1.4G High Compression Ratio Combustion by Piston Speed Control

Yasuo MORIYOSHI
Chiba Univ., 1-33 Yayoi-cho Inage-ku Chiba 263-8522, Japan
E-mail: ymoriyos@faculty.chiba-u.jp

Koji MORIKAWA, Makoto KANEKO
Fuji Heavy Industries Ltd., 3-9-6, Osawa, Mitaka, Tokyo 181-8577, Japan

A new combustion method of high compression ratio SI engine was studied and proposed in order to achieve high thermal efficiency. A special cranking mechanism was adopted which allowed the piston to move rapidly near TDC by using a set of gears. Numerical simulations were performed to achieve high thermal efficiency. As a result, this concept can be operated at the compression ratio of 14 using regular gasoline. A new single cylinder engine was designed and built for proving its performance. The experimental results show that the knocking limit has improved and better indicated thermal efficiency has been obtained.

Keywords: Engine Combustion, Computer Application, Knocking, SI engine

1. INTRODUCTION

Various methods have been tried in order to improve the thermal efficiency of the gasoline engine; to enhance theoretical thermal efficiency by increasing the compression ratio, or to induce lean burn and to improve mechanical efficiency by lowering the friction loss have been the prime methods. However, no method for the gasoline engine to achieve greater brake thermal efficiency than that of the diesel engine has been put to practical use. For substantial improvement of thermal efficiency, the ways to realize the low-cost gasoline engine that can be operated with high compression ratio have been sought. The major obstacle for the development is the knocking. Although many research works have been conducted to suppress knocking in the aspect of combustion and fuel, the fundamental solution is yet to be found [1-6]. We therefore focused on suppressing knocking in the aspect of the cranking mechanism with the engine of which compression ratio is increased for higher thermal efficiency. The results from numerical simulations, actual engine tests, and combustion analysis are shown in this paper, and progress in the thermal efficiency improvement and its mechanisms are also discussed.

2. HOW TO SUPPRESS KNOCKING

2.1 INCONSTANT CRANK SPEED MECHANISM

A method was created in which the knocking is inhibited by the special cranking mechanism that allows the pistons to move faster near top dead center and expand the gas faster. With this method, the time for heat transmission to the combustion chamber wall decreases, which results in the smaller heat loss. Inconstant angle speed gears are used for the cranking system that realizes the above. The gear systems are shown in Fig.1

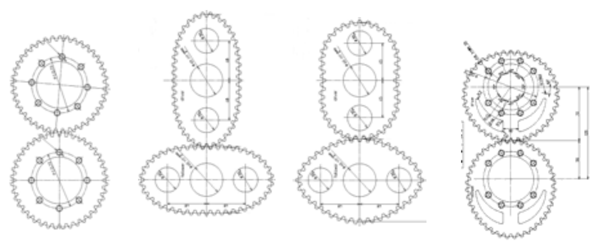

Fig. 1 Gear systems

The Base gear system, which was made for performing normal cranking system tests, has circular gears. The Elliptic and the Leaf-shape gear systems consist of ellipse and leaf-shaped gears respectively, and both gear systems accelerate piston speed near top and bottom dead center. The Leaf-shape (N-1) gear system also has leaf-shaped gears, but it accelerates the piston speed only near top dead center. The piston behavior of each gear system is shown in Fig.2. The horizontal axis represents the power-shaft angle, and 0 degree equals to top dead center. The vertical axis represents the piston displacement, in which 0 mm equals to bottom dead center and the piston position is represented by the piston upward displacement from the bottom dead center. The Base system shows substantially sine curve. With the Elliptic system, the piston speed is the fastest near top dead center. The Leaf-shape and Leafshape (N-1) showed very similar characteristics. The piston speed near bottom dead center is the slowest with the Leaf-shape (N-1) system.

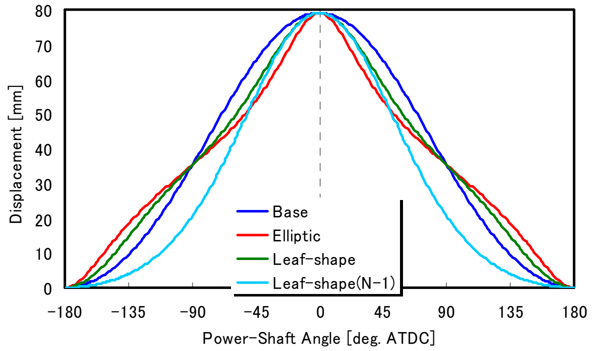

Fig. 2 Piston displacement vs. power-shaft angle for various cranking systems

2.2 OPTIMIZATION BY NUMERICAL SIMULATION

A numerical simulation was performed in order to quantify suppression of knocking and improvement of the thermal efficiency of the inconstant angle speed cranking system. It was performed in the aspect of suppression of knocking and heat loss reduction in order to optimize them. The Woschini formula (1) and integration values of Livengood-Wu(2) (hereafter referred to as L-W) were respectively applied in order to calculate heat loss and a prediction of knocking phenomena. Fig.3 shows the calculated thermal efficiency versus the combustion period for various cranking systems under the following conditions: fixed compression ratio of 14, ignition timing of MBT (Minimum Advance for Best Torque), an equivalence ratio of 1, engine speed of 2000rpm, volumetric efficiency of 100% and heat release rate pattern of an isosceles triangle. Compared to the Base system, the systems with piston moving faster near top dead center achieve higher thermal efficiency when the combustion period is shorter than 40 degrees. It is attributed to the fact that the thermal efficiency of inconstant angle speed cranking systems declines to lower than that of the Base

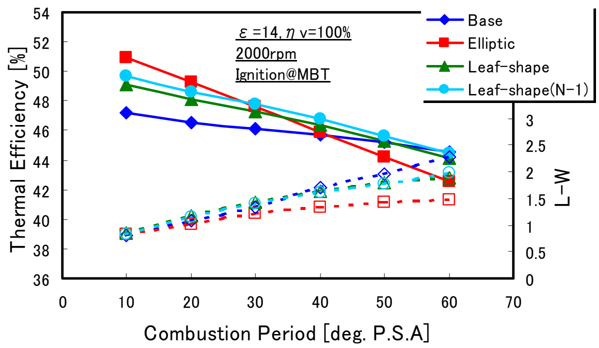

Fig. 3 Calculated thermal efficiency vs. combustion period for various cranking systems

system as the combustion period is prolonged due to the decrease in degree of constant volume while thermal loss is reduced at the same time. In Fig.4, the normalized L-W integrals are shown. A knocking is predicted when L-W integral value exceeds 1. In order to understand the result easier, the maximum value of the L-W integral was normalized as 1 when the compression ratio was 10, volumetric efficiency was 100%, and combustion period was 40 degrees in the case of the Base system. In the graph, the normalized L-W values when the ignition timing was set at TDC and the compression ratio was changed from 10 to 12 to 14 are shown. Note that the L-W integral value of the Elliptic system did not exceed 1 albeit the compression ratio was 14, which theoretically means no knocking. This suggests that this system can operate with high compression ratio without knocking. The Leaf-shape and Leaf-shape (N-1)

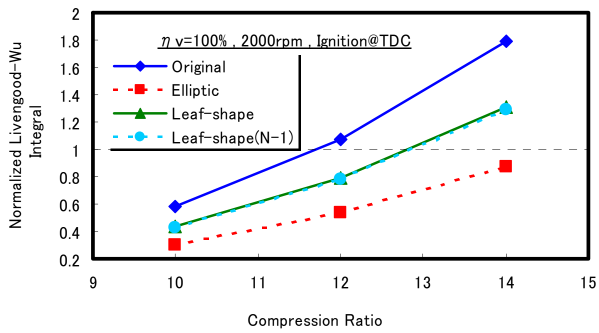

Fig. 4 Calculated thermal efficiency vs. combustion period for various cranking systems (ε =14)

systems showed the similar results, which also suggest the possibility of higher compression ratio without knocking.

According to the simulation results above, the thermal efficiency can be improved without altering the compression ratio by shortening the combustion period using the Elliptic, Leaf-shape, or Leaf-shape (N-1) systems. The results also suggest that the knocking may be suppressed even with the compression ratio of 14. In order to validate these simulation results, a prototype single-cylinder engine was designed and built.

3. EXPERIMENTAL APPARATUS

The specifications for the single-cylinder engine are shown in Table 1. The engine has a typical port fuel injection system. Tests were performed using the regular gasoline and with compression ratio of 10, 12 and 14.

Table 1 Engine specifications

Engine Type	4-stroke Single Cylinder
Bore x Stroke	ϕ 99.5 x 79 mm
Fuel Supply	Port Injection
Displacement	614cm^3
Compression Ratio	10, 12, 14
Fuel	Regular Gasoline (RON91)

Fig.5 shows the outline of the experimental apparatus. Each gear system was installed in a gearbox on the output end of the crankshaft for changing crank angle speed. The output side of the gearbox is connected to a dynamometer, which controls the apparatus operation. The camshaft is driven by the output shaft of the gearbox in order to keep its angle speed constant.

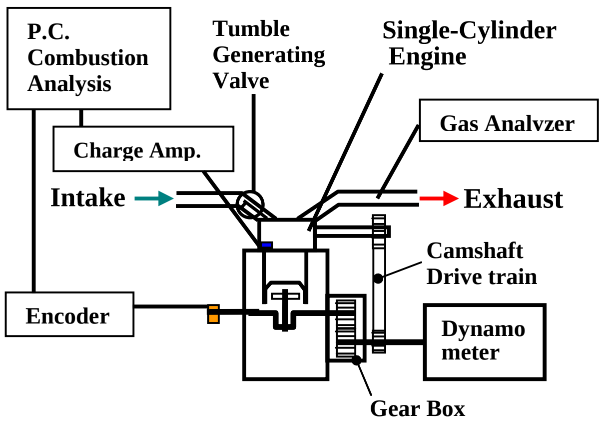

Fig.5 Experimental apparatus

The tests were performed using the Leaf-shape and the Leaf-shape (N-1) gear systems described in Section 2.1. (The Elliptic type was not used for testing since it induced intense engine vibration.) With these systems, the output shaft runs at constant angular velocity while the crankshaft runs at inconstant angular velocity, which result in piston displacement shown in Fig.1.

4. TEST RESULTS AND DISCUSSION

4.1 CHARACTERISTICS FOR KNOKING SUPPRESSION

The characteristics of knocking suppression were investigated in extremely low engine speed range where knocking is prone to occur. Fig.6 shows knocking occurrence characteristics of the Base and Leaf-shape system under the following conditions: engine speed of 600rpm, 80% load, an equivalent ratio of 1, and a compression ratio of 12. The horizontal axis represents the ignition timing (crank angle: advanced angle is shown in +) to graph out IMEP alteration. Since the Base system was unable to run on regular gasoline due to excessive knocking, high-octane gasoline (RON=100) was used and run at MBT in order to compare its effect to that of inconstant speed crank system. In case of the Leaf-shape system, the ignition timing could not be advanced to MBT, but the engine could run on regular gasoline when the ignition timing was retarded, which demonstrated the effects from accelerated piston speed near top dead center. However, the knocking could not be completely suppressed in case of the Leaf-shape system and the fuel consumption was not as good as that of the Base system due to longer combustion period. So a TGV (Tumble Generating Valve) was attached to the Leaf-shape system in order to generate turbulence and facilitate quick combustion. This not only reduced required ignition advance angle but also allowed ignition at MBT, resulting in fuel economy improvement

4.2 IMPROVEMENT IN FUEL ECONOMY AND CONTRIBUTING FACTORS

Fig.7 shows a comparison of indicated thermal efficiency under the conditions specified in Fig.6. The indicated thermal efficiency of the Base system with the compression ratio of 10 is also shown here for comparison. The Leaf-shape system with the TGV showed improvement in fuel economy from the Base system, approximately 8% and 12% at the compression ratio of 12 and 10 respectively.

Results of the combustion analysis are shown in Fig.8 (P- θ diagram) and Fig.9 (dQ/d θ - θ diagram). The compression ratio was 12 in all cases. In the case of the Leaf-shape system, the ignition timing was retarded from the target in order to suppress knocking and its heat release ratio and combustion speed was slower compared to the Base system. In case of the Leaf-shape system with the TGV, on the other hand, combustion speed was recovered and active combustion was seen especially in the last half, indicating a highly knocking-suppressive combustion pattern. However, combustion speed and compression ratio alone do not explain the difference in fuel economy between this system and the Base system.

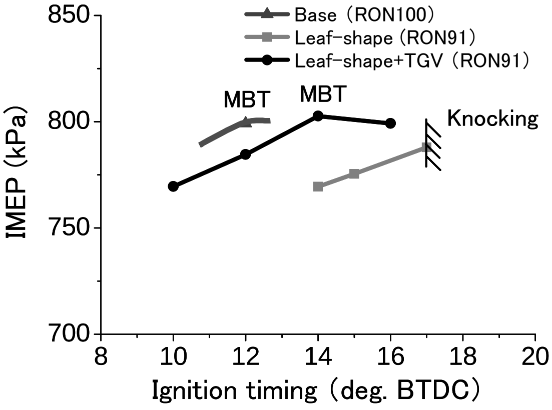

Fig.6 Ignition timing VS. IMEP with the base engine, the leaf-shape gear engine and the leaf-shape gear engine + TGV

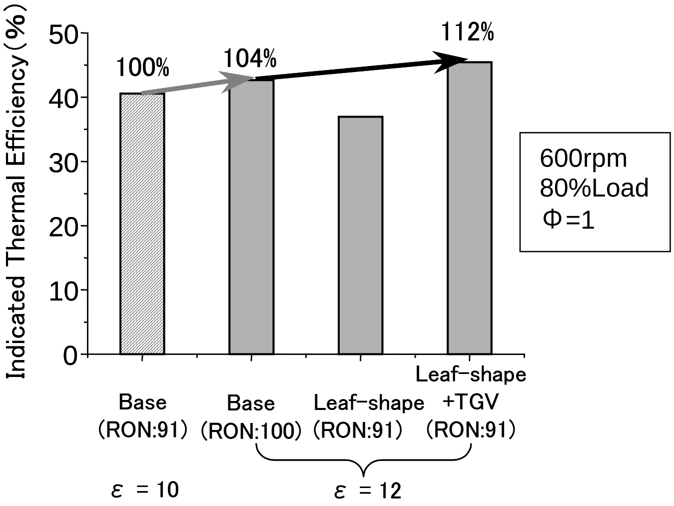

Fig.7 A comparison of indicated thermal efficiency among three engines

Fig.10 shows a comparison of the calculated heat balance rate by above three systems. The Leaf-shape system produces small cooling loss, and it is believed to be a major factor for the fuel economy improvement.

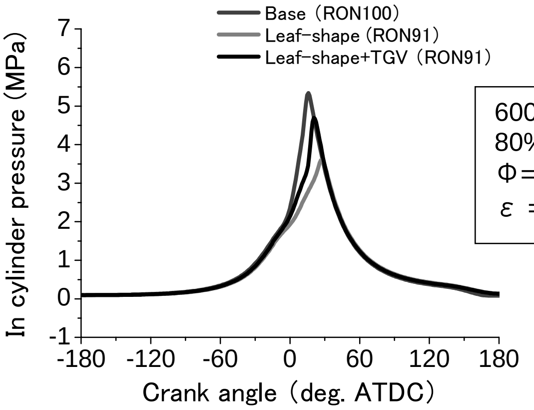

Fig.8 P- θ Diagram of three engines

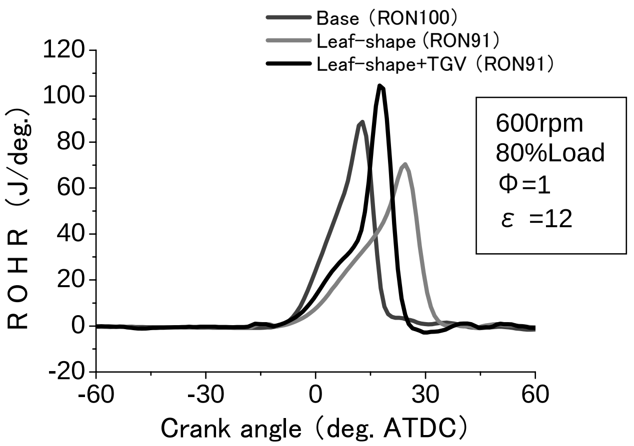

Fig.9 DQ/D θ - θ Diagram of three engines

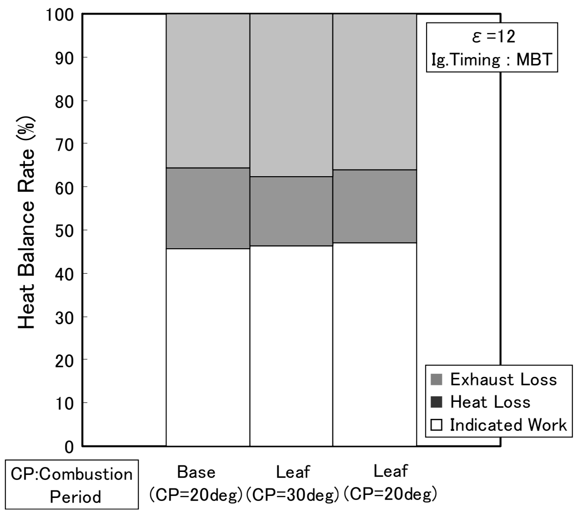

Fig.10 Calculated heat balance

4.3 OPERATION WITH COMPRESSION RATIO OF 14

With a measure to the vibration that becomes more intense as the engine speed increases, tests using the Leaf-shape (N-1) system with compression ratio of 14 have been performed, and so far it has been confirmed that knock-free operation is possible up to 1600rpm and 600KPa.

In order to clarify the knocking suppression effect and cooling loss reduction, high-octane gasoline (RON=100) tests using the Base system and the Leaf-shape (N-1) system with compression ratio of 14 have also been performed. Results of the combustion analysis are shown in Fig.11 (P- θ diagram) and Fig.12 (dQ/d θ - θ diagram). The compression ratio was 14 in all cases.

In this condition pressure trace curves are very similar, but indicated efficiency of the Leaf-shape system is 5% better than that of the Base system in the same compression ratio (Fig.13). Fig.14 shows the constant volume degree and cooling loss comparison. Less cooling loss caused the better fuel consumption.

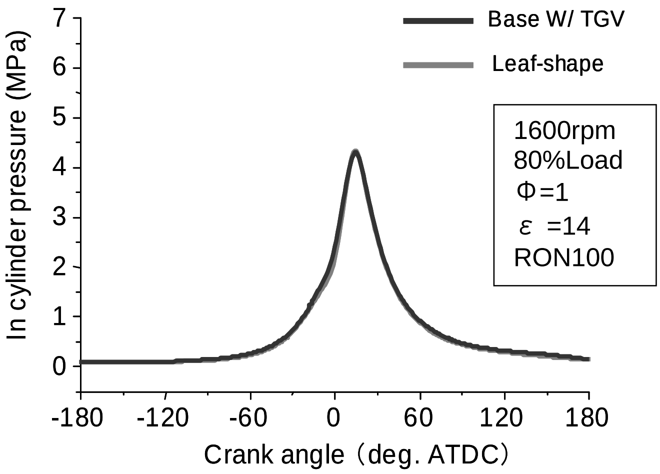

Fig.11 P- θ Diagram

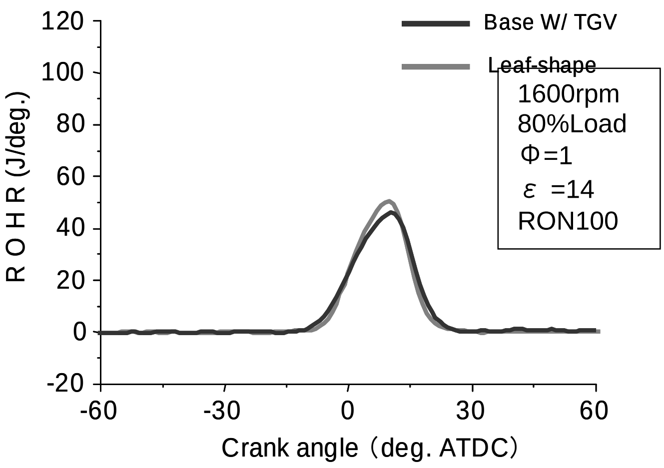

Fig.12 DQ/D θ - θ Diagram

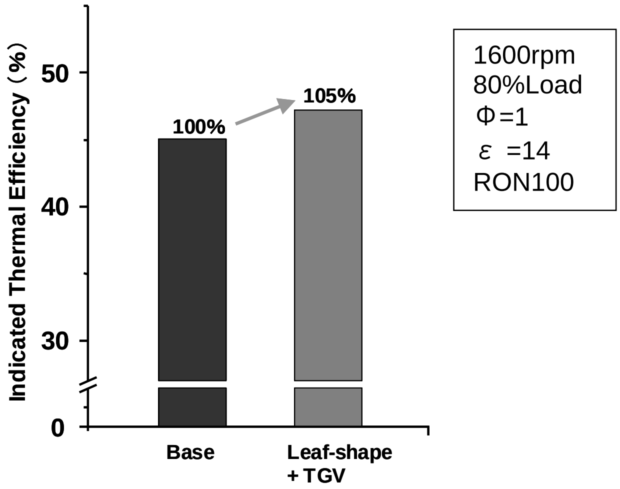

Fig.13 A comparison of indicated thermal efficiency

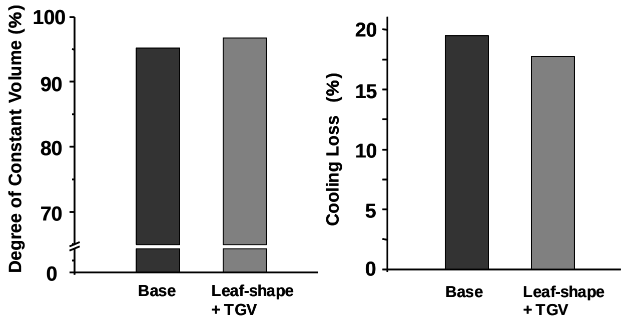

Fig.14 A comparison of degree of constant volume and cooling loss

4.4 EXHAUST EMISSION CHARACTERISTICS

Fig.15 shows the exhaust emissions comparison of the three engines. The Leaf-shape + TGV system emitted less HC and NOx than the other two. It seems that the quick piston motion helped shortening the time for heat transfer from the hot gas to the combustion chamber wall and thus reduced cooling loss, and it resulted in reduction in HC emission. In addition, since a very quick combustion speed in the last half of the combustion is suggested, phenomenon close to the auto-ignition may be taking place in the cylinder, which could be another contributing factor to HC reduction. As for NOx, it is believed that the rapid expansion reduced high temperature retention time, and it inhibited NOx generation. Those results confirmed that the Leaf-shape + TGV system is effective in emissions reduction as well.

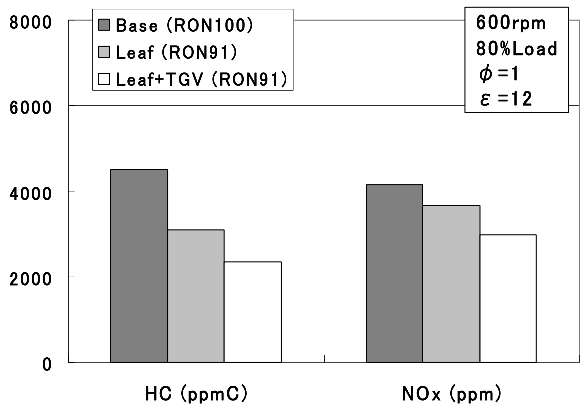

Fig.15 Exhaust gas emissions results

5. CONCLUSIONS

(1) It was clarified that the heat loss is reduced and thermal efficiency is improved by moving pistons rapidly near top dead center.
(2) It is predicted that the inconstant crank angle speed system may realize knocking-free operation with compression ratio of 14.
(3) According to the test results with the single-cylinder experimental apparatus, the inconstant crank angle speed systems allow engine operation at low engine speed and high load range where the base engine cannot operate on regular gasoline because of knocking. In addition, it was confirmed that the TGV could expedite combustion speed and thus improve fuel economy.
(4) Though under limited conditions, the inconstant crank angle speed systems showed approximately 12% improvement from the base engine (compression ratio: 10) in the indicated thermal efficiency.
(5) Both HC and NOx emissions were reduced.

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