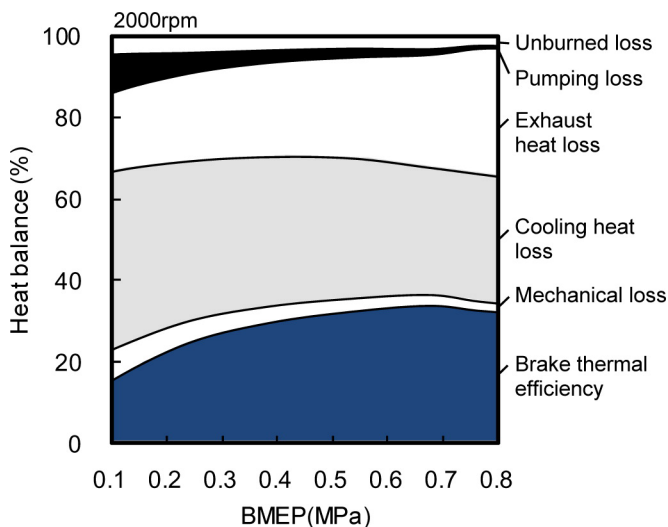


Figure 2. The relation between engine load and heat balance

Figure 2 shows the relation between engine load and heat balance. In low load areas, the proportion of pumping loss, cooling heat loss, and mechanical losses is high. In high load areas, the proportion of exhaust heat loss is high. The factors behind these trends are thought to be as follows. As engine load increases, intake manifold pressure increases due to bigger throttle opening, and hence pumping loss is reduced. The proportion of mechanical loss decreases because engine friction changes very little as load increases. As for cooling heat loss, higher load leads to a decrease in cooling heat loss because the amount of heat release is increased where the combustion chamber's

surface area is constant. As a result, exhaust heat loss increases as the engine load increases. Especially exhaust heat loss is increased when knocking occurs because ignition timing should be delayed.

These relationships demonstrate that mitigating knocking and reducing engine cooling heat loss are extremely important aspects of enhancing the engine thermal efficiency. As mentioned above, cooled EGR is regarded as a key technology for achieving both of these objectives. For this reason, it has been adopted in a wide range of both hybrid and conventional vehicles in recent years.

EFFECT OF FAST COMBUSTION

In gasoline engine combustion, the air-fuel mixture is compressed by the piston and ignited by a spark plug for forming a flame kernel. After this process, the flame propagates toward the walls of the combustion chamber. It is essential to understand the phenomena which have large effect on combustion characteristics. In this part, the direction for enhancing combustion is explained.

Figure 3 shows the one example of relationship between EGR limit and the change of combustion duration. Test condition is 2000RPM at 0.4MPa of BMEP. 0-10% and 10-90% combustion duration become longer with EGR ratio increase. It is known that combustion in real engines is turbulent combustion, characteristics of which are defined by turbulent intensity and laminar burning velocity. Since it is considered that turbulent intensity is almost same even when EGR ratio is increased, the effect of laminar burning velocity is considered.

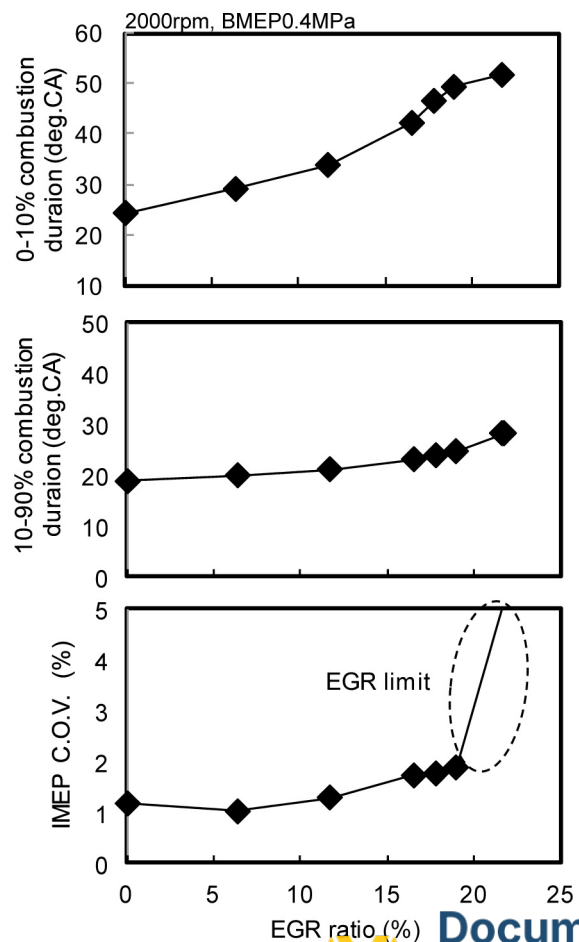


Figure 3. The effect of EGR ratio on combustion duration

Equation (3) shows one research result of laminar burning velocity [6].

$$S_L = [30.5 - 54.9(\Phi - 1.21)] \left(\frac{T_u}{T_0} \right)^\alpha \left(\frac{p}{p_0} \right)^\beta \quad (3)$$

$$\alpha = 2.18 - 0.8(\Phi - 1) \quad (4)$$

$$\beta = -0.16 + 0.22(\Phi - 1) \quad (5)$$

$T_0=298K$, and $p_0=1atm$ are the reference temperature and pressure. α and β are constants for a given fuel equivalence ratio Φ .

Equation (3) shows that laminar burning velocity decreases due to reduce the oxygen concentration in the mixture of air, fuel, and gas temperature. This is one indication of elongated combustion duration with increasing EGR ratio.

To enhance combustion, intensifying air turbulence is essential.

Figure 4 shows the one example of effect of fast combustion on EGR limit and fuel consumption reduction.

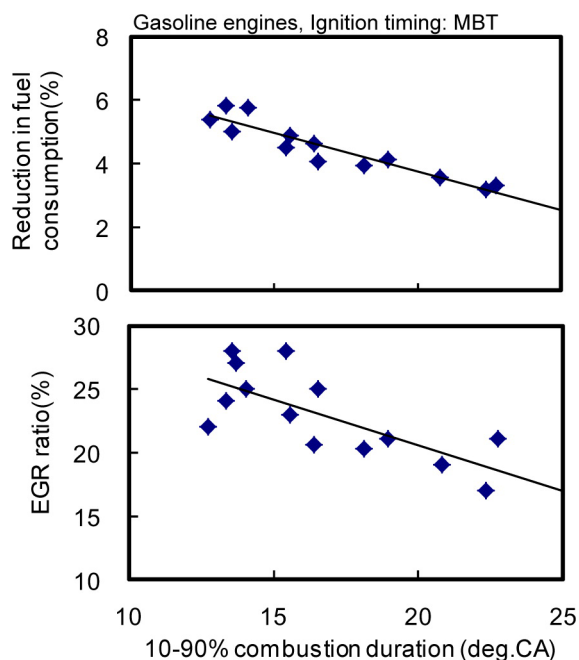


Figure 4. The effect of fast combustion on EGR limits and fuel consumption reduction.

This data is obtained by analyzing a number of production engines and test engines under MBT conditions. It is indicated that fast combustion realizes expanding EGR limit and reduction in fuel consumption.

Figure 5 shows the effect of turbulence intensity on combustion duration. X-axis shows turbulence intensity and Y-axis shows bore diameter divided by 10-90% combustion duration. This y-axis

quantity enables the analysis of flame propagation coming from engines of various bore diameters. The turbulence intensity is defined as the peak value of time trace of mean turbulence intensity coming from CFD. 10-90% combustion duration is measured with experiments. As it can be seen, it is an effective way to increase turbulence intensity for enhancing combustion.

From these result, it is considered that the most effective way of maximizing the effect of EGR is to achieve fast combustion.

In the subsequent sections, detailed analysis is conducted to clarify the effect of fast combustion.

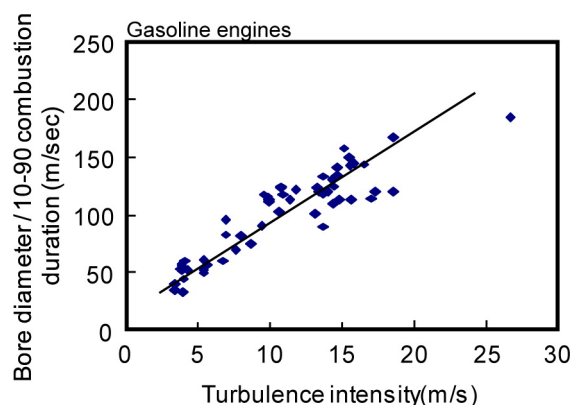


Figure 5. The effect of turbulence intensity on combustion duration

ENGINE SPECIFICATIONS

Two engines with specifications described in Table 1 are used to examine fast combustion. Firstly, fast combustion is investigated by using Test engine 1, a 2.5-liter 2AR-FE mass production engine. Subsequently, 3ZR-FE-based 2.0-liter Test Engine 2 is added to the test to analyze turbulence and combustion speed. STAR-CD is used to calculate in-cylinder flow and turbulence, and Laser Doppler Velocimeter (LDV) is used to measure the turbulence. Furthermore, ignition energy is not modified.

Table 1. Test engine specifications

Engine	Test Engine1	Test Engine2
Bore(mm)	90	80.5
Stroke(mm)	98	97.6
Cylinder Number	4	4
Displacement(cc)	2493.8	1987.0
Compression Ratio	10.4	10
Tumble Ratio	1.2-3.3	0.8-3.3
Fuel type	Gasoline	Gasoline
Valvetrain System	DOHC 4valve	DOHC 4valve
EGR System	Cooled EGR	–
Injector position	Port	Port
Boost	NA	NA