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DRASTIC IMPROVEMENT OF THERMAL EFFICIENCY BY RAPID PISTON-MOVEMENT NEAR TDC

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ABSTRACT–A new combustion method of high compression ratio SI engine was studied and proposed in order to achieve high thermal efficiency, comparable to that of CI engine. Compression ratio of SI engine is generally restricted by the knocking phenomena. A combustion chamber profile and a cranking mechanism were studied to avoid knocking with high compression ratio. Because reducing the end-gas temperature will suppress knocking, a combustion chamber was considered to have a wide surface at the end-gas region. However, wide surface will lead to large heat loss, which may cancel the gain of higher compression ratio operation. Thereby, a special cranking mechanism was adapted which allowed the piston to move rapidly near TDC. Numerical simulations were performed to optimize the cranking mechanism for achieving high thermal efficiency. An elliptic gear system and a leaf-shape gear system were employed in numerical simulations. Livengood-Wu integral, which is widely used to judge knocking occurrence, was calculated to verify the effect for the new concept. As a result, this concept can be operated at compression ratio of fourteen using a regular gasoline. A new single cylinder engine with compression ratio of twelve and TGV (Tumble Generation Valve) to enhance the turbulence and combustion speed was designed and built for proving its performance. The test results verified the predictions. Thermal efficiency was improve over 10% with compression ratio of twelve compared to an original engine with compression ratio of ten when strong turbulence was generated using TGV, leading to a fast combustion speed and reduced heat loss.

KEY WORDS : Gasoline engine, Knocking, Thermal efficiency, High compression ratio, Cranking mechanism

1. INTRODUCTION

Theoretically, Otto-cycle has higher thermal efficiency than that of Diesel-cycle in case of the same compression ratio. However, particularly in low load condition, Ottocycle's thermal efficiency is inferior to that of Dieselcycle in practical engines. This is based on the following criterion: 1) Compression ratio of gasoline engine is necessarily fixed low in order to suppress knocking phenomenon; 2) Pumping loss increases with an intake throttling. In order to retrieve the thermal efficiency in low load condition, stratified charge gasoline direct injection systems have been introduced into the market. Accordingly, developing a higher compression ratio gasoline engine is desired to improve thermal efficiency in middle and high load conditions. Although many research works have been conducted to suppress knocking in the aspect of combustion and fuel, there are no ideal solution yet (Pan *et al.*, 1988; Maly, *et al.*, 1990; Konig *et al.*, 1990; Konig and Sheppard, 1990; Pan and Sheppard, 1994; Hirooka *et al.*, 2004). Therefore, the authors have examined how to avoid knocking in the aspect of cranking mechanism.

2. NEW IDEA TO SUPPRESS KNOCKING

Unsteady Cranking Speed

To reduce the end gas temperature in a combustion chamber, which would have a high temperature caused by compression of burned gas, is effective to suppress knocking. Therefore, a combustion chamber is arranged to have a wide surface area at the end gas region. If the surface area is simply enlarged, heat loss would increase and furthermore it would cancel the effect of thermal efficiency improvement caused by high compression ratio. A special mechanism was introduced to move a piston faster near TDC and expand faster to reduce thermal loss. The authors have examined four methods to realize this; an ununiform speed joint, a 3 dimensional cam, an elliptic gear and a leaf-shape gear. As a result, the elliptic gear and the leaf-shape gear were adopted for this study due to the ease to install.

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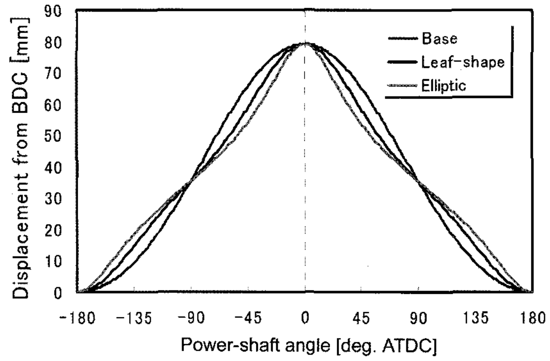

Figure 1. Piston displacement vs. power-shaft angle for various cranking systems.

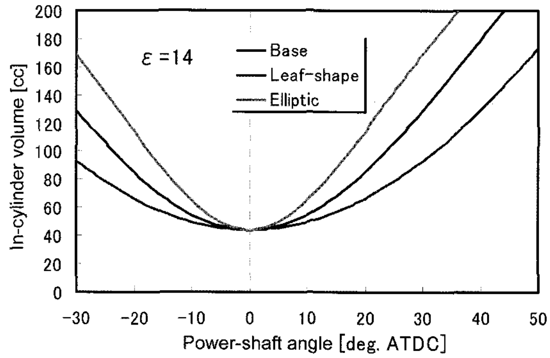

Figure 2. In-cylinder volume vs. power-shaft angle for various cranking systems.

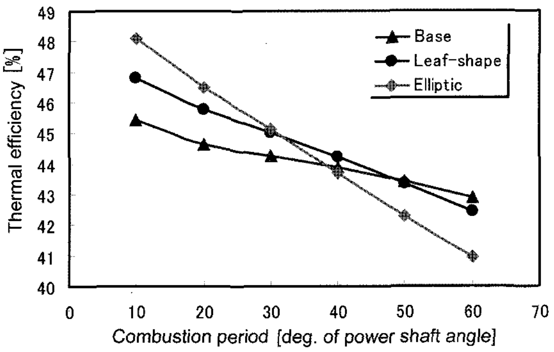

Figure 3. Calculated thermal efficiency vs. combustion period for various cranking systems (ε=10).

Figure 1 shows the piston positions of each mechanism. A test engine has bore × stroke of 99.5x79 mm. Horizontal-axis shows a power-shaft angle and 0 deg. means TDC. Vertical-axis shows the piston displacement from BDC. The action of general cranking mechanism is shown as "Base" which is similar to a sine curve. The action of elliptic crank mechanism is shown as "Elliptic". The action of leaf-shape gear mechanism is shown as "Leaf-Shape". In the case of "Elliptic", the highest piston speed near TDC was attained shown in Figure 1. The "Leaf-Shape" was the second and the "Base" was the lowest speed. Figure 2 shows an in-cylinder volume change near TDC vs. power-shaft angle. The order of volume change rate vs. power-shaft angle was the same as that in Figure 1.

3. OPTIMIZATION BY NUMERICAL ANALYSIS

A zero-dimensional simulation was performed with the following conditions: one cylinder, working fluid of air, no gas exchange losses, volumetric efficiency of 100%, one-zone combustion, equivalence ratio of 1, engine speed of 2000rpm, and heat release profile of isosceles triangle shape. A prediction of the heat loss was calculated by Woschni formula (Woschni, 1967). Optimized piston moving was clarified quantitatively in two aspects -reduction of heat loss and suppression of knocking. A prediction of knocking phenomenon was calculated by Livergood-Wu integral (Livenwood and Wu, 1955). In this calculation, a two-zone combustion model as burned and unburned areas was applied. The calculation result shows knocking occurrence probability as an index value.

Figure 3 shows calculated results of thermal efficiency vs. combustion period for each engine when the ignition timing is fixed to MBT (Minimum advance for Best Torque). The engines with piston moving faster near TDC are suitable for fast combustion and are expected to achieve high thermal efficiency when combustion period is shorter than 40deg. Thermal efficiency was determined by a tradeoff between heat loss reduction due to a fast moving piston and deterioration of constant volume degree.

Figure 4 shows the calculated results of combustion period vs. thermal efficiency with compression ratio of 14. Other conditions are the same as Figure 3. A tend-

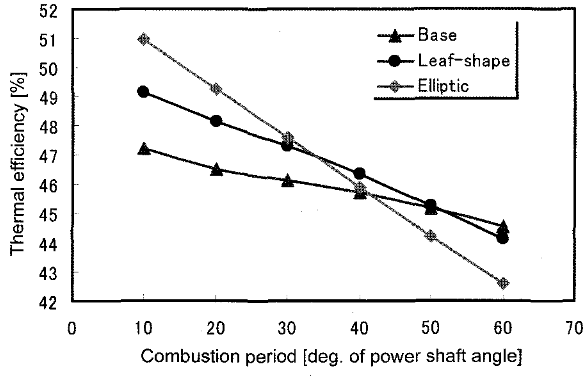

Figure 4. Calculated thermal efficiency vs. combustion period for various cranking systems (ε=14).

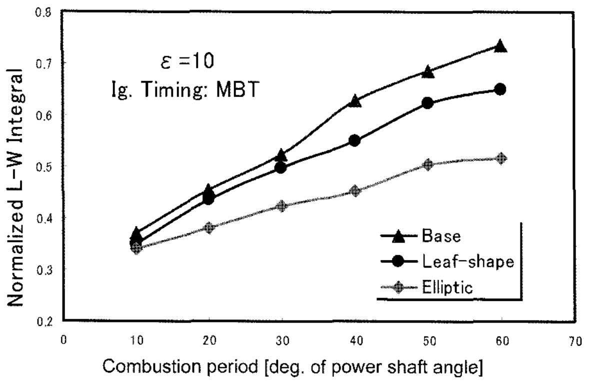

Figure 5. Normalized Livengood-Wu integral value vs. combustion period for various cranking systems (ε=10, MBT).

ency is the same as that of Figure 3.

Figure 5 shows combustion period vs. normalized Livengood-Wu integral value at the ignition timing of MBT. Livengood-Wu integral is considered as the knocking index value and an initiation of knocking is predicted when it exceeds unity.

In order to understand the result easier, this value was normalized as unity when the compression ratio was 10 and the combustion period was 40 deg. in the case of "Base" engine. (The ignition timing was chosen for the largest Livengood-Wu integral value.) When combustion period was extended, the normalized Livengood-Wu integral value increased because of a longer retaining time under high temperature. In the case of "Elliptic", the Livengood-Wu integral value is smaller than that of the "Base". This is based on the quick expansion by quick piston moving. Therefore, this suggests a possibility of higher compression ratio operation without knocking.

Figure 6 shows combustion period vs. normalized Livengood-Wu integral in compression ratio of 14 at the ignition timing of MBT. The Livengood-Wu integral exceeds unity except for 10 deg. point. This shows a possibility of knocking, while the value of "Elliptic" is less than of "Basic", leading to a tolerance for knocking. On the other hand, this value does not exceed unity in the case of the "Elliptic" and the "Leaf-Shape" in Figure 7 when combustion period and ignition timing are fixed to 40 deg. and TDC, respectively. This suggests a possibility of higher compression ratio operation without knocking by adjusting the ignition timing. It would be a trade-off with fuel consumption.

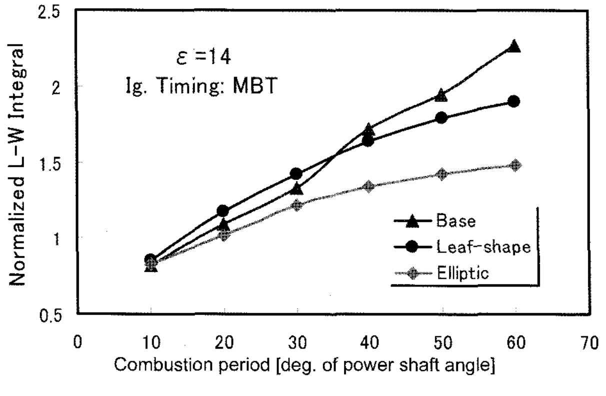

Figure 6. Normalized Livengood-Wu integral value vs. combustion period for various cranking systems (ε=14, MBT).

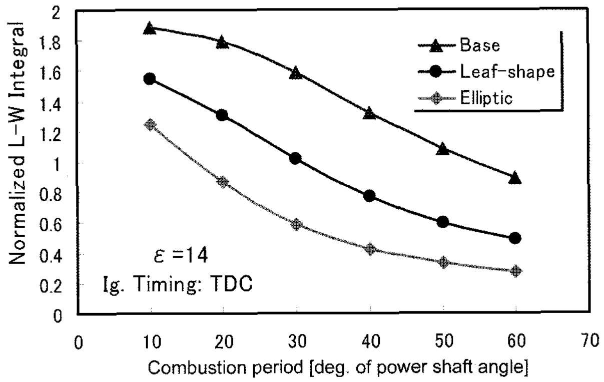

Figure 7. Normalized Livengood-Wu integral value vs. combustion period for various cranking systems (ε=14, Ig.T: TDC).

Figure 8 shows power-shaft angle vs. normalized Livengood-Wu integral value comparing compression ratio of 10 and 14 with "Base" and "Elliptic". Ignition timing is fixed to TDC. In the case of "Base", knocking is inevitable, judging from a rapid increase in Livengood-Wu integral when the compression ratio is 14. On the other hand, in the case of "Elliptic" with compression ratio of 14, the peak value of Livengood-Wu integral is almost the same as that of "Base" with compression ratio of 10 and is smaller than unity. This means that knocking can be avoided.

As a result of these numerical simulations, the follow-

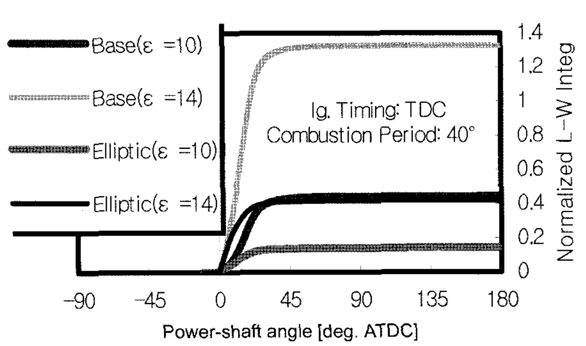

Figure 8. Variation of Livengood-Wu integral value for different crank/compression ratio systems.

Table 1. Engine specifications.

Engine type	4-stroke single cylinder
Bore x Stroke	ϕ 99.5 x 79 mm
Fuel supply	Port injection
Displacement	614 cm^3
Compression ratio	10, 12, 14
Fuel	Regular gasoline (RON91)

ing two aspects were deduced.

1) Improvement of thermal efficiency can be achieved by "Elliptic" and "Leaf-Shape" systems with the same compression ratio as "Base".

2) Even though compression ratio is raised up around 14, knocking is possibly suppressed using "Elliptic" and "Leaf-Shape" systems.

Furthermore, a prototype single cylinder engine was designed and built in order to validate these simulation results.

4. EXPERIMENTAL STUDY

4.1. Engine Specifications and Experimental Apparatus

Table 1 shows the engine specifications. Bore x stroke was chosen as a "large bore" to clarify the effect to suppress knocking. A regular gasoline (RON 91) was mainly used for tests. Compression ratio was adjusted by the piston shape which would not affect much for charge air motion. The combustion chamber shape for the experimental study was not modified from a production engine.

Figure 9 shows an experimental apparatus. Between an engine crank-shaft and a power-shaft, there is a gear set for changing piston speed near TDC. A flywheel is equipped to the power-shaft.

4.2. Mechanism of Ununiform Cranking Speed

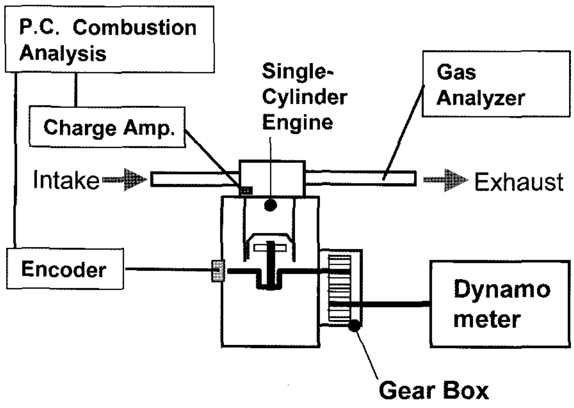

Figure 9. Experimental apparatus.

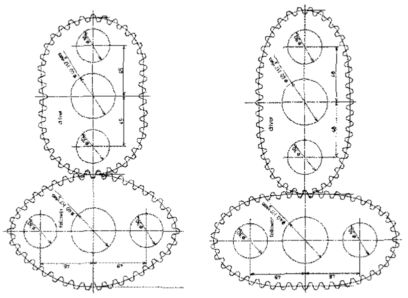

Figure 10. Leaf-shape gear (Leftside) and Elliptic gear systems.

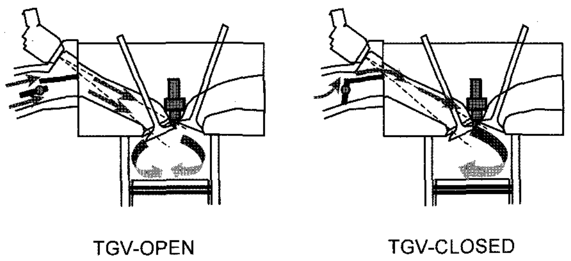
TGV-OPEN TGV-CLOSED

Figure 11. Single cylinder TGV.

Figure 10 shows the special gears - leaf-shape gear and elliptic gear. Maximum angular velocity ratio of leaf-shape and elliptic gear sets are 1.4 and 2.0 respectively. In the case of using ununiformt cranking speed mechanism, constant volume degree tends to be reduced because of a fast movement near TDC. A tumblegenerating-valve (TGV) was developed in order to enforce a gas flow and turbulence inside the cylinder. Strong turbulence would cause a rapid combustion and constant volume degree would be recovered. Furthermore, heat loss would be reduced by shorter period of combustion.

4.3. Development of Tumble Generation Valve

Figure 11 shows a current production TGV part showing "TGV-open" and "TGV-close" operations. TGV for a single cylinder engine was modified and optimized from a production TGV.

4.4. Test Results and Discussion

The single cylinder engine test was conducted by the following cases:

(1) A base engine with cycloid gear

(2) An engine with leaf-shape gear

(3) An engine with leaf-shape gear + TGV

Experiments were conducted at low speed knocking region as a main issue of high compression ratio engine. The standard test conditions are 80% load (throttle open) and engine speed at 600 r/min. As the elliptic gear engine caused heavy vibration, experiment using the elliptic gear engine was not performed at this stage.

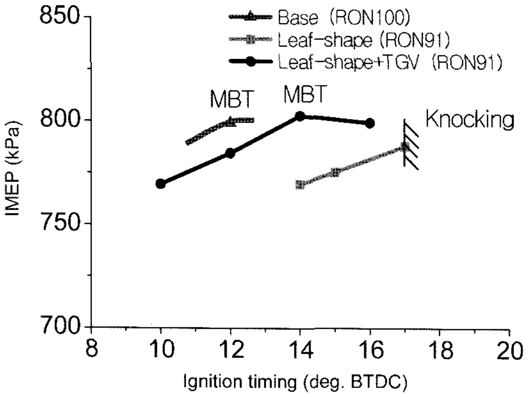

Figure 12. Ignition timing VS. IMEP with the base engine, the leaf-shape gear engine and the leaf-shape gear engine + TGV.

Figure 12 shows ignition timing (in crank angle) vs. IMEP with the base engine, the leaf-shape gear engine and the leaf-shape gear engine + TGV. Compression ratio was fixed to 12 and an equivalence ratio was 1.0. Only base engine was tested by using a high-octane gasoline (RON=100). The leaf-shape gear engine requires an ignition advance since combustion speed is slow. However, knocking phenomena had prevented a further ignition advance to increase IMEP before the maximum IMEP. Nevertheless, by attaching TGV, combustion speed became faster and MBT was achieved. Moreover, IMEP was equivalent to that of the base engine by using a high-octane gasoline. The base engine could not be operated by using a regular gasoline because of knocking.

Figure 13 shows a comparison of indicated thermal efficiency among three engines with compression ratio of 12 and also the base engine with compression ratio of 10. The leaf-shape gear engine without TGV cannot be operated at MBT. Therefore, the fuel consumption was worse than of the base engine due to its slow combustion. Furthermore, a strong turbulence enabled a better fuel consumption due to faster combustion.

As a result, by using the leaf-shape gear and TGV, 8% improvement in thermal efficiency was achieved compared to the base engine with compression ratio of 12.

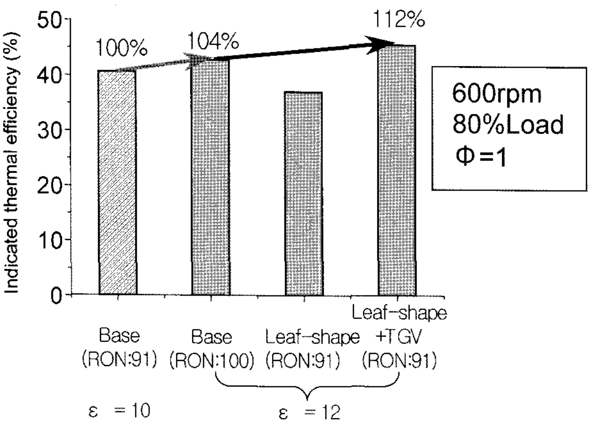

Figure 13. A comparison of indicated thermal efficiency among three engines.

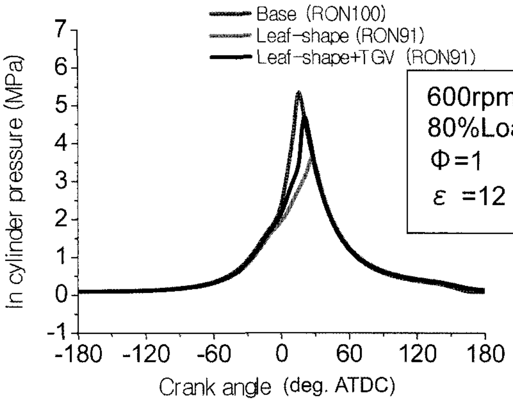

Figure 14. P-θ Diagram of three engines.

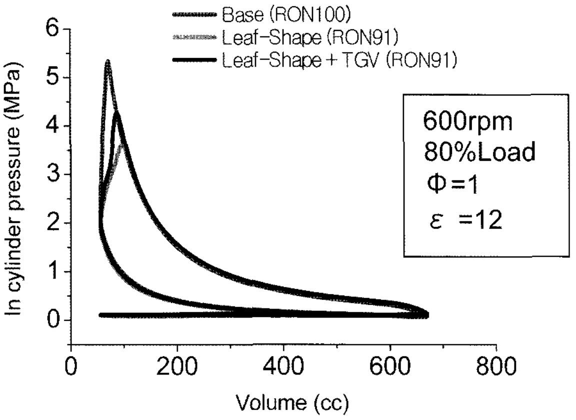

Figure 15. P-V Diagram of three engines.

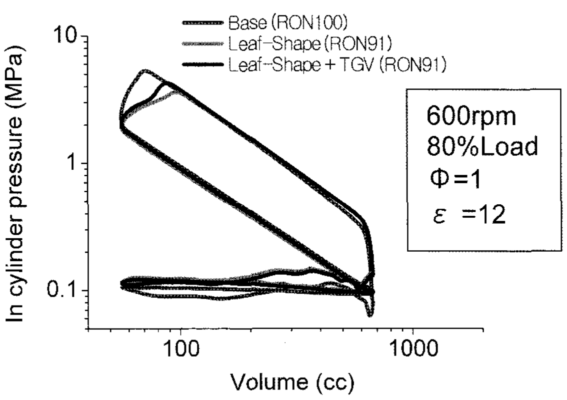

Figure 16. Log P-Log V Diagram of three engines.

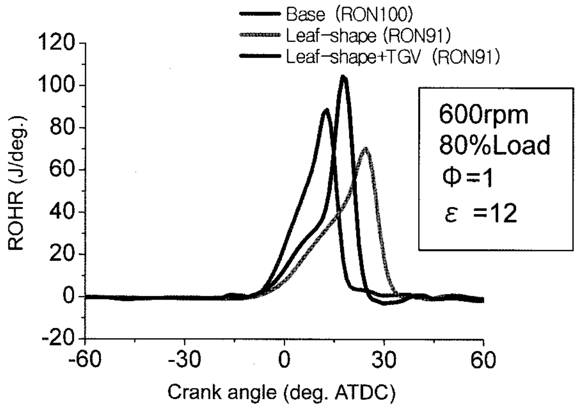

Figure 17. DQ/D θ-θ Diagram of three engines.

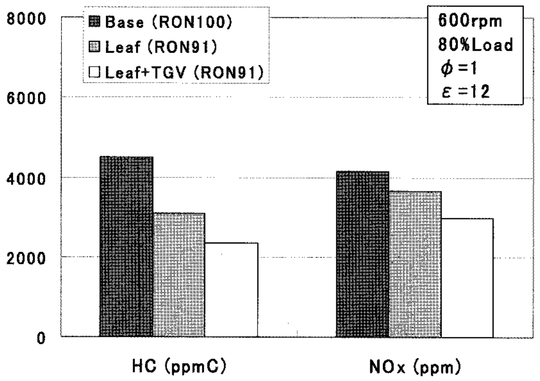

Figure 18. Exhaust gas emissions results.

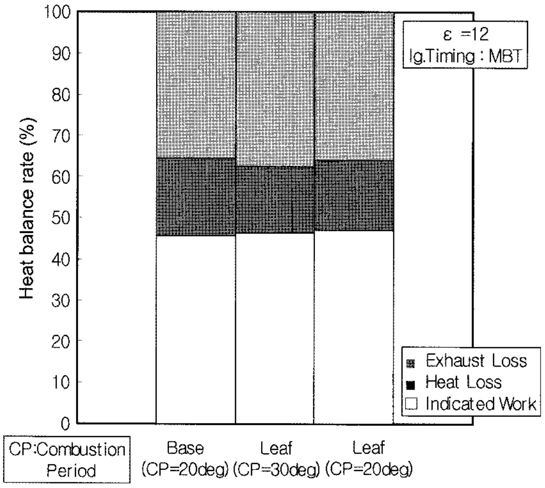

Figure 19. Calculated heat balance.

Moreover 12% improvement was obtained compared to the base engine with compression ratio of 10. The base engine with compression ratio of 10 with TGV could not be operated because of heavy knocking.

Figures 14, 15, 16 and 17 indicate the combustion analysis results. Comparing the base engine with the leafshape gear engine + TGV, the timing of peak ROHR (Rate of Heat Release) for the latter engine is retarded. Meanwhile, a larger heat release can be seen in the latter half of the combustion with the leaf-shape gear engine + TGV, but its peak pressure is less than of the base engine.

Figure 18 shows the exhaust gas emissions for the three engines. Both HC and NOx were apparently improved by this concept. Rapid combustion with less heat loss may caused a reduced HC emission. NOx emission also decreased due to less maintaining time of burned gas under high temperature by rapid expansion.

Figure 19 indicates the calculated heat balance rate of the three cases, "Base" (Combustion Period=20 deg), "Leaf" (Combustion Period=30 deg) and "Leaf" (Combustion Period=20 deg) which simulates "Leaf + TGV". The main reason of thermal efficiency improvement was found due to the heat loss reduction.

5. CONCLUSIONS

In order to realize a high compression ratio gasoline engine without knocking, a zero-dimensional numerical simulation was performed in terms of a crank mechanism. As a result, heat loss can be reduced and thermal efficiency would be improved by introducing a mechanism of ununiform cranking speed with piston moving faster near TDC when fast combustion can be achieved without deteriorating constant volume degree.

(1) Livengood-Wu integral was calculated to predict the initiation of knocking. An ununiform cranking speed mechanism was effective for reducing the Livengood-Wu integral value. This suggests a possibility of higher compression ratio operation without knocking. Further parametric study predicted that knocking would be suppressed even with compression ratio of 14.

(2) A single cylinder test engine was designed and built to achieve an ununiform cranking speed whose piston moves faster near TDC and whose powershaft moves at a constant angular velocity. This was realized by adopting a pair of gears between the crank-shaft and the power-shaft. The maximum angular velocity ratio of the leaf-shaped gear was 1.4, while that was set at 2.0 with the elliptic gears.

(3) At 80% load and low engine speed of 600 r/min condition, approximately 12% better indicated thermal efficiency was achieved with the leaf-shape gear engine + TGV in compression ratio of 12 than of the base engine in compression ratio of 10.

(4) The combustion period became longer and the peak of ROHR was retarded in the leaf-shape gear engine compared to the base engine. Adding TGV to the leafshape gear engine, the timing of peak ROHR was

advanced and the combustion period was shortened. As a resutl, better thermal efficiency due to less heat loss and knocking free operation could be conducted at MBT with compression ratio of 12.

(5) HC and NOx exhaust gas emissions were also improved simultaneously by this concept. Rapid combustion with reduced heat loss and rapid temperature drop enabled these results.

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