

Study of Oil Consumption in Small-displacement 4-stroke Air-cooled Engines

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ABSTRACT

A causal analysis of oil consumption was conducted for 4-stroke small-displacement air-cooled engines, which experience high temperature operations. The majority of oil consumption occurs as a result of oil loss that goes up into the combustion chamber, and the temperature of the cylinder walls affects the oil consumption rate. Results indicated that it was possible to control the oil consumption rate by reducing the cylinder wall temperature. It was also shown that the reduction of the width of the oil ring assembly and the increase of its coefficient of flexibility, in addition to the alleviation of the piston slap, were effective means to reduce the oil consumption rate. It was further demonstrated that the NOACK volatility of the oil has a significant effect on oil consumption in an air-cooled engine, in every part of which the temperature gets high.

1. Introduction

In 4-stroke engines, as in other types of engines, oil consumption is uneconomical and may result in a cause of functional failures due to the carbon deposits accumulated in the combustion chamber. A great deal of researches have attempted to analyze oil consumption in order to resolve these issues⁽¹⁾⁻⁽⁹⁾.

The air-cooled engines extensively used in motorcycles are characterized by higher operating temperatures than water-cooled engines. Because small-displacement engines in particular are often used in the high-load and in high-speed range, they are usually put under high temperature operating conditions. In addition, small-displacement engines have smaller cylinder-bore diameters but the tolerances for manufacturing of their pistons, piston rings and other parts cannot be proportionally reduced to their smaller bores, resulting in a comparative disadvantage to larger engines, in terms of accuracy assurance. Because few studies of oil consumption have focused on these characteristics, in this paper, a causal analysis on oil consumption is conducted using an air-cooled 49 cm³ scooter engine for Japanese domestic market, aiming at the reduction of oil consumption. This paper will present the results of this research.

2. Test Method

2.1. Oil Consumption Measurement Method

As a method of measuring the oil consumption rate, a volumetric method, in which the rate of oil consumption is measured directly from the difference between the volumes of oil before and after engine operation, is available. This is a simple and highly precise method of measuring oil consumption, but it necessitates a prolonged period of testing, and can be used only when specific operating conditions are maintained. Furthermore, by this method, it is impossible to measure the instantaneous oil consumption rate during transient operation. On the other hand, the SO₂ tracer method is also available for the measurement of oil consumption. In this method, sulfur is added to the oil and the oil consumption rate is measured from the concentration of sulfur in the exhaust gas⁽¹⁰⁾. This method makes it possible to measure the instantaneous oil consumption rate under transient operating conditions in a short period.

Tests described in this paper were conducted using either of these measurement methods. The measurement conditions and methods will be described in detail in the relevant sections below. SAE viscosity 10W-30 oil was used in the tests, and the MEXA-1170SX exhaust SO₂ analyzer manufactured by HORIBA, Ltd. was employed as the measurement device for the SO₂ tracer method.

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Table 1 Specifications of test engine

Engine type	4-stroke, SI engine
Cooling system	Forced air-cooling
Bore x Stroke	37.8 x 44.0 mm
Number of cylinders	1
Displacement	49 cm ³
Compression ratio	10.1
Valve drive system	OHC
Maximum output	3.0 kW / 8250 r/min
Cylinder	Cast-iron sleeve
Oil ring	Multi-piece steel rail ring (2.0 mm width)

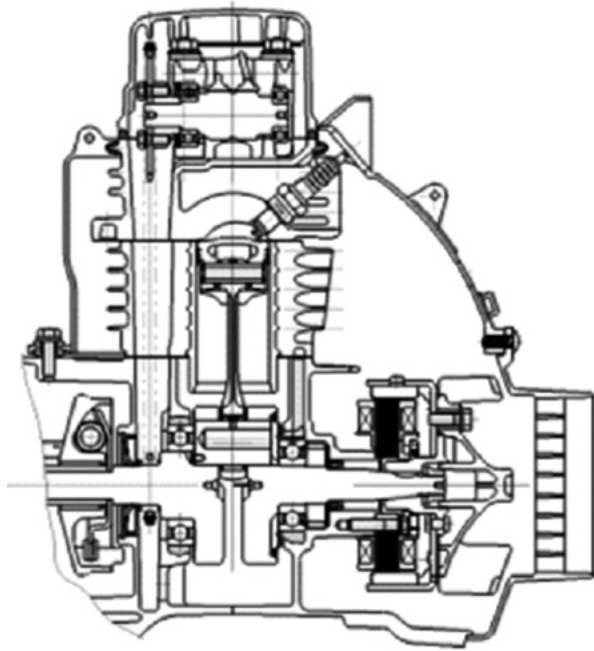


Fig. 1 Layout of test engine

2.2. Test Engine

Table 1 shows the specifications, and Fig. 1 shows the layout, of the small-displacement, forced air-cooled scooter engine used in the tests.

3. Factor Analysis of Oil Consumption

3.1. Oil Consumption in Small-displacement Air-cooled Engines

In order to obtain a macroscopic understanding of oil consumption, the oil consumption rate was measured using the SO₂ tracer method in relation to the temperature conditions and/or the operating conditions in small-displacement air-cooled engines. The oil consumption rate was measured while increasing oil temperature from cold engine temperature to the maximum temperature under actual driving condition of the fixed vehicle speed of 50 km/h (engine speed: 8000 rpm; throttle opening: 52%). The results are shown in Fig. 2. This graph shows that the oil consumption rate increases with increasing oil

temperature, and that the measured value is not stable in the higher oil temperature conditions.

Figure 3 shows the results of measurements of the oil consumption rate in relation to the engine speed and the load conditions. The measurements were carried out when the oil temperature became stable in steady driving mode. This graph indicates that the oil consumption rate tends to increase as load and engine speed increase. In Fig. 4, the vertical axis is altered to the oil temperature for the same tests as shown in Fig. 3. This graph indicates that the oil temperature has the same tendency of increase with the rise of the engine load and the engine speed just as the oil consumption rate mentioned above. Figure 5 shows the results of a survey of oil temperature in Honda motorcycle engines using different cooling systems. This figure shows maximum oil temperatures under actual driving conditions, and indicates that oil temperature tends to become higher in air-cooled engines than in water-cooled engines. Thus, in terms of oil consumption, small-displacement engines are in adverse conditions such as frequent use with heavy loads, high engine speed, and high oil temperature with air-cooled systems.

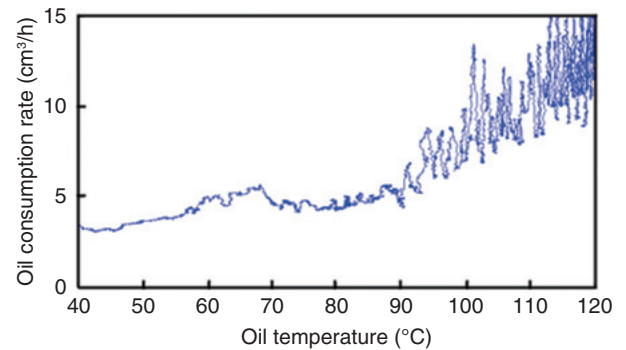


Fig. 2 Relation between consumption rate and temperature of engine oil

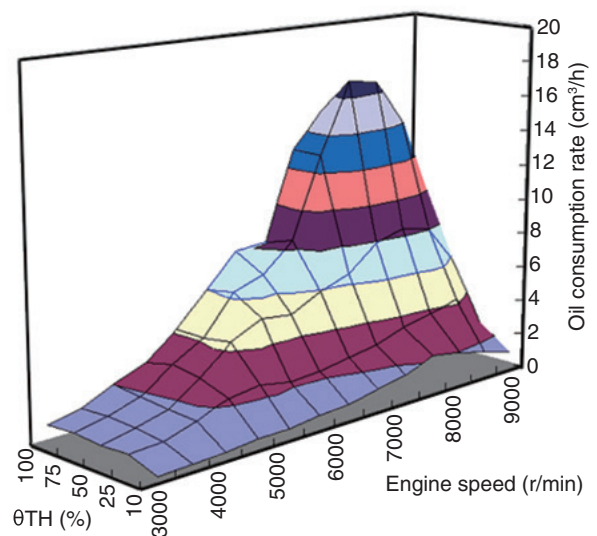


Fig. 3 3D-map of engine oil consumption rate

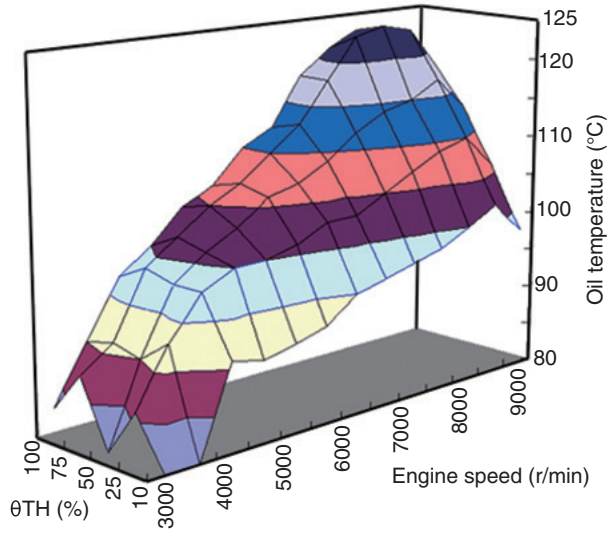


Fig. 4 3D-map of engine oil temperature

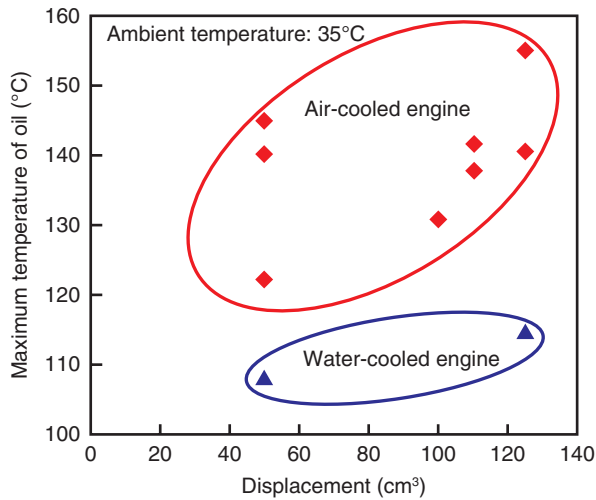


Fig. 5 Difference of oil temperature by cooling system and engine displacement

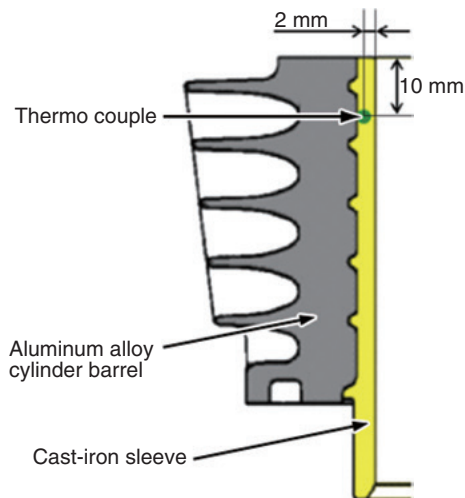


Fig. 6 Measurement point of cylinder wall temperature

3.2. Temperature Factors which Affect Oil Consumption

The results discussed in Section 3.1 indicate that the oil consumption rate is correlated to temperature, but the dominant temperature factors were not known yet. Therefore, the oil temperature (in the oil pan), the temperature at the spark plug seat, and the cylinder wall temperature were measured, as they are considered to be the potential factors to give a large amount of effects on oil consumption. Figure 6 shows the measurement point for cylinder wall temperature. In this research, the cylinder wall temperature on the inlet port is selected as the representing value. In order to investigate the effect of the temperature factors on oil consumption which is outlined above, the oil consumption rate was measured using the SO_2 tracer method while varying temperatures in those three measurement points by changing flow rate of cooling air against the engine in steady driving mode. The results of these measurements are shown in Fig. 7. These graphs indicate that the oil consumption rate has the highest correlation with cylinder wall temperature. Therefore, the cylinder wall temperature was chosen as the reference point in this research.

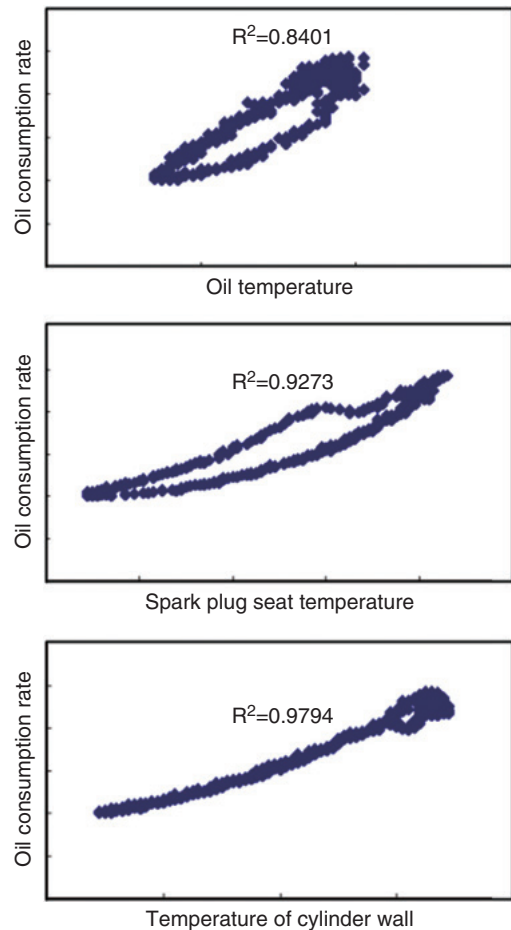


Fig. 7 Relation between oil consumption rate and temperature in each part of engine

3.3. Oil Dissipation Paths

Oil dissipation processes can be divided broadly into the following categories:

- (1) Discharge from the crankcase together with blow-by gas
- (2) Oil that goes up into the combustion chamber via gaps among the piston, the piston ring and the cylinder
- (3) Oil that goes down into the port via gaps among the valve, the valve stem seal and the valve guide

With regard to (1), blow-by gas normally flows back into the intake system, and no difference is observed in the oil consumption rate even when it is discharged to the atmosphere without introduction to the intake system. Given this, it was understood that (1) represents an extremely small amount. Regarding (2) and (3), the engine with special configuration shown in Fig. 8 was employed to measure the ratio between (2) and (3). In this configuration, the internal space within the engine casing where the lubrication oil circulates is divided into two areas: the area where the oil might go up into the combustion chamber (hereafter “Area *a*”); and the area where the oil might go down into the port (hereafter “Area *b*”). The SO₂ tracer method was employed as the measurement method, and oils with sulfur and without sulfur were used.

Vehicle speed was fixed at 50 km/h (engine speed: 8000 rpm; throttle opening: 52%) for the tests, and the oil consumption rate was measured as the cylinder wall temperature increased from cold engine temperature. In the first round of measurements, oil with added sulfur was used

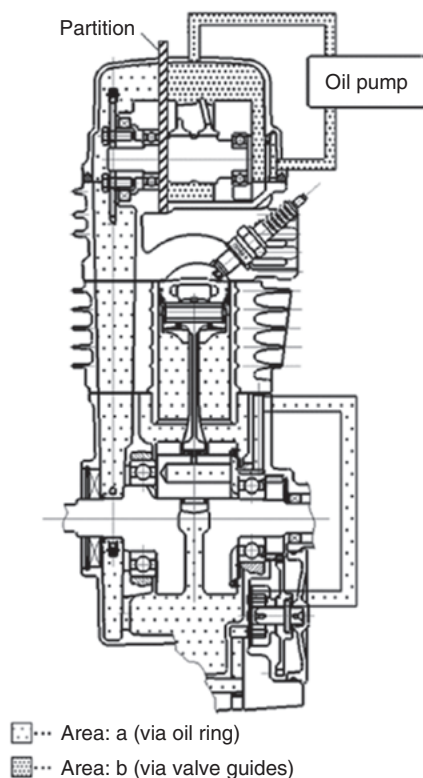


Fig. 8 Isolated structure of lubrication area for analyzing inflow path to combustion chamber

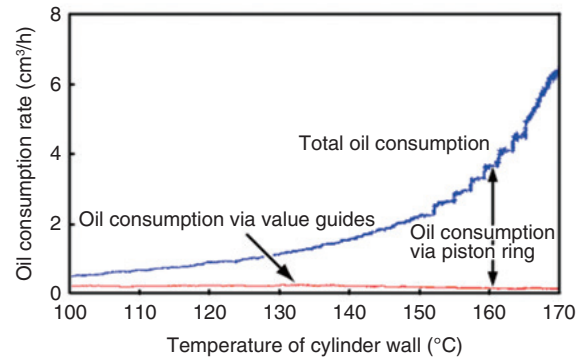


Fig. 9 Analysis of inflow path to combustion chamber

in both Area *a* and Area *b*, and the total oil consumption rate was measured. Next, oil without added sulfur was used in Area *a* and oil with added sulfur was used in Area *b*, and only the oil consumption rate due to oil loss via the valve guides was measured. The results of these measurements are shown in Fig. 9. This graph shows the total oil consumption rate and the oil consumption rate due to oil loss via the valve guides. The difference between the two rates is the oil consumption rate due to oil loss via the piston rings. These results indicate that as the temperature of the cylinder wall increases, the oil consumption rate due to oil loss via the piston ring goes up extensively, making up large portion of the total. Temperature has almost no effect on the rate of oil consumption which arises from the oil loss via the valve guides.

4. Methods of Reduction of Oil Consumption Rate

4.1. Method of Reduction of Oil Consumption Rate by Modifying Oil Rings

The fact that the oil consumption rate is not stable at high temperatures, as indicated by the results shown in Fig. 2 (Section 3.1.) was considered, focusing on the effect of cylinder deformation on this phenomenon. The test engine used in this research employed an aluminum cylinder with a cast-iron sleeve which is shown in Fig. 6. Figure 10 shows the deformation that appears in the cylinder bore and

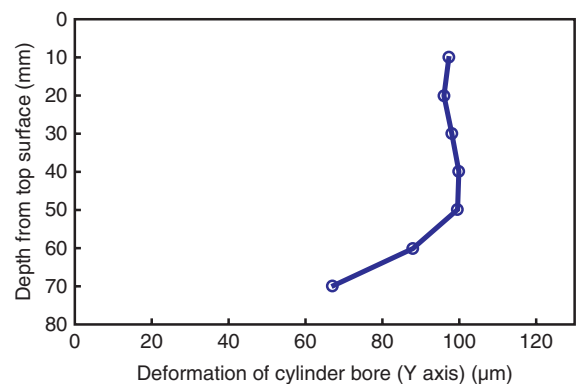


Fig. 10 Deformation of cast-iron sleeve type cylinder bore at 160°C

Fig. 11 shows deformation in circularity of the cylinder on the condition of the cylinder block fixed with bolts tightened at the specific torque and heated up to 160°C. The potential of reduction of oil consumption by enhancing the performance of the oil ring in relation to this deformation of the cylinder was investigated. The test engine used in this research employed a three-piece oil ring type shown in Fig. 12. It has been reported for the systems using this type of oil rings that, when piston slap is occurring, oil consumption rate gets lower if the post-assembly width h_1 of the oil ring is small, because the smaller the width h_1 is, the smaller the separation distance away from the cylinder wall is (shown in Fig. 12)⁽¹¹⁾. The coefficient of flexibility is available as an index of the flexibility of the oil ring in relation to deformation of the cylinder in the radial direction⁽¹¹⁾. The coefficient of flexibility, k , is defined by Equation (1). Higher values for k indicate higher flexibility.

$$k = \frac{3 \cdot Ft \cdot d_1^2}{E \cdot h_2 \cdot a_1^3} \quad (1)$$

k : Coefficient of flexibility

Ft : Tension (N)

d_1 : Cylinder diameter (mm)

E : Young's modulus (MPa)

h_2 : Width of side rail (mm)

a_1 : Thickness of side rail (mm)

Based on these facts, an experimental oil ring (Oil ring b), in which h_1 , h_2 , and a_1 were reduced in relation to the

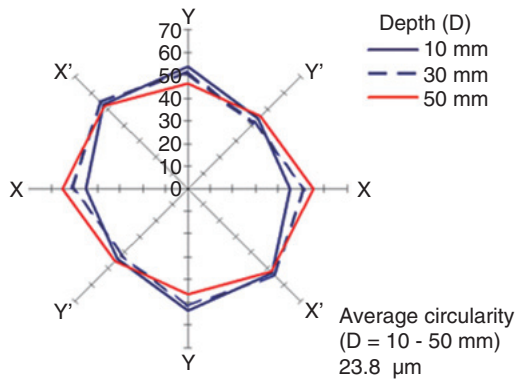


Fig. 11 Circularity of cast-iron sleeve cylinder bore at 160°C

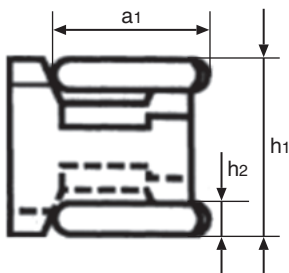


Fig. 12 Structure of oil ring

Table 2 Specifications of oil ring

	a(Standard)	b(Modified)
h_1 (mm)	2.0	1.5
h_2 (mm)	0.35	0.3
a_1 (mm)	1.7	1.1
Piston ring closed gap (mm)	0.45	0.35
Tension(N)	11.7	13.2
Coefficient of flexibility: k	0.15	0.72

standard ring (Oil ring a), was produced. Table 2 shows the specifications of the oil rings. Using Oil ring b , the oil consumption rate was measured using the SO_2 tracer method as the temperature of the cylinder walls increased from cold engine temperature, at a fixed vehicle speed of 50 km/h (engine speed: 8000 rpm; throttle opening: 52%). The results are shown in Fig. 13 (as “B (Oil ring b)”). The result of oil consumption rate shown as A in Fig. 13 is plotted against the temperature of the cylinder wall, which is altered from the oil temperature shown in Fig. 12, where both temperatures are detected simultaneously in the test. The use of oil ring b in place of oil ring a reduced the oil consumption rate at a cylinder wall temperature of 170°C from approximately 15 cm^3/h to 8 cm^3/h , a reduction of approximately 45%. At the same time, the fluctuations in the high-temperature range disappeared. This is believed to be because of an increase in the flexibility of the oil ring in relation to the piston-slap phenomenon and the deformation of the cylinder. This demonstrates that the reduction of the abovementioned dimensions is an effective method of reducing the oil consumption rate even in small-displacement engines with small cylinder bores.

4.2. Reduction of Cylinder Wall Temperature

Modification of cooling fins and the cooling fan in order to enhance cooling performance may be considered among methods of reducing the temperature of the cylinder walls, but the present research studied the effect of the use of a solid aluminum cylinder in reducing the

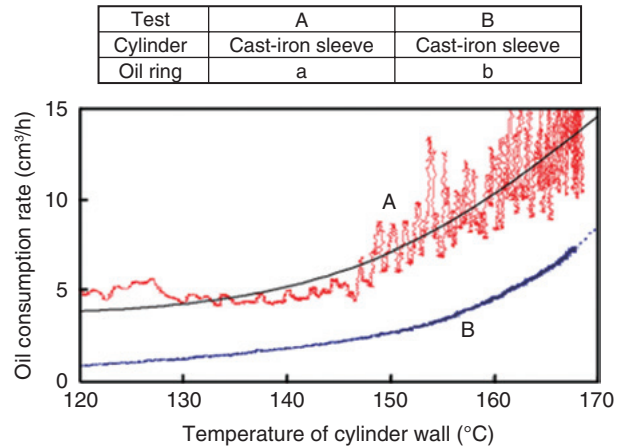


Fig. 13 Effect of modified oil ring for oil consumption rate

oil consumption rate. Cylinders of this type are generally indicated as displaying good heat radiation and as offering advantages in relation to thermal deformation. The cylinder is equivalent to the aluminum cylinder with a cast-iron sleeve in its external shape and the roughness of cylinder wall surfaces, and in the tolerance of the internal diameter in its preassembled state. Oil ring *b*, shown in Section 4.1 to be effective in reducing the oil consumption rate, was used as the piston ring. Figure 14 shows the maximum cylinder wall temperature by engine speed. The temperature in the case of the solid aluminum cylinder is lower than for the aluminum cylinder with a cast-iron sleeve, with a difference of approximately 15°C in maximum temperatures between the two.

Figures 15 and 16 respectively show the deformation that appears in the cylinder bore and the circularity of the solid aluminum cylinder when it was tightened at the specific torque and heated to 160°C. Compared to the degree of deformation of the aluminum cylinder with a cast-iron sleeve, the circularity of the solid aluminum cylinder was lower, but the deformation of the cylinder bore due to thermal expansion was greater.

The oil consumption rate, while the temperature of the cylinder wall was increased from the temperature of cold

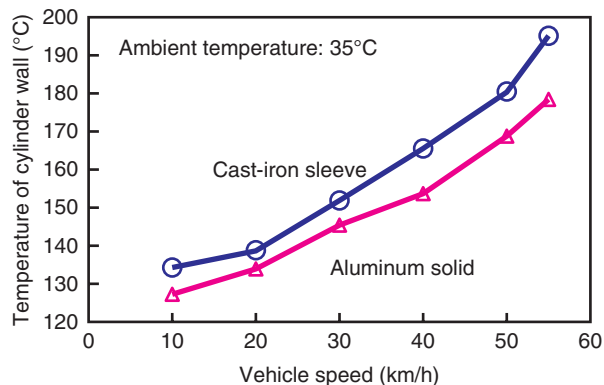


Fig. 14 Comparison of cylinder wall temperatures by difference of material

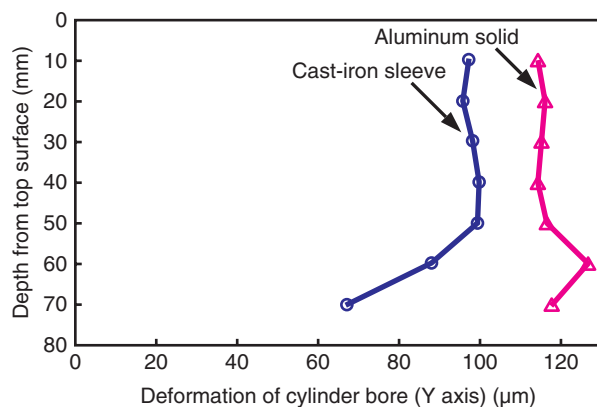


Fig. 15 Deformation of aluminum solid cylinder bore at 160°C

engine at a fixed vehicle speed of 50 km/h (engine speed: 8000 rpm; throttle opening: 52%), was measured by SO₂ tracer method and compared with that in the case of the aluminum cylinder with a cast-iron sleeve. The results are shown in Fig. 17 (as "C"). The oil consumption rate for the solid aluminum cylinder is slightly higher at identical cylinder wall temperatures, and the level of fluctuation in the oil consumption rate was also higher in the high-temperature range. This is thought to be because, despite the fact that results for circularity were better in the solid aluminum cylinder, piston slap increased due to an increase in the deformation of the cylinder bore.

In order to alleviate piston slap, tests were therefore conducted under the conditions described above using a piston in which the top land diameter and the second land diameter were increased by 50 μm. The results are shown (as "D") in Fig. 17. The results show that increasing the land diameters reduced the oil consumption rate. This effect could also be verified by the fact that the figures were lower than those for "B (Oil ring: b)" in Fig. 13, and that the fluctuation in the high-temperature range was also not present.

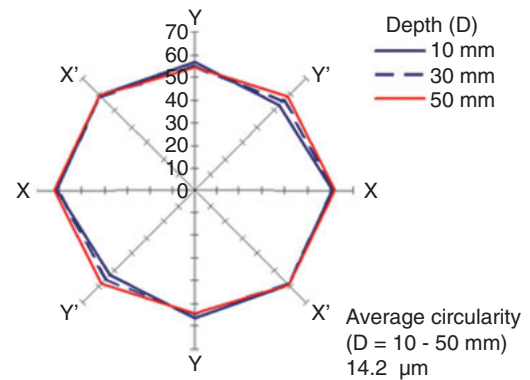


Fig. 16 Circularity of aluminum solid cylinder bore at 160°C

Test	B	C	D
Cylinder	Cast-iron sleeve	Aluminum solid	Aluminum solid
Oil ring	b	b	b
Piston	Standard	Standard	Top/2nd land+ 50 μm

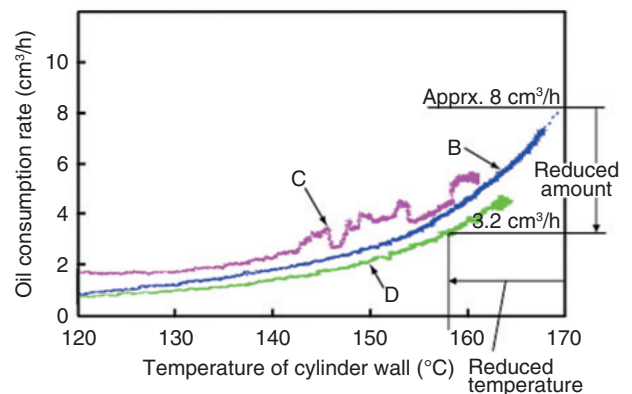


Fig. 17 Effect of aluminum solid cylinder with modified piston for oil consumption rate

Given the above, a significant reduction in the oil consumption rate can be expected from this modification when combined with the reduction in the maximum temperature of the cylinder walls, as shown in Fig. 14. Assuming a cylinder wall temperature of 170°C in the aluminum cylinder with a cast-iron sleeve and projecting a temperature of 158°C in the solid aluminum cylinder (from the temperature difference at a vehicle speed of 50 km/h in Fig. 14) under identical conditions, the oil consumption rate for a combination of the solid aluminum cylinder and the piston modified to counter piston slap would be reduced from approximately $8\text{ cm}^3/\text{h}$ to $3.2\text{ cm}^3/\text{h}$, a reduction of approximately 60%. Compared to the unmodified base engine, the oil consumption rate would be reduced from approximately $15\text{ cm}^3/\text{h}$ to $3.2\text{ cm}^3/\text{h}$, a reduction of approximately 80%.

4.3 Effect of NOACK Volatility on Oil Consumption

Because the cylinder walls of small-displacement air-cooled engines reach high temperatures, it is thought that oil consumption due to oil loss via the piston ring also includes a significant proportion of oil consumption due to oil evaporation. NOACK volatility (amount of evaporation over one hour at 250°C in a vacuum) is generally used as an index of the amount of oil evaporation. In the tests described above in this paper the oil with NOACK volatility of 14.5% was used. Oils with NOACK volatility figures of 10.5% and 3.2% were created and compared. Because it is considered that fixed operating conditions must be maintained in order to measure the oil consumption rate due to evaporation, the maximum oil temperature under actual driving conditions was maintained at a fixed vehicle speed of 55 km/h (engine speed: 8800 rpm; throttle opening: 100%), and measurements were conducted following 20 hours of continuous operation using the volumetric method. In addition to the test engine, the same measurements were conducted in a water-cooled engine of identical displacement. The results of these measurements are shown in Fig. 18. The reduction of NOACK volatility reduced the

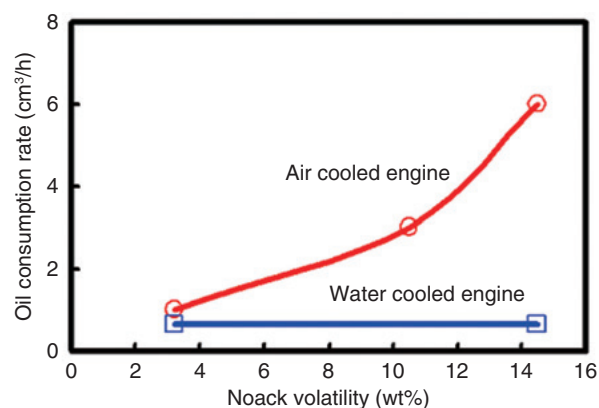


Fig. 18 Influence of NOACK volatility for oil consumption rate

oil consumption rate in the air-cooled engine. By contrast, there was virtually no change in the oil consumption rate in the case of the water-cooled engine. The reduction of NOACK volatility can therefore be indicated as an effective method of reducing the oil consumption rate in high-temperature, small-displacement air-cooled engines.

5. Conclusion

The dominant factors in oil consumptions in 4-stroke small-displacement air-cooled engines, and the methods of reducing those oil consumptions were studied. The following results were obtained.

- (1) It was demonstrated that the oil consumption rate tended to increase with increasing temperature. In addition, the temperature of the cylinder walls was the temperature factor which displayed the highest correlation with the oil consumption rate.
- (2) With regard to oil flow paths, a high proportion of oil consumption in the high temperature range occurs due to oil loss into the combustion chamber via gaps between the pistons, piston rings, and cylinders.
- (3) The following methods are effective in reducing the oil consumption rate in small-displacement air-cooled engines.
 - The oil consumption rate can be reduced by reducing the temperature of the cylinder walls.
 - Enhancing the flexibility of the oil rings in relation to cylinder deformation and piston slap, and alleviating piston slap, are effective methods of reducing the oil consumption rate even in small-displacement air-cooled engines, which has comparative disadvantages to larger engines in terms of accuracy assurance for the pistons, piston rings and other parts.
 - The use of the two measures described above can be expected to reduce the oil consumption rate of the test engine by approximately 80% against the unmodified base engine (cylinder wall temperature: 170°C).
 - The oil consumption rate can be reduced through the use of an oil with a reduced NOACK volatility. The effect is significant in small-displacement air-cooled engines, which operate at higher temperatures than water-cooled engines.

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