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EFFECT OF OVER-EXPANSION CYCLE IN A SPARK-IGNITION ENGINE USING LATE-CLOSING OF INTAKE VALVE AND ITS THERMODYNAMIC CONSIDERATION OF THE MECHANISM

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ABSTRACT–This paper presents further investigation into the effect of over-expansion cycle in a spark-ignition engine. On the basis of the results obtained in previous studies, several combinations of late-closing (LC) of intake valve and expansion ratio were tested using a single-cylinder production engine. A large volume of intake capacity was inserted into the intake manifold to simulate multi-cylinder engines. With the large capacity volume, LC can decrease the pumping loss and then increase the mechanical efficiency. Increasing the expansion ratio from 11 to 23.9 with LC application can produce about 13% improvement of thermal efficiency which was suggested to be caused by the increased cycle efficiency. The decrease of compression ratio from 11 to 5.5 gives little effect on the thermal efficiency if the expansion ratio could be kept constant. Thus, the expansion ratio is revealed to be a determining factor for cycle efficiency, while compression ratio is no more important, which suggests the usefulness of controlling the intake charge with intake valve closure timing. These were successfully explained by simple thermodynamic calculation and thus the mechanism could be verified by the estimation.

KEY WORDS : Over-expansion cycle, Late-closing of intake valve, Intake valve timing, Pumping loss, Mechanical efficiency, Cycle efficiency, Thermodynamic estimation, T-S diagram

1. INTRODUCTION

As one of the methods to improve the thermal efficiency of reciprocating internal combustion engines, there has been a concept of over-expansion or more-expansion cycle. This is mentioned in Taylor's book (Taylor, 1979) and has been realized in a motor cycle engine in the old days (Tomizuka, 1969) which was called as Atkinson cycle engine. Heywood (1998) made a simple thermodynamic calculation and the improvement of thermal efficiency and the decrease of the specific output were estimated as a function of the ratio of expansion ratio to compression ratio, where 12% increase in thermal efficiency and 50% reduction of specific output due to the decrease of volumetric efficiency were reported at a ratio of expansion to compression of 2.

One method to utilize the over-expansion effect is to apply early- or late-closing of intake valve. Cho *et al.* (1995) reported that a 10% BSFC benefit could be attained in a cogeneration supercharged spark-ignition gas engine by applying both early-closing of rotary valve and late-closing of the original intake valve. Ueda *et al.* (1998) developed a commercial hybrid vehicle using an NA (Natural Aspirating) gasoline engine. It has accomplished about 12% improvement of thermal efficiency at the expansion ratio of 14.7 where late-closing and the expected compression ratio of 9 were applied.

The authors have conducted a study on the over-expansion effect in a gasoline engine in order to reveal the nominal advantage of the concept of over-expansion cycle (Shiga *et al.*, 1996; Shiga *et al.*, 1998). For the first step, early-closing was applied together with several pistons of increased expansion ratios in a production single cylinder DOHC motorcycle engine. Since the substantial start of compression varies with the intake valve closure timing, the term of expansion ratio designates the geometrical compression ratio regularly called compression ratio. It was mainly revealed that the early-closing (EC), can lead to 7% improvement of thermal efficiency at the expansion ratio greater than 16 when comparison was made at a constant BMEP, and the substantial compression start can correspond to the intake valve

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closure timing determined as 1 mm lift point (Shiga *et al.*, 1996).

At the next step (Shiga *et al.*, 1998), LC was applied, since the maximum valve lift for EC was limited to 3 mm which is less than a half of the original value and it seemed to give several limiting behaviors such as the maximum BMEP and the limiting tendency of the benefit at higher engine speed. By applying the LC, the improvement of the thermal efficiency was shown to be increased to 10% and even the minimum BSFC was better than that of original value. Thus, the over-expansion cycle was shown to be effective as a tool to improve the thermal efficiency although it unavoidably accompanies the reduction of BMEP.

In the present study, to clarify the mechanism of the beneficial effect obtained in the previous experiments, further combinations of valve timings and the expansion ratios were prepared and analyzed on the basis of thermodynamic consideration. Moreover, in order to simulate a multi-cylinder engine, a chamber with large capacity of volume was installed in between the intake valve and the throttle valve. The behavior of mechanical loss was also examined.

2. EXPERIMENTAL SETUP AND PROCEDURE

Schematic of experimental setup is shown in Figure 1, which is basically the same as that used in previous studies (Shiga *et al.*, 1996; Shiga *et al.*, 1998). Since the capacity volume of single-cylinder engines at the intake manifold is much less than that of multi-cylinder engines, the intake manifold vacuum of single-cylinder engine is usually less due to the gas dynamic effect. Then, an intake chamber with a volume of 5.15 L was installed at the intake manifold. The test engine was a production

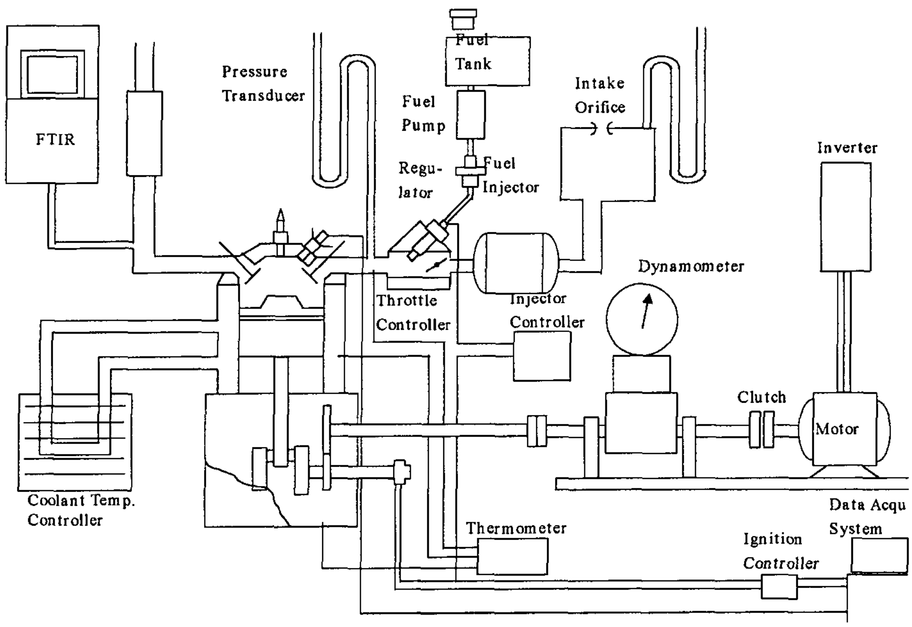

Figure 1. Schematic of experimental apparatus.

Table 1. Valve timings used in the experiment.

	Original	LC90	LC100
Intake lift	8.1 mm	←	←
Intake Opening (IVO)	10 deg BTDC	10 deg BTDC	2 deg BTDC
Closure (IVC)	40 deg ATDC	90 deg BTDC	102 deg BTDC
Exhaust lift	7.5 mm	←	←
Exhaust Opening (IVO)	10 deg BTDC	←	←
Closure (IVC)	5 deg BTDC	←	←

single cylinder DOHC 4 valves type with liquid cooling, stroke volume of 249 cc (70 mm bore), original compression ratio of 11, and a maximum BMEP of 1.17 MPa at 7000 rpm.

In Table 1, values of valve timing are shown for two kinds of LC at 1 mm lift point. LC90 has the IVC timing of 90 deg ABDC and the same IVC timing as the original, whereas LC100 was realized by just shifting the cam phase of 12 deg and thus the exact value of I.V.C. is 102 deg ABDC.

The applied A/F was held constant at 12.5. Two engine speeds of 3500 rpm and 4500 rpm were tested at wide range of load from the BMEP of 0.2 MPa to WOT.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Effect of Installing Intake Capacity Chamber on the Mechanical Efficiency

In terms of the application of variable valve timing method, it can be expected to control the charge input instead of throttling. Then the pumping loss generated by the throttling would be reduced. However, if EC or LC is applied with keeping the expansion ratio constant, the substantial compression ratio is decreased, which may decrease the cycle efficiency. Therefore, controlling the charge amount by variable valve timing method has two contrasting effect on the brake thermal efficiency, increasing the mechanical efficiency and decreasing the cycle efficiency. Here, the former effect will be clarified, and later the latter effect will be discussed.

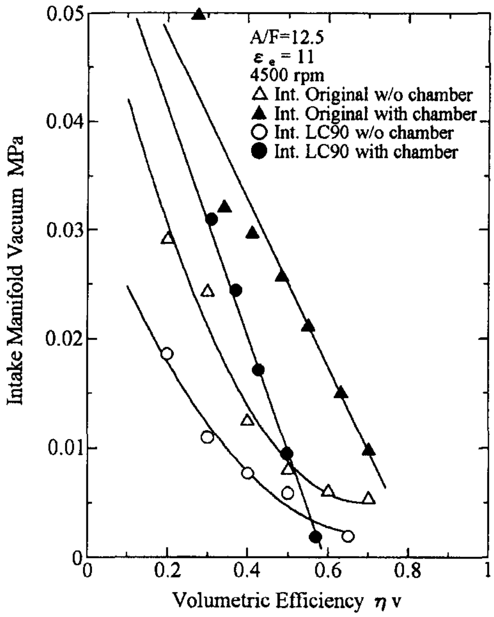

Figure 2-2. Effect of intake capacity chamber and IVC timing on the intake vacuum (4500 rpm).

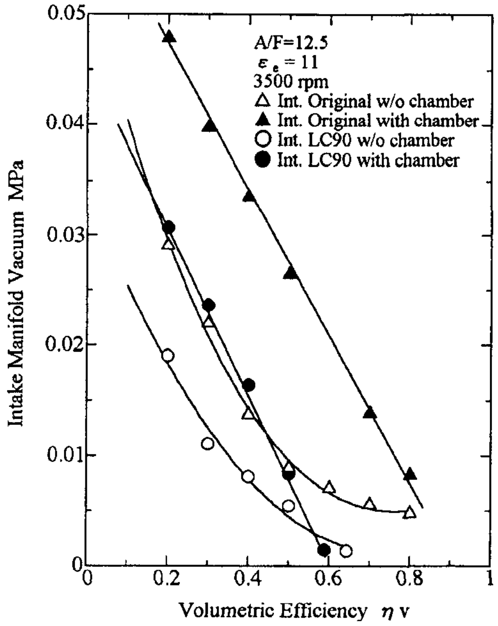

Figure 2-1. Effect of intake capacity chamber and IVC timing on the intake vacuum (3500 rpm).

In Figure 2, the intake manifold vacuum is shown against the volumetric efficiency η_v for both cases with and without the intake capacity chamber at the original expansion ratio of 11. For both engine speeds, increasing the intake capacity remarkably increases the intake manifold vacuum by more than twice. In terms of LC application, LC90 has an effect of reducing the vacuum, but there is much difference of the extent between the cases with and without the chamber. For the case without chamber, it is less than 0.02 MPa of the intake manifold vacuum reduction at most, and it goes to 0.03 MPa for the case with chamber. Thus, late closing is shown to reduce intake manifold vacuum remarkably, and the absolute value of the reduction is much more for the case of larger intake capacity volume which simulates the multi-cylinder engines.

In Figure 3, pumping mean effective pressure (PMEP) is shown against BMEP. For both cases with and without chamber, PMEP can be decreased by applying LC90 which is in accordance with the behavior of intake manifold vacuum. The absolute value of the PMEP decrease is much more for the case with chamber than without chamber, which also corresponds to the behavior of the intake manifold vacuum. The difference of both PMEP (Figure 3) and the intake manifold vacuum (Figure 2) between the original and the LC90 for the case with chamber tends to decrease with the decrease of

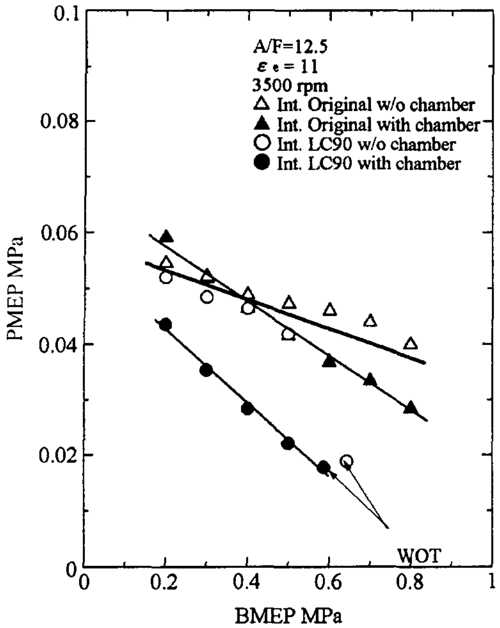

Figure 3-1. Effect of intake capacity chamber and IVC timing on the pumping loss (3500 rpm).

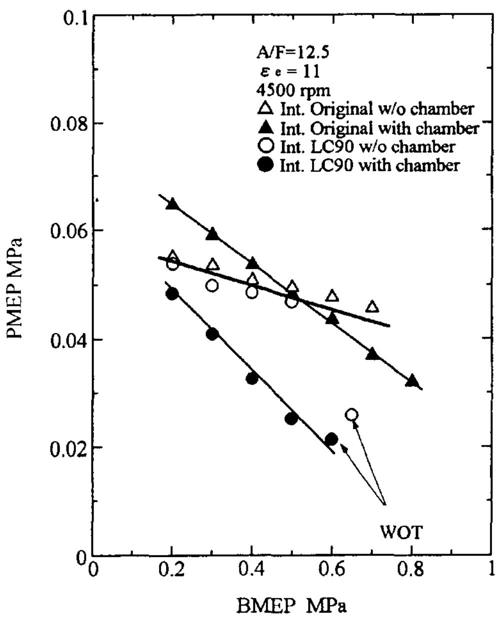

Figure 3-2. Effect of intake capacity chamber and IVC timing on the pumping loss (4500 rpm).

BMEP. This is due to throttling effect at lower load.

In Figure 4, log p-log v diagrams are shown for the condition of BMEP 0.5 MPa which is close to the maximum BMEP for LC90 (BMEP=0.58 MPa at WOT).

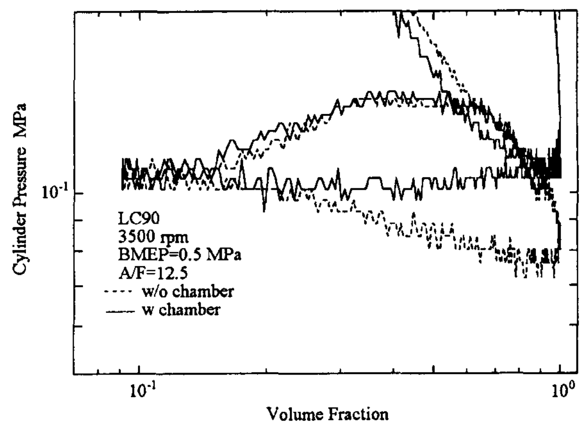

Figure 4-1. Effect of intake capacity chamber and IVC timing on the log p-log v diagram (3500 rpm).

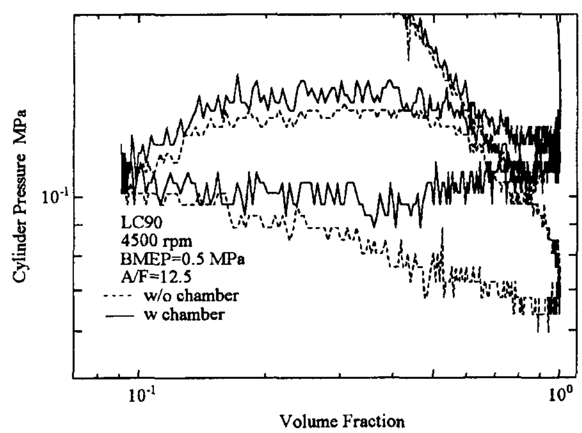

Figure 4-2. Effect of intake capacity chamber and IVC timing on the log p-log v diagram (4500 rpm).

For both cases, it is clear that the pumping work for the case without chamber is larger than that with chamber. This is due to the fact that the residual gas fraction that remained during the valve overlapping period is greater for with chamber, since the intake manifold pressure is low enough to flow the exhaust gas back to the intake manifold. As for LC90, the pumping work is clearly decreased for the case with chamber comparing with the original condition. On the other hand, as for the case without chamber even for LC90, the pumping work is not so decreased comparing with the original condition which is ascribed for the pressure decrease near the end of suction stroke. So far, the detail of this mechanism is not yet clarified.

3.2. Effect of Expansion Ratio on the Engine Performance

Since the intake capacity chamber installation is effective in reducing the absolute value of pumping loss by applying LC, the effect of expansion ratio ε_e was examined under the condition for the case with chamber. The values of ε_e tested here were, 11 (original), 14.8, 18.6, 20, 23.9, and the intake valve timings were original, LC90 and LC100. The original timing was of course applied only to the condition of ε_e=11. Both LC90 and LC100 were successfully applied to all the conditions of ε_e until WOT without knock occurrence.

In Figure 5, the pumping loss, PMEP, is shown for all the test combinations. For both engine speeds, almost three trends can be identified. These trends correspond to the intake valve timings of, the original, LC90 and LC100, although there is some variation with the expansion ratio at LC90 and LC100. Thus it can be seen that the pumping loss is not appreciably affected by the expansion ratio, but it is mostly determined by the intake valve closure timing, and thus it is confirmed that the

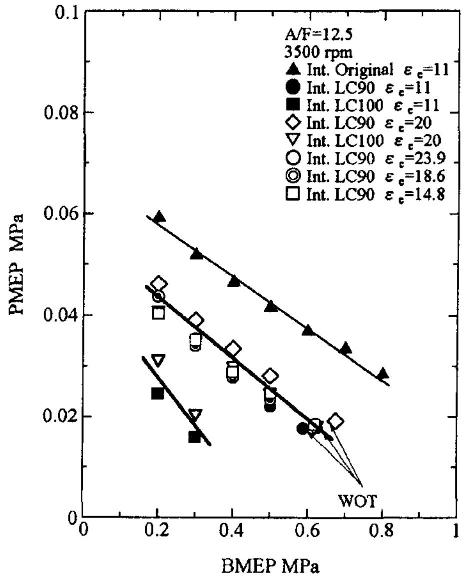

Figure 5-1. Effect of IVC timing on the pumping loss for various expansion ratios (3500 rpm).

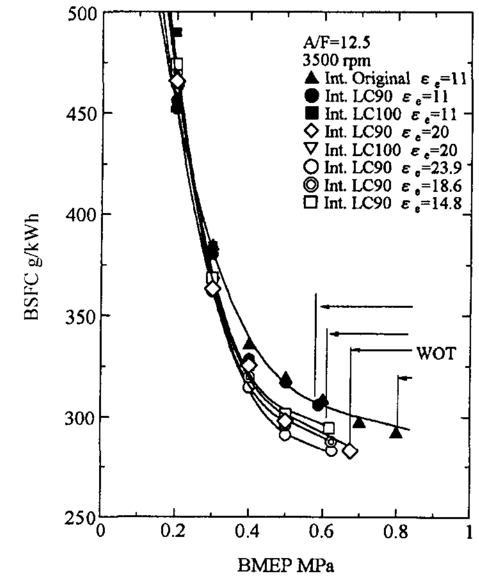

Figure 6-1. Effect of IVC timing on BSFC (3500 rpm).

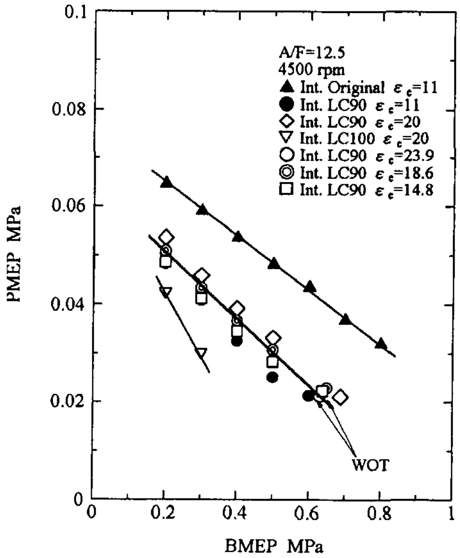

Figure 5-2. Effect of IVC timing on the pumping loss for various expansion ratios (4500 rpm).

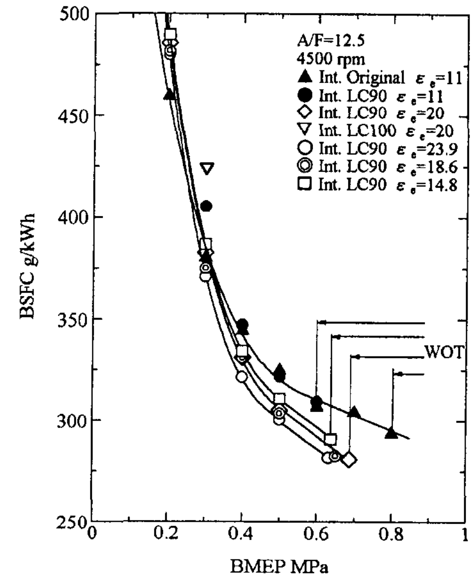

Figure 6-2. Effect of IVC timing on BSFC (4500 rpm).

pumping loss can be systematically decreased by applying LC. This suggests that the charge control by the inlet valve timing can decrease the pumping loss, but it simultaneously decreases the substantial compression ratio leading to the lower thermal efficiency as will be mentioned later.

Figure 6 shows the BSFC against BMEP for various combinations of intake valve timing and the expansion ratio. At a constant expansion ratio of ε_e=11, there is no clear difference of BSFC. There are two contrasting factors influencing the BSFC in this case. LC application causes lower pumping loss which results in higher mechanical efficiency and it decreases the compression ratio which may decrease the cycle efficiency. Due to these contrasting factors, there is no clear effect of intake valve closure timing on BSFC. At a constant intake valve closure timing of LC90, BSFC monotonically decreases with increasing the expansion ratio. The improvement of the BSFC reaches to 13% at the maximum when comparison is made at a constant BMEP. This improvement rate is even better than the value of 12% estimated by (Heywood, 1998). This would be partly due to the reduction of pumping loss mentioned above. However, it is hard to separate each factor that contributes to the BSFC improvement due to the limit of experimental accuracy. Considering that the pumping loss reduction does not contribute so much to the BSFC improvement, the major part of the improvement would be caused by the increase in the expansion ratio ε_e leading to the improvement of the cycle efficiency. However, since at the constant intake valve timing the expansion ratio was varied widely, not only the expansion ratio but also the substantial compression ratio is changed with keeping the ratio of expansion to compression ratios constant. Then it is hard to see which is more important, compression ratio or expansion ratio. If this is going to be revealed, with keeping ε_e constant the inlet valve closure timing has to be varied, or the inlet valve closure timing has to be made earlier with increasing the ε_e. The former can be recognized when comparison is made between original, LC90 and LC100 at ε_e=11 or 20 in Figure 6. When ε_e=11, the compression ratio varies as 5.5 (LC100), 6.0 (LC90) and 10.1 (original). When ε_e=20, ε_c=10 (LC100) and ε_c=10.9 (LC90). Then the BSFC does not change. Therefore it can be seen that the variation of compression ratio from 5.5 to 10.1 or from 10 to 10.9 does not give a significant effect on BSFC. As for the case of LC90, variation of ε_e from 11 to 23.9 generates the change of compression ratio of 6.0 to 12.5. Considering that the compression ratio tends to have a saturating effect on the thermal efficiency, the effect of ε_e for the case of LC90 is suggested to be mainly caused by the increased expansion ratio that can be said as the "over-expansion effect".

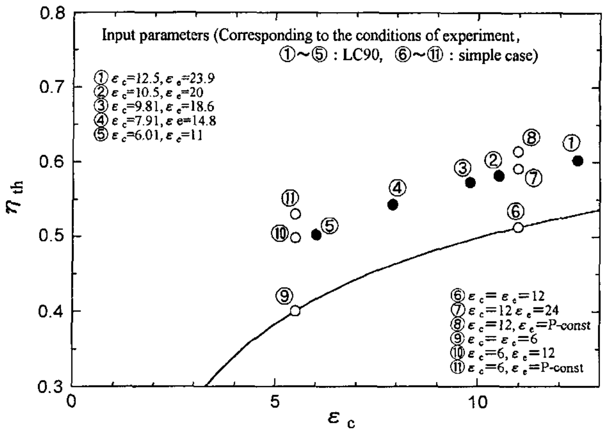

Figure 7. Estimation of thermal efficiency with a simple thermodynamic model.

4. ESTIMATION OF THE OVER-EXPANSION EFFECT WITH A SIMPLE THERMO-DYNAMIC CALCULATION

In order to verify this, a simple calculation was carried out using Heywood's method (Heywood, 1998). Results are shown in Figure 7. The specific heat ratio was kept constant at 1.3 throughout the calculation. The solid line represents the thermal efficiency of simple Otto cycle. For convenience in comparison, all the data points are plotted against the compression ratio. The input energy is also kept constant at 2204 kJ/cycle which is typical value used in the experiment.

Input parameters of ① to ⑤ correspond to the experimental condition of LC90, where the effect of expansion ratio and then the compression ratio on the thermal efficiency can be seen. Input parameters of ⑥ to ⑪ are the simple cases for the purpose of showing the individual effect of expansion ratio or compression ratio, in which the original condition of ε_c=ε_e=12 is included as ⑥. As the simple case, combinations of input parameters are selected as the following criteria.

⑥ ε_c=ε_e; Almost the original condition. (Exactly the ε_c=10.1, since the I.V.C. timing is 40 deg ABDC.).

⑦ ε_c=12, ε_e=24; 2 of the ratio of expansion to compression ratios is applied.

⑧ ε_c=12, ε_e=P-const.; So-called Atkinson cycle. Expanded to the atmospheric pressure.

⑨ ε_c=ε_e=6; Decreasing the compression ratio to half of the original condition.

⑩ ε_c=6, ε_e=12; 2 of the ratio of expansion to compression ratios is applied. This can simulate the case that the intake charge is controlled by I.V.C. mentioned in the previous section.

⑪ ε_c=6, ε_e=P-const.; So-called Atkinson cycle for the half value of compression ratio of the original condition

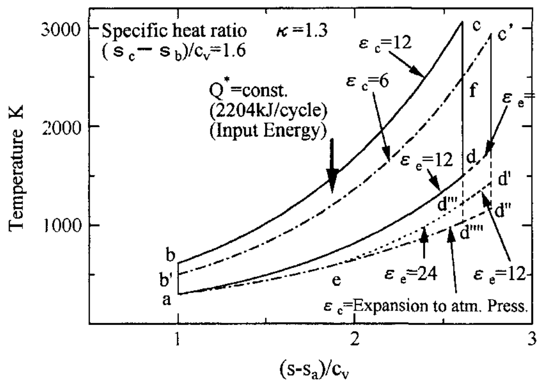

Figure 8. T-s diagrams of representative conditions corresponding to the "simple case" shown in Figure 7.

By increasing ε_e from 11 (①) to 23.9 (⑤), the thermal efficiency increases 15%, and the increasing rate becomes less with increasing ε_e. This trend is consistent with the results obtained in the experiment. As for the simple case, by comparing ⑥ with ⑩, the effect of compression ratio decrease can be separately identified at the constant expansion ratio of 12. Although the compression ratio is decreased to half of the original, the decrease of thermal efficiency is only 2%. This is also consistent with the experimental result which shows that there is little difference of BSFC between the original condition and LC90 with the same ε_e shown in Figure 7. In contrast to this, by comparing ⑪ with ⑨, the effect of expansion ratio can be separately identified at the constant compression ratio of 6, and remarkable increase of thermal efficiency can be clearly shown which reaches to almost 20%. By comparison of these three cases, ⑥, ⑩, ⑨, the sensitivity of the expansion ratio to the thermal efficiency is roughly 10 times as much as that of the compression ratio. Therefore, the thermal efficiency is mostly determined by the expansion ratio, and then the decrease of substantial compression ratio does not matter so much if the expansion ratio could be maintained to some extent. This is favorable from the viewpoint of utilizing the variable I.V.C. for controlling the charge amount.

The thermal efficiency can be graphically expressed on the T-S diagram as the wideness of the cycle area. A T-S diagram for "simple case" shown in Figure 7 is illustrated in Figure 8. Effect of compression ratio at a constant expansion ratio can be expressed by comparing areas of a-b-c-d (ε_c=ε_e=12) and a-b'-c'-d'-e-a (ε_c=6, ε_e=12). The decrease of area b'-b-c-f is almost compensated by the increase of area f-c'-g-d'-d"-e-a-d-f. Effect of expansion ratio is expressed by comparing areas of a-b'-c'-g-d-a (ε_e =ε_e=6) and a-b'-c'-g-d'-d"-e-a (ε_c=6, ε_e=12). The area a-d-g-d'-d"-e can be nominally added as the increased expansion ratio's contribution.

5. CONCLUSIONS

(1) Late-closing (LC) can effectively reduce the pumping loss and increase the mechanical efficiency with a large capacity volume installed to simulate a multi-cylinder engine. This reduction of pumping loss is mostly determined by the LC timing, while it is independent from the expansion and compression ratios.

(2) With the expansion ratio kept constant at 11, the thermal efficiency is little influenced by the decrease in the compression ratio from 11 to 6.01. This may have a favorable effect on the application of LC to controlling the charge amount by the IVC timing.

(3) The thermal efficiency can be increased up to the maximum of 13% with the increase in the expansion ratio from 11 to 23.9. It is primarily due to improvement in the gas cycle efficiency. This suggests that the over-expansion cycle is a valid concept to improve the engine thermal efficiency.

(4) The experimental results can be successfully explained by simple cycle calculations. It is illustrated in the T-S diagrams that the expansion ratio is ten times as effective as the compression ratio in increasing the thermal efficiency.

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