

Downsizing as Evolution of High Thermal Efficiency Gasoline Engine

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ABSTRACT

In order to achieve downsizing as an evolution in the high thermal efficiency engine, the possibilities of increasing specific power were examined.

In order to achieve a balance between the specific power that is required for downsizing the engine and the high compression ratio (high expansion ratio) that is the basis for thermal efficiency, high knock resistance in the high engine speed range is necessary. The issue in realizing high power was that sufficient reduction in effective compression ratio through valve timing could not be obtained in the high engine speed range. It became possible to reduce the effective compression ratio by enhancing the intake system, and an increase in specific power was obtained by knock enhancement, but the increase was limited to the equivalent of a naturally aspirated engine. Raising thermal efficiency and downsizing are mutually contradictory techniques, and it became clear that any further increase in specific power would necessitate lowering the mechanical compression ratio itself.

At the same time that downsizing is a technique for improving fuel economy by reducing the displacement, it can also be expected to heighten dynamic performance by achieving lighter weight and greater compactness. In that sense, the approach of downsizing by increasing specific power is crucial for achieving evolution of the high thermal efficiency gasoline engine. In order to achieve this, it will be necessary to build and apply variable compression ratio mechanisms and other such radical technology.

1. Introduction

It has been predicted⁽¹⁾ that the number of vehicles with internal combustion engines will continue increasing up to the year 2040. Even as the electrification of vehicles progresses in the future, it will be important for the internal combustion engine to evolve (Fig. 1).

The societal significance of the electrification of vehicles is in the reduction of CO₂ emissions. Consequently, the issue faced for internal combustion engines that support that advance is the reduction of CO₂ emissions, or in other words

the comprehensive enhancement of thermal efficiency.

An engine is a machine that converts the energy in fuel into motive power. The higher the efficiency of that conversion, or in other words the thermal efficiency, the more superior the machine can be said to be. On the other hand, if the engine is considered as one of the devices that make up a vehicle, then there is a demand for lighter weight and compactness in the interest of installability and weight balance. In other words, no matter how high the thermal efficiency of an engine may be, it cannot be expected to contribute very much to limiting the impact on

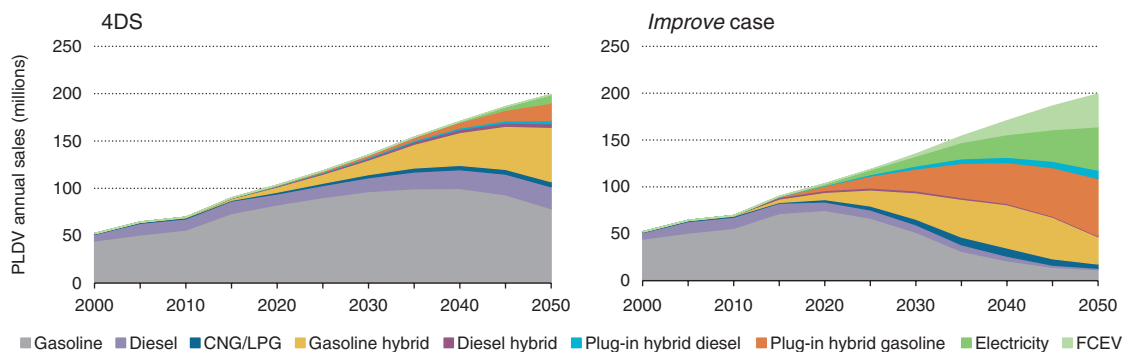


Fig. 1 Global portfolio of technologies for passenger LDVs, (4DS: 4°C scenario, Improve case: Technology improvements that lowers GHG emissions)

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the environment if there are such issues with installing the engine that the vehicles in which it can be used are limited.

Automobiles are not just a means of mobility, since they also embody an element of fun experienced in driving them. This is where they differ from public means of transportation, and it is also important to manufacture automobiles that are able to provide customers with fun while also curbing the environmental impact. Making the engine lighter in weight and more compact is an important element that ultimately contributes to reducing the vehicle weight and enhancing its dynamic performance.

This paper focuses on achieving a balance between high thermal efficiency and downsizing (Fig. 2) as an engine technology for seeking a balance between limiting environmental impact and providing fun. It will describe the issues faced in this effort and the techniques for addressing them.

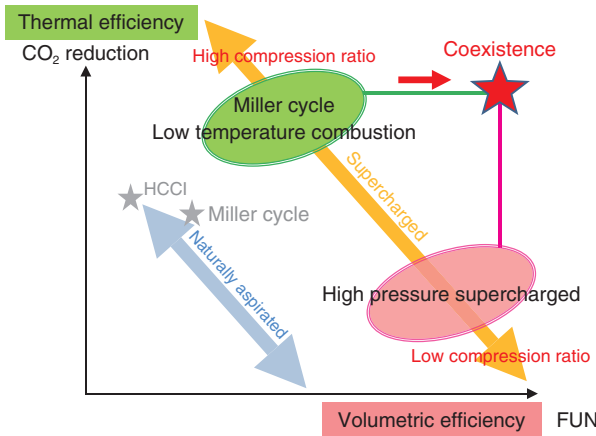


Fig. 2 Coexistence of thermal efficiency and volumetric efficiency

2. Value of Downsizing

The downsizing and boosting⁽²⁾ technique for fuel economy improvement came into widespread use mainly in Europe, and now has become standard technology. It was introduced into the United States nearly a decade late, and in Japan, too, its introduction began to accelerate as more of these vehicles were imported.

Downsizing and boosting is not a technique for raising thermal efficiency. Rather, thermal efficiency is diminished as downsizing progresses. The main factor in that is the reduction in compression ratio made to match with supercharging. The tendency for a rise in maximum brake mean effective pressure (BMEP) to be accompanied by a decrease in the compression ratio (Fig. 3) can also be observed in the configuration of commercially available engines. Care needs to be taken, therefore, to note that fuel economy and thermal efficiency are not synonymous.

The mechanism by which fuel economy improves with

downsizing is the shift of the engine operating point into a high thermal efficiency region. This effect is obtained by optimizing the displacement (reducing the displacement) with respect to the driving load, and the usual practice is to combine this with boosting in order to recover power (Fig. 4). A displacement matched to fuel economy can generally be envisioned as downsizing of approximately 65% (equivalent to a change from 2.4 L to 1.5 L), in which case obtaining dynamic performance on a par with a conventional naturally aspirated (NA) engine would necessitate boosting to a level of 2200 kPa at maximum load.

Downsizing is not simply a matter of bringing down the displacement. As the term indicates, it is also important to make the engine lightweight and compact. Making the engine more lightweight contributes to reducing the weight

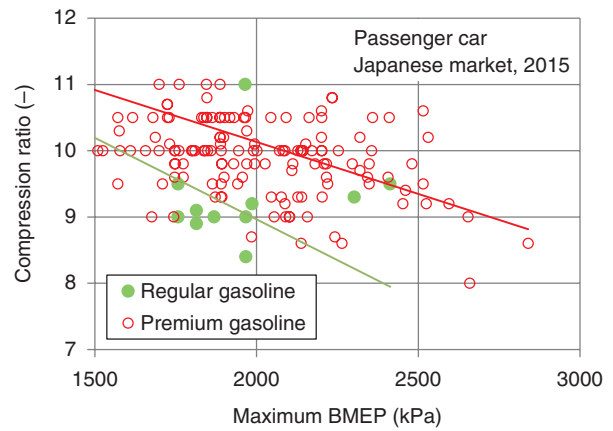


Fig. 3 Tendency of compression ratio to move inversely to BMEP of gasoline engine

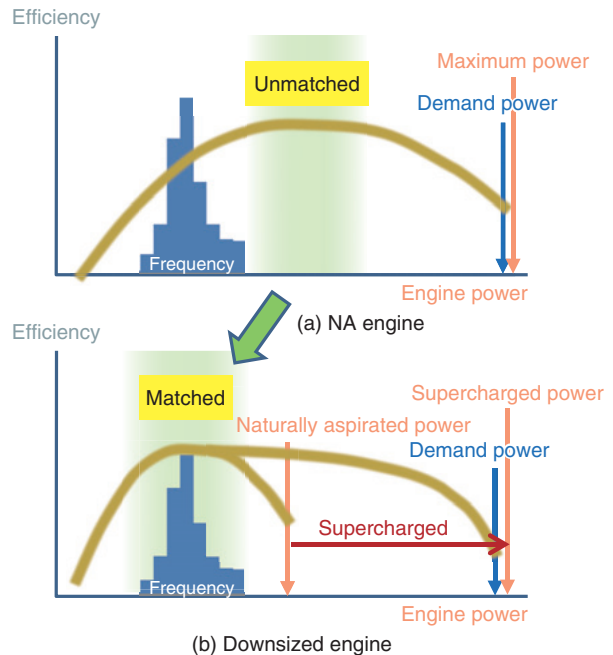


Fig. 4 Fuel economy improvement by downsizing

of the chassis, which supports the engine, and the reduction in driving energy improves the fuel economy. The dynamic performance obtained by making the chassis lighter can also be used to advantage by further reducing the engine displacement and weight, giving rise to a virtuous cycle. A lightweight, compact engine enlarges the freedom to distribute weight in the vehicle, and enhancement of maneuverability can also be expected. These are important elements of fun, the pleasure of driving the vehicle.

On the other hand, the technology to achieve the thermal efficiency of 45% that is assumed for the present project involves reducing the effective compression ratio, which means a real reduction in the displacement. In other words, the increase in specific power due to boosting does not go beyond the level of making up for the displacement reduction. This means that in order to assure dynamic performance, the displacement will remain as it was. However, thermal efficiency enhancement is obtained in all regions, so even when a region with greater frequency of use does not coincide with the region of high thermal efficiency, the amount of enhancement in thermal efficiency will still contribute directly to improved fuel economy (Fig. 5).

If the operating point and the region of high thermal efficiency could be made to coincide, further fuel economy improvement could be expected. The main methods used include reducing the displacement, concentration of

operating points in application to a hybrid electric vehicle (HEV), expansion of the high thermal efficiency region to lower loads by lean burn or other such means, but the only one of these approaches that contributes to weight reduction and greater compactness is reducing the displacement.

3. Characteristics of a High Thermal Efficiency Engine

A variety of different measures have been used to increase the thermal efficiency of gasoline engines. According to the research of Tagishi et al.⁽³⁾, the main specifications that have achieved brake thermal efficiency of 45.2% with regular gasoline and a stoichiometric air-fuel ratio are as follows:

- (1) Mechanical compression ratio of 17, exhaust gas recirculation (EGR) rate of 35%;
- (2) Stroke bore ratio (S/B ratio) of 1.5; and
- (3) Intensification of in-cylinder turbulence kinetic energy and high-energy ignition.

The thermal efficiency achieved was the result of having a displacement of 626 cm³ per cylinder. The lean-burn approach, which has a higher specific heat ratio than EGR, has greater theoretical efficiency, but given the aftertreatment and knocking issues, efficiency is being pursued instead with a stoichiometric air-fuel ratio.

The following will discuss the issues in achieving a balance between high thermal efficiency and downsizing with these specifications.

3.1. Requirements of Enhanced Thermal Efficiency

In order to seek thermal efficiency, it is necessary to combine enhancement of theoretical efficiency with reduction of relevant types of loss, and a high compression ratio is the precondition that is a basis for enhancing theoretical efficiency. Figure 6 shows a correlation diagram of the technical items necessary in enhancing thermal efficiency. The respective specifications are not simply added together to make a contribution to enhanced efficiency, but instead function interdependently. One example of this follows.

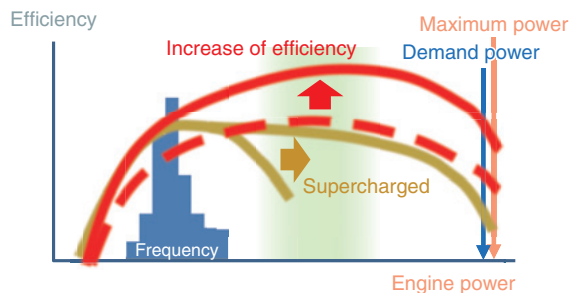


Fig. 5 Fuel economy improvement by increase of thermal efficiency

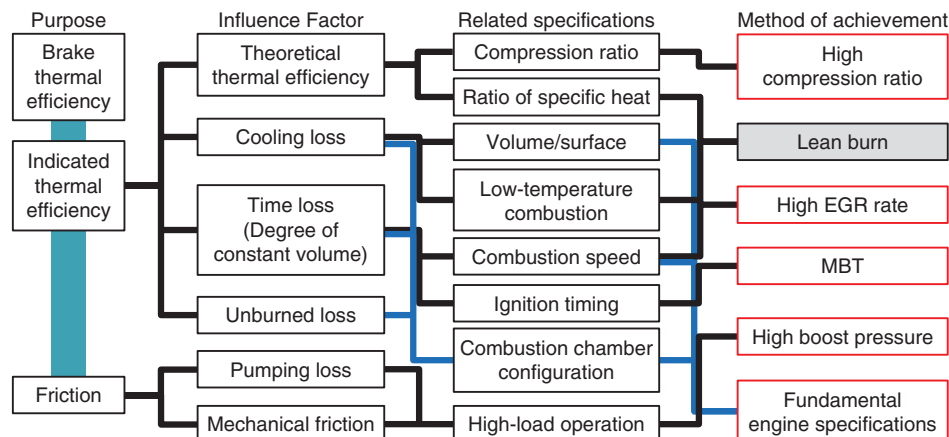


Fig. 6 Analysis of factors influencing brake thermal efficiency

Setting the displacement and S/B ratio properly brings a reduction in combustion chamber surface/volume ratio (S/V ratio) that yields amelioration of cooling loss, but it also helps enable the combustion of diluted mixture at a high compression ratio. In order to realize high-efficiency combustion, it is necessary to have a combustion chamber with a height that does not inhibit flame propagation, and at high compression ratios that result in a flat combustion chamber, the demanded S/B ratio will be correspondingly larger. With a compression ratio of 17, an S/B ratio of 1.4 or greater is necessary (Fig. 7). If an S/B ratio of 1.2 were to be chosen, then not only would there be a simple decrease in efficiency due to the increased cooling loss, but there would also be a failure to achieve combustion itself with a compression ratio of 17. Thermal efficiency so high that it reaches 45% can only be obtained when all the specifications are configured without compromise.

In the mass-production automobile gasoline engines made by Honda over the past 10 years, the specifications have included compression ratios ranging from 8.8 to 13.0, single-cylinder displacement from 220 to 610 cm³, and S/B ratios from 1.0 to 1.2. A compression ratio of 17, single-cylinder displacement of 626 cm³, and S/B ratio of 1.5 achieving brake thermal efficiency of 45% greatly exceeds that range. Figure 8 shows the influence of S/B ratio and displacement on thermal efficiency. The maximum thermal efficiency point is located in the vicinity of a single-cylinder displacement from 600 to 650 cm³ and S/B ratio of around 1.5. This configuration of specifications is a necessary condition for achieving 45% thermal efficiency.

3.2. Output Power Characteristics of the High Thermal Efficiency Engine

With the high compression ratio that is a basis for

enhancement of thermal efficiency, the reduction of burning velocity, increase in unburned loss, and knocking become significant issues. Combustion issues are addressed, as described above, by setting a high S/B ratio. Knocking is addressed mainly by introducing EGR and retarding the intake valve close (IVC) timing in order to lower the effective compression ratio (Miller cycle) and reduce the temperature at compression top dead center (TDC).

Introducing EGR and retarding the IVC timing results in a decrease in actual engine displacement. When EGR of 35% is introduced in combination with a mechanical compression ratio of 17 as the basis for retarding the IVC timing to yield an effective compression ratio of 12.5, then the actual displacement decreases to about 50% of the mechanical displacement (0.65 for EGR $\times$ 0.72 for IVC = 0.47) (Fig. 9).

A brake thermal efficiency of 45% is achieved with BMEP of 800 kPa at 2000 rpm, and the charging efficiency

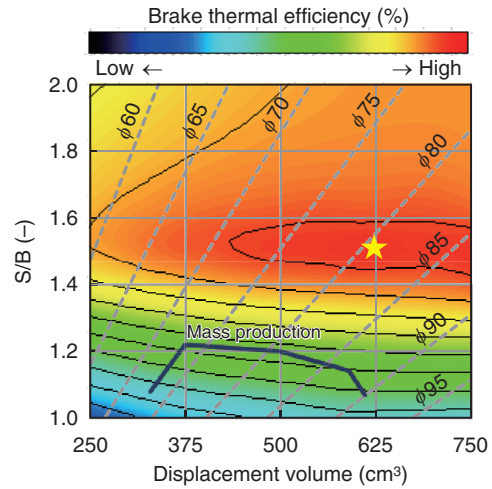


Fig. 8 Engine displacement and S/B in relation to maximum brake thermal efficiency

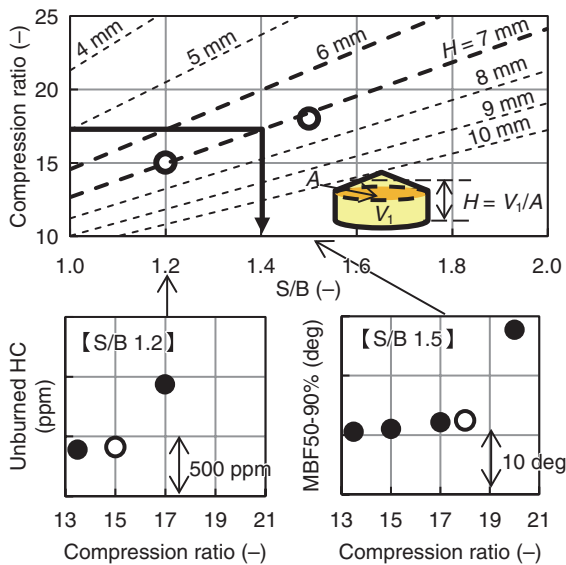


Fig. 7 Average combustion chamber height at TDC for different S/B and compression ratios

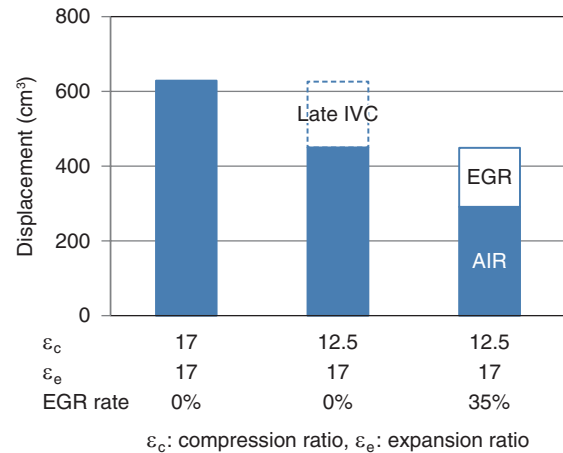


Fig. 9 Reduction of actual displacement by late intake valve close (IVC) timing and exhaust gas recirculation (EGR)

(η_c) then is approximately 60%. If it is an NA engine, η_c 60% can be achieved in the throttling range; however, for the reasons noted above, boosting to 20 kPa (gauge pressure) is necessary in order to assure the air quantity obtained.

Raising the BMEP to a high level in a high thermal efficiency engine has the following issues:

- (1) Obtaining the boosting pressure to force in the necessary quantity of air; and
- (2) Limitations due to the trade-off between increasing the air quantity and retarding the ignition timing at which knocking occurs.

Since a high thermal efficiency engine has a large S/B ratio, there are limitations on how high the engine speed can go. When transposition from an NA engine with the same displacement is envisioned, the maximum load demand value to achieve equal dynamic performance is about BMEP 1400 kPa, and the maximum power output speed is about 5000 rpm.

In order to provide for η_c at the maximum load point, EGR is not introduced and only IVC timing is used for knocking avoidance. Even then, however, there is only about 70% of actual displacement. In order to obtain 1400 kPa at 2000 rpm, an η_c of 100% is necessary, and the boosting pressure to achieve that is estimated at 70 kPa (gauge pressure). General downsizing of boost engines can achieve BMEP 2000 kPa at this boost pressure level.

Boosting systems use turbochargers for the efficiency. The turbocharger size was configured on the maximum power flow side, but the high expansion ratio (mechanical compression ratio of 17) by comparison with ordinary boost engines means that the exhaust enthalpy is low. This became an issue in providing boost pressure of 2000 rpm. Having exhaust enthalpy remains an issue for realizing a boost system in a high thermal efficiency engine.

If the actual displacement is increased, the boost pressure for obtaining the same air quantity could be lower and the maximum boost pressure could be made even higher (Fig. 10) so that the demand air quantity was obtained by

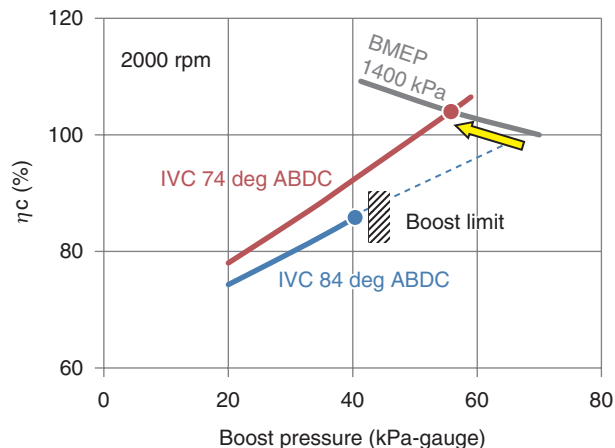


Fig. 10 BMEP limit by air quantity

advancing the IVC timing. While advancing the IVC timing causes the effective compression ratio to increase together with the actual displacement, it also retards the ignition timing at which knocking occurs. Consequently, thermal efficiency decreases, but even so, assuring the air quantity (heating value) makes the target of 1400 kPa achievable (Fig. 11). In the low-speed range, the actual boost pressure limit becomes the BMEP limit.

On the other hand, even if the IVC timing is retarded in the high-engine-speed range, the resistance that returns fresh mixture to the intake port side is large and the effective compression ratio is higher than at low speeds. In both cases shown in Fig. 12 of cylinder pressure at engine speeds of 2000 and 5000 rpm, although the IVC is set to the same delayed closure timing, no rise in pressure was observed after bottom dead center at 2000 rpm. It is

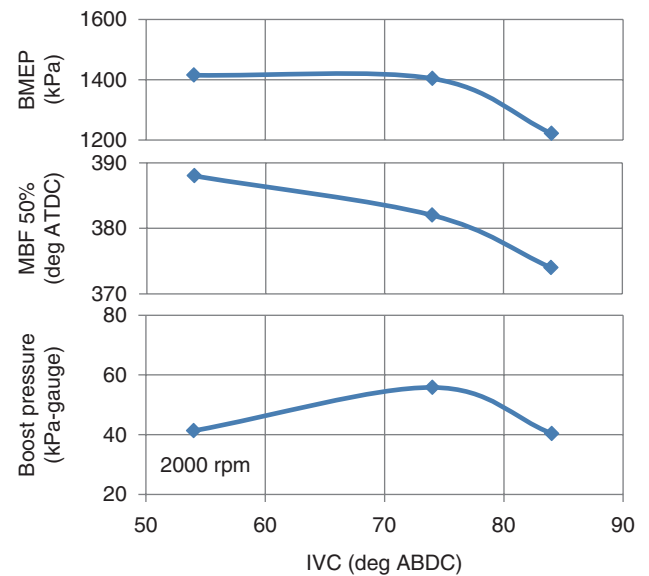


Fig. 11 Influence of effective compression ratio

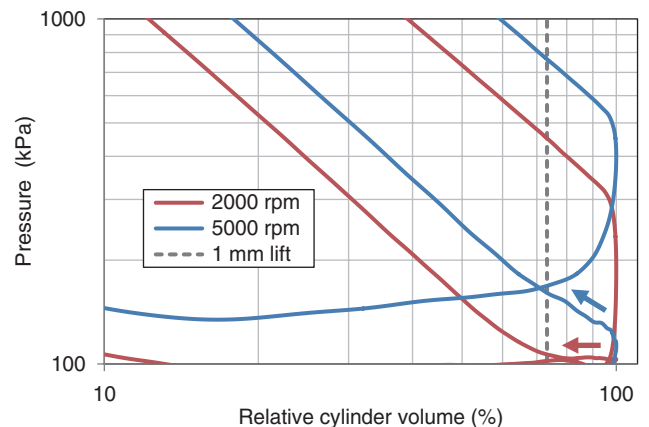


Fig. 12 Effective compression comparison

apparent that during that time, fresh mixture returns to the intake port side so that the effective compression ratio can be lowered. At 5000 rpm, on the other hand, compression begins from bottom dead center even though the intake valve is open. The effective compression ratio is not lowered, so that the temperature at compression TDC rises to about 900 K. The temperature rises to the region where homogeneous charge compression ignition (HCCI) can occur, but since the reaction time is short at high speeds, HCCI combustion does not occur. The ignition timing is retarded for knocking avoidance, so that even if the air quantity (heating value) is increased, it is canceled out by the reduced thermal efficiency, and the BMEP upper limit was reached (Fig. 13).

Knocking is a phenomenon that occurs when the pressure and temperature of unburned mixture in the vicinity of the combustion chamber wall (end-gas) rise due to compression and the influence of that rise results in auto-ignition. The ignition delay time becomes shorter because of the rise in temperature and pressure, so that higher temperatures and higher pressures make knocking more likely to occur. Ordinary regular gasoline is known to have a region with a negative temperature coefficient, called the NTC region. In this region, the ignition delay time is not shortened even when the temperature rises (Fig. 14). Ordinarily, long ignition delay times at low temperatures make knocking less likely to occur, but in this region, it appears likely that even lowering the air-fuel mixture temperature will not mitigate knocking.

The fact is that at 5000 rpm, where the temperature at compression TDC reaches 900 K, no knocking mitigation at all was obtained, even when intake air cooling with direct fuel injection and intercooler is used to realize a temperature reduction of about 30 K. The difference of 30 K is, empirically, the level of change that is obtained by advancing the ignition timing at which knocking occurs by about five degrees. Figure 15 shows the temperature at

compression TDC (calculated values) for each compression ratio together with the temperature sensitivity of the knocking phenomenon.

The reaction process that leads to auto-ignition goes through the cycle of air-fuel mixture compression by the piston and the process of end-gas compression by the combustion gases. When the conditions of this reaction process largely overlap the temperature and pressure of the NTC region, then the temperature sensitivity with respect to ignition delay time will be lower than when the process passes through other regions. In this case, it can be surmised that the reduction of temperature from direct fuel injection and other such factors did not yield an anti-knock effect because of the NTC influence.

A high compression ratio is an essential condition of high thermal efficiency. However, obtaining high power with a high compression ratio involves issues that can be summarized as follows.

- (1) Lowering the effective compression ratio by retarded IVC timing is a means of knocking avoidance that does not operate effectively at high engine speeds.
- (2) As a result, air-fuel mixture temperature in the cylinder

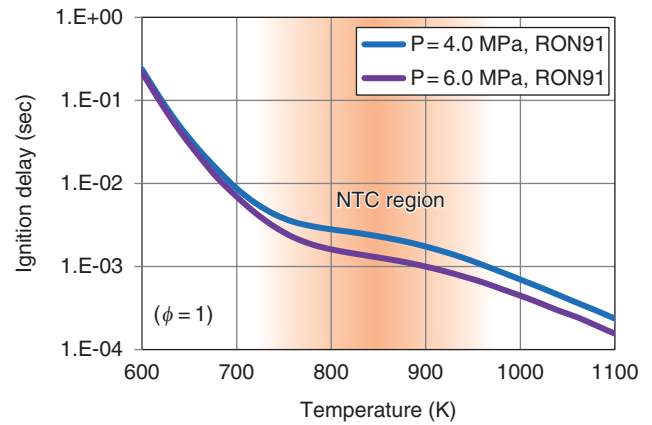


Fig. 14 Negative temperature coefficient (NTC) region of ignition delay

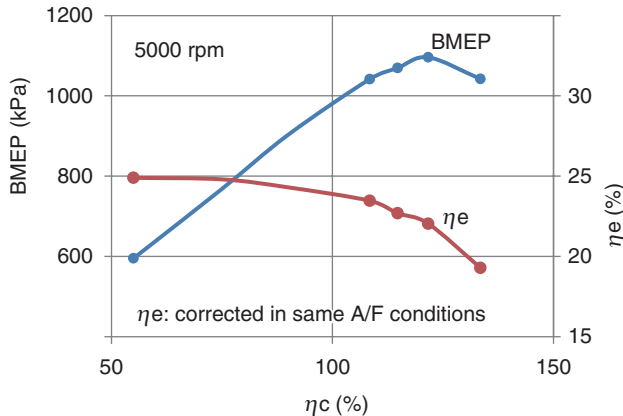


Fig. 13 BMEP limit by reduction of thermal efficiency (η_c : charging efficiency; η_e : brake thermal efficiency)

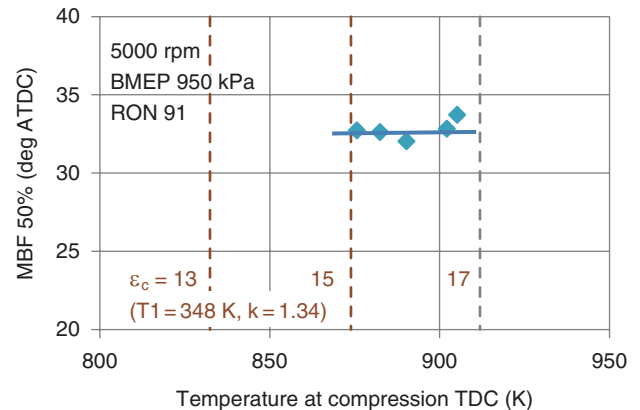


Fig. 15 Temperature sensitivity in knocking

is high so that direct fuel injection and other such measures do not produce a sufficient cooling effect.

With specifications that obtained a brake thermal efficiency of 45%, the BMEP did not rise beyond about 1100 kPa at 5000 rpm. This did not reach the level of 1400 kPa that is necessary for transposition from an NA engine.

4. Examining Possibilities for Realizing High Power

In order to achieve a transition from the already existing NA engine to the high thermal efficiency engine, and to further realize a balance with downsizing, measures are taken to mitigate knocking, which impedes the realization of high power. Those measures and their effects are discussed here. Table 1 shows the specifications of the engine used in this examination.

4.1. Seeking Power Output with a Boost Miller Cycle

Under conditions in which no temperature sensitivity is observed in knocking, it may mistakenly appear as though these various techniques have no effect on knocking. However, it is reasonable to expect knocking to be mitigated if the combination of further measures made it possible to lower the temperature of the air-fuel mixture to a region where temperature sensitivity can be observed.

Figure 16 shows the envisioned knock enhancement logic. First, in order to obtain a reduction of the effective compression ratio by retarding the IVC timing, it is necessary to smooth out the flow returning from the cylinder to the port. As a result of reduction in the resistance of the intake port and the area surrounding the intake valve, IVC timing becomes an effective method for reducing the effective compression ratio. This then enables steps to lower the temperature at compression TDC (Fig. 17). Reducing the intake resistance reduces the work of boosting so that pumping mean effective pressure (PMEP) is decreased. When the exhaust pressure becomes relatively low and the internal EGR is diminished, the effect of reducing the air-fuel mixture temperature can take place. Reducing the intake resistance lowers the velocity of flow into the cylinder so that there is also thought to have been an effect of reduced heat transfer from high-temperature areas. The magnitude of the respective effects attributable to the various factors cannot be separated out at present, but they are all consistent in being measures oriented toward temperature reduction. In port selection, consideration of a flow volume sufficient to help ensure power output and reduction of the air-fuel mixture temperature are necessary, in addition to the high-intensity turbulence demanded for high-efficiency combustion in the low-speed range.

The result of lowering the air-fuel mixture temperature in the cylinder and taking knock enhancement measures was that the target of power output equal to that of an NA engine was met with a BMEP of 1400 kPa at 5000 rpm (Table 2).

Table 1 Specifications of test engine

Bore (mm) × Stroke (mm)	φ 73 × 109.5, S/B 1.5
Compression ratio (-)	Variable by IVC timing
Expansion ratio (-)	17.0
Engine type	DOHC 4-valve
Number of cylinders	4
Displacement (cm ³)	1833
Intake port	Tumble port
Air supply	Turbo charger
Fuel supply	Direct injection
Gasoline	RON91

Table 2 Port flow comparison and test result

	Base port	High flow port
Mean effective opening area (cm ²)	3.55	5.04
Intake valve diameter (mm)	φ 28	φ 29
Temperature at TDC (K), η_c 100%	826	772
Exhaust pressure (kPa), η_c 100%	128	143
MBF 50% (deg), η_c 100%	36.4	33.1
Maximum BMEP (kPa)	1100	1400

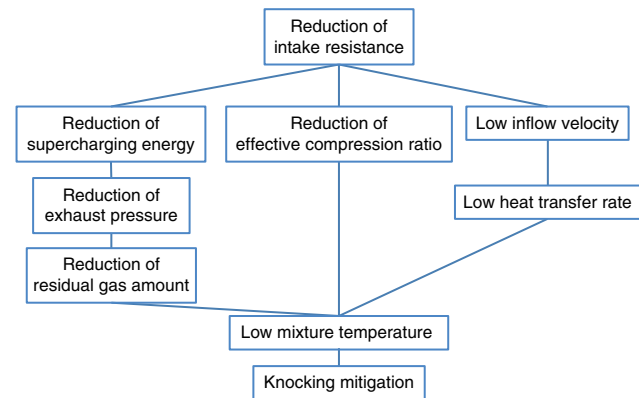


Fig. 16 Knocking mitigation by reduction of intake resistance

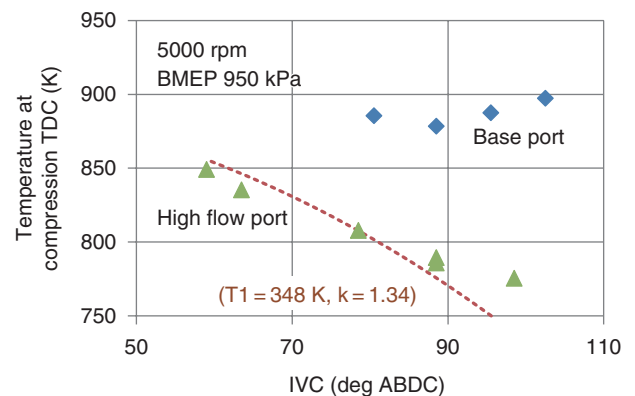


Fig. 17 Relationship between IVC and effective compression ratio

4.2. Variable Compression Ratio

The result of increasing power output by enhancing the specifications was confirmed up to equality with an NA engine. However, a level that would enable downsizing the engine was not achieved. In order to obtain further increased power output, drastic countermeasures against knocking will be necessary.

Figure 18 shows the relationship between the maximum BMEP and compression ratio of engines in commercially available vehicles. They reach a BMEP on the level of 2000 kPa at a compression ratio of 11. This means that if the compression ratio can be lowered to this degree, then a BMEP at a level enabling engine downsizing can be obtained.

With a high thermal efficiency engine, the effective compression ratio reduction effect obtained 5000 rpm and 1400 kPa even with a compression ratio of 17. Using a similar delayed closure of the intake valve, it is possible that a BMEP on a par with a commercially available vehicle could be obtained with a compression ratio higher than that of a commercially available vehicle. An increase in the BMEP attributable to the thermal efficiency resulting from a high S/B ratio can also be expected. The high thermal efficiency engine specification allows for the possibility of a compression ratio set higher than 11 at a BMEP of 2200 kPa, and it also has greater potential for high-load efficiency than commercially available boost-downsizing engines.

If the specific power can be increased from a BMEP of 1400 kPa to 2200 kPa, then the engine displacement can be reduced to about 65%. In order to obtain the fuel economy improvement from downsizing, the driving load and thermal efficiency need to be matched. This matching was considered in terms of a FIT-class vehicle with inertia weight 1090 kg envisioned driving in Worldwide harmonized Light vehicle Test Procedures (WLTP) mode. When the frequency distribution of the power output is calculated on the basis of fuel consumption, the power

of 14 kW at 50% cumulative frequency is the equivalent of 15% of the maximum output of 96 kW of a currently available NA engine (Fig. 19). Figure 20 shows the relationship between the iso-power contour line and thermal efficiency that obtains when this engine is envisioned in terms of a boost engine with a maximum thermal efficiency point at 2000 rpm and 800 kPa and a maximum power output point at 5000 rpm and 2200 kPa. Power output at the maximum thermal efficiency point is 15% of maximum power output, and can be made to coincide with power output at 50% cumulative frequency. Power output at 80% cumulative frequency is 23% of maximum power output, and the efficiency is within -2 points of maximum thermal efficiency. This suggests that in an engine with a maximum power output point at 5000 rpm and 2200 kPa, the driving load in WLTP mode would generally fall within the high thermal efficiency range.

For each operating range of the engine, there is an optimal compression ratio in terms of thermal efficiency or maximum load. However, a complex mechanism would be necessary in order to implement continuously variable compression that can be optimized to all ranges. In the

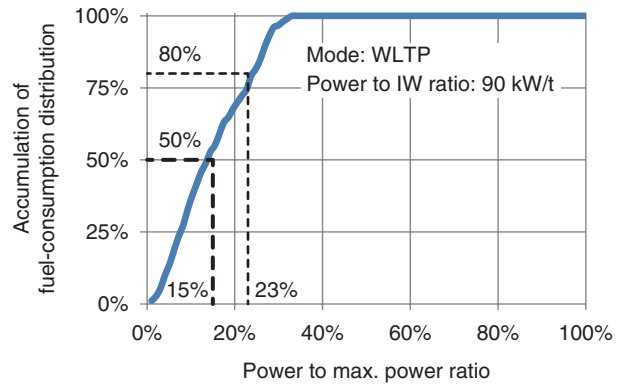


Fig. 19 Fuel consumption distribution

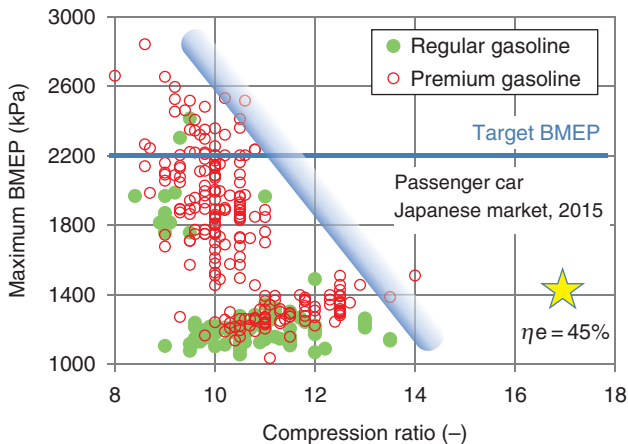


Fig. 18 BMEP limit by mechanical compression ratio

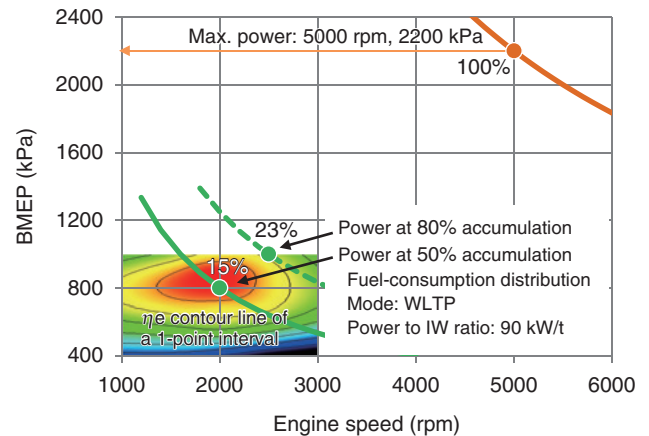


Fig. 20 Relationship of power ratio to max. power and thermal efficiency

event that the variable compression ratio is selected, it would be preferable to have a simple and easy switching mechanism in line with the compactness that is the original aim. As described above, an examination was made of one example of an engine with the specific power of 2200 kPa at 5000 rpm in which mode driving using relatively high loads fits within the high thermal efficiency region. The high compression ratio that achieved high thermal efficiency (17: η_e 45%) was therefore made a basic specification, and a two-stage shift that realizes a lower compression ratio in order to yield power output (11: BMEP 2200 kPa) was used for specifications that simultaneously produce high thermal efficiency, downsizing, and compactness.

5. Conclusion

The possibilities of increasing specific power were examined as a way of achieving downsizing as an evolution in the high thermal efficiency engine.

- (1) By reducing the air-flow resistance at the intake valve and intake port, it became possible to return fresh mixture from the cylinder to the port by delayed closure of the intake valve even at 5000 rpm. As a result, it became possible to lower the effective compression ratio, and advancing the ignition timing at which knocking occurs obtained a higher BMEP. The maximum BMEP at 5000 rpm became 1400 kPa, making it clear that specific power up to a level equivalent to an NA engine could be achieved with a mechanical compression ratio of 17.
- (2) In order to obtain further increased specific power output, drastic countermeasures against knocking become necessary, and enabling a variable mechanical compression ratio is an effective approach. If the compression ratio demand value of 17 in the high thermal efficiency region and the compression ratio of 11 in the power output region could be made variable, it would become possible to achieve a balance of 45% brake thermal efficiency and 2200 kPa. Using this engine, WLTP mode driving in a vehicle with a 90 kW/t power-weight ratio could generally fit within the high thermal efficiency range.

6. Afterword

The automobile society will come sooner or later to the developing countries and to the base of the pyramid (BoP), and it is one of the duties of the automobile manufacturers to guide this society into a healthy environment. In that sense, limiting the environmental impact is a fundamental element of performance demanded of a low-cost basic engine.

When pursuing thermal efficiency, expensive and complex devices such as boosting systems and EGR systems become necessary. In order for a basic engine to obtain high thermal efficiency with the minimum device,

it is especially important for it to have outstanding basic performance.

The foundation for thermal efficiency enhancement techniques is appropriate selection of the basic structure and specifications of the engine. By means of configuration, even a non-boost engine can obtain brake thermal efficiency of around 42%. Depending on the power output required, upsizing may become necessary, but such an engine may become an option in a market that places value on high thermal efficiency, high reliability, and low cost.

The development of a high thermal efficiency engine should be pursued in a form that, in addition to outstanding basic performance, allows the selection of appropriate devices suited to market demands.

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