

Research on Extended Expansion General-Purpose Engine (Part 2)

– Heat Release and Brake Performance –

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ABSTRACT

The combustion and efficiency of an extended expansion general-purpose engine employing a multiple linkage system was compared to that of a conventional engine consisting of the same component parts with the exception of the linkage system.

The results show that this extended expansion increases indicated thermal efficiency from 29.6% to 33.2%. In addition, as the piston speed near the compression top dead center of this engine is slow, mass fraction burned depends upon the change in the cylinder volume with respect to the capacity of the combustion chamber during the combustion period. The change of the minimum spark advance for best torque (MBT) timing relative to load is smaller than that of the conventional engine. Brake thermal efficiency of the test engine was increased by approximately 13%, from 20.1% for the conventional engine to 22.7%, under the EPA mode with fixed ignition timing operation.

1. Introduction

As concerns mount over global warming and the depletion of fossil fuels, fuel costs are also rising due to the recent surge in oil prices, and as a result, demands are growing for enhanced thermal efficiency, even for work equipment with general-purpose engines. The authors previously reported⁽¹⁾ the theory and overview of the mechanism of an extended expansion engine that realizes an Atkinson cycle through the use of a piston-crank system with a multiple linkage system as shown in Fig. 1. In that study, an actual prototype engine was manufactured, and the indicated thermal efficiency was compared with that of mass-produced engines in the same power class. However, the bore, spark plugs and valve arrangement of the mass-produced engines used for comparison differ from those of the test engine. The difference in the indicated thermal efficiency therefore included the difference due to these factors, in addition to the effects of extended expansion. The valve train also differs, which is thought to produce a difference in mechanical loss, so a comparative evaluation of brake performance was not achieved.

For this study, a prototype conventional engine with the same structure and combustion chamber shape as the

test engine was manufactured, and the performance of this conventional engine was compared with a multiple linkage extended expansion engine under roughly the same conditions to verify the effects of extended expansion in

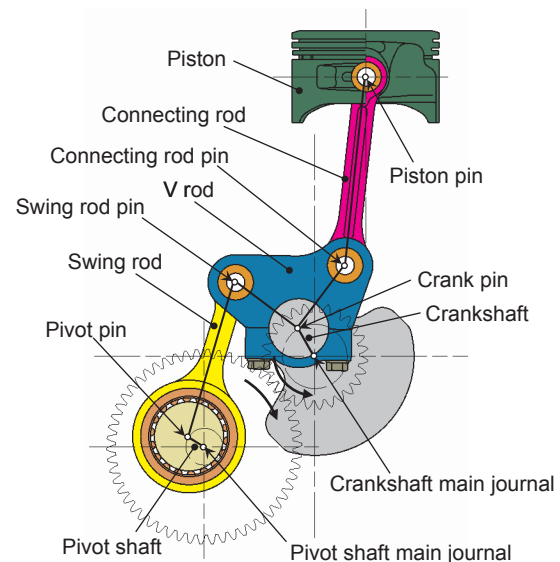


Fig. 1 Configuration of multi-link system

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increasing the indicated thermal efficiency. In addition, this paper also reports the brake performance of the test engine.

2. Test Method

2.1. Test Engine Specifications

Figure 2 shows an external view of the previously reported multiple linkage extended expansion engine, and Table 1 lists the main specifications of this test engine and of the prototype conventional engine used for comparison.

The comparison assumed the case with an extended expansion for the conventional engine, and the stroke volume of the conventional engine was therefore set for the maximum output power to be roughly equal for both engines.

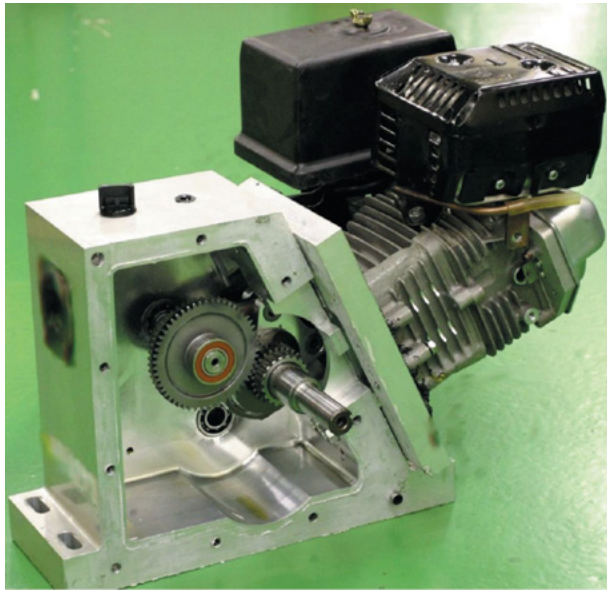


Fig. 2 External view of test engine

Table 1 Engine specifications

		Extended expansion	Conventional
Engine type		Air-cooled 4 stroke OHC single-cylinder spark-ignition	
Bore (mm)		64	64
Stroke (mm)	Intake and compression	42.1	51.0
	Expansion and exhaust	63.3	
Displacement (cm ³)	Intake and compression	135	164
	Expansion and exhaust	204	
Combustion chamber volume (cm ³)		18.1	21.9
Compression ratio		8.5	8.5
Expansion ratio		12.3	
Fuel		Gasoline	
Air-fuel ratio		12.5	

Both engines had the same bore and combustion chamber shape, and the combustion chamber volume was adjusted to match the compression ratios by inserting shims into the bottom of the cylinders. Identical parts were used for all structural parts, such as the cylinder head, spark plugs, inlet and exhaust valves, valve train, pistons and cylinder block, as well as for all intake and exhaust system auxiliary parts, such as the air cleaner, carburetor and muffler.

In addition, the test extended expansion engine uses a multiple linkage system, so the crank angle between the top and bottom dead center positions is not precisely 180° (Fig. 3). Therefore, the exhaust valve open timing and inlet valve close timing were set using the crank angle at the bottom dead center point of each piston as the reference for $\Delta\theta$ to be the same for both intake and exhaust as shown in Fig. 4.

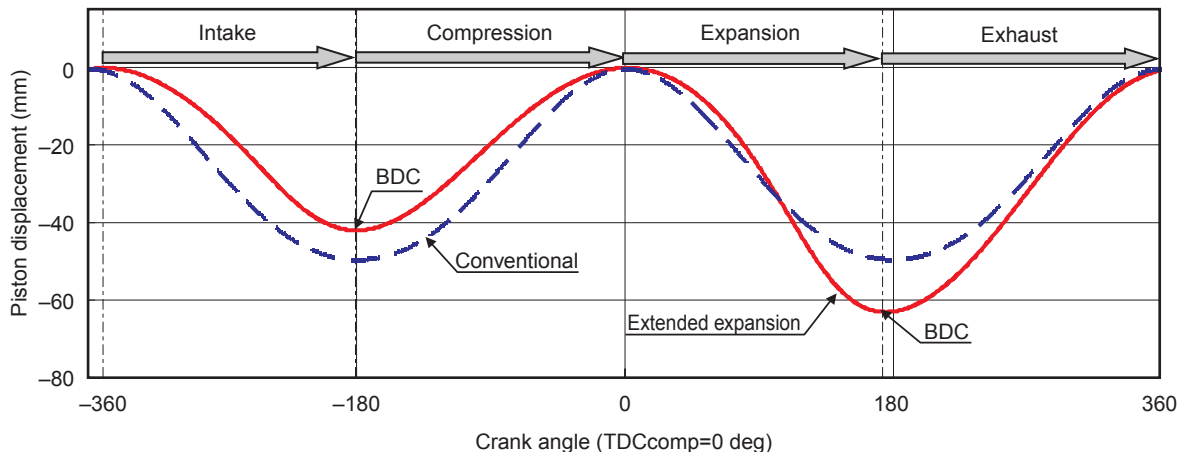


Fig. 3 Piston displacement of test engine

2.2. Mean Effective Pressure of Extended Expansion Engine

The mean effective pressure is generally used to compare the performance of engines with different stroke volumes. However, the mean effective pressure is generally defined under the condition that the each stroke volume is equal as expressed by Eqs. (1) and (2).

$$IMEP_{net} = \frac{W_i}{V_d} \quad (1)$$

$$BMEP = \frac{W_e}{V_d} \quad (2)$$

Here, W_i represents the indicated work, W_e the brake work, and V_d the stroke volume.

This study compared engines with different stroke volumes for each stroke, so the indicated mean effective pressure (IMEP_{net}) and the brake mean effective pressure (BMEP) were defined as follows.

$$IMEP_{net} = \frac{W_i}{\oint |dV|} \quad (3)$$

$$BMEP = \frac{W_e}{\oint |dV|} \quad (4)$$

In Eq. (3), the indicated work W_i can be obtained from the P-V diagram area as shown below in the normal manner even during the extended expansion cycle^{(2), (3)}. (Fig. 5)

$$W_i = \oint p dV \quad (5)$$

W_i here represents the indicated work including the pumping loss as shown in Fig. 5.

2.3. Test Conditions

The test shown below was performed in conformance with the EPA exhaust emission control⁽⁴⁾ operating mode prescribed as the typical operating mode for general-

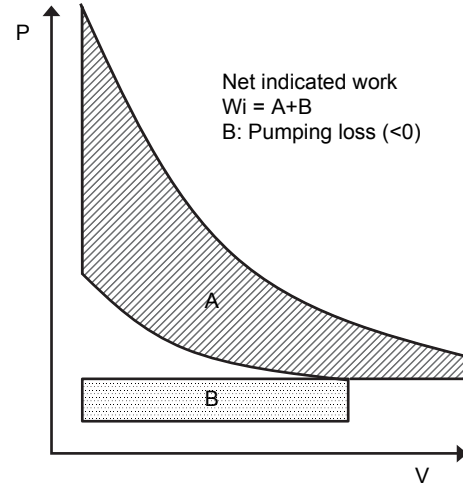


Fig. 5 Definition of net indicated work

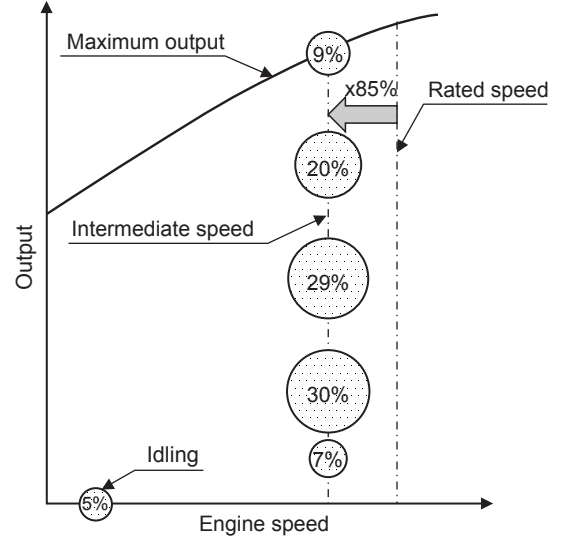


Fig. 6 Weighting factor of test cycle (subpart E of 40 CFR part 90)

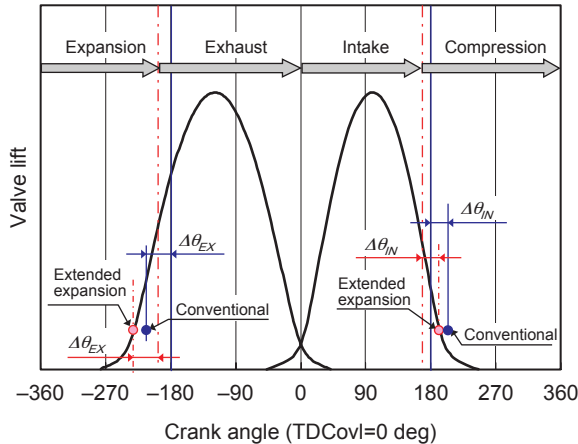


Fig. 4 Valve lift curve

purpose engines. This operating mode consists of six test cycles with different engine speeds and loads as specified in each circle in Fig. 6. The output, fuel flow and cylinder pressure were compared at an engine speed of 3060 rpm, which is prescribed as 85% of the rated speed. The stroke work was calculated by measuring the cylinder pressure using piezoelectric pressure sensors (Kistler 6041A) mounted on the cylinder head. Mode thermal efficiency was calculated by taking the weighted average of the results for each test mode using the weighting factor represented by the size of the circles in Fig. 6.

3. Test Results

3.1. Enhanced Indicated Thermal Efficiency

The indicated work and loss of each stroke during operation with wide open throttle (WOT) were compared

Table 2 Measured work and loss of each cycle

		Extended expansion	Conventional
Work or loss of each stroke (J/stroke)	Intake	-1.2	-3.6
	Compression	-34.5	-41.2
	Expansion	186.3	190.4
	Exhaust	-4.5	-2.9
Total work (J/cycle)		146.1	142.7
Supplied Heat (J/cycle)		439.5	481.8
Indicated efficiency (net)		33.2%	29.6%

for the test engine and conventional engine to verify the effects of extended expansion in increasing the indicated thermal efficiency. Table 2 shows the work per cycle, which is the total of the indicated work and loss of each stroke, the amount of heat supplied per cycle as obtained from the amount of fuel consumed, and the indicated thermal efficiency.

The total amount of work is approximately the same for both engines, but less heat is supplied to the test engine. This indicates that an equal amount of indicated work is obtained from less fuel. The indicated thermal efficiency of the test engine is 33.2%, which is an increase of 3.6 points over the 29.6% for the conventional engine. This corresponds to an enhancement of approximately 12% compared to the conventional engine.

Focusing on the loss within the cycle, the exhaust stroke loss of the test engine increased by 1.6 J compared to that of the conventional engine, but the intake stroke and compression stroke loss were 9.1 J lower than those of the conventional engine. This is thought to be due to the following reasons. The expansion stroke of the test engine is longer than that of the conventional engine and

the exhaust stroke loss increases, but the expansion ratio is higher, resulting in a lower exhaust pressure and smaller increase in loss. On the other hand, the test engine has shorter intake and compression stroke lengths, so the loss during both strokes is reduced. This led to the result where the total loss for the test engine was lower than that of the conventional engine.

The pumping loss of both engines was compared using the pumping mean effective pressure (PMEP) to evaluate the intake stroke and exhaust stroke loss at each load. As shown in Fig. 7, the PMEP of the test engine decreases over the entire load range, indicating that extended expansion effectively reduces loss, even in the lower load range where throttling loss occurs due to the throttle valve.

3.2. Combustion Characteristics of Multiple Linkage Engines

There are a number of reports concerning the relationship between piston speed and combustion characteristics of reciprocating engines⁽⁵⁾⁻⁽⁷⁾, such as on the degree of constant volume.

The authors' previously reported research compared the cylinder pressure of a multiple linkage extended expansion engine and conventional engines using numerical simulations. The multiple linkage engine was predicted to have a higher maximum cylinder pressure (P_{max}) than the conventional engine, and this was said to be due to the change in piston speed near the top dead center⁽¹⁾. Figure 8 compares the volumetric change inside the cylinder near the compression top dead center for the multiple linkage engine and conventional engine. The horizontal axis shows the crank angle, and the vertical axis shows the ratio of the cylinder volume to the combustion chamber volume (volumetric ratio). The multiple linkage engine exhibits slower volumetric change, so assuming identical heat release relative to the crank

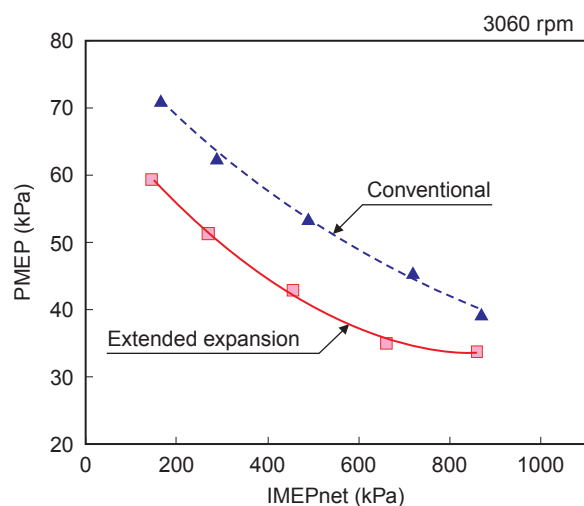


Fig. 7 Pumping mean effective pressure

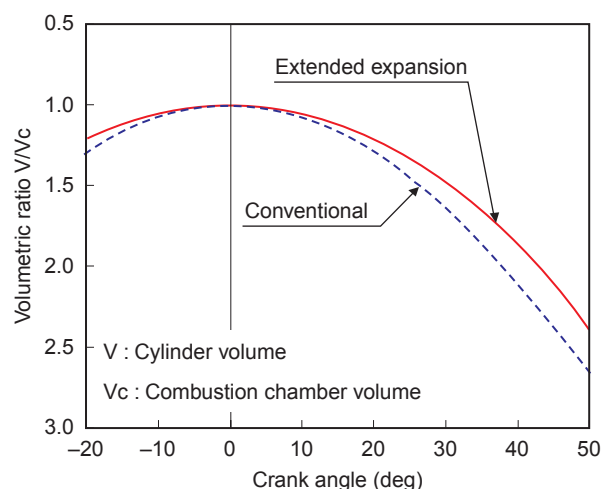


Fig. 8 Volumetric change during combustion

angle, a larger P_{max} value can be expected. Figure 9 shows the change in the cylinder pressure measured during operation with WOT at minimum spark advance for best torque (MBT) timing. Contrary to expectations, however, the P_{max} value for the multiple linkage engine was lower than that of the conventional engine.

The mass fraction burned (MFB) relative to the crank angle was compared to investigate this discrepancy. (Fig. 10) Compared to the conventional engine, the multiple linkage engine exhibited slower combustion from 10% mass fraction burned and onward, so the main combustion period (10 to 90% MFB) was 8° longer and the heat release of the two engines differed. On the other hand, comparing the mass fraction burned of both engines over

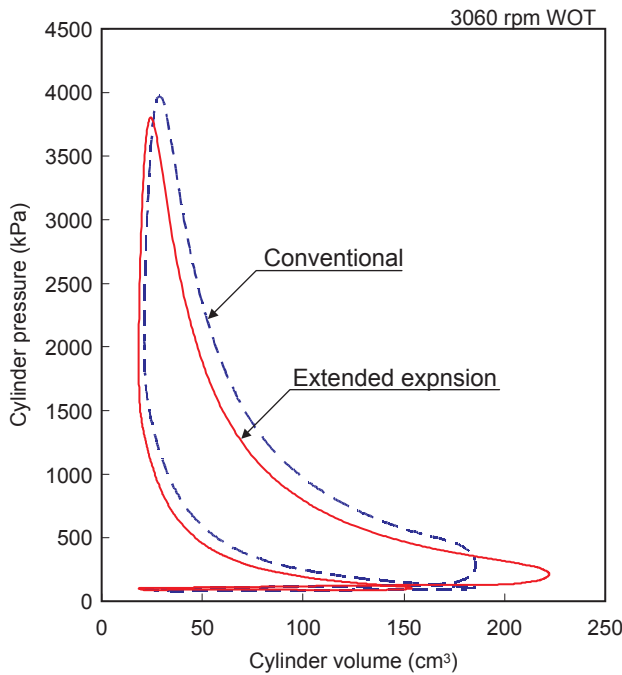


Fig. 9 Measured P-V diagram

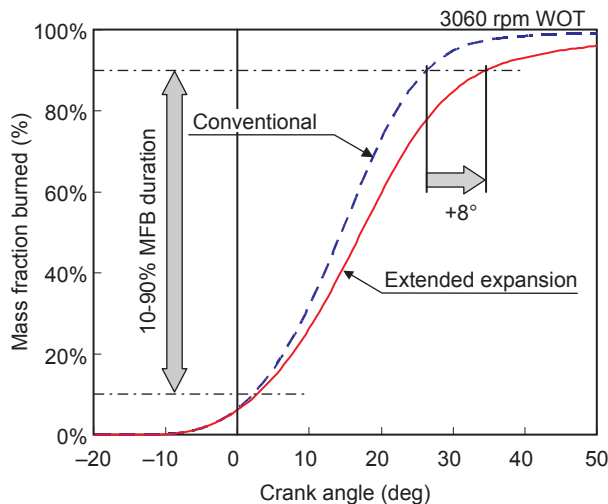


Fig. 10 MFB versus crank angle

the same period relative to the change in the above-mentioned volumetric ratio (Fig. 11) showed that the tendencies match over most of the main combustion period.

Based on these results, the assumption previously reported does not hold, and the actual heat release can be judged to be highly dependent on the volumetric ratio.

3.3. Ignition Timing Characteristics

The fact that heat release is governed more by the volumetric ratio than the crank angle means that the ignition timing characteristics that serve as the crank angle reference also differ from the conventional engine. Figure 12 compares the output at WOT when the ignition timing is changed relative to the MBT timing. According to this diagram, when the ignition timing is changed, the change in output is less for the multiple linkage engine than for the conventional engine.

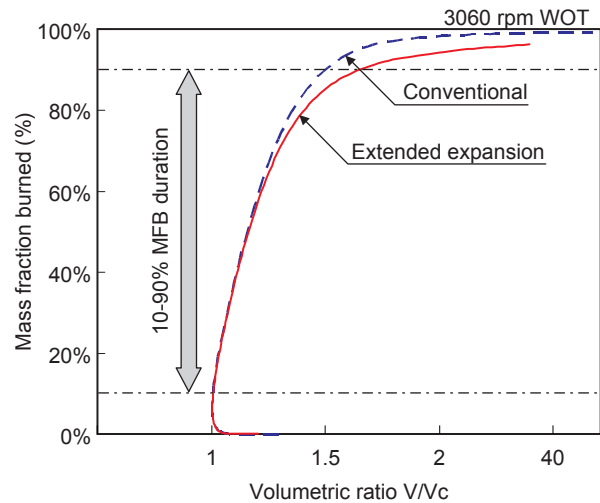


Fig. 11 MFB versus volumetric change

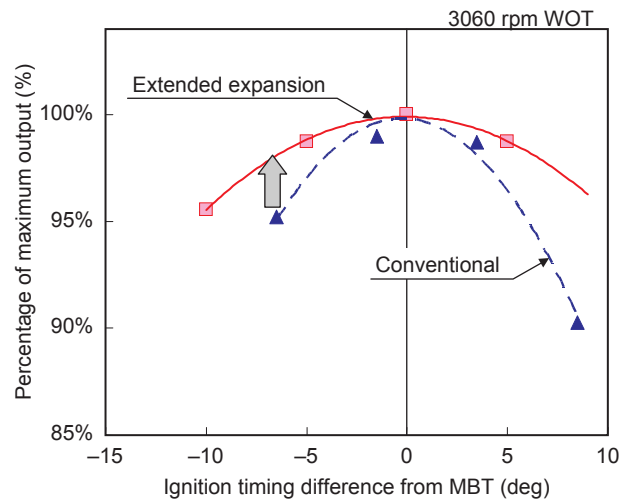


Fig. 12 Ignition timing characteristic at WOT

In addition, Fig. 13 shows the change in the ignition timing characteristics when the load is varied. The horizontal axis shows the load percentage, and the vertical axis shows the difference in MBT at each load from the MBT at WOT (MBT_{WOT}). The combustion period generally becomes longer during operation at lower loads, so the MBT timing advances and the difference relative to MBT_{WOT} becomes larger as the load becomes lower. However, this diagram shows that this tendency is less for the multiple linkage engine than that for the conventional engine.

The fact that the MBT timing at lower loads does not change much from when the throttle is wide open means that enhanced thermal efficiency at lower loads can be expected for general-purpose engines that do not usually have an ignition timing control device to simplify the ignition system. To examine this, the indicated thermal efficiency was compared at a 25% load (Fig. 14), which has the largest test cycle weighting factor of 30% within the EPA mode (Fig. 6). When operated with the ignition

timing fixed to the MBT_{WOT} for each load, the test engine efficiency was 2.1 points higher than that of the conventional engine. In contrast, when operated with the variable ignition timing of the MBT for each load, the indicated thermal efficiency increased by only 1.6 points. This confirmed that a multiple linkage engine using this system has combustion characteristics suitable for general-purpose engines that are operated with fixed ignition timing.

3.4. Brake Thermal Efficiency and Thermal Efficiency in EPA Mode

Figure 15 compares the relationship between the brake mean effective pressure and brake thermal efficiency for the test engine and conventional engine. The brake thermal efficiency of the extended expansion engine, operated with the ignition timing fixed to the MBT_{WOT} , is higher than that of the conventional engine, even in the lower load range. Figure 16 shows the brake thermal efficiency for the EPA mode. The mode thermal efficiency for fixed ignition timing operation is 22.7%, which is 2.6

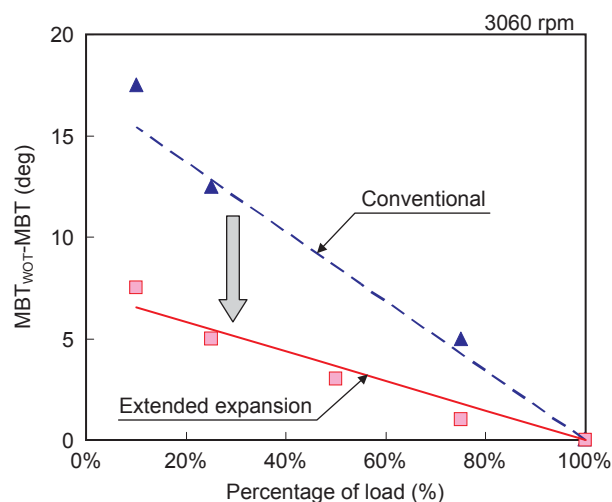


Fig. 13 MBT difference from MBT_{WOT}

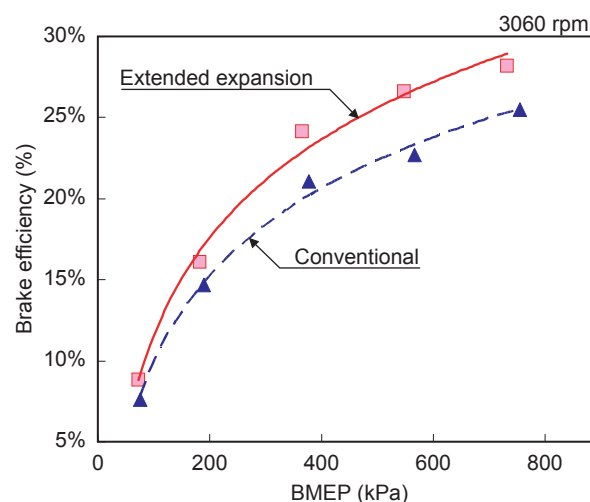


Fig. 15 Brake efficiency ($\theta_{ig}=MBT_{WOT}$)

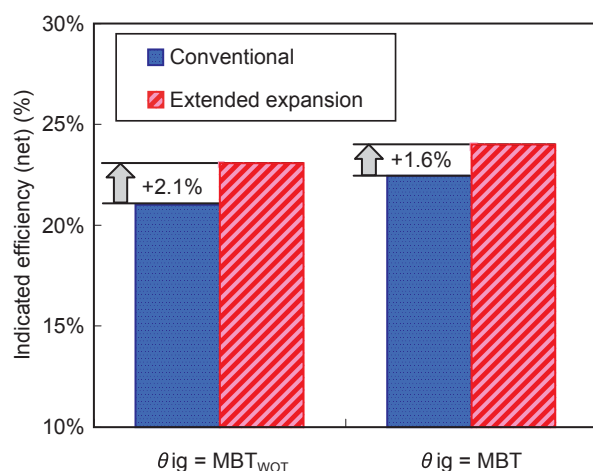


Fig. 14 Indicated efficiency (net) at 25% load

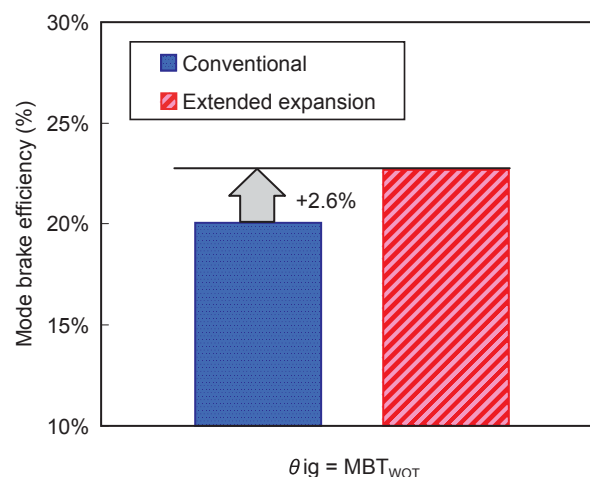


Fig. 16 Mode brake efficiency comparison

points higher than the 20.1% for the conventional engine. This corresponds to an increase in fuel economy of approximately 13%. These results showed that the test engine has better thermal efficiency than that of the conventional engine in these cases, and that the increase in the indicated thermal efficiency due to extended expansion leads to an increase in the brake thermal efficiency.

4. Conclusion

The performance of an extended expansion engine employing a multiple linkage system was compared to that of a conventional engine consisting of the same component parts with the exception of the linkage system, and the following results were obtained.

- (1) The indicated thermal efficiency of the test engine with WOT was 33.2%, which was an increase of 3.6 points over the 29.6% for the conventional engine. In addition to the increase in indicated thermal efficiency due to the increased expansion ratio, this was also due to a reduction of the intake stroke loss.
- (2) The heat release of the test engine depends on the change in cylinder volume during the combustion period relative to the combustion chamber volume. The piston speed near the compression top dead center of this engine is slow, so the heat release of the test engine relative to the crank angle is slower than that for the conventional engine. But the heat release relative to the cylinder volumetric ratio matches closely with the conventional engine over the main combustion period.
- (3) The change in MBT timing relative to the load is smaller for the test engine than that of the conventional engine. As a result, the mode thermal efficiency during fixed ignition timing operation under the EPA mode increased by 2.6 points from 20.1% in the conventional engine to 22.7%. This corresponds to an increase in fuel economy of approximately 13%.

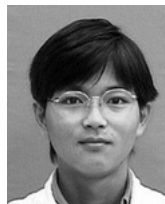
As mentioned above, extended expansion general-purpose engines that employ a multiple linkage system are a technology that can contribute to increasing the efficiency of general-purpose engines. However, a number of issues for practical application remain, such as reducing the reciprocating part vibration that differs from that of conventional engines, establishing a strong and rigid design for each linkage component, and selecting weight reduction methods, materials and manufacturing methods based on these requirements. The authors intend to continue efforts to overcome these issues with the aim of further reducing the environmental load of general-purpose engines that are used in a wide range of work equipment.

Note that Fig. 6 on page 84 of the previous Technical Review⁽¹⁾ “Research on Extended Expansion General-Purpose Engine” contained an error. “ $\kappa = 3.1$ ” should be “ $\kappa = 1.3$ ”.

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